Manual
Aeration System Analysis Program (ASAP™)

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Preface

The ASAP manual consists of 26 Microsoft Word® 97 files named *asap_01.doc*, *asap_02.doc*, *asap_03.doc … asap_26.doc*. These 26 files were used to create a single PDF file containing the entire ASAP manual, which is available through the **Help** menu in the ASAP software. Note that low print quality is observed when printing the PDF version of this manual for the screen captures that comprise many of the figures. For this reason, the 26 word files are also available with the software and should produce considerably higher print quality than the PDF version of the manual. The procedure for printing the 26 Word files is explained in the **Help** menu. However, the authors have observed formatting changes when printing these Word files on different computers. It is not unexpected that a user printing the 26 Word files may not achieve a printed version of the manual that agrees completely with the page numbering shown in the Table of Contents.

CenCITT will send licensed users of the software a printed copy of the manual for a fee. To request information about obtaining a printed copy of the manual, please contact:

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Please note that the equation numbering, table numbering and figure numbering are not continuous throughout the entire ASAP manual, but rather restart at the number 1 in each word file. Appendix B presents a complete table of contents, divided up according to each word file, and including a list of figures and tables for each word file.

Table of Contents

I.   Getting Started

A.   Requirements

To use Aeration System Analysis Program (ASAP™), you need:

- A Pentium or more recent processor.
- An English-language version of Windows 95, Windows 98, or Windows NT 4.0. In the case of Windows NT 4.0, Service Pack 3 or more recent is required.
- At least 50 megabytes of hard drive space
- At least 64 megabytes of RAM is recommended
- A graphic VGA or more recent video display
- A CD-ROM drive, which is used to install the software
- A Windows compatible mouse (or any compatible point device) is recommended

B.   Installing ASAP Ô

To install ASAP™ on your computer, you must have the CD-ROM installation disk labeled "ETDOT Programs". The installation program will copy files from the installation disk to your hard drive. The installation program will cancel the process if you do not have sufficient hard drive space. If anything goes wrong during the installation, you will always be able to quit the install program and run it again. If a previous release of ASAP™ was installed, you should install the new version on top of the old version; this is done by installing to the same directory that the original version was installed to.

1. Log in to Windows normally.
2. Insert the CD-ROM labeled "ETDOT Programs" in the CD-ROM drive.
3. From the Start menu, choose Run.
4. Type **z:\setup** (replace z with the letter of the CD-ROM drive).
5. Press ENTER.
6. Follow the setup instructions on the screen.

Note: Steps 3, 4 and 5 are equivalent to double-clicking on the setup.exe program icon in Explorer or File Manager.

If the software does not work correctly after the installation, you can reach Dr. David W. Hand at (906) 487-2777.

II.   Introduction to Aeration System Analysis Program (ASAP™)

Aeration processes are widely used in the removal of volatile organic compounds (VOCs) from aqueous solution. Proper design of such processes is essential to avoid unnecessary expenses. Carefully controlled laboratory and/or pilot plant studies can be used to design aeration processes. However, these studies can be time consuming and expensive if they are not properly planned. An increasingly popular approach used to design aeration systems involves taking advantage of the predictive capabilities of mathematical models. Mathematical models can be used to: (1) assess the preliminary design and economic feasibility of using aeration processes by estimating power requirements, (2) plan the scope of laboratory and/or pilot plant studies, (3) interpret laboratory and pilot plant results, and (4) be directly used for process design if site specific model parameters are available.

ASAP™ was developed as a part of the Clean Process Advisory System (CPAS™) to aid design engineers in performing air stripping design calculations for pollution prevention (Radecki, et al, 1994). ASAP™ will assist CPAS in evaluating the technical and economic feasibility of source reduction versus end-of-pipe treatment using aeration processes.

ASAP™ consists of three aeration models used to remove volatile organic chemicals from water: (1) packed tower aeration (2) bubble (diffused) aeration, and (3) surface aeration. The program is linked to a physical property resource tool (Software to Estimate Physical Properties - StEPP™) designed to supply physical and chemical properties of contaminants. Use of the models combined with this physical property resource tool allows for the evaluation of potential aeration system designs with minimal external input requirements.

ASAP™ is designed for the Microsoft Windows™ environment with a graphical user interface (GUI) in order to maximize user-friendliness. Making use of the Microsoft Windows interface, with its built-in file and hardware control features, frees the engineer from concerns over printer drivers and other "machine" issues and allows more attention to the computational algorithms. The GUI consists of a front-end shell written in Visual Basic™ that calls FORTRAN subroutines to perform the calculations.

This manual presents a detailed description of the ASAP™ models. The theoretical development of the ASAP™ models is presented first. Then sample calculations and program runs are presented for each module: packed tower aeration, bubble aeration, and surface aeration.

III. Sample Calculations and Program Runs for ASAP™

A. *Packed Tower Aeration - Design Mode*

The following problem will be used to show sample calculations for packed tower aeration in design mode. In addition, a sample program run of ASAP™ will be used to verify that the program is correctly duplicating the results of the sample calculations.

1. Problem Statement

The city of Anytown, USA recently discovered that one of its wells was contaminated with the compounds listed in Table 1. In order for them to continue using the well, they are required to remove these compounds below their MCLs also shown in Table 1. During normal pumping operations, the well produces about 2000 gpm and the water temperature is 10°C.

Design a packed tower aeration system that can remove all the VOCs below their MCLs. Physical and chemical properties should be retrieved from StEPP™. Make use of the following packing material: 3.5 inch plastic tri-packs. The design air to water ratio should be set to 3.5 times the minimum air to water ratio. The pressure drop per unit length should be specified as 50 N/m^2/m. A safety factor of 0.6 (Design $K_L a$ / Onda $K_L a$) should be applied to the mass transfer coefficient calculated from the Onda correlations.

Also calculate the total power requirement (blower and pump brake power) for this design. Assume a blower efficiency of 35% and a pump efficiency of 80%.

Table 1 - Contaminants - Influent Concentrations and Treatment Objectives

Compound	Concentration Discharged, C_0 (µg/L)	MCL, C_{TO} (µg/L)
Trichloroethylene	200.0	5.0
Tetrachloroethylene	150.0	5.0
Vinyl Chloride	60.0	1.0
Ethylbenzene	30.0	5.0
Toluene	80.0	5.0
1,1-Dichloroethene	85.0	7.0

a) Properties Needed to Perform Sample Calculations and Program Run

Table 2 shows the chemical properties retrieved from StEPP™ required for packed tower aeration at 10°C and 1 atm.

Table 2 - Chemical Properties from StEPP™ at 10°C and 1 atm

Compound	MW (kg/kmol)	H (-)	V_b (m³/kmol)	T_{NBP} (°C)	D_l (m²/s)	D_g (m²/s)
Trichloroethylene	131.39	0.230	0.1020	87.0	6.44E-10	7.89E-06
Tetrachloroethylene	165.84	0.361	0.1190	121.0	5.86E-10	7.13E-06
Vinyl Chloride	62.50	0.546	0.0665	-13.9	8.26E-10	1.08E-05
Ethylbenzene	106.17	0.170	0.1400	136.0	5.33E-10	6.88E-06
Toluene	92.15	0.167	0.1190	111.0	5.86E-10	7.57E-06
1,1-Dichloroethene	96.95	0.680	0.0840	31.6	7.20E-10	9.05E-06

Table 3 shows the physical properties of air and water retrieved from StEPP™ at 10°C and 1 atm.

Table 3 - Properties of Air and Water

Property	Units	Value
Water Density, ρ_l	kg/m³	999.75
Water Viscosity, μ_l	kg/m/s	0.00131
Water Surface Tension, σ	N/m	0.0742
Air Density, ρ_g	kg/m³	1.25
Air Viscosity, μ_g	kg/m/s	1.72E-05

Table 4 shows the packing properties for 3.5 inch plastic tri-packs.

Table 4 - Packing Properties

Property	Units	Value
Nominal Diameter of Packing, d_p	m	0.0889
Packing Factor, C_f	(-)	12.0
Specific Surface Area of Packing, a_t	m²/m³	124.7
Critical Surface Tension of Packing, σ_c	N/m	0.033

In certain cases, the numbers that appear in the sample calculations are slightly different from the values displayed in the sample program run. These variations can be attributed to rounding.

2. Sample Design Mode Calculation of Tower Length for Trichloroethylene as the Design Compound Including Supplementary Parameter Calculations

a) *Packing Height*

Calculation of packing height, L, for the case described above is shown in Eq. 1:

$$L = \frac{Q}{A\,K_L a}\left[\frac{C_o - C_{TO}}{C_o - C_{TO} - C_0^*}\right]\ln\left[\frac{C_0 - C_0^*}{C_{TO}}\right]$$

$$= \frac{0.1262\,\frac{m^3}{s}}{3.48\,m^2 * 0.0111\,s^{-1}}\left[\frac{200\,\frac{\mu g}{L} - 5.0\,\frac{\mu g}{L}}{200\,\frac{\mu g}{L} - 5.0\,\frac{\mu g}{L} - 57.1\,\frac{\mu g}{L}}\right]\ln\left[\frac{200\,\frac{\mu g}{L} - 57.1\,\frac{\mu g}{L}}{5.0\,\frac{\mu g}{L}}\right] = 15.5\,m$$

Eq. 1

Note that a 15.5 m (equals 50.9 ft) packing height may not be practical. This manual was written to illustrate the use of the software. In order to design a practical tower size, the user may want to increase the air to water ratio (or air flow rate), but that activity is beyond the scope of this manual.

The parameters required to determine L in Eq. 1 can be found as follows:

Parameter	Location
Q	Given and see Eq. 2
C_0	Table 1
C_{TO}	Table 1
C_0^*	Eq. 3
A	Eq. 11
$K_L a$	Eq. 20

(1)   Water Flowrate

The water flowrate, Q, is given in the problem statement as 2000 gpm. Conversion to the units shown in Eq. 1 is as follows:

$$Q = \left(2000 \tfrac{gal}{min}\right)\left(\tfrac{1\,min}{60\,sec}\right)\left(\tfrac{1\,m^3}{264.17\,gal}\right) = 0.1262 \tfrac{m^3}{s}$$

<div align="right">

Eq. 2

</div>

(2)   Liquid Phase Concentration in Equilibrium with Exiting Gas

Calculation of C_0^* required in Eq. 1 is given in Eq. 3:

$$C_0^* = \left[\frac{1}{\left(\frac{\dot{V}}{Q}\right)*H}\right]\left(C_0 - C_{TO}\right) = \left[\frac{1}{\left(14.84 \tfrac{m^3}{m^3}\right)*0.230}\right]\left(200.0 \tfrac{\mu g}{L} - 5.0 \tfrac{\mu g}{L}\right) = 57.1 \tfrac{\mu g}{L}$$

<div align="right">

Eq. 3

</div>

The parameters required to find C_0^* in Eq. 3 can be found as follows:

Parameter	Location
C_0	Table 1
C_{TO}	Table 1
$\frac{\dot{V}}{Q}$	Eq. 4
H	Table 2

(a)   Air to Water Ratio

The calculation of air to water ratio for this design case is shown in Eq. 4. In packed tower aeration design, it is possible to specify either $\left(\frac{\dot{V}}{Q}\right)_{mult}$, $\frac{\dot{V}}{Q}$, or $\dot{V}$ with the other two parameters calculated. In this design case, the user specifies $\left(\frac{\dot{V}}{Q}\right)_{mult}$ and $\frac{\dot{V}}{Q}$ and $\dot{V}$ are calculated in Eq. 4 and Eq. 6, respectively.

Case 1: Specify $\left(\frac{\dot{V}}{Q}\right)_{mult}$, Calculate $\frac{\dot{V}}{Q}$ and $\dot{V}$

Air to Water Ratio

The air to water ratio, $\frac{\dot{V}}{Q}$, is found from the following equation:

$$\frac{\dot{V}}{Q} = \left(\frac{\dot{V}}{Q}\right)_{min} \times \left(\frac{\dot{V}}{Q}\right)_{mult} = 4.24 \tfrac{m^3}{m^3} \times 3.5 = 14.84 \tfrac{m^3}{m^3}$$

<div align="right">

Eq. 4

</div>

The parameters required to calculate $\frac{\dot{V}}{Q}$ in Eq. 4 can be found as follows:

Parameter	Location
$\left(\frac{\dot{V}}{Q}\right)_{min}$	Eq. 5
$\left(\frac{\dot{V}}{Q}\right)_{mult}$	Specified in problem statement

Minimum Air to Water Ratio

The minimum air to water ratio, $\left(\frac{\dot{V}}{Q}\right)_{min}$, is found from the following:

$$\left(\frac{\dot{V}}{Q}\right)_{min} = \left(\frac{C_0 - C_{TO}}{C_0}\right)\frac{1}{H} = \left(\frac{200.0\frac{\mu g}{L} - 5.0\frac{\mu g}{L}}{200.0\frac{\mu g}{L}}\right)\frac{1}{0.230} = 4.24$$

Eq. 5

The parameters required to calculate $\left(\frac{\dot{V}}{Q}\right)_{min}$ in Eq. 5 can be found as follows:

Parameter	Location
C_0	Table 1
C_{TO}	Table 1
H	Table 2

Air Flow Rate

The air flow rate, $\dot{V}$, through the tower is found by the following relationship:

$$\dot{V} = \left(\frac{\dot{V}}{Q}\right) \times Q = 14.84\frac{m^3\,air}{m^3\,H_2O} \times 0.1262\frac{m^3\,H_2O}{s} = 1.87\frac{m^3}{s}$$

Eq. 6

The parameters required to calculate $\left(\frac{\dot{V}}{Q}\right)_{min}$ in Eq. 6 can be found as follows:

Parameter	Location
$\frac{\dot{V}}{Q}$	Eq. 4
Q	Given and see Eq. 2

Case 2: Specify $\frac{\dot{V}}{Q}$, Calculate $\left(\frac{\dot{V}}{Q}\right)_{mult}$ and $\dot{V}$

Multiple of Minimum Air to Water Ratio

The multiple of minimum air to water ratio, $\left(\frac{\dot{V}}{Q}\right)_{mult}$, can be calculated using the following relationship.

$$\left(\frac{\dot{V}}{Q}\right)_{mult} = \frac{\dot{V}}{Q} / \left(\frac{\dot{V}}{Q}\right)_{min} = 14.84 / 4.24 = 3.5$$

Eq. 7

The parameters required to calculate $\left(\frac{\dot{V}}{Q}\right)_{mult}$ in Eq. 7 can be found as follows:

Parameter	Location
$\frac{\dot{V}}{Q}$	User-specified
$\left(\frac{\dot{V}}{Q}\right)_{min}$	Eq. 5

Air Flow Rate

The air flow rate, $\dot{V}$, through the tower can be calculated by the following relationship:

$$\dot{V} = \left(\frac{\dot{V}}{Q}\right) \times Q = 14.84 \frac{m^3\,air}{m^3\,H_2O} \times 0.1262 \frac{m^3\,H_2O}{s} = 1.87 \frac{m^3}{s}$$

Eq. 8

The parameters required to calculate $\left(\frac{\dot{V}}{Q}\right)_{min}$ in Eq. 8 can be found as follows:

Parameter	Location
$\frac{\dot{V}}{Q}$	User-specified
Q	Given and see Eq. 2

Case 3: Specify $\dot{V}$, Calculate $\frac{\dot{V}}{Q}$ and $\left(\frac{\dot{V}}{Q}\right)_{mult}$

Air to Water Ratio

The air to water ratio, $\frac{\dot{V}}{Q}$, can be calculated using the following relationship.

$$\frac{\dot{V}}{Q} = \dot{V} / Q = 1.87 \frac{m^3}{s} / 0.1262 \frac{m^3}{s} = 14.84$$

Eq. 9

The parameters required to calculate $\frac{\dot{V}}{Q}$ in Eq. 9 can be found as follows:

Parameter	Location
$\dot{V}$	User-specified
Q	Given and see Eq. 2

Multiple of Minimum Air to Water Ratio

The multiple of minimum air to water ratio, $\left(\frac{\dot{V}}{Q}\right)_{mult}$, can be calculated using the following relationship.

$$\left(\frac{\dot{V}}{Q}\right)_{mult} = \frac{\dot{V}}{Q} / \left(\frac{\dot{V}}{Q}\right)_{min} = 14.84 / 4.24 = 3.5$$

Eq. 10

The parameters required to calculate $\left(\frac{\dot{V}}{Q}\right)_{mult}$ in Eq. 7 can be found as follows:

Parameter	Location
$\frac{\dot{V}}{Q}$	User-specified
$\left(\frac{\dot{V}}{Q}\right)_{min}$	Eq. 9

(3) Tower Area

The tower cross-sectional area, A, required in Eq. 1 can be found using the following relationship (Eq. 11).

$$A = \frac{Q \rho_l}{L_m} = \frac{0.1262\,\frac{m^3}{s} * 999.75\,\frac{kg}{m^3}}{36.3\,\frac{kg}{\frac{m^2}{s}}} = 3.48\,m^2$$

Eq. 11

The parameters required to calculate A in Eq. 11 can be found as follows:

Parameter	Location
Q	Given and see Eq. 2
ρ_l	Table 3
L_m	Eq. 12

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(a)   Liquid Mass Loading Rate

The liquid mass loading rate, L_m, required in Eq. 11 can be estimated by the following:

$$L_m = \frac{G_m}{\left(\frac{\dot{V}}{Q}\right)\left(\frac{\rho_g}{\rho_l}\right)} = \frac{0.673\frac{kg}{m^2 s}}{\left(14.84\frac{m^3}{m^3}\right)\left(\frac{1.25\frac{kg}{m^3}}{999.75\frac{kg}{m^3}}\right)} = 36.3\frac{kg}{m^2 s}$$

Eq. 12

The parameters required to calculate L_m in Eq. 12 can be found as follows:

Parameter	Location
G_m	Eq. 13
$\frac{\dot{V}}{Q}$	Eq. 4
ρ_g	Table 3
ρ_l	Table 3

Gas Mass Loading Rate

The gas mass loading rate, G_m, needed in Eq. 12 can be found using Eq. 13:

$$G_m = \sqrt{\frac{M\rho_g\left(\rho_l - \rho_g\right)}{C_f\left(\mu_l\right)^{0.1}}} = \sqrt{\frac{0.002239 * 1.25\frac{kg}{m^3}\left(999.75\frac{kg}{m^3} - 1.25\frac{kg}{m^3}\right)}{12\left(0.00131\frac{kg}{m s}\right)^{0.1}}} = 0.673\frac{kg}{m^2 s}$$

Eq. 13

The parameters required to calculate G_m in Eq. 13 can be found as follows:

Parameter	Location
M	Eq. 14
ρ_g	Table 3
ρ_l	Table 3
C_f	Table 4
μ_l	Table 3

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Empirical Parameter, M

The empirical parameter M in Eq. 13 is defined by the following relationship:

$$\log_{10}\left(M\right) = a_0 + a_1\,E + a_2\,E^2$$
$$= \left(-2.45762\right) + \left(-0.63313\right) * 0.280417548 + \left(-0.18683\right) * 0.280417548^2$$
$$= -\,2.6498519526 \Rightarrow$$
$$M = 0.002239$$

Eq. 14

The parameters required to calculate M in Eq. 14 can be found as follows:

Parameter	Location
E	Eq. 15
a_0	Eq. 16
a_1	Eq. 17
a_2	Eq. 18

Parameter, E

The parameter E needed in Eq. 14 is defined in Eq. 15 below:

$$E = -\log_{10}\left(\left(\frac{\dot{V}}{Q}\right)\sqrt{\left(\rho_g\,/\,\rho_l\right) - \left(\rho_g\,/\,\rho_l\right)^2}\,\right)$$
$$= -\log_{10}\left(\left(14.84\,\tfrac{m^3}{m^3}\right)\sqrt{\left(1.25\,\tfrac{kg}{m^3}\,/\,999.75\,\tfrac{kg}{m^3}\right) - \left(1.25\,\tfrac{kg}{m^3}\,/\,999.75\,\tfrac{kg}{m^3}\right)^2}\,\right)$$
$$= 0.280328471$$

Eq. 15

The parameters required to calculate E in Eq. 15 can be found as follows:

Parameter	Location
$\frac{\dot{V}}{Q}$	Eq. 4
ρ_g	Table 3
ρ_l	Table 3

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Empirical Parameters a_0, a_1, and a_2

The parameters a_0, a_1, and a_2 in Eq. 13 are given in the following three equations:

$$a_0 = -6.6599 + 4.3077\,F - 1.3503\,F^2 + 0.15931\,F^3$$
$$= -6.6599 + 4.3077*1.69897 - 1.3503*1.69897^2 + 0.15931*1.69897^3$$
$$= -2.45762$$

Eq. 16

$$a_1 = 3.0945 - 4.3512\,F + 1.6240\,F^2 - 0.20855\,F^3$$
$$= 3.0945 - 4.3512*1.69897 + 1.6240*1.69897^2 - 0.20855*1.69897^3$$
$$= -0.63313$$

Eq. 17

$$a_2 = 1.7611 - 2.3394\,F + 0.89914\,F^2 - 0.11597\,F^3$$
$$= 1.7611 - 2.3394*1.69897 + 0.89914*1.69897^2 - 0.11597*1.69897^3$$
$$= -0.18683$$

Eq. 18

The parameters required to calculate a_0, a_1, and a_2 in Eq. 16 through Eq. 18 can be found as follows:

Parameter	Location
F	Eq. 19

Parameter, F

The parameter F that appears in Eq. 16 through Eq. 18 is defined below (note that $\Delta P/L$ was specified in the problem statement as 50.0 N/m^2/m and that the units of $\Delta P/L$ in Eq. 19 must be N/m^2/m):

$$F = \log_{10}\left(\Delta P/L\right) = \log_{10}\left(50.0\,\tfrac{\frac{N}{m^2}}{m}\right) = 1.69897$$

Eq. 19

The parameters required to calculate F in Eq. 19 can be found as follows:

Parameter	Location
$\Delta P/L$	Given in problem statement

(4) Design Mass Transfer Coefficient

Design mass transfer coefficient, $K_L a$, in Eq. 1 is calculated as follows:

$$K_L a = \left[K_L a\right]_{Onda} \times \left[SF\right]_{K_L a} = 0.0185\,s^{-1} \times 0.6$$
$$= 0.0111\,s^{-1}$$

Eq. 20

The parameters required to calculate $K_L a$ in Eq. 20 can be found as follows:

Parameter	Location
$\left[K_L a\right]_{Onda}$	Eq. 21
$\left[SF\right]_{K_L a}$	Given in problem statement

(a) Overall Mass Transfer Coefficient from Onda Correlation

The Onda mass transfer coefficient, $\left[K_L a\right]_{Onda}$, required in Eq. 1 was estimated by the following equation:

$$\frac{1}{\left[K_L a\right]_{Onda}} = \frac{1}{k_l a} + \frac{1}{k_g a\, H} = \frac{1}{\left[3.30E - 04\,\frac{m}{s}\right]\left[84.2\,\frac{m^2}{m^3}\right]} + \frac{1}{\left[2.82E - 03\,\frac{m}{s}\right]\left[84.2\,\frac{m^2}{m^3}\right]\left[0.230\right]}$$
$$= 54.3\,s \Rightarrow$$
$$\left[K_L a\right]_{Onda} = 0.0185\,s^{-1}$$

Eq. 21

The parameters required to calculate $\left[K_L a\right]_{Onda}$ in Eq. 21 can be found as follows:

Parameter	Location
k_l	Eq. 22
a	Eq. 23
k_g	Eq. 27
H	Table 2

Liquid Phase Mass Transfer Coefficient

The liquid phase mass transfer coefficient, k_l, required in Eq. 21 can be calculated using the following equation:

$$k_l = 0.0051 \left[\frac{L_m}{a_w \mu_l} \right]^{2/3} \left[\frac{\mu_l}{\rho_l D_l} \right]^{-0.5} \left(a_t d_p \right)^{0.4} \left[\frac{\rho_l}{\mu_l g} \right]^{-1/3}$$

$$= 0.0051 \left[\frac{36.3 \, \frac{kg}{m^2 s}}{84.2 \, \frac{m^2}{m^3} * 0.00131 \, \frac{kg}{m s}} \right]^{2/3} \left[\frac{0.00131 \, \frac{kg}{m s}}{999.75 \, \frac{kg}{m^3} * 6.44E\text{-}10 \, \frac{m^2}{s}} \right]^{-0.5} \times$$

$$\left(124.7 \, \tfrac{m^2}{m^3} * 0.0889 \, m \right)^{0.4} \left[\frac{999.75 \, \frac{kg}{m^3}}{0.00131 \, \frac{kg}{m s} * 9.81 \, \frac{m}{s^2}} \right]^{-1/3}$$

$$= 3.30E\text{-}04 \, \tfrac{m}{s}$$

Eq. 22

The parameters required to calculate k_l in Eq. 22 can be found as follows:

Parameter	Location
L_m	Eq. 12
a_w	Eq. 23
μ_l	Table 3
ρ_l	Table 3
D_l	Table 2
a_t	Table 4
d_p	Table 4
g	Constant - Known = 9.8 m/s^2

Area Available for Mass Transfer Divided by Vessel Volume

The area available for mass transfer divided by the vessel volume, a, required in Eq. 21 is shown by the following relationship:

$$a = a_w$$

$$a_w = a_t \left\{ 1 - \exp\left[-1.45 \left(\frac{\sigma_c}{\sigma} \right)^{0.75} \left(Re \right)^{0.1} \left(Fr \right)^{-0.05} \left(We \right)^{0.2} \right] \right\}$$

$$= 124.7 \tfrac{m^2}{m^3} \left\{ 1 - \exp\left[-1.45 \left(\frac{0.033 \tfrac{N}{m}}{0.0742 \tfrac{N}{m}} \right)^{0.75} \left(222 \right)^{0.1} \left(0.0167 \right)^{-0.05} \left(0.142 \right)^{0.2} \right] \right\}$$

$$= 84.2 \tfrac{m^2}{m^3}$$

Eq. 23

The parameters needed to find a_w in Eq. 23 can be found as shown below:

Parameter	Location
a_t	Table 4
σ_c	Table 4
σ	Table 3
Re	Eq. 24
Fr	Eq. 25
We	Eq. 26

Reynolds Number

Reynolds Number, *Re*, needed for the calculation of a_w in Eq. 23 is defined by:

$$Re = \frac{L_m}{a_t \mu_l} = \frac{36.3 \tfrac{kg}{m^2 s}}{124.7 \tfrac{m^2}{m^3} * 0.00131 \tfrac{kg}{m \cdot s}} = 222$$

Eq. 24

The parameters required to calculate *Re* in Eq. 24 can be found as follows:

Parameter	Location
L_m	Eq. 12
a_t	Table 4
μ_l	Table 3

Froude Number

The Froude Number, *Fr*, used to calculate a_w in Eq. 23 is found by the following relationship:

$$Fr = \frac{\left(L_m\right)^2 a_t}{\left(\rho_l\right)^2 g} = \frac{\left(36.3\frac{kg}{m^2 \cdot s}\right)^2 124.7\frac{m^2}{m^3}}{\left(999.75\frac{kg}{m^3}\right)^2 9.81\frac{m}{s^2}} = 0.0167$$

Eq. 25

The parameters required to calculate *Fr* in Eq. 25 can be found as follows:

Parameter	Location
L_m	Eq. 12
a_t	Table 4
ρ_l	Table 3
g	Constant - Known $= 9.8$ m/s^2

Weber Number

The Weber Number, *We*, used to find a_w in Eq. 23 is found by the following:

$$We = \frac{\left(L_m\right)^2}{\rho_l \, a_t \, \sigma} = \frac{\left(36.3\frac{kg}{m^2 \cdot s}\right)^2}{999.75\frac{kg}{m^3}*124.7\frac{m^2}{m^3}*0.0742\frac{N}{m}} = 0.142$$

Eq. 26

The parameters required to calculate *We* in Eq. 26 can be found as follows:

Parameter	Location
L_m	Eq. 12
ρ_l	Table 3
a_t	Table 4
σ	Table 3

Gas Phase Mass Transfer Coefficient

The gas phase mass transfer coefficient, k_g, required in Eq. 21 is calculated from:

$$k_g = 5.23 \left(a_t D_g \right) \left[\frac{G_m}{a_t \mu_g} \right]^{0.7} \left[\frac{\mu_g}{\rho_g D_g} \right]^{1/3} \left(a_t d_p \right)^{-2}$$

$$= 5.23 \left(124.7 \, \tfrac{m^2}{m^3} * 7.89\text{E-}06 \, \tfrac{m^2}{s} \right) \left[\frac{0.673 \, \frac{kg}{\frac{m^2}{s}}}{124.7 \, \tfrac{m^2}{m^3} * 0.0000172 \, \frac{kg}{\frac{m}{s}}} \right]^{0.7} \times$$

$$\left[\frac{0.0000172 \, \frac{kg}{\frac{m}{s}}}{1.25 \, \tfrac{kg}{m^3} * 7.89\text{E-}06 \, \tfrac{m^2}{s}} \right]^{1/3} \left(124.7 \, \tfrac{m^2}{m^3} * 0.0889 \, m \right)^{-2}$$

$$= 2.82\text{E-}03 \, \tfrac{m}{s}$$

Eq. 27

The parameters required to calculate k_g in Eq. 27 can be found as follows:

Parameter	Location
a_t	Table 4
D_g	Table 2
G_m	Eq. 13
μ_g	Table 3
ρ_g	Table 3
d_p	Table 4

b)   *Tower Diameter*

The tower diameter, D, is calculated knowing the tower area, A, from Eq. 11.

$$D = \sqrt{\frac{4A}{\pi}} = \sqrt{\frac{4 \left(3.48 \, m^2 \right)}{\pi}} = 2.10 \, m$$

Eq. 28

The parameters required to calculate D in Eq. 28 can be found as follows:

Parameter	Location
A	Eq. 11

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c)   Tower Volume

The tower volume, V, is calculated as follows.

$$V = A \times L = 3.48\,m^2 \times 15.5\,m = 53.9\,m^3$$

The parameters required to calculate V in Eq. 29 can be found as follows:

Parameter   Location

A Eq. 11

L Eq. 1

d)   Total Power Requirement

The total power requirement for packed tower aeration, P_{Total}, is calculated as the sum of the blower brake power and the pump brake power:

$$P_{Total} = P_{Blower} + P_{Pump} = 4.56\,kW + 24.0\,kW = 28.6\,kW$$

The parameters required to calculate P_{Total} in Eq. 30 can be found as follows:

Parameter   Location

P_{Blower} Eq. 31

P_{Pump} Eq. 35

(1)   Blower Brake Power

The blower brake power, P_{Blower}, is calculated below:

$$P_{blower} = \left[\frac{G_{me}\, R_g\, T_{air}}{1000\, n_a\, Eff_b} \right] \left[\left(\frac{P_{in}}{P_{out}} \right)^{n_a} - 1 \right]$$

$$= \left[\frac{2.34\,\frac{kg}{s} \cdot 286.7\,\frac{J}{kg \cdot K} \cdot 283.15\,K}{1000\,\frac{W}{kW}\,(0.283)(0.35)} \right] \left[\left(\frac{102179\,\frac{N}{m^2}}{101325\,\frac{N}{m^2}} \right)^{0.283} - 1 \right] \left(\frac{1\,W}{1\,\frac{J}{s}} \right) = 4.56\,kW$$

The parameters required to calculate P_{Blower} in Eq. 31 can be found as follows:

Parameter	Location
G_{me}	Eq. 32
R_g	Universal gas constant
T	Given in problem statement
n_a	Constant (see nomenclature)
Eff_b	Given in problem statement
P_{in}	Eq. 33
P_{out}	Assumed equal to $P_{ambient}$

(a)   Air Mass Flow Rate

The air mass flow rate, G_{me}, is calculated below:

$$G_{me} = \dot{V} \cdot \rho_g = 1.87 \tfrac{m^3}{s} \cdot 1.25 \tfrac{kg}{m^3} = 2.34 \tfrac{kg}{s}$$

Eq. 32

The parameters required to find G_{me} in Eq. 32 can be found:

Parameter	Location
$\dot{V}$	Eq. 6
ρ_g	Table 3

(b)   Inlet Air Pressure to Packed Tower

P_{in} refers to the pressure at the bottom of the tower, which is the inlet for the gas stream. P_{in} is calculated as the sum of the ambient pressure and the pressure drop caused by the packing media, demister, packing support plate, duct work, inlet and outlet of the tower. The equation used to find P_{in} is:

$$P_{in} = P_{ambient} + \left[\left| \frac{\Delta P}{L} \right| L \right] + \Delta P_{losses} = 101325 \tfrac{N}{m^2} + \left[\left| 50 \tfrac{N/m^2}{m} \right| 15.5m \right] + 79.4 \tfrac{N}{m^2} = 102179 \tfrac{N}{m^2}$$

Eq. 33

The parameters required to calculate P_{in} in Eq. 33 can be found as follows:

Parameter	Location
$P_{ambient}$	Given in problem statement
$\frac{\Delta P}{L}$	Given in problem statement
L	Eq. 1
ΔP_{losses}	Eq. 34

Pressure Drop due to Losses at the Ends of the Tower

ΔP_{losses} represents the pressure drop through the demister, packing support plate, duct work, inlet and outlet of the tower. It is assumed that turbulent flow conditions prevail and most of the losses occur in the tower (i.e., in the packing support plate and the demister). ΔP_{losses} is found from the following:

$$\Delta P_{losses} = \left(\frac{\dot{V}}{A} \right)^2 k_p = \left(\frac{1.87 \frac{m^3}{s}}{3.48 m^2} \right)^2 275 \ N \ s^2 / m^4 = 79.4 \frac{N}{m^2}$$

Eq. 34

The parameters required to calculate ΔP_{losses} in Eq. 34 can be found as follows:

Parameter	Location
$\dot{V}$	Eq. 6
A	Eq. 11
k_p	Constant (see nomenclature)

(2) Pump Brake Power

The pump brake power, P_{Pump}, is calculated below:

$$P_{pump} = \frac{\rho_l \ Q \ L \ g}{1000 \ Eff_p} = \left(\frac{999.75 \frac{kg}{m^3} \cdot 0.1262 \frac{m^3}{s} \cdot 15.5 m \cdot 9.81 \frac{m}{s^2}}{1000 \frac{W}{kW} \cdot 0.80} \right) \left(\frac{1W}{1 \frac{kg \ m}{s^2} \cdot \frac{m}{s}} \right) = 24.0 \ kW$$

Eq. 35

The parameters required to calculate P_{Pump} in Eq. 35 can be found as follows:

Parameter	Location
ρ_l	Table 3
Q	Given in problem statement
L	Eq. 1
g	Acceleration due to gravity
Eff_p	Given in problem statement

3. Sample Program Run of ASAP™ to Verify Sample Calculations for Packed Tower Aeration in Design Mode

To start the ASAP™ program, double click on the ASAP™ icon in the *ETDOT Programs* group icon in windows. The screen shown in Figure 1 will appear.
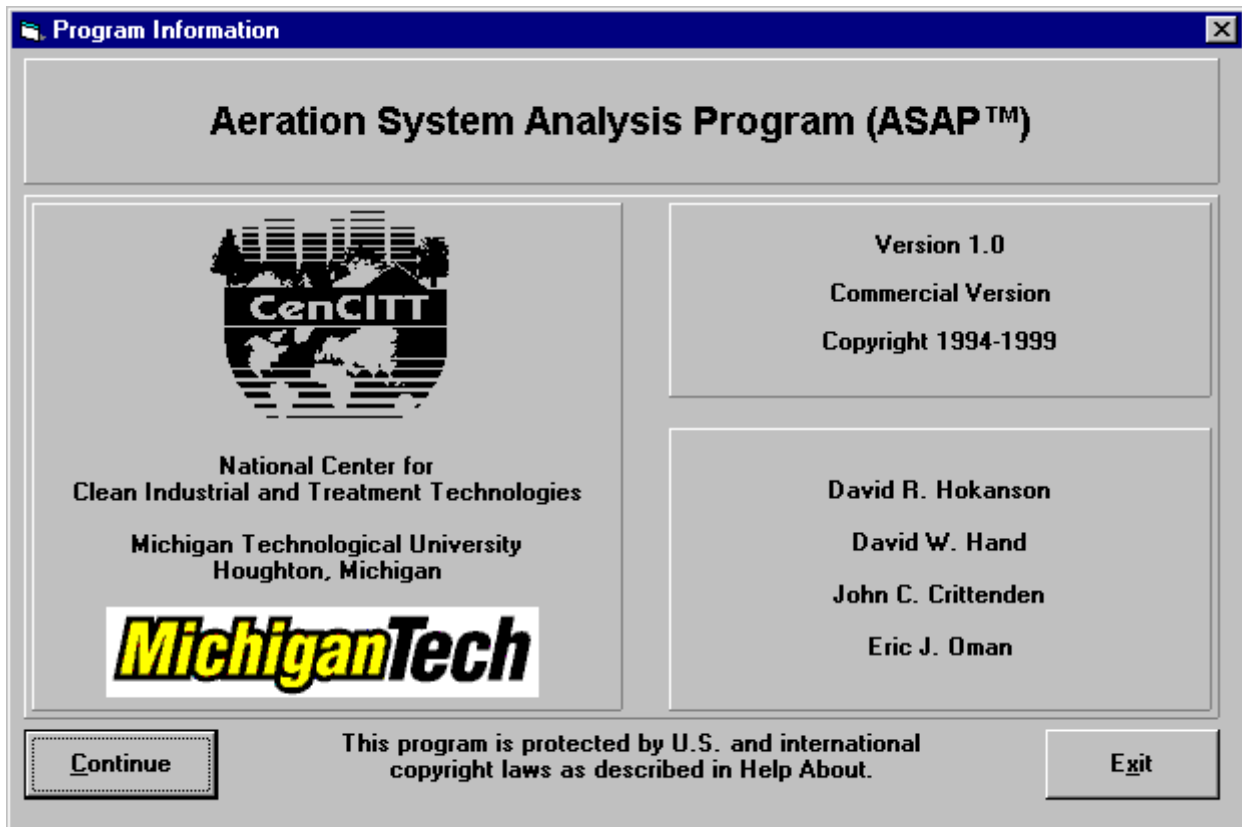
Figure 1 - ASAP™ Title Window

Click on the *Continue* button on the screen shown in Figure 1 and the menu shown in Figure 2 will appear.

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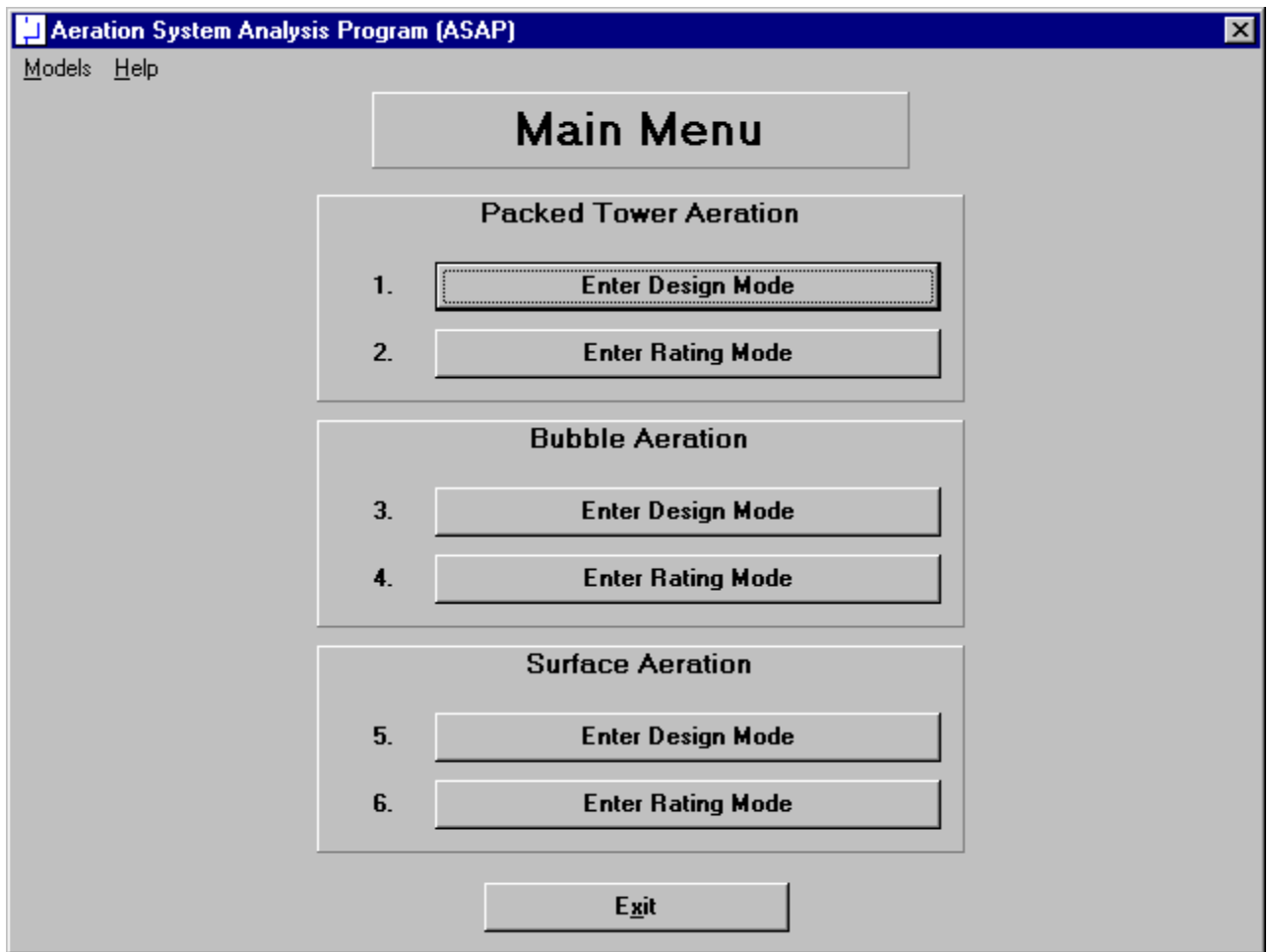
Figure 2 - Main Menu Window in ASAP™

Click on the *Enter Design Mode* button for Packed Tower Aeration (option 1 in Figure 2) and the design mode screen for packed tower aeration shown in Figure 3 will appear.

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Figure 3 - Design Mode Window for Packed Tower Aeration

a) *Physical Properties of Air and Water*

Specify pressure and temperature in the upper left-hand corner of the window shown in Figure 3. This portion of the packed tower aeration design mode window is shown in Figure 4.

Figure 4 - Operating Conditions Portion of Design Mode Window

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Click on the *Display Physical Properties of Air and Water* button in Figure 3 (and highlighted in Figure 4) to show the properties of air and water at the specified temperature and pressure (101325 Pa and 10°C). Figure 5 shows the air and water properties window for this case.

Figure 5 - Air and Water Properties Window

The properties shown in Figure 5 are by default calculated from correlations so the user should not have to change their values. In the rare case that the user would like to enter a value for any of these properties instead of using the correlations, it is possible to do so on the window shown in Figure 5. Click on the *OK* button shown in Figure 5 to close the window.

It can be seen that the air and water properties shown in Figure 3 agree with the properties shown in Table 3.

b)   *Packing Properties*

The next step is to choose the appropriate packing. Packing selection is located in the middle of the left-hand side of the design mode window shown in Figure 3. This portion of Figure 3 is highlighted in Figure 6.
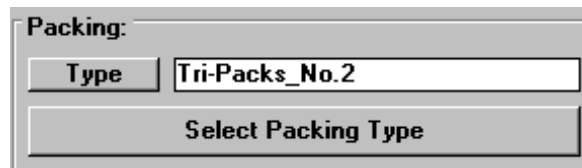
Figure 6 - Packing Selection Portion of Design Mode Window

Click on the *Select Packing Type* button shown in Figure 3 (and highlighted in Figure 6). The packing database window shown in Figure 7 will appear.
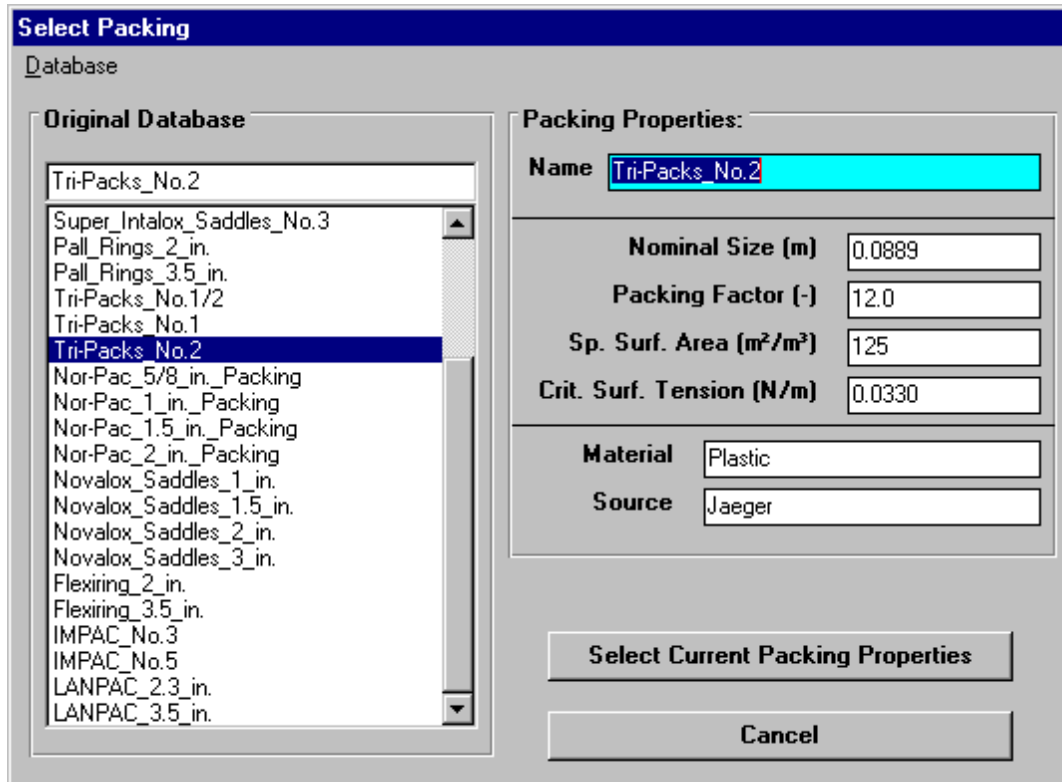
Figure 7 - Select Packing Type Window

ASAP™ contains a database of packing properties available from vendor data. The packing properties used in development of the product are shown in Figure 7. The left-hand side of the packing database window shown in Figure 8 contains a listing of available packings. The item called "Tri-packs No. 2" in the list is the 3.5 inch plastic tri-packs requested in the problem statement. Click on this item in the list as shown in Figure 7 so that this item is selected. Then select the properties of this packing for use in the design by clicking on the *Select Current Packing Properties* button shown in Figure 7.

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It should be noted that it is also possible for the user to enter properties of additional packings. It is not possible for the user to modify the list of packings from vendor data supplied with the program (called the "Original Database"). However, there is a separate database of packing properties from user input available with the software. An alternative method to enter the properties of 3.5 inch plastic tri-packs is as follows. Click on the *Select Packing Type* button in the window shown in Figure 3 (and highlighted in Figure 6). The window shown in Figure 7 will appear again. In the *Database* menu shown in Figure 8, it is seen that currently the "Original Database" option is selected.
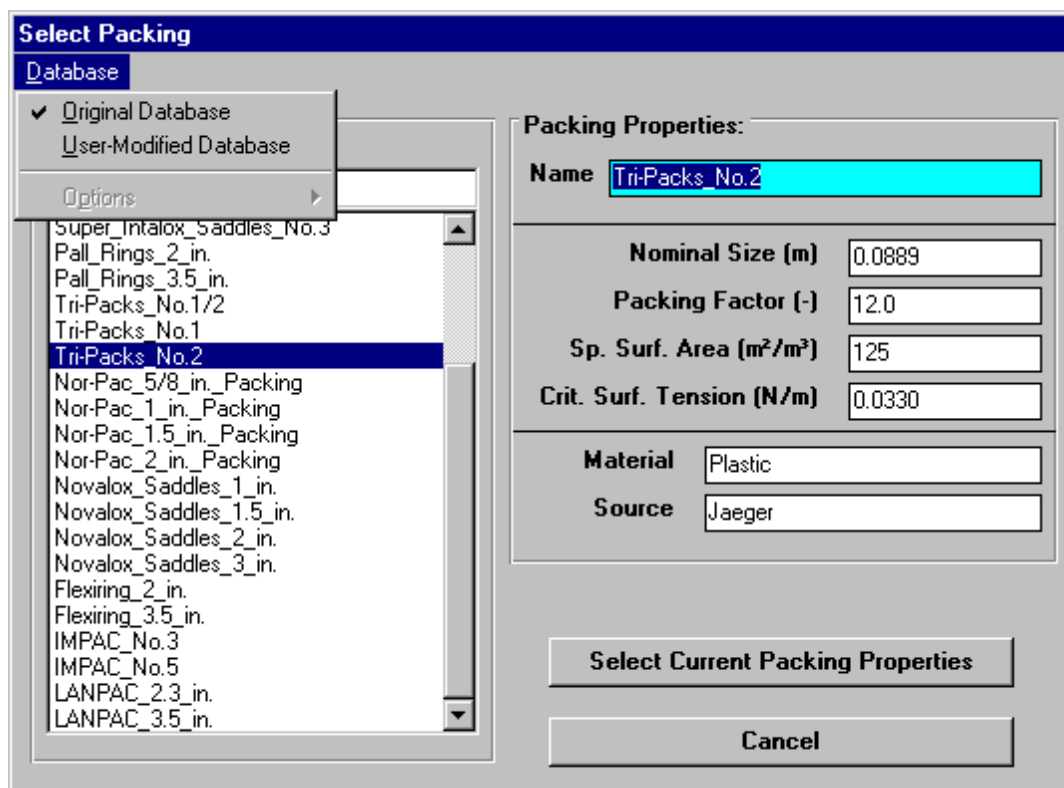
Figure 8 - Database Menu in Select Packing Type Window

To input data, the user must click on the "User Modified Database" item in the menu shown in Figure 8. Then the *Select Packing Type* window will show a database of user input packing parameters, as shown in Figure 9.

Figure 9 - User Modified Database in Select Packing Type Window

On the screen shown in Figure 9, it is possible to input values for all packing properties. Figure 9 shows the screen after the properties of 3.5 inch plastic tri-packs have been input. To select these properties for use in the current design, click on the *Select Current Packing Properties* button shown in Figure 9.

It can be seen that the packing properties shown in both Figure 7 and Figure 9 agree with the properties shown in Table 4.

c) *Chemical Properties*

Chemical properties for each of the six components can be retrieved from StEPP™. When the screen shown in Figure 3 loads, the properties of six contaminants load as a default design case. Before retrieving the chemical properties of the six chemicals required in the current design, it is necessary to delete the six default chemicals shown in the Design Contaminant list box on the bottom of the left-hand column shown in Figure 3. This portion of the design mode window is highlighted in Figure 10.

Figure 10 - Contaminant Selection Portion of Design Mode Window

To delete each chemical click on the *Delete* button located in between the *Add* and *Edit Properties* buttons shown in Figure 3 (and highlighted in Figure 10). Click the *Delete* button once for each chemical until all chemicals have been deleted from the *Design Contaminant* list box.

It is now possible to add the chemicals required for the current design. To do so, click on the *Add* button shown on the bottom left-hand corner of the window shown in Figure 3 (and highlighted in Figure 10). Figure 11 shows the window that will appear.

Figure 11 - Contaminant Properties Input Window

The following properties (with their default units in parentheses) are required for each component:

- Name

- Molecular weight (*mg/mmol*)

- Henry's constant (*dimensionless*)

- Molar volume at the normal boiling point temperature ($m^3/kmol$)

- Normal boiling point (*K*)

- Liquid diffusivity (m^2/s)

- Gas diffusivity (m^2/s)

- Initial (influent) concentration (*mg/L*)

- Treatment objective (*mg/L*)

The user can input data by clicking on a text box and typing in the corresponding value. By pressing the Enter key, the Tab key or clicking on another text box or button, the data is updated. The default units can be changed in the pull-down menus to the right of the text boxes.

(1)   Transferring Properties from StEPP™ to ASAP™

ASAP™ has the capability of transferring the physical properties of contaminants from Software to Estimate Physical Properties (StEPP™). There are two options for transferring data from StEPP™ into ASAP™: (a) Create Export File for AdDesignS/ASAP and (b) Copy to Clipboard for AdDesignS/ASAP. Both choices are available in the *Options* menu within StEPP™. The StEPP™ main window highlighting the *Options* menu is shown in Figure 12.

Figure 12 - StEPP™ Main window

The operating temperature and pressure, with units of degrees Celsius and Pascals respectively, must be entered. Chemicals can be selected using the scroll bar on the *Available Contaminants* block or the *Find, Find Next Occurrence,* or *Synonyms* buttons, highlighting the chemical, and clicking on the *Select Current Contaminant* button. Repeat this process for all contaminants of interest. After the contaminants have been selected in StEPP™ and their properties calculated at the proper temperature and pressure, they can be transferred from StEPP to ASAP using either of two options, which are described below: (a) Create Export File for AdDesignS/ASAP and (b) Copy to Clipboard for AdDesignS/ASAP.

(a) Transferring Chemical Properties from StEPPÔ to ASAPÔ Using the Create Export File for AdDesignS/ASAP *Option*

To create a StEPP™ export file, select *Create Export File for AdDesignS/ASAP™* from the *Options* menu. The window shown in Figure 13 will appear. Enter a file name to save the export file. This file will be available for use in ASAP™.

Figure 13 - Save StEPP™ Export File window

To import the chemicals and their physical properties to ASAP™ from the StEPP™ export file, click on the *Add* button in the *Component Properties* block of the ASAP™ main window. The Component Properties window shown in Figure 14 will appear.

Figure 14 - Component Properties window (adding new components)

To open the StEPP™ export file, click the *Import StEPP™ export file* button on the Component Properties window. The Load StEPP™ Export File window shown in Figure 15 will appear.

Figure 15 - Load StEPP™ Export File window

The file which was previously saved in StEPP™ can be selected in this window. The window shown in Figure 16 announcing the successful import of the components will appear. To return to the ASAP™ main window, click on *OK*.
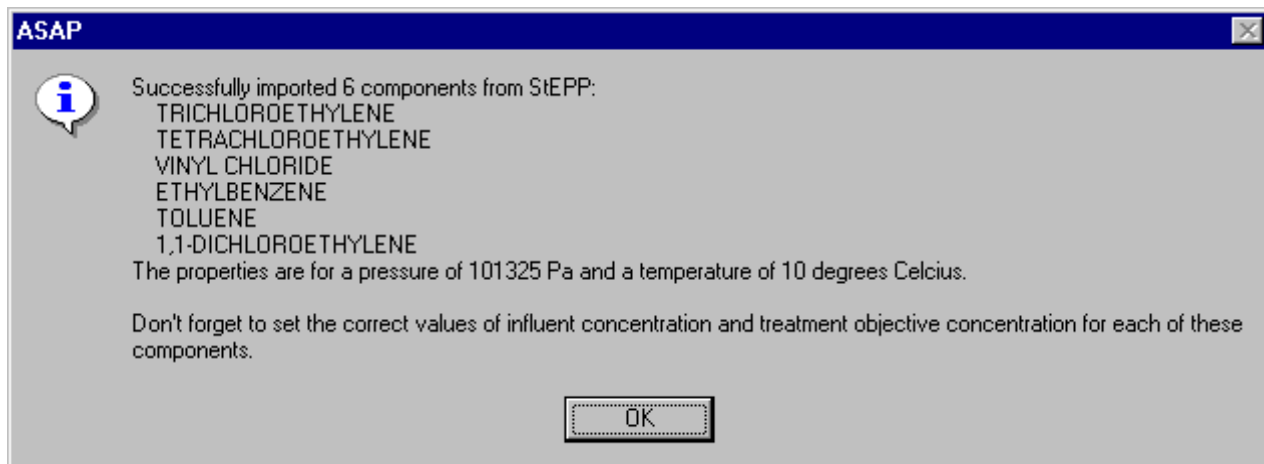
Figure 16 - Successful Import of Components from StEPP™ window

> *(b)   Transferring Chemical Properties from StEPPÔ to ASAPÔ Using the Copy to Clipboard for AdDesignS/ASAP Option*

To copy selected StEPP™ data to the Windows clipboard for export into ASAP, select *Copy to Clipboard for AdDesignS/ASAP* from the <u>*Options*</u> menu within StEPP. The message box shown in Figure 17 will appear, verifying that all of the StEPP data is now stored in the Windows clipboard.
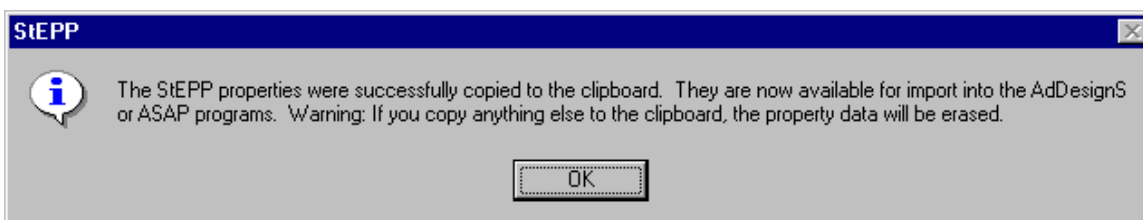

Figure 17 – Successful Copy to Clipboard from StEPP™ Message Box

To import the chemicals and their physical properties to ASAP™ from the data on the clipboard, click on the <u>*Add*</u> button in the *Component Properties* block of the ASAP™ main window. The Component Properties window shown in Figure 18 will appear.

Figure 18 - Component Properties window (adding new components)

To import the StEPP™ data from the Windows clipboard, click the *Import from Clipboard* button on the Component Properties window. The window shown in Figure 19 will appear, showing that the properties have been successfully transferred into ASAP.

Figure 19 – Successful Import from StEPP™ Window

(2) Manipulation of Data Required after
Transferring Properties from StEPP™ to
ASAP™

The following properties will be transferred to ASAP™ from StEPP™, unless these are not available:

- Molecular weight (*mg/mmol*)

- Henry's constant (*dimensionless*)

- Molar volume at the normal boiling point temperature (*mL/gmol*)

- Normal boiling point (*Celsius*)

- Liquid diffusivity (m^2/s)

- Gas diffusivity (m^2/s)

The name of the chemical will also be transferred. If any of the properties above are not available in StEPP™ for a selected chemical, the chemical with missing properties will not be imported and a warning message will be displayed.

Click on the *OK* button to continue. Figure 3 appears. As shown in Figure 16 or Figure 19, it is necessary to input influent concentrations and treatment objectives for each of the six components retrieved. To do so, select each contaminant one at a time in the Design Contaminant list box shown in the lower left-hand corner of Figure 3. Then click on the *Edit Properties* button. Figure 20 shows the window that appears for trichloroethylene.

Figure 20 - Specify Contaminant Properties Window for Trichloroethylene

The properties molecular weight, Henry's constant, molar volume, normal boiling point, liquid diffusivity, and gas diffusivity are already correct since they were retrieved from StEPP™. The influent concentration and treatment objective shown at the bottom of the screen must be input since they will vary from case to case. These properties shown in Figure 20 already reflect the values for the current design case. It is seen that the properties shown in Figure 20 agree with the trichloroethylene properties shown in Tables 1 and 2.

Figure 21 shows the *Specify Contaminant Properties* window for tetrachloroethylene. It can be seen that the properties shown in Figure 21 agree with the properties of tetrachloroethylene shown in Tables 1 and 2.

Figure 21 - Specify Contaminant Properties Window for Tetrachloroethylene

Figure 22 shows the *Specify Contaminant Properties* window for vinyl chloride. It can be seen that the properties shown in Figure 22 agree with the properties of vinyl chloride shown in Tables 1 and 2.

Figure 22 - Specify Contaminant Properties Window for Vinyl Chloride

Figure 23 shows the *Specify Contaminant Properties* window for ethylbenzene. It can be seen that the properties shown in Figure 22 agree with the properties of ethylbenzene shown in Tables 1 and 2.

Figure 23 - Specify Contaminant Properties Window for Ethylbenzene

Figure 24 shows the *Specify Contaminant Properties* window for toluene. It can be seen that the properties shown in Figure 22 agree with the properties of toluene shown in Tables 1 and 2.

Figure 24 - Specify Contaminant Properties Window for Toluene

Figure 25 shows the *Specify Contaminant Properties* window for 1,1-dichloroethene. It can be seen that the properties shown in Figure 22 agree with the properties of 1,1-dichloroethene shown in Tables 1 and 2.

Figure 25 - Specify Contaminant Properties Window for 1,1-Dichloroethene

d)   *Flow, Loading, and Pressure Drop Parameters*

Flow, loading, and pressure drop parameters are shown in the upper right-hand side of Figure 3. This portion of Figure 3 is reproduced here as Figure 26.

Figure 26 - Flow, Loading, and Pressure Drop Parameters

Explanation of the origin of the values for the properties shown in Figure 26 is provided here. The water flow rate of 2000 gpm was specified in the problem statement. The minimum air to water ratio of 4.24 was calculated by the program. This value agrees with the value calculated in the sample calculation for this design case (see Eq. 5 in the sample calculations section). The multiple of minimum air to water ratio was specified in the problem statement as 3.5. The air to water ratio was calculated by the program as 14.8. This value agrees with the sample calculations (see Eq. 4 in sample calculations section). The air flow rate was calculated in the program as 1.87 m^3/s. This value agrees with the sample calculations section (see Eq. 6). The air pressure drop was user-specified as 50 N/m^2/m. The air loading rate was calculated by the program as 0.67 kg/m^2/s. This value agrees with the sample calculations section (see Eq. 13). The water loading rate was calculated by the program as 36.3 kg/m^2/s. This number agrees with the sample calculations section (see Eq. 12).

e)   *Mass Transfer Parameters*

The mass transfer parameters are shown on the middle of the right-hand column of the design mode window shown in Figure 3. This portion of the window is highlighted in Figure 27.

Figure 27 - Mass Transfer Parameters Section of Design Mode Window

The mass transfer coefficient from the Onda correlations is calculated by the program as 0.0185 1/s. This agrees with the value from the sample calculations section (see Eq. 21). Supplementary properties in the calculation of Onda mass transfer coefficient can be viewed by clicking on the *Onda KLa* label shown in Figure 3 (and highlighted in Figure 27). After the click, the following window appears:

Figure 28 - Supplementary Onda KLa Properties Window

The values shown in Figure 28 agree with the values shown previously in the sample calculations. Reynolds number calculated by the program is 223, which agrees with the sample calculations (see Eq. 24). Froude number calculated in the program is 0.0168, which is in agreement with the sample calculations (see Eq. 25). Weber number is calculated by the program as 0.142, which matches the value given in the sample calculations (see Eq. 26). Packing wetted surface area is determined in the program as 84.3 m^2/m^3, which agrees with the sample calculations (see Eq. 23). Liquid phase mass transfer coefficient is calculated by the program as 3.31E-04 m/s, which matches the sample calculations (see Eq. 22). Gas phase mass transfer coefficient is determined by the program as 2.82E-03 m/s, which agrees with the sample calculations (see Eq. 27).

The KLa safety factor shown in Figure 3 (and highlighted in Figure 27) is specified in the problem statement. The design KLa was calculated by the program as 0.0111 1/s (see Figure 3 and Figure 27) and this value agrees with the sample calculations shown earlier (Eq. 20).

f) *Tower Parameters*

The tower parameters are shown on the bottom of the right-hand column of the design mode window shown in Figure 3. This portion of the window is highlighted in Figure 29.

Figure 29 - Tower Parameters Section of Design Mode Window

The values of the tower parameters shown in Figure 3 (and highlighted in Figure 29) agree with the sample calculations section. Tower cross-sectional area was calculated in the program as 3.48 m^2, which agrees with the sample calculations (see Eq. 11). Tower diameter was determined in the program as 2.10 m, which matches the sample calculations (see Eq. 28). The tower height calculated by the program is 15.5 m, which is in agreement with the sample calculations (see Eq. 1). The tower volume was determined by the program as 54.0 m^3, which agrees with the sample calculations (see Eq. 29).

g) *Power Parameters*

By clicking on the *Perform Power Calculations* option in the *Brake Power* menu shown in Figure 3, the power window for packed tower aeration appears. This power window is shown below in Figure 30.

Figure 30 - Power Window for Packed Tower Aeration

The values of the power parameters shown in Figure 30 agree with the sample calculations shown earlier. The blower brake power was calculated in the program as 4.56 kW, which agrees with the sample calculations (see Eq. 31). Pump brake power was calculated in the program as 24.0 kW, which matches Eq. 35 in the sample calculations. Total brake power was determined by the program as 28.6 kW, which is in agreement with the sample calculations (see Eq. 30).

h) Viewing Effluent Concentration Results for Contaminants Other than the Design Contaminant

For a given design, it is useful to see what the effluent concentrations of contaminants other than the design contaminant would be. ASAP provides a convenient method for seeing these results without having to switch to rating mode. (of course, the user will have to switch to rating mode to investigate commercially available packed tower sizes).

By clicking on the ***Concentration Results*** button in the lower left-hand corner of the packed tower aeration – design mode window shown in Figure 3, the user will see the concentration results for all contaminants using the given design.

View Concentration Results for All Contaminants

Concentration Results

CN	Cinf	Cto	D % R	Ceff	A % R
1	200	5.00	97.5	5.00	97.5
2	150	5.00	96.7	1.89	98.7
3	60.0	1.00	98.3	0.138	99.8
4	30.0	5.00	83.3	1.83	93.9
5	80.0	5.00	93.8	4.44	94.5
6	85.0	7.00	91.8	0.220	99.7

Contaminant Glossary:

CN	Contaminant Name
1	trichloroethylene
2	tetrachloroethylene
3	vinyl chloride
4	ethylbenzene
5	toluene
6	1.1-dichloroethylene

Glossary:

Label	Description
CN	Contaminant Number
Cinf	Influent Concentration (ug/L)
Cto	Treatment Objective (ug/L)
D % R	Desired Percent Removal
Ceff	Effluent Concentration (ug/L)
A % R	Achieved Percent Removal

OK

Figure 31 – View Concentration Results for All Contaminants Window

This window provides a quick method to see whether the given design will meet the treatment objectives for all contaminants.

i)   *Example of Optimize with All Contaminants Feature*

For packed tower aeration in design mode, ASAP contains an optimization routine to attempt to determine an appropriate design contaminant for the given problem statement. This feature is described in detail in the Theoretical Development section of the manual (see section *III.D. Optimization Routine for Packed Tower Aeration (Design Mode)*.   In order to demonstrate the feature, run ASAP and choose packed tower aeration, design mode from the main menu. The packed tower aeration , design mode window appears as shown previously in Figure 3. Change the design contaminant to Toluene. The packed tower aeration, design mode window now appears as shown in Figure 32.

Figure 32 – Packed Tower Aeration, Design Mode Window with Toluene as the Design Contaminant

Click the ***Concentration Results*** button. The *Concentration Results* window for this case with toluene as the design contaminant is shown in Figure 33.

Figure 33 – Concentration Results Window with Toluene Selected as the Design Contaminant

From Figure 33, it is clear that trichloroethylene fails to meet its treatment objective with toluene chosen as the design contaminant. Hence, toluene is not the proper design contaminant and it is expected that trichloroethylene is the appropriate design contaminant. Clicking on the *Optimize with All Contaminants* button should produce this result, choosing the proper design contaminant. Click the *Optimize with All Contaminants* button. Figure 34 shows the Optimize with All Contaminants window that appears, which shows that the optimization routine has chosen trichloroethylene as the design contaminant, which is expected. Click Ok to close this window and then click the *Concentration Results* button. Figure 35 shows the *Concentration Results* window with trichloroethylene as the design contaminant, which clearly demonstrates that all compounds meet their treatment objectives for this design case. This shows that trichloroethylene is the proper design contaminant, suggesting that the optimization routine has functioned properly in this case.

Important Note: There are situations where the optimization routine *will be unable to determine* the proper design contaminant. This is described in the theoretical section of this manual (see section III.D). The user should pay close attention to the results of using the ***Optimize with All Contaminants*** feature to assure that a proper design is developed, which meets all design specifications.

Figure 34 – Optimize with All Contaminants Window

Figure 35 - Concentration Results Window with Trichloroethylene Selected as the Design Contaminant

j) *Switching to Rating Mode*

Once the packed tower has been specified in design mode, the user can take the established properties and switch to rating mode in order to see the effect of modifications of various properties. The procedure for switching to rating mode is described here.

Figure 36 shows the **File** menu for packed tower aeration, design mode.
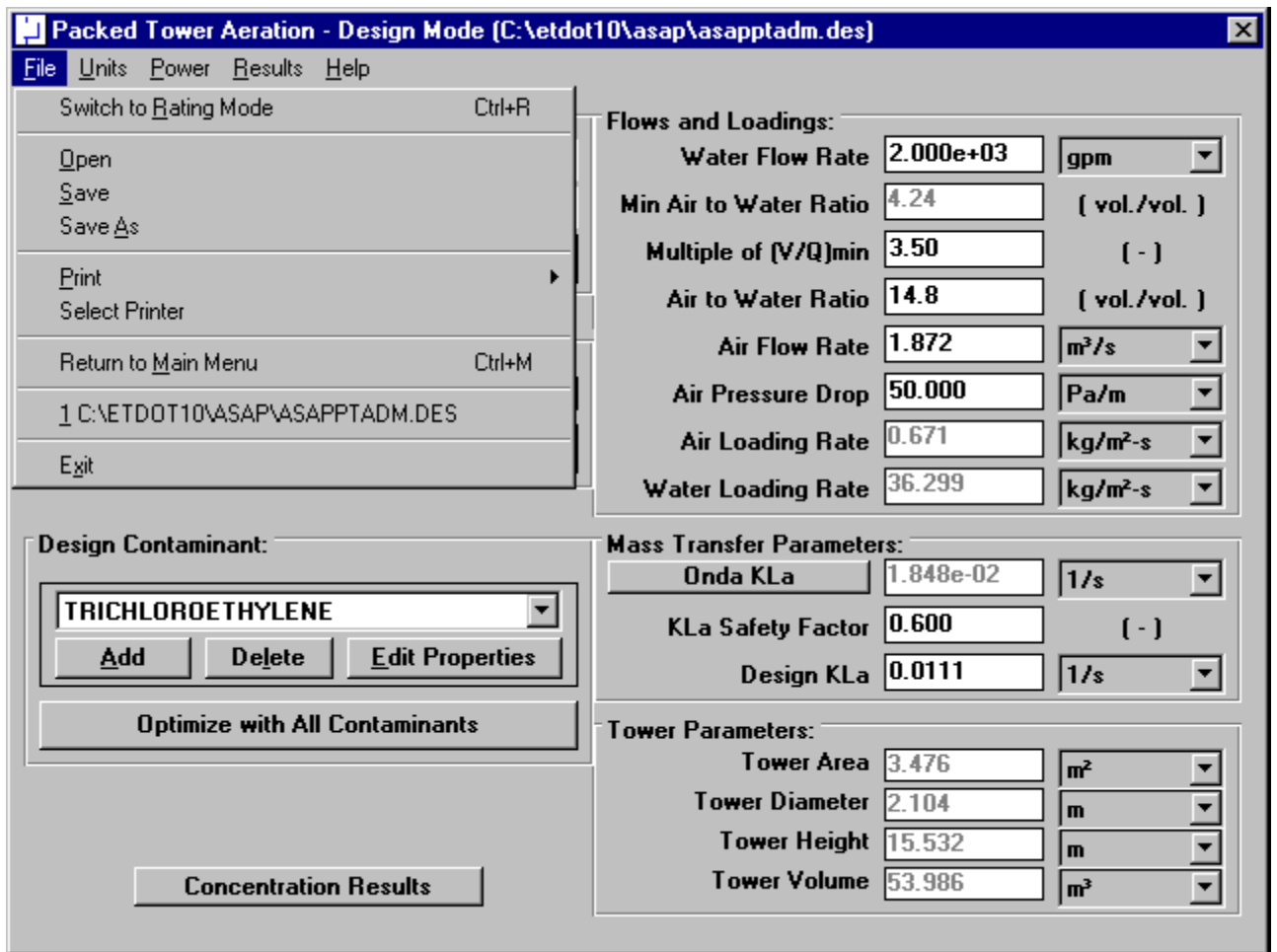
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Figure 36 – File Menu for Packed Tower Aeration – Design Mode

Click on the menu option called *Switch to Rating Mode* in Figure 36. The packed
tower aeration – rating mode window will appear, as shown in Figure 37.

Figure 37 – Packed Tower Aeration – Rating Mode Window

Use of *Packed Tower Aeration – Rating Mode* will be described in the next section.

B. *Packed Tower Aeration - Rating Mode*

The following problem will be used to show sample calculations for packed tower aeration in rating mode. In addition, a sample program run of ASAP™ will be used to verify that the program is correctly duplicating the results of the sample calculations.

1. Problem Statement

The city of Anytown, USA recently discovered that one of its wells was contaminated with the compounds listed in. In order for them to continue using the well, they were required to remove these compounds below their MCLs, also shown in Table 1. During normal pumping operations, the well produces about 2000 gpm and the water temperature is 10°C.

A packed tower aeration system was designed to remove all the VOCs below their MCLs. Physical and chemical properties for the design were retrieved from StEPP™. The following packing material was used in design: 3.5 inch plastic tripacks. The air to water ratio is 14.8 m^3/m^3. A safety factor of 0.6 (Design K_La/ Onda K_La) was applied to the mass transfer coefficient calculated from the Onda correlations in the design mode calculations. The tower was designed to have a height of 15.5 m. and a diameter of 2.10m (Note that a 15.5 m [equals 50.9 ft] packing height may not be practical. This manual was written to illustrate the use of the software. In order to design a practical tower size, the user may want to increase the air to water ratio [or air flow rate], but that activity is beyond the scope of this manual.).

Determine the effluent concentrations and tower pressure drop given influent concentrations from Table 1. Show a sample calculation of the effluent concentration for TCE. Show a sample calculation for pressure drop. Present a table showing the influent concentration, treatment objective, design mass transfer coefficient, stripping factor, and effluent concentration for each component.

Table 1 - Contaminants - Influent Concentrations

Compound	Concentration Discharged, C_0 (μg/L)	MCL, C_{TO} (μg/L)
Trichloroethylene (TCE)	200.0	5.0
Tetrachloroethylene (PCE)	150.0	5.0
Vinyl Chloride	60.0	1.0
Ethylbenzene	30.0	5.0
Toluene	80.0	5.0
1,1-Dichloroethene (1,1-DCE)	85.0	7.0

a) *Properties Needed to Perform Sample Calculations and Program Run*

Table 2 shows the chemical properties retrieved from StEPP™ required for packed tower aeration at 10°C and 1 atm.

Table 2 - Chemical Properties from StEPP™ at 10° C and 1 atm

Compound	MW (kg/kmol)	H (-)	V_b (m³/kmol)	T_{NBP} (°C)	D_l (m²/s)	D_g (m²/s)
Trichloroethylene	131.39	0.230	0.1020	87.0	6.44E-10	7.89E-06
Tetrachloroethylene	165.84	0.361	0.1190	121.0	5.86 E-10	7.13 E-06
Vinyl Chloride	62.50	0.546	0.0665	-13.9	8.26 E-10	1.08E-05
Ethylbenzene	106.17	0.170	0.1400	136.0	5.33 E-10	6.88 E-06
Toluene	92.15	0.167	0.1190	111.0	5.86 E-10	7.57 E-06
1,1-Dichloroethene	96.95	0.680	0.0840	31.6	7.20 E-10	9.05 E-06

Table 3 shows the physical properties of air and water retrieved from StEPP™ at 10°C and 1 atm.

Table 3 - Physical Properties from StEPP™ at 10° C and 1 atm

Property	Units	Value
Water Density, ρ_l	kg/m³	999.75
Water Viscosity, μ_l	kg/m/s	0.00131
Water Surface Tension, σ	N/m	0.0742
Air Density, ρ_g	kg/m³	1.25
Air Viscosity, μ_g	kg/m/s	1.72E-05

Table 4 shows the packing properties for 3.5 inch plastic tripacks.

Table 4 - Packing Properties for 3.5 Inch Plastic Tripacks

Property	Units	Value
Nominal Diameter of Packing, d_p	m	0.0889
Packing Factor, C_f	(-)	12.0
Specific Surface Area of Packing, a_t	m^2/m^3	124.7
Critical Surface Tension of Packing, σ_c	N/m	0.033

b) *Note Regarding Comparison of Sample Calculation Values to Sample Program Run*

In certain cases, the numbers that appear in the sample calculations are slightly different from the values displayed in the sample program run. These variations can be attributed to rounding.

2. Sample Rating Mode Calculation of Effluent Concentration for Trichloroethylene as the Design Compound Including Supplementary Parameter Calculations

a) *Effluent Concentration*

The calculation of effluent concentration, C_e, of TCE is shown in Eq. 1.

$$C_e = \frac{C_0 (R-1)}{R \exp\left[\frac{L K_L a (R-1)}{\left(\frac{Q}{A}\right) R}\right] - 1} = \frac{200 \frac{\mu g}{L} (3.404 \frac{m^3}{m^3} - 1)}{3.404 \frac{m^3}{m^3} \exp\left[\frac{15.5\,m \times 0.0110925\,s^{-1} (3.404 \frac{m^3}{m^3} - 1)}{\left[\frac{0.1262 \frac{m^3}{s}}{3.4636\,m^2}\right] 3.404 \frac{m^3}{m^3}}\right] - 1}$$

$$= 5.1 \frac{\mu g}{L}$$

Eq. 1

The parameters required to calculate C_e in Eq. 1 can be found as follows:

Parameter   Location

C_O Table 1

R Eq. 2

L Given in problem statement

$K_L a$ Eq. 10

Q Given in problem statement

A Eq. 18

(1) Stripping Factor

Calculation of stripping factor, R, required in Eq. 1 is given in Eq. 2:

$$R = \frac{\dot{V}}{Q} H = 14.8 \frac{m^3}{m^3} \times 0.230 = 3.404 \frac{m^3}{m^3}$$

Eq. 2

The parameters required to find R in Eq. 2 can be found as follows:

Parameter	Location
$\frac{\dot{V}}{Q}$	3 Possible Cases (see next section)
H	Table 2

(a) Air Flow Rate ($\dot{V}$), Water Flow Rate (Q), Air to Water Ratio ($\frac{\dot{V}}{Q}$), Liquid Mass Loading Rate (L_m), and Air Mass Loading Rate (G_m)

In packed tower aeration rating mode, it is possible to specify either Q and $\frac{\dot{V}}{Q}$, Q and $\dot{V}$, or L_m and G_m with the other three parameters calculated. For the rating case presented in the problem statement, Q and $\frac{\dot{V}}{Q}$ are given as shown in Case 1.

Case 1: Specify Q and $\frac{\dot{V}}{Q}$, Calculate $\dot{V}$, L_m, and G_m

Air Flow Rate

The air flow rate, $\dot{V}$, through the tower can be calculated by the following relationship:

$$\dot{V} = \left(\frac{\dot{V}}{Q}\right) \times Q = \left(14.8 \frac{m^3 \, air}{m^3 \, H_2O}\right) \times 0.1262 \frac{m^3 \, H_2O}{s} = 1.87 \frac{m^3 \, air}{s}$$

Eq. 3

The parameters required to calculate $\dot{V}$ in Eq. 3, can be found as follows:

Parameter	Location
$\frac{\dot{V}}{Q}$	Given in problem statement
Q	Given in problem statement

Water Loading Rate

The water mass loading rate, L_m, can be calculated by the following equation:

$$L_m = \frac{Q\rho_l}{A} = \frac{0.1262 \frac{m^3}{s} \times 999.75 \frac{kg}{m^3}}{3.4636 \, m^2} = 36.427 \frac{kg}{\frac{m^2}{s}}$$

Eq. 4

The parameters required to calculate L_m in Eq. 4 can be found as follows:

Parameter	Location
Q	Given
ρ_l	Table 3
A	Eq. 18

Air Loading Rate

The air mass loading rate, G_m, can be calculated by the following relationship:

$$G_m = \frac{\dot{V}\rho_g}{A} = \frac{1.87 \frac{m^3}{s} \times 1.25 \frac{kg}{m^3}}{3.4636 \, m^2} = 0.675 \frac{kg}{\frac{m^2}{s}}$$

Eq. 5

The parameters required to calculate G_m in Eq. 5 can be found as follows:

Parameter	Location
$\dot{V}$	Eq. 3
ρ_g	Table 3
A	Eq. 18

Case 2: Specify Q and $\dot{V}$, Calculate $\frac{\dot{V}}{Q}$, L_m, and G_m

Air to Water Ratio

The air to water ratio, $\frac{\dot{V}}{Q}$, can be calculated using the following equation:

$$\frac{\dot{V}}{Q} = \frac{\dot{V}}{Q} = \frac{1.87 \frac{m^3}{s}}{0.1262 \frac{m^3}{s}} = 14.8$$

Eq. 6

The parameters required to calculate $\frac{\dot{V}}{Q}$ in Eq. 6 can be found as follows:

Parameter	Location
$\dot{V}$	User-specified
Q	User-specified

Water Loading Rate

The water loading rate, L_m, through the tower can be calculated using Eq. 4 shown above.

Air Loading Rate

The air loading rate, G_m, can be calculated from Eq. 5 given above.

Case 3: Specify L_m and G_m , Calculate Q, $\dot{V}$, and $\frac{\dot{V}}{Q}$

Water Flow Rate

The water flow rate, Q, is calculated by the following equation:

$$Q = \frac{A\,L_m}{\rho_l} = \frac{3.4636\,m^2 \times 36.427\,\frac{kg}{m^2\,s}}{999.75\,\frac{kg}{m^3}} = 0.1262\,\frac{m^3}{s}$$

<div align="right">

Eq. 7

</div>

The parameters required to calculate Q in Eq. 7 can be found as follows:

Parameter	Location
A	Eq. 18
L_m	User-specified
ρ_l	Table 3

Air Flow Rate

The air flow rate, $\dot{V}$, is found by the following relationship:

$$\dot{V} = \frac{A\,G_m}{\rho_g} = \frac{3.4636\,m^2 \times 0.675\,\frac{kg}{m^2\,s}}{1.25\,\frac{kg}{m^3}} = 1.87\,\frac{m^3}{s}$$

<div align="right">

Eq. 8

</div>

The parameters required to calculate $\dot{V}$ in Eq. 8 can be found as follows:

Parameter	Location
A	Eq. 18
G_m	User-specified
ρ_g	Table 3

Air to Water Ratio

The air to water ratio, $\frac{\dot{V}}{Q}$, can be calculated using the following equation:

$$\frac{\dot{V}}{Q} = \frac{\dot{V}}{Q} = \frac{1.87\,\frac{m^3}{s}}{0.1262\,\frac{m^3}{s}} = 14.8$$

Eq. 9

The parameters required to calculate $\frac{\dot{V}}{Q}$ in Eq. 9 can be found as follows:

Parameter	Location
$\dot{V}$	Eq. 8
Q	Given

(2)   Actual Mass Transfer Coefficient

The mass transfer coefficient $K_L a$ is calculated using the following relationship:

$$K_L a = \left(K_L a \right)_{Onda} \times \left(SF \right)_{K_L a} = 0.01848758\,s^{-1} \times 0.6 = 0.0110925\,s^{-1}$$

Eq. 10

The parameters required to calculate $K_L a$ in Eq. 10 can be found as follows:

Parameter	Location
$\left(K_L a \right)_{Onda}$	Eq. 11
$\left(SF \right)_{K_L a}$	Given in problem statement

The Onda mass transfer coefficient $\left(K_L\,a\right)_{Onda}$ is found using Eq. 11:

$$\frac{1}{\left(K_L\,a\right)_{Onda}} = \frac{1}{k_l\,a} + \frac{1}{H\,k_g\,a}$$

$$= \frac{1}{\left(3.309E-04\,\tfrac{m}{s}\right)\left(84.328\,\tfrac{m^2}{m^3}\right)} + \frac{1}{\left(0.230\right)\left(2.8246E-03\,\tfrac{m}{s}\right)\left(84.328\,\tfrac{m^2}{m^3}\right)}$$

$$= 54.090367\,s \Rightarrow$$

$$\left(K_L\,a\right)_{Onda} = 0.01848758\,s^{-1}$$

Eq. 11

The parameters required to calculate $\left(K_L\,a\right)_{Onda}$ in Eq. 11 can be found as follows:

Parameter	Location
k_l	Eq. 12
a	Eq. 13
H	Table 2
k_g	Eq. 17

Liquid Phase Mass Transfer Coefficient

The liquid phase mass transfer coefficient k_l is calculated by the following relationship:

$$k_l = 0.0051\left(\frac{L_m}{a_w\,\mu_l}\right)^{2/3}\left(\frac{\mu_l}{\rho_l\,D_l}\right)^{-0.5}\left(a_t\,d_p\right)^{0.4}\left(\frac{\rho_l}{\mu_l\,g}\right)^{-1/3}$$

$$= 0.0051\left(\frac{36.427\,\tfrac{kg}{m^2\,s}}{84.328\,\tfrac{m^2}{m^3}\times 0.00131\,\tfrac{kg}{m\,s}}\right)^{2/3}\left(\frac{0.00131\,\tfrac{kg}{m\,s}}{999.75\,\tfrac{kg}{m^3}\times 6.44E-10\,\tfrac{m^2}{s}}\right)^{-0.5}\times$$

$$\left(124.7\,\tfrac{m^2}{m^3}\times 0.0889\,m\right)^{0.4}\left(\frac{999.75\,\tfrac{kg}{m^3}}{0.00131\,\tfrac{kg}{m\,s}\times 9.81\,\tfrac{m}{s^2}}\right)^{-1/3}$$

$$= 3.309E-04\,\tfrac{m}{s}$$

Eq. 12

The parameters required to calculate k_l in Eq. 12 can be found as follows:

Parameter	Location
L_m	Eq. 4
a_w	Eq. 13
μ_l	Table 3
ρ_l	Table 3
D_l	Table 2
a_t	Table 4
d_p	Table 4
g	Constant - Known = 9.81 m/s^2

Area Available for Mass Transfer Divided by Vessel Volume

The area available for mass transfer divided by the vessel volume, a, required in Eq. 12 is calculated in the following equation:

$$a = a_w$$

$$a_w = a_t \left\{ 1 - \exp\left[-1.45 \left[\frac{\sigma_c}{\sigma} \right]^{0.75} \left(Re \right)^{0.1} \left(Fr \right)^{-0.05} \left(We \right)^{0.2} \right] \right\}$$

$$= 124.7 \tfrac{m^2}{m^3} \left\{ 1 - \exp\left[-1.45 \left[\frac{0.033 \tfrac{N}{m}}{0.0742 \tfrac{N}{m}} \right]^{0.75} \left(222.99 \right)^{0.1} \left(0.016876 \right)^{-0.05} \left(0.1434 \right)^{0.2} \right] \right\}$$

$$= 84.328 \tfrac{m^2}{m^3}$$

Eq. 13

The parameters required to calculate a_w in Eq. 13 can be found as follows:

Parameter	Location
a_t	Table 4
σ_c	Table 4
σ	Table 3
Re	Eq. 14
Fr	Eq. 15
We	Eq. 16

Reynolds Number

The Reynolds Number, *Re*, needed for the calculation of a_w is defined by:

$$Re = \frac{L_m}{a_t \, \mu_l} = \frac{36.427 \, \frac{kg}{m^2 \, s}}{124.7 \, \frac{m^2}{m^3} \times 0.00131 \, \frac{kg}{m \, s}} = 222.99$$

Eq. 14

The parameters required to calculate *Re* in Eq. 14 can be found as follows:

Parameter	Location
L_m	Eq. 4
a_t	Table 4
μ_l	Table 3

Froude Number

The Froude Number, *Fr*, is calculated using the equation below:

$$Fr = \frac{\left(L_m\right)^2 a_t}{\left(\rho_l\right)^2 g} = \frac{\left(36.427 \, \frac{kg}{m^2 \, s}\right)^2 124.7 \, \frac{m^2}{m^3}}{\left(999.75 \, \frac{kg}{m^3}\right)^2 9.81 \, \frac{m}{s^2}} = 0.016876$$

Eq. 15

The parameters required to calculate *Fr* in Eq. 15 can be found as follows:

Parameter	Location
L_m	Eq. 4
a_t	Table 4
ρ_l	Table 3
g	Constant - Known = 9.81 m/s^2

Weber Number

The Weber Number, *We*, used to find a_w is found by the following:

$$We = \frac{\left(L_m\right)^2}{\rho_l \, a_t \, \sigma} = \frac{\left(36.427 \, \frac{kg}{m^2 \, s}\right)^2}{999.75 \, \frac{kg}{m^3} \times 124.7 \, \frac{m^2}{m^3} \times 0.0742 \, \frac{N}{m}} = 0.1434$$

Eq. 16

63

The parameters required to calculate *We* in Eq. 16 can be found as follows:

Parameter	Location
L_m	Eq. 4
ρ_l	Table 3
a_t	Table 4
σ	Table 3

Gas Phase Mass Transfer Coefficient

The gas phase mass transfer coefficient, k_g, used in the calculation of $\left(K_L a \right)_{Onda}$ is found by using the equation below:

$$k_g = 5.23 \left(a_t D_g \right) \left[\frac{G_m}{a_t \mu_g} \right]^{0.7} \left[\frac{\mu_g}{\rho_g D_g} \right]^{1/3} \left(a_t d_p \right)^{-2}$$

$$= 5.23 \left(124.7 \tfrac{m^2}{m^3} \times 7.89E - 06 \tfrac{m^2}{s} \right) \left[\frac{0.675 \tfrac{kg}{m_s}}{124.7 \tfrac{m^2}{m^3} \times 0.0000172 \tfrac{kg}{m_s}} \right]^{0.7} \times$$

$$\left[\frac{0.0000172 \tfrac{kg}{m_s}}{1.25 \tfrac{kg}{m^3} \times 7.89E - 06 \tfrac{m^2}{s}} \right]^{1/3} \left(124.7 \tfrac{m^2}{m^3} \times 0.0889\, m \right)^{-2}$$

$$= 2.8246E - 03 \tfrac{m}{s}$$

Eq. 17

The parameters required to calculate k_g in Eq. 17 can be found as follows:

Parameter	Location
a_t	Table 4
D_g	Table 2
G_m	Eq. 5
μ_g	Table 3
ρ_g	Table 3
d_p	Table 4

b) *Sample Rating Mode Calculations of Cross-Sectional Area and Volume*

(1) Tower Cross-Sectional Area

The cross-sectional area, A, of the tower can be calculated from the tower diameter given in the problem statement using the following relationship:

$$A = \pi \times \left(\frac{D}{2}\right)^2 = \pi \times \left(\frac{2.10\,m}{2}\right)^2 = 3.4636\,m^2$$

Eq. 18

The parameters required to calculate A in Eq. 18 can be found as follows:

Parameter	Location
D	Given in problem statement

(2) Tower Volume

Tower volume, V, is calculated from design area and tower height using Eq. 19:

$$V = L \times A = 15.5\,m \times 3.4636\,m^2 = 53.686\,m^3$$

Eq. 19

The parameters required to calculate V in Eq. 19 can be found as follows:

Parameter	Location
L	Given in problem statement
A	Eq. 18

c) *Sample Power Calculation for Packed Tower Aeration Rating Mode*

This calculation is the same as for design mode and will not be repeated here.

d) *Sample Pressure Drop Calculation for Packed Tower Aeration Rating Mode*

The pressure drop is calculated by an iterative process, described below. In rating mode, all the parameters necessary to calculate the value of the y-axis on the Eckert curves are known. The value of the y-axis on the Eckert curves, y_{actual}, can be calculated from the following equation. Note that the relationships involved are empirical so the input units must be as shown here but the output units are not meaningful.

$$y_{actual} = \frac{\left(G_m\right)^2 C_f \left(\mu_l\right)^{0.1}}{\rho_g \left(\rho_l - \rho_g\right)} = \frac{\left(0.675\frac{kg}{m^2 \cdot s}\right)^2 12.0 \left(0.00131\frac{kg}{m \cdot s}\right)^{0.1}}{1.25\frac{kg}{m^3}\left(999.75\frac{kg}{m^3} - 1.25\frac{kg}{m^3}\right)} = 0.0022556$$

<div align="right">**Eq. 20**</div>

The parameters required to determine y_{actual} in Eq. 20 as follows:

Parameter	Location
G_m	Eq. 5
C_f	Table 4
μ_l	Table 3
ρ_g	Table 3
ρ_l	Table 3

Once y_{actual} is known, it is necessary to iterate the value of pressure drop until the calculated value of the y-axis on the Eckert curve, $y_{calculated}$, matches the actual value, y_{actual} within 1 %. Pressure drop per packing height is usually iterated between the values of 50 and 1200 N/m²/m since that is the region for which the correlations were developed. In the program, the pressure drop is iterated from 1 to 1200 N/ m²/m. The pressure drop iteration step is initially set to 1.0 N/m²/m. If convergence is not achieved between 1 and 1200 N/ m²/m, the step is lowered to 0.1 N/m²/m. If convergence is not achieved between 0.1 and 1200 N/ m²/m, then the step is lowered to 0.01 N/m²/m. If convergence is still not achieved, then the process ends and the user is alerted that the program is unable to converge on a pressure drop per unit length value. If convergence is achieved for a value less than 50 N/m²/m, a warning message will be displayed saying that the convergent pressure drop is outside the range for which the correlation was developed. The iteration process is described below. For the sample calculations here, the process will be shown for a pressure drop per unit length that does not achieve convergence (40 N/m²/m) and then for the convergent pressure drop per unit length value (50 N/m²/m).

Iteration Process to Calculate Pressure Drop:

(1) Calculate the parameter, E:

$$E = -\log_{10}\left\{\left|\frac{\dot{V}}{Q}\right|\sqrt{\left|\rho_g/\rho_l\right| - \left|\rho_g/\rho_l\right|^2}\right\}$$

$$= -\log_{10}\left\{\left|14.8\right|\sqrt{\left|1.25\tfrac{kg}{m^3}/999.75\tfrac{kg}{m^3}\right| - \left|1.25\tfrac{kg}{m^3}/999.75\tfrac{kg}{m^3}\right|^2}\right\} = 0.2815006563$$

Eq. 21

The parameters required to calculate E in Eq. 21 can be found as follows:

Parameter	Location
G_m	Eq. 5
C_f	Table 4
μ_l	Table 3
ρ_g	Table 3
ρ_l	Table 3

(2) Specify a pressure drop, $\Delta P/L$, in N/m^2/m $= 40$

(3) Calculate the parameter, F:

$$F = \log_{10}\left(\Delta P/L\right) = \log_{10}\left(40\tfrac{N}{m^2\cdot m}\right) = 1.6020599913$$

Eq. 22

(4) Calculate the parameters, a_0, a_1, and a_2:

$$a_0 = -6.6599 + 4.3077\,F - 1.3503\,F^2 + 0.15931\,F^3$$
$$= -6.6599 + 4.3077\left(1.6020599913\right) - 1.3503\left(1.6020599913\right)^2 + 0.15931\left(1.6020599913\right)^3$$
$$= -2.5693236381$$

Eq. 23

$$a_1 = 3.0945 - 4.3512\,F + 1.6240\,F^2 - 0.20855\,F^3$$
$$= 3.0945 - 4.3512\left(1.6020599913\right) + 1.6240\left(1.6020599913\right)^2 - 0.20855\left(1.6020599913\right)^3$$
$$= -0.56575564354$$

Eq. 24

$$a_2 = 1.7611 - 2.3394\,F + 0.89914\,F^2 - 0.11597\,F^3$$
$$= 1.7611 - 2.3394\left(1.6020599913\right) + 0.89914\left(1.6020599913\right)^2 - 0.11597\left(1.6020599913\right)^3$$
$$= -\,0.15588003590$$

<div align="right">**Eq. 25**</div>

(5) Determine the value of $y_{calculated}$ from the following equation:

$$y_{calculated} = 10^{\left(a_0 + a_1\left(E\right) + a_2\left(E\right)^2\right)}$$
$$= 10^{\left(-2.5693236381 + \left(-0.56575564354\right)\left(0.2815006563\right) + \left(-0.15588003590\right)\left(0.2815006563\right)^2\right)} = 0.00182$$

<div align="right">**Eq. 25**</div>

(6) Calculate the percent difference between $y_{calculated}$ and y_{actual}:

$$\%\ Difference = \left|\frac{y_{actual} - y_{calculated}}{y_{actual}}\right| \times 100 = \left|\frac{0.0022556 - 0.00182}{0.00224}\right| \times 100 = 19.3\%$$

<div align="right">**Eq. 26**</div>

Since $y_{calculated}$ is not within 1 % of y_{actual} then pressure drop is set equal to the next iterative value and the process returns to step (2) above. Here we will skip to the correct pressure drop and show how the process is complete.

(2) Specify a pressure drop, $\Delta P / L$, in N/m^2/m $= 50$

(3) Calculate the parameter, F:

$$F = \log_{10}\left(\Delta P / L\right) = \log_{10}\left(50\,\tfrac{N}{m^2 \cdot m}\right) = 1.698970004$$

<div align="right">**Eq. 27**</div>

(4) Calculate the parameters, a_0, a_1, and a_2:

$$a_0 = -6.6599 + 4.3077\,F - 1.3503\,F^2 + 0.15931\,F^3$$
$$= -6.6599 + 4.3077\left(1.698970004\right) - 1.3503\left(1.698970004\right)^2 + 0.15931\left(1.698970004\right)^3$$
$$= -2.457618371$$

<div align="right">**Eq. 28**</div>

$$a_1 = 3.0945 - 4.3512\,F + 1.6240\,F^2 - 0.20855\,F^3$$
$$= 3.0945 - 4.3512\,(1.698970004) + 1.6240\,(1.698970004)^2 - 0.20855\,(1.698970004)^3$$
$$= -0.633128698$$

<div align="right">**Eq. 29**</div>

$$a_2 = 1.7611 - 2.3394\,F + 0.89914\,F^2 - 0.11597\,F^3$$
$$= 1.7611 - 2.3394\,(1.698970004) + 0.89914\,(1.698970004)^2 - 0.11597\,(1.698970004)^3$$
$$= -0.186829267$$

<div align="right">**Eq. 30**</div>

(5) Determine the value of $y_{calculated}$ from the following equation:

$$y_{calculated} = 10^{\left(a_0 + a_1\,(E) + a_2\,(E)^2\right)}$$
$$= 10^{\left(-2.457618371 + (-0.633128698)(0.2815006563) + (-0.186829267)(0.2815006563)^2\right)} = 0.002235$$

<div align="right">**Eq. 31**</div>

(6) Calculate the percent difference between $y_{calculated}$ and y_{actual}:

$$\% \ Difference = \left|\frac{y_{actual} - y_{calculated}}{y_{actual}}\right| \times 100 = \left|\frac{0.002256 - 0.002235}{0.002222556}\right| \times 100 = 0.91\%$$

<div align="right">**Eq. 32**</div>

Since $y_{calculated}$ is within 1 % of y_{actual}, the iterative process is complete and pressure drop per unit length is equal to the value specified in step (2) = 50 N/m^2/m.

e) *Results for All Compounds*

Table 5 below shows the effluent concentration results for all contaminants for this sample rating mode case of packed tower aeration. The calculation of parameters shown in Table 5 is done using the methods shown above for TCE.

Table 5 - Results for All Contaminants in Rating Mode

Compound	C_0 (µg/L)	C_{TO} (µg/L)	$K_L a$ (1/s)	R (-)	C_e (µg/L)
Trichloroethylene (TCE)	200.0	5.0	0.01109	3.404	5.1
Tetrachloroethylene (PCE)	150.0	5.0	0.0120	5.3428	1.9
Vinyl Chloride	60.0	1.0	0.0158	8.0808	0.14
Ethylbenzene	30.0	5.0	0.00903	2.516	1.9
Toluene	80.0	5.0	0.00946	2.4716	4.5
1,1-Dichloroethene (1,1-DCE)	85.0	7.0	0.0152	10.064	0.23

3. Sample Program Run of ASAP™ to Verify Sample Calculations for Packed Tower Aeration in Rating Mode

To start the ASAP™ program, double click on the ASAP™ icon in the *ETDOT Programs* group in windows. The screen shown in Figure 1 will appear.

Figure 1 - ASAP™ Title Window

Click on the *Continue* button on the screen shown in Figure 1 and the menu shown in Figure 2 will appear.

70
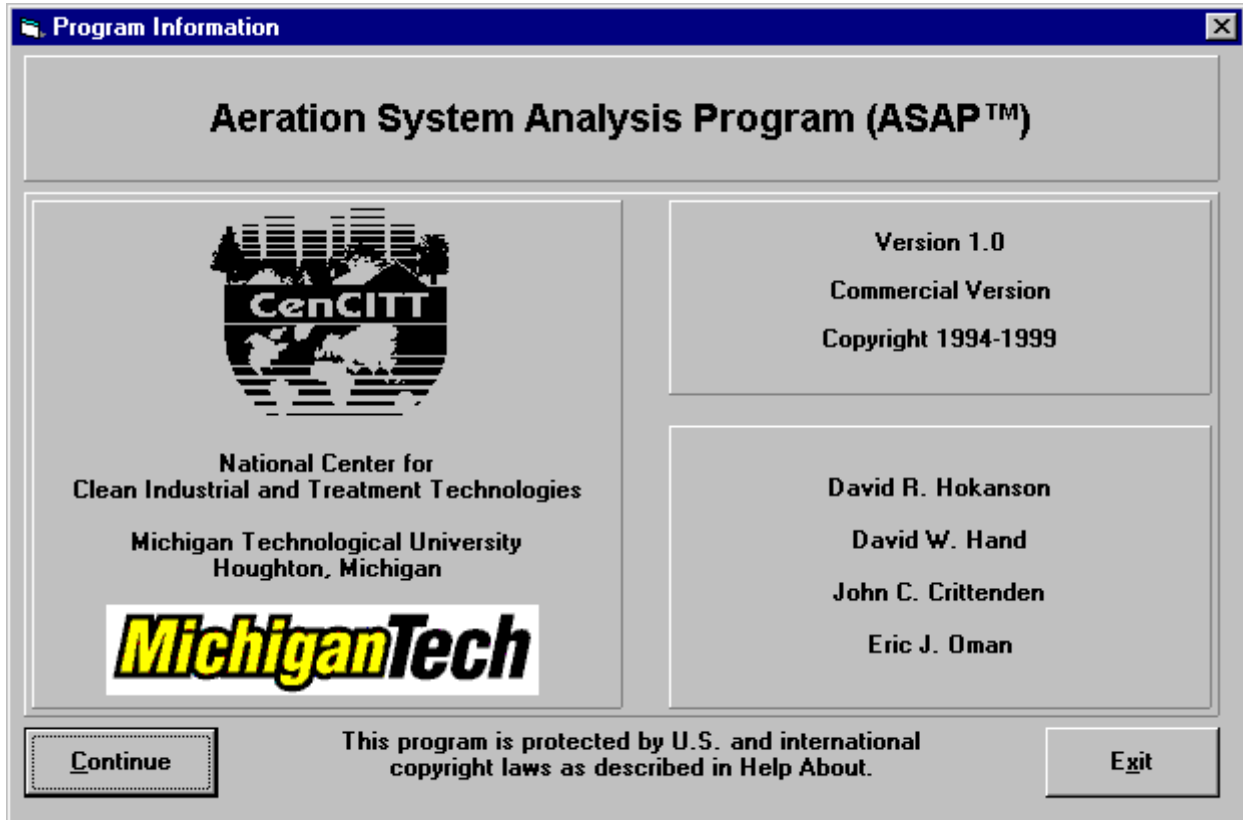
Figure 2 - Main Menu Window in ASAP™

Click on the *Enter Rating Mode* button for Packed Tower Aeration (option 2 in Figure 2) and the rating mode screen for packed tower aeration shown in Figure 3 will appear.

Figure 3 - Rating Mode Window for Packed Tower Aeration

a) Tower Parameters

The tower parameters can be found in the middle of the left-hand column of the rating mode window as shown in Figure 3 (and highlighted in Figure 4).

Figure 4 - Tower Parameters Portion of Rating Mode Window

The tower parameters used in this rating situation are those previously calculated in the design mode case for packed tower aeration. The tower diameter used in this case is 2.10m . The tower height is 15.5 m. The tower area calculated by the program as 3.46 m^2 agrees with the sample calculations (see Eq. 18). The tower volume determined by the program to be 53.7 m^3 is also in agreement with the sample calculations (see Eq. 19).

b)   Physical Properties of Air and Water

Specify pressure and temperature in the lower left-hand corner of the window shown in Figure 3. This portion of the packed tower aeration rating mode window is shown in Figure 5.

Figure 5 - Operating Conditions Portion of Rating Mode Window

Click on the *Display Physical Properties of Air and Water* button in Figure 3 (and highlighted in Figure 5) to show the properties of air and water at the specified temperature and pressure (101325 Pa and 10°C). Figure 6 shows the air and water properties window for this case.

Figure 6 - Air and Water Properties Window

The properties shown in Figure 6 are by default calculated from correlations so the user should not have to change their values. In the rare case that the user would like to enter a value for any of these properties instead of using the correlations, it is possible to do so on the window shown in Figure 6. Click on the *OK* button shown in Figure 6 to close the window.

It can be seen that the air and water properties shown in Figure 3 agree with the properties shown in Table 3.

c)   *Packing Properties*

The next step is to choose the appropriate packing. Packing selection is located on the bottom of the left-hand side of the design mode window shown in Figure 3. This portion of Figure 3 is highlighted in Figure 7.
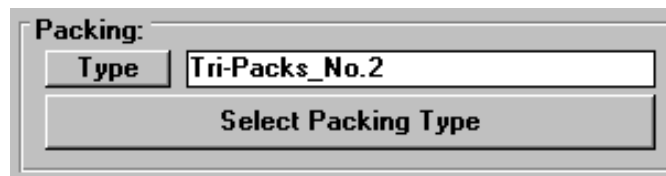
Figure 7- Packing Selection Portion of Rating Mode Window

Click on the *Select Packing Type* button shown in Figure 3 (and highlighted in Figure 7). The packing database window shown in Figure 8 will appear.
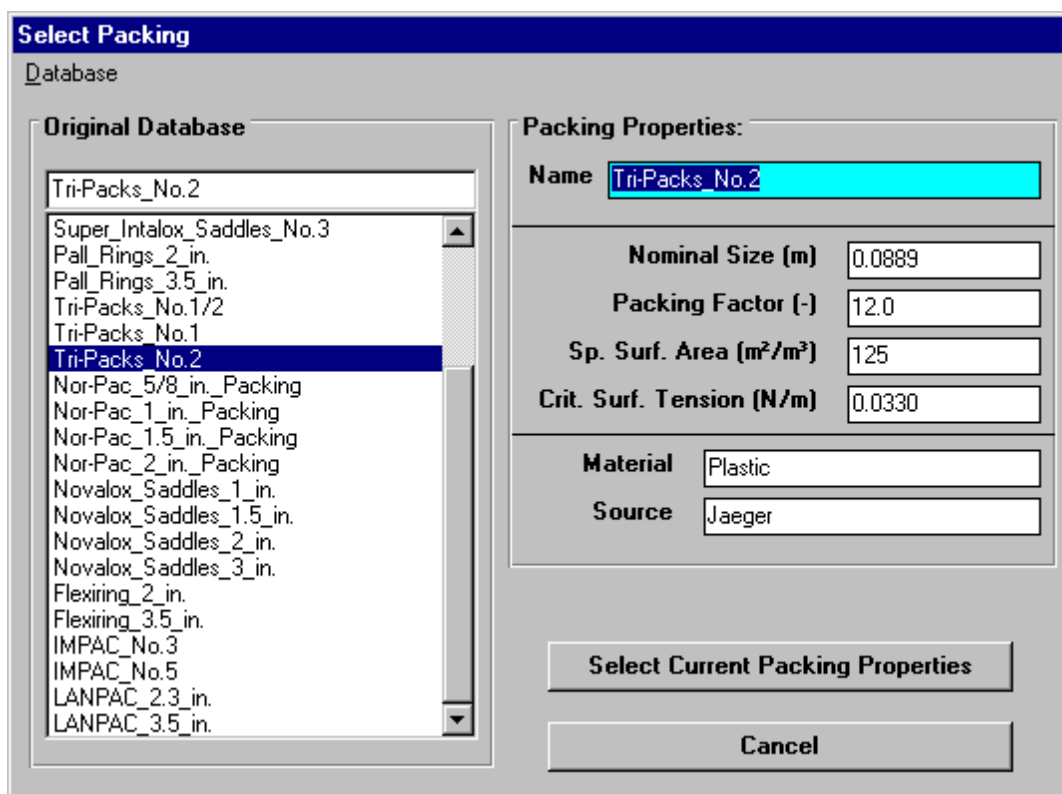
Figure 8- Select Packing Type Window

ASAP™ contains a database of packing properties available from vendor data. The packing properties used in development of the product are shown in Figure 8. The left-hand side of the packing database window shown in Figure 9 contains a listing of available packings. The item called "Tripacks No. 2" in the list is the 3.5 inch plastic tripacks requested in the problem statement. Click on this item in the list as shown in Figure 8 so that this item is selected. Then select the properties of this packing for use in the design by clicking on the *Select Current Packing Properties* button shown in Figure 8.

It is also possible for the user to enter properties of additional packings. It is not possible for the user to modify the list of packings from vendor data supplied with the program (called the "Original Database"). However, there is a separate database of packing properties from user input available with the software. An alternative method to enter the properties of 3.5 inch plastic tripacks is as follows. Click on the *Select Packing Type* button in the window shown in Figure 3 (and highlighted in 8). The window shown in Figure 8 will appear again. In the *Database* menu shown in Figure 9, it is seen that currently the "Original Database" option is selected.
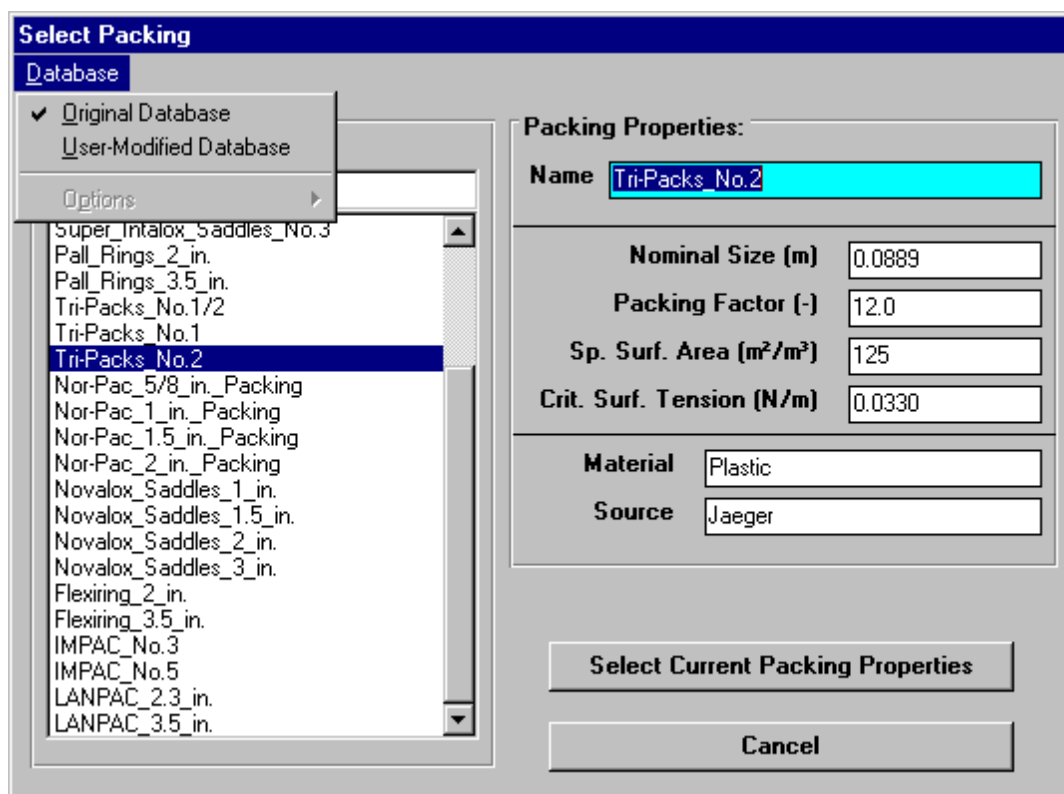
Figure 9- Database Menu in Select Packing Type Window

To input data, the user must click on the "User Modified Database" item in the menu shown in Figure 9. Then the *Select Packing Type* window will show a database of user input packing parameters, as shown in Figure 10.

Figure 10- User Modified Database in Select Packing Type Window

On the screen shown in Figure 10, it is possible to input values for all packing properties. Figure 10 shows the screen after the properties of 3.5 inch plastic tripacks have been input. To select these properties for use in the current design, click on the *Select Current Packing Properties* button shown in Figure 10.

d) *Flow and Loading Parameters*

Flow and loading parameters are shown in the upper right-hand side of Figure 3. This portion of Figure 3 is reproduced here as Figure 11.

Figure 11 - Flow and Loading Parameters

Explanation of the origin of the values for the properties shown in Figure 11 is provided here. The water flow rate of 2000 gpm which converts to 0.1262 m^3/s was specified in the problem statement. The air to water ratio used in this rating case is 14.8. The air flow rate was calculated in the program as 1.87 m^3/s. This value agrees with the sample calculations section (see Eq. 3). The air loading rate was calculated by the program as 0.67 kg/m^2/s. This value agrees with the sample calculations section (see Eq. 5). The water loading rate was calculated by the program as 36.4 kg/m^2/s. This number agrees with the sample calculations section (see Eq. 4).

Click on the *Pick Flow and Loading Parameters to Specify* button to view the window shown in Figure 12.
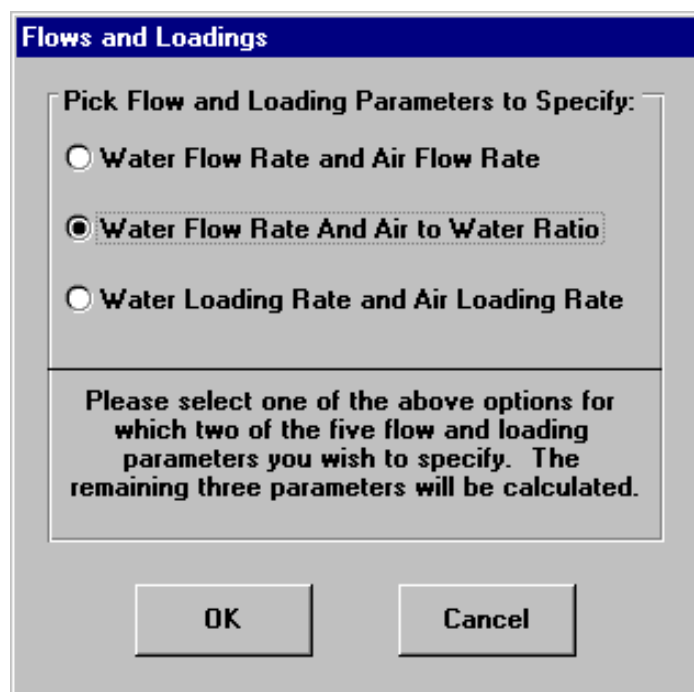
Figure 12 - Flows and Loadings Parameter Specification Window

This window allows the user to chose which flow and loading parameters are specified for design rating. The calculations for the flows and loadings shown above in Figure 4 (and highlighted in Figure 11) will be based on whichever option is selected here. Click on the *OK* button to return to the rating mode window.

e)   *Chemical Properties*

Chemical properties for each of the six components can be retrieved from StEPP™. When the screen shown in Figure 3 loads, the properties of six contaminants load as a default rating situation. Before retrieving the chemical properties of the six chemicals required in the current rating situation, it is necessary to delete the six default chemicals shown in the Contaminant of Interest list box in the middle of the right-hand column shown in Figure 3. This portion of the rating mode window is highlighted in Figure 13.

Figure 13 - Contaminant Selection Portion of Rating Mode Window

To delete each chemical click on the *Delete* button located in between the *Add* and *Edit Properties* buttons shown in Figure 3 (and highlighted in Figure 13). Click the *Delete* button once for each chemical until all chemicals have been deleted from the *Contaminant of Interest* list box.

It is now possible to add the chemicals required for the current design. To do so, click on the *Add* button shown on the bottom left-hand corner of the window shown in Figure 3 (and highlighted in Figure 13). Figure 14 shows the window that will appear.

Figure 14 - Contaminant Properties Input Window

The following properties (with their default units in parentheses) are required for each component:

- Name

- Molecular weight (*mg/mmol*)

- Henry's constant (*dimensionless*)

- Molar volume at the normal boiling point temperature (m^3/*kmol*)

- Normal boiling point (*K*)

- Liquid diffusivity (m^2/*s*)

- Gas diffusivity (m^2/*s*)

- Initial (influent) concentration (*mg/L*)

- Treatment objective (*mg/L*)

The user can input data by clicking on a text box and typing in the corresponding value. By pressing the Enter key, the Tab key or clicking on another text box or button, the data is updated. The default units can be changed in the pull-down menus to the right of the text boxes.

(1) Transferring Properties from StEPP™ to ASAP™

ASAP™ has the capability of transferring the physical properties of contaminants from Software to Estimate Physical Properties (StEPP™). There are two options for transferring data from StEPP into ASAP: (a) Create Export File for AdDesignS/ASAP and (b) Copy to Clipboard for AdDesignS/ASAP. Both choices are available in the *Options* menu within StEPP. The StEPP™ main window highlighting the *Options* menu is shown in Figure 15.

Figure 15 - StEPP™ Main window

The operating temperature and pressure, with units of degrees Celsius and Pascals respectively, must be entered. Chemicals can be selected using the scroll bar on the *Available Contaminants* block or the *Find, Find Next Occurrence,* or *Synonyms* buttons, highlighting the chemical, and clicking on the *Select Current Contaminant* button. Repeat this process for all contaminants of interest. After the contaminants have been selected in StEPP™ and their properties calculated at the proper temperature and pressure, they can be transferred from StEPP to ASAP using either of two options, which are described below: (a) Create Export File for AdDesignS/ASAP and (b) Copy to Clipboard for AdDesignS/ASAP.

To create a StEPP™ export file, select *Create Export File for AdDesignS/ASAP™* from the *Options* menu. The window shown in Figure 16 will appear. Enter a file name to save the export file. This file will be available for use in ASAP™.

Figure 16 - Save StEPP™ Export File window

To import the chemicals and their physical properties to ASAP™ from the StEPP™ export file, click on the *Add* button in the *Component Properties* block of the ASAP™ main window. The Component Properties window shown in Figure 17 will appear.

Figure 17 - Component Properties window (adding new components)

To open the StEPP™ export file, click the *Import StEPP™ export file* button on the Component Properties window. The Load StEPP™ Export File window shown in Figure 18 will appear.
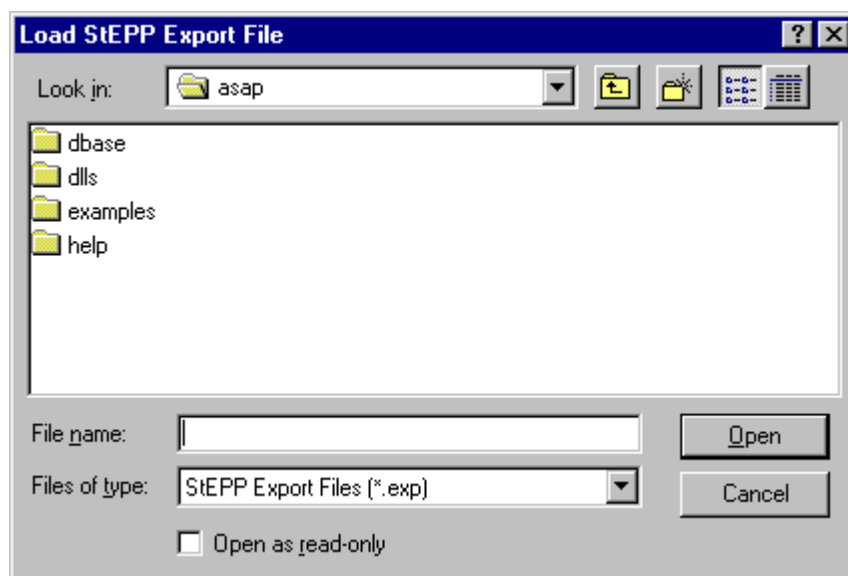
Figure 18 - Load StEPP™ Export File window

The file which was previously saved in StEPP™ can be selected in this window. The window shown in Figure 19 announcing the successful import of the components will appear. To return to the ASAP™ main window, click on *OK*.
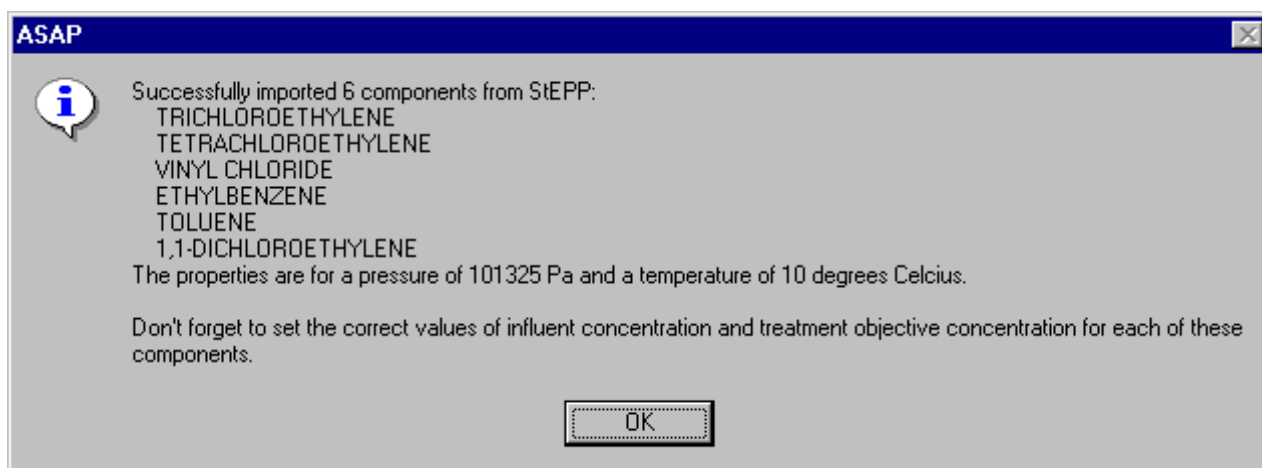
Figure 19 - Successful Import of Components from StEPP™ window

*(b)   Transferring Chemical Properties from
StEPPÔ to ASAPÔ Using the Copy to
Clipboard for AdDesignS/ASAP Option*

To copy selected StEPP™ data to the Windows clipboard for export into ASAP™,
select *Copy to Clipboard for AdDesignS/ASAP* from the *Options* menu within StEPP™.
The message box shown in Figure 20 will appear, verifying that all of the StEPP™ data is
now stored in the Windows clipboard.
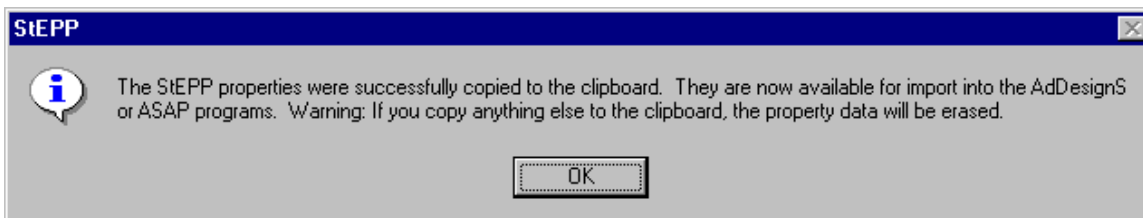
Figure 20 – Successful Copy to Clipboard from StEPP™ Message Box

To import the chemicals and their physical properties to ASAP™ from the data on
the clipboard, click on the *Add* button in the *Component Properties* block of the ASAP™
main window. The Component Properties window shown in Figure 21 will appear.

Figure 21 - Component Properties window (adding new components)

To import the StEPP™ data from the Windows clipboard, click the *Import from Clipboard* button on the Component Properties window. The window shown in Figure 22 will appear, showing that the properties have been successfully transferred into ASAP.
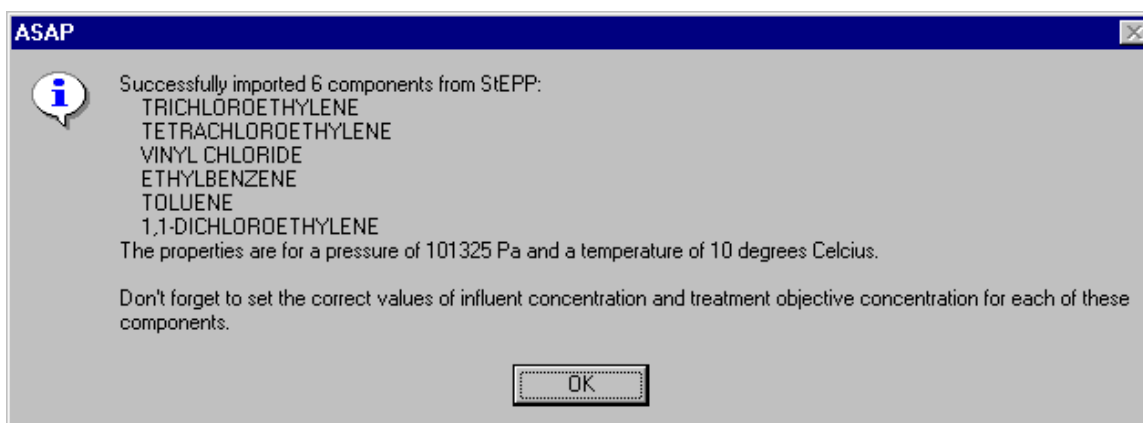
Figure 22 – Successful Import from StEPP™ Window

The following properties will be transferred to ASAP™ from StEPP™, unless they are not available:

- Molecular weight (*mg/mmol*)

- Henry's constant (*dimensionless*)

- Molar volume at the normal boiling point temperature (*mL/gmol*)

- Normal boiling point (*Celsius*)

- Liquid diffusivity (m^2/s)

- Gas diffusivity (m^2/s)

The name of the chemical will also be transferred. If any of the properties above are not available in StEPP™ for a selected chemical, the chemical with missing properties will not be imported and a warning message will be displayed.

Click on the *OK* button to continue. Figure 3 appears. As shown in Figure 19 or Figure 22, it is necessary to input influent concentrations and treatment objectives for each of the six components retrieved. To do so, select each contaminant one at a time in the Design Contaminant list box shown in the lower right-hand corner of Figure 3. Then click on the *Edit Properties* button. Figure 23 shows the window that appears for trichloroethylene.

Figure 23 - Specify Contaminant Properties Window for Trichloroethylene

The properties molecular weight, Henry's constant, molar volume, normal boiling point, liquid diffusivity, and gas diffusivity are already correct since they were retrieved from StEPP™. The influent concentration and treatment objective shown at the bottom of the screen must be input since they will vary from case to case. These properties shown in Figure 23 already reflect the values for the current design case. It is seen that the properties shown in Figure 23 agree with the trichloroethylene properties shown in Tables 1 and 2.

Figure 24 shows the *Specify Contaminant Properties* window for tetrachloroethylene. It can be seen that the properties shown in Figure 24 agree with the properties of tetrachloroethylene shown in Tables 1 and 2.

Figure 24 - Specify Contaminant Properties Window for Tetrachloroethylene

Figure 25 shows the *Specify Contaminant Properties* window for vinyl chloride. It can be seen that the properties shown in Figure 25 agree with the properties of vinyl chloride shown in Tables 1 and 2.

Figure 25 - Specify Contaminant Properties Window for Vinyl Chloride

Figure 26 shows the *Specify Contaminant Properties* window for ethylbenzene. It can be seen that the properties shown in Figure 25 agree with the properties of ethylbenzene shown in Tables 1 and 2.

Figure 26 - Specify Contaminant Properties Window for Ethylbenzene

Figure 27 shows the *Specify Contaminant Properties* window for toluene. It can be seen that the properties shown in Figure 25 agree with the properties of toluene shown in Tables 1 and 2.

Figure 27 - Specify Contaminant Properties Window for Toluene

Figure 28 shows the *Specify Contaminant Properties* window for 1,1-dichloroethene. It can be seen that the properties shown in Figure 25 agree with the properties of 1,1-dichloroethene shown in Tables 1 and 2.

Figure 28 - Specify Contaminant Properties Window for 1,1-Dichloroethene

f) *Mass Transfer Parameters and Effluent Results*

The mass transfer parameters and effluent results are shown on the lower right-hand corner of the rating mode window shown in Figure 3. This portion of the window is highlighted in Figure 29.

Figure 29 - Mass Transfer Parameters and Effluent Results for Trichloroethylene

This section of the rating mode window lists various parameters for rating mode calculations of the effluent concentrations such as the Onda K_La, K_La safety factor, design K_La, influent concentration, treatment objective and air pressure drop. The Onda K_La and design K_La values match the values for the sample calculations (see Eq. 10 and Eq. 11, respectively). The effluent concentration calculated by the program is 5.1 µg/L, which agrees with the sample calculations (see Eq. 1). This reflects a percent removal of 97.5. The air pressure drop calculated by the program for this rating mode case is 50.0 Pa/m, which matches the sample calculations (see Eq. 20 - Eq. 32).

The mass transfer parameters and effluent results portion of the main window is shown for the other components in Figure 30 - Figure 34. The mass transfer parameters and effluent results for each component shown in the figures match the values given in the sample calculations (see Table 5).

Figure 30 - Mass Transfer Parameters and Effluent Results for Tetrachloroethylene

Figure 31 - Mass Transfer Parameters and Effluent Results for Vinyl Chloride

Figure 32 - Mass Transfer Parameters and Effluent Results for Ethylbenzene

Figure 33 - Mass Transfer Parameters and Effluent Results for Toluene

Figure 34 - Mass Transfer Parameters and Effluent Results for 1,1-Dichloroethylene

g)   *Power Parameters*

By clicking on the *Perform Power Calculations* option in the *Power* menu shown in Figure 3, the power calculations for this rating case are made. The resultant window is shown in Figure 35. The sample power calculations were given in the design mode case and not repeated for rating mode so there are no values for comparison available.

Figure 35 - Power Parameters

h) *Viewing Effluent Concentration Results for All Contaminants*

For the current design, it is useful to see what the effluent concentrations of all contaminants on the same window. ASAP provides a convenient method for seeing these results.

By clicking on the ***Concentration Results*** button in the lower left-hand corner of the packed tower aeration – rating mode window shown in Figure 3, the user will see the concentration results for all contaminants using the given design (see Figure 36).

Concentration Results

CN	Cinf	Cto	D % R	Ceff	A % R
1	200	5.00	97.5	5.05	97.5
2	150	5.00	96.7	1.91	98.7
3	60.0	1.00	98.3	0.141	99.8
4	30.0	5.00	83.3	1.85	93.8
5	80.0	5.00	93.8	4.47	94.4
6	85.0	7.00	91.8	0.225	99.7

Contaminant Glossary:

CN	Contaminant Name
1	trichloroethylene
2	tetrachloroethylene
3	vinyl chloride
4	ethylbenzene
5	toluene
6	1,1-dichloroethylene

Glossary:

Label	Description
CN	Contaminant Number
Cinf	Influent Concentration (ug/L)
Cto	Treatment Objective (ug/L)
D % R	Desired Percent Removal
Ceff	Effluent Concentration (ug/L)
A % R	Achieved Percent Removal

OK

Figure 36 – View Concentration Results for All Contaminants Window

This window provides a quick method to see whether the given design will meet the treatment objectives for all contaminants.

C. Packed Tower Aeration - Nomenclature

A Tower area (m^2)

a Area available for mass transfer divided by vessel volume (m^2/m^3)

a_t Specific surface area of packing (m^2/m^3)

a_w Wetted surface area of packing which is equal to a for a packed tower (m^2/m^3)

a_0 Empirical parameter (dimensionless)

a_1 Empirical parameter (dimensionless)

a_2 Empirical parameter (dimensionless)

C_e Effluent Concentration (mg/L)

C_f Packing factor (dimensionless)

C_0 Concentration discharged (mg/L)

C_o^* Liquid phase concentration in equilibrium with exiting gas (mg/L)

C_{TO} Treatment objective concentration (mg/L)

D Tower diameter (m)

D_g Gas diffusivity (m^2/s)

D_l Liquid diffusivity (m^2/s)

d_p Nominal diameter of packing material (m)

E Empirical parameter (dimensionless)

Eff_b Blower efficiency (expressed as decimal), which is a net efficiency accounting for both the fan and motor on the blower

Eff_p Pump efficiency (expressed as decimal)

F Empirical parameter (dimensionless)

Fr Froude number (dimensionless)

g Gravitational constant $(m/s^2) = 9.81$

G_m Gas mass loading rate $(kg/m^2/s)$

G_{me}	Mass flow rate of air (kg/s)
H	Henry's constant (dimensionless)
k_g	Gas phase mass transfer coefficient (m/s)
k_l	Liquid phase mass transfer coefficient (m/s)
$K_L a$	Design mass transfer coefficient ($1/s$)
$(K_L a)_{Onda}$	Onda mass transfer coefficient ($1/s$)
k_p	Constant used to estimate gas pressure drop in tower for losses other than that in the tower packing ($N\,s^2/m^4$) = 275
L	Packing height (m)
L_m	Liquid mass loading rate ($kg/m^2/s$)
M	Empirical parameter (dimensionless)
MW	Molecular weight ($kg/kmol$)
n_a	Constant used in determining blower brake power = 0.283 for air
% Difference	Percent difference between y_{actual} and $y_{calculated}$ for a trial pressure drop per unit length, $\Delta P / L$
$P_{ambient}$	Ambient air pressure (N/m^2)
P_{blower}	Blower brake power (kW)
P_{in}	Inlet air pressure to packed tower (bottom of tower) (N/m^2)
P_{out}	Outlet air pressure from packed tower (top of tower) (N/m^2)
P_{Pump}	Pump brake power (kW)
P_{Total}	Total power requirement for packed tower aeration (kW)
$(\Delta P / L)$	Pressure drop per unit length ($N/m^2/m$)
ΔP_{losses}	Pressure drop through the demister, packing support plate, duct work, inlet and outlet of the tower (N/m^2)
Q	Water flowrate (m^3/s)
R	Stripping Factor (dimensionless)
Re	Reynolds number (dimensionless)
R_g	Universal gas constant ($J/kg/K$) = 286.7

$\left\|SF\right\|_{K_L a}$	Safety factor (dimensionless)
T	Operating temperature (K)
T_{air}	Air temperature (K)
T_{NBP}	Normal boiling point temperature ($^\circ C$)
V	Tower volume (m^3)
$\dot{V}$	Air flowrate (m^3/s)
$\frac{\dot{V}}{Q}$	Air to water ratio (dimensionless)
$\left(\frac{\dot{V}}{Q}\right)_{min}$	Minimum air to water ratio (dimensionless)
$\left(\frac{\dot{V}}{Q}\right)_{mult}$	User-specified air to water ratio (dimensionless)
V_b	Molar volume ($m^3/kmol$)
We	Weber number (dimensionless)
y_{actual}	Actual value of the y-axis on the Eckert curve for rating mode
$y_{calculated}$	Calculated value of the y-axis on the Eckert curve for rating mode based on a trial pressure drop per unit length value, $\Delta P / L$

Greek Letters

μ_g	Air viscosity ($kg/m/s$)
μ_l	Water viscosity ($kg/m/s$)
ρ_g	Air density (kg/m^3)
ρ_l	Water density (kg/m^3)
σ	Water surface tension (N/m)
σ_c	Critical surface tension of packing (N/m)

D.   Bubble Aeration - Design Mode

The following problem will be used to show sample calculations for bubble aeration in design mode. In addition, a sample program run of ASAP™ will be used to verify that the program is correctly duplicating the results of the sample calculations.

1.   Problem Statement

The city of Anytown, USA recently discovered that one of its wells was contaminated with the compounds listed in Table 1. In order for them to continue using the well, they were required to remove these compounds below their MCLs, also shown in Table 1. During normal pumping operations, the well produces about 2000 gpm, the water temperature is 10°C, and the barometric pressure is 1 atm. The air flow rate through each tank is 1.388 m^3/s.

Design a bubble aeration system with trichloroethylene as the basis for design consisting of three tanks in series. Obtain physical and chemical properties for the design from StEPP™. Use oxygen as the reference compound in finding mass transfer coefficient. Estimate the oxygen mass transfer coefficient from clean water oxygen transfer test data: SOTR = 1469.6 kg O_2/d, volumetric air flow rate = 1699 m^3/h, tank volume = 485.6 m^3 (note that this is for the oxygen transfer test conditions, not the current design). Assume a water depth of 4 m.

Calculate the effluent concentrations of trichloroethylene (both liquid and gas phase) from each tank. Estimate the blower brake power requirements (assume a blower efficiency of 35%).

Table 1 - Contaminant Influent Concentrations and Treatment Objectives (MCLs)

Compound	Concentration Discharged, C_0 (μg/L)	MCL, C_{TO} (μg/L)
Trichloroethylene	200.0	5.0
Tetrachloroethylene	150.0	5.0
Vinyl Chloride	60.0	1.0
Ethylbenzene	30.0	5.0
Toluene	80.0	5.0
1,1-Dichloroethene	85.0	7.0

Properties Needed to Perform Sample Calculations and Program Run

Table 2 shows the chemical properties retrieved from StEPP™ required for bubble aeration at 10°C and 1 atm.

Table 2 - Chemical Properties from StEPP™ at 10° C and 1 atm

Compound	MW (kg/kmol)	H (-)	V_b (m³/kmol)	T_{NBP} (°C)	D_l (m²/s)	D_g (m²/s)
Trichloroethylene	131.39	0.230	0.1020	87.0	6.44E-10	7.89E-06
Tetrachloroethylene	165.84	0.361	0.1190	121.0	5.86E-10	7.13 E-06
Vinyl Chloride	62.50	0.546	0.0665	-13.9	8.26 E-10	1.08E-05
Ethylbenzene	106.17	0.170	0.1400	136.0	5.33 E-10	6.88 E-06
Toluene	92.15	0.167	0.1190	111.0	5.86 E-10	7.57 E-06
1,1-Dichloroethene	96.95	0.680	0.0840	31.6	7.20 E-10	9.05 E-06

Table 3 shows the properties used in the calculation of oxygen mass transfer coefficient in bubble aeration.

Table 3 - Properties for Calculation of Oxygen Mass Transfer Coefficient

from StEPP™ and ASAP™ at 10° C and 1 atm

Property	Units	Value
Tabulated Value of Dissolved Oxygen Surface Saturation Concentration at 20°C, C_s^*	mg/L	9.09
Molecular Weight, M_{o_2}	amu	32.0
Henry's Constant, H_{O_2}	mg/L*atm	50
Weight Density of Water, γ_w	lb/ft³	62.4
Vapor Pressure of Water at 20°C, P_v	kPa	2.34
Molecular Weight of Air, M_a	amu	28.95
Density of Air at 20°C, ρ_a	mg/L	1240
Barometric Pressure at Standard Conditions, P_s	atm	1.0
Parameter Used for Temperature Correlation, θ	(-)	1.024
Water Depth, D	m	4
Fitting Parameter, A	(-)	3.15
Fitting Parameter, B	(-)	-831.0

Table 4 shows the physical properties of water used in this bubble aeration design.

Table 4 - Properties of Water

Property	Units	Value
Water Density, ρ_l	kg/m³	999.75
Water Viscosity, μ_l	kg/m/s	0.00131

b)   Note Regarding Comparison of Sample Calculation Values to Sample Program Run

In certain cases, the numbers that appear in the sample calculations are slightly different from the values displayed in the sample program run. These variations can be attributed to rounding.

2.   Sample Design Mode Calculation of Tank Volume for Trichloroethylene as the Design Compound Including Supplementary Parameter Calculations

a)   Total Volume

The total volume of the system, V_n, is calculated using the volume of each tank in the series found in Eq. 2. This relationship is shown in Eq. 1:

$$V_n = V \times 3 = 633 m^3 \times 3 = 1899 m^3$$

Eq. 1

The parameters required to calculate V_n in Eq. 1 can be found as follows:

Parameter	Location
V	Eq. 2
n_{tanks}	Given in problem statement

(1)   Tank Volume

The calculation of the volume of each tank, V, in the series for the case described above at an air flow rate of 1.388 m³/s is shown in Eq. 2.

$$V = -\frac{H\dot{V}}{K_L a} \ln \left\{ 1 - \left[\left(\frac{C_0}{C_{TO}} \right)^{1/n} - 1 \right] \left[\frac{1}{\frac{\dot{V}}{Q} H} \right] \right\}$$

$$= -\frac{0.230 \times 1.388 \frac{m^3}{s}}{0.0015823 \frac{1}{s}} \ln \left\{ 1 - \left[\left(\frac{200 \frac{\mu g}{L}}{5.0 \frac{\mu g}{L}} \right)^{1/3} - 1 \right] \left[\frac{1}{10.998 \frac{m^3}{m^3} \times 0.230} \right] \right\} = 633 m^3$$

Eq. 2

The parameters required to calculate V in Eq. 2 can be found as follows:

Parameter	Location
H	Table 2
$\dot{V}$	User-specified
$K_L a$	Eq. 4
C_0	Table 1
C_{TO}	Table 1
n	Given in problem statement
$\frac{\dot{V}}{Q}$	Eq. 3

(a)   Air to Water Ratio

Calculation of $\frac{\dot{V}}{Q}$ required in Eq. 2 is given in Eq. 3:

$$\frac{\dot{V}}{Q} = \frac{\dot{V}}{Q} = \frac{1.388 \, \frac{m^3}{s}}{0.1262 \, \frac{m^3}{s}}$$

$$= 10.998 \, \frac{m^3}{m^3}$$

Eq. 3

The parameters required to calculate $\frac{\dot{V}}{Q}$ in Eq. 3 can be found as follows:

Parameter	Location
$\dot{V}$	User-specified
Q	Given in the problem statement

(b)   Mass Transfer Coefficient

In order to determine overall mass transfer coefficient of a compound for bubble aeration, $K_L a$, it is necessary to relate the mass transfer coefficient of a given compound, $K_L a_i$, to the mass transfer coefficient of a reference compound, $K_L a_{ref}$ as shown in Eq. 4. For the purposes of this design, oxygen will be used as the reference compound.

$$K_L a_i = K_L a_{O_2} \left[\frac{D_{l,i}}{D_{l,O_2}} \right]^{0.6} \left[1 + \frac{1}{H_i \left(100 \right)} \right]^{-1}$$

$$= 0.002894 \tfrac{1}{s} \left[\frac{6.44\text{E-}10\,\tfrac{m^2}{s}}{1.641\text{E-}09\,\tfrac{m^2}{s}} \right]^{0.6} \left[1 + \frac{1}{0.230 \left(100 \right)} \right]^{-1} = 0.0015823 \tfrac{1}{s}$$

<div align="right">**Eq. 4**</div>

The parameters required to calculate $K_L a_i$ in Eq. 4 can be found as follows:

Parameter	Location
$K_L a_{O_2}$	Eq. 5
$D_{l,i}$	Table 2
D_{l,O_2}	Eq. 11
H_i	Table 2

Mass Transfer Coefficient of Oxygen

The true mass transfer coefficient of oxygen, $K_L a_T^*$, can be estimated using Eq. 5.

$$K_L a_{O_2} = K_L a_T^*$$

$$K_L a_T^* = K_L a_{20}^* \, \theta^{\,T-20} = 0.0036686 \tfrac{1}{s} \times 1.024^{10^\circ C - 20} = 0.002894 \tfrac{1}{s}$$

<div align="right">**Eq. 5**</div>

The parameters required to calculate $K_L a_{10}^*$ in Eq. 5 can be found as follows:

Parameter	Location
$K_L a_{20}^*$	Eq. 6
θ	Table 3
T	Given in problem statement

Mass Transfer Coefficient of Oxygen at 20°C

The true mass transfer coefficient of oxygen, $K_L a_{O_2}$, can be calculated at 20°C, $K_L a_{20}^*$, by the following relationship:

$$K_L a_{20}^* = \frac{K_L a_{20}}{1 - \dfrac{K_L a_{20}}{2\,\phi_O}} = \frac{0.003404 \tfrac{1}{s}}{1 - \dfrac{0.003404 \tfrac{1}{s}}{2 \times 0.0235986}} = 0.0036686 \tfrac{1}{s}$$

<div align="right">**Eq. 6**</div>

The parameters required to calculate $K_L a_{20}^*$ in Eq. 6 can be found as follows:

<u>Parameter</u>   <u>Location</u>

$K_L a_{20}$ Eq. 9

ϕ_O Eq. 7

Oxygenation Coefficient

The oxygenation coefficient, ϕ_O, required in Eq. 6 is found with Eq. 7.

$$\phi_O = \frac{M_{O_2}\, \rho_a\, Q_a}{M_a\, H_{O_2}\, V_{test}\left(P_b + \gamma_w\, d_e\right)}$$

$$= \frac{32 \times 1240\frac{\text{mg}}{\text{L}} \times \dfrac{1699\,\frac{\text{m}^3}{hr}}{3600\,\frac{s}{hr}}}{28.95 \times 50\frac{\text{mg}}{\text{L·atm}} \times 485.6\ m^3 \left[1atm + \dfrac{62.4\frac{\text{lb}}{\text{ft}^3} \times 1.3333\ \text{m} \times 3.281\frac{ft}{m}}{144\frac{in^2}{ft^2} \times 14.696\frac{psi}{atm}}\right]} = 0.0235986\tfrac{1}{s}$$

Eq. 7

The parameters required to calculate ϕ_O in Eq. 7 can be found as follows:

<u>Parameter</u>   <u>Location</u>

M_{O_2} Table 3

ρ_a Table 3

Q_a Given in problem statement from clean water oxygen transfer test data

M_a Table 3

H_{O_2} Table 3

P_b Given in problem statement

V_{test} Given in problem statement from clean water oxygen transfer test data

γ_w Table 3

d_e Eq. 8

Effective Saturation Depth

Effective saturation depth, d_e, at water depth of 4 m is found using Eq. 8:

$$d_e = \tfrac{1}{3} \times D = \tfrac{1}{3} \times 4\,\text{m} = 1.3333\,\text{m}$$

Eq. 8

The parameters required to calculate d_e in Eq. 8 can be found as follows:

Parameter	Location
D	User-specified

Observed Mass Transfer Coefficient for Oxygen at 20°C

The observed mass transfer coefficient for oxygen at 20°C, $K_L a_{20}$, can be calculated for a volume of 485.6 m³ by the following equation:

$$K_L a_{20} = \frac{SOTR}{V_{test}\, C_\infty^*} = \frac{1469.6\frac{\text{kg } O_2}{\text{day}} \times 10^6\frac{mg}{kg}}{485.6\,\text{m}^3 \times 10.29\frac{mg}{L} \times 10^3\frac{L}{m^3} \times 24\frac{hr}{day} \times 3600\frac{s}{hr}} = 0.003404\tfrac{1}{s}$$

Eq. 9

The parameters required to calculate $K_L a_{20}$ in Eq. 9 can be found as follows:

Parameter	Location
$SOTR$	Given in problem statement from clean water oxygen transfer test data
V_{test}	Given in problem statement from clean water oxygen transfer test data
C_∞^*	Eq. 10

Dissolved O$_2$ Saturation Concentration Attained at Infinite Time

The dissolved oxygen saturation concentration attained at infinite time, C_∞^*, can be calculated by the following relationship:

$$C_\infty^* = C_s^* \left[\frac{P_b - P_v + \gamma_w d_e}{P_s - P_v} \right]$$

$$= 9.09\tfrac{mg}{L}\left[\frac{1\,atm - \dfrac{2.34\text{E}+03\ Pa}{101325.0\frac{Pa}{atm}} + \dfrac{62.4\frac{lb}{ft^3} \times 1.3333\,\text{m} \times 3.281\frac{ft}{m}}{144\frac{in^2}{ft^2} \times 14.696\frac{psi}{atm}}}{1\,atm - \dfrac{2.34\text{E}+03\ Pa}{101325.0\frac{Pa}{atm}}} \right] = 10.29\tfrac{mg}{L}$$

Eq. 10

The parameters required to calculate C_∞^* in Eq. 10 can be found as follows:

Parameter	Location
C_s^*	Table 3
P_b	Given in problem statement
P_v	Table 3
γ_w	Table 3
d_e	Eq. 8
P_s	Table 3

Liquid Diffusivity of Oxygen

The liquid diffusivity of oxygen, $D_{l_{O_2}}$, is calculated in the following equation:

$$D_{l_{O_2}} = \left[10^{\left(A + B/T\right)}\right]\left(1.0\times 10^{-9}\right) = \left[10^{\left(3.15 + (-831.0)/283\right)}\right]\left(1.0\times 10^{-9}\right) = 1.641E - 09\,\frac{m^2}{s}$$

Eq. 11

To calculate $D_{l_{O_2}}$ in Eq. 11, the following parameters are required:

Parameter	Location
A	Table 3
B	Table 3
T	Given in problem statement

(c)   *Hydraulic Retention Time*

The hydraulic retention time of one tank, τ, in the series is calculated as follows:

$$\tau = \frac{V}{Q} = \frac{633\,\mathrm{m}^3}{0.1262\,\frac{\mathrm{m}^3}{s}} = 1.393\,\mathrm{hr}$$

Eq. 12

To calculate τ in Eq. 12, the following parameters are needed:

Parameter	Location
V	Eq. 2
Q	Given in problem statement

(d) Total Hydraulic Retention Time

The total hydraulic retention time of the system, τ_n, is estimated using the following equation:

$$\tau_n = \tau \times n = 1.393\,hr \times 3 = 4.179\,hr$$

Eq. 13

To find τ_n in Eq. 13, the following parameters are required:

Parameter	Location
τ	Eq. 12
n	Given in problem statement

b) Liquid Phase Effluent Concentration from Tank Number i

The calculation of liquid phase effluent concentration from tank number i, C_i, of a bubble aeration system with tanks in series is shown in Eq. 14.

$$C_i = \frac{C_{i-1}}{1+\frac{\dot{V}}{Q}H\left(1-e^{-\phi}\right)} = \frac{C_0}{\left[1+\frac{\dot{V}}{Q}H\left(1-e^{-\phi}\right)\right]^i} = \frac{C_{i-1}}{1+\frac{\dot{V}}{Q}H\left(1-e^{-\phi}\right)} = \frac{C_0}{\left[1+\frac{\dot{V}}{Q}H\left(1-e^{-\phi}\right)\right]^i}$$

Eq. 14

The parameters required to calculate C_i in Eq. 14 can be found as follows:

Parameter	Location
C_{i-1}	Calculated value
$\frac{\dot{V}}{Q}$	Eq. 3
H	Table 2
ϕ	Eq. 15
C_0	Table 1
i	User-specified

(1) Stanton Number, ϕ

Stanton number, ϕ is calculated with the following relationship:

$$\phi = \frac{K_L aV}{H\dot{V}} = \frac{0.0015828\frac{1}{s} \times 633\,m^3}{0.230 \times 1.388\frac{m^3}{s}} = 3.1384$$

Eq. 15

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The parameters required to calculate ϕ in Eq. 15 can be found as follows:

Parameter	Location
$K_L a$	Eq. 4
V	Eq. 2
H	Table 2
$\dot{V}$	User-specified

(2) Liquid Phase Effluent Concentration from Tank Number 1

Calculation of C_1 from Eq. 14 is given in Eq. 16:

$$C_1 = \frac{C_0}{\left[1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)\right]^1} = \frac{200.0\frac{\mu g}{L}}{\left[1 + 10.998\frac{m^3}{m^3} \times 0.230\left(1 - e^{-3.1384}\right)\right]^1} = 58.48\frac{\mu g}{L}$$

Eq. 16

The parameters required to determine C_1 in Eq. 16 can be found as follows:

Parameter	Location
$\frac{\dot{V}}{Q}$	Eq. 3
H	Table 2
ϕ	Eq. 15
C_0	Table 1

(3) Liquid Phase Effluent Concentration from Tank Number 2

Calculation of the liquid phase effluent concentration from tank number *2* in the series of tanks forming the bubble aeration system, C_2 from Eq. 14 is given in Eq.17:

$$C_2 = \frac{C_0}{\left[1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)\right]^2} = \frac{200.0\frac{\mu g}{L}}{\left[1 + 10.998\frac{m^3}{m^3} \times 0.230\left(1 - e^{-3.1384}\right)\right]^2} = 17.10\frac{\mu g}{L}$$

Eq. 17

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The parameters required to obtain C_2 in Eq. 17 can be found as follows:

Parameter	Location
$\frac{\dot{V}}{Q}$	Eq. 3
H	Table 2
ϕ	Eq. 15
C_0	Table 1

(4) Liquid Phase Effluent Concentration from Tank Number 3

The liquid phase effluent concentration from tank number *3* in the series, C_3 is calculated in Eq. 18:

$$C_3 = \frac{C_0}{\left[1 + \frac{\dot{V}}{Q} H \left(1 - e^{-\phi}\right)\right]^3} = \frac{200.0 \frac{\mu g}{L}}{\left[1 + 10.998 \frac{m^3}{m^3} \times 0.230 \left(1 - e^{-3.1384}\right)\right]^3} = 5 \frac{\mu g}{L}$$

Eq. 18

The parameters required to determine C_3 in Eq. 18 can be found as follows:

Parameter	Location
$\frac{\dot{V}}{Q}$	Eq. 3
H	Table 2
ϕ	Eq. 15
C_0	Table 1

c) Gas Phase Effluent Concentration from Tank Number i

The gas phase effluent concentration, y_i, corresponding to the liquid phase effluent concentrations for each tank calculated above can be found using Eq. 19:

$$y_i = \frac{C_{i-1} - C_i}{\frac{\dot{V}}{Q}} = \frac{C_{i-1} - C_i}{\frac{\dot{V}}{Q}}$$

Eq. 19

The parameters required to find y_i in Eq. 19 can be found as follows:

Parameter	Location
C_{i-1}	Eq. 14
C_i	Eq. 14
$\frac{\dot{V}}{Q}$	Eq. 3

(1) Gas Phase Effluent Concentration from Tank Number 1

Gas phase effluent concentration from tank number 1, y_1, is found using Eq. 20:

$$y_1 = \frac{C_0 - C_1}{\frac{\dot{V}}{Q}} = \frac{200.0\frac{\mu g}{L} - 58.48\frac{\mu g}{L}}{10.998\frac{m^3}{m^3}} = 12.87\ \frac{\mu g}{L}$$

Eq. 20

The parameters required to find y_1 in Eq. 20 can be found as follows:

Parameter	Location
C_0	Table 1
C_1	Eq. 16
$\frac{\dot{V}}{Q}$	Eq. 3

(2) Gas Phase Effluent Concentration from Tank Number 2

The gas phase effluent concentration tank number 2, y_2, is calculated using Eq. 21:

$$y_2 = \frac{C_1 - C_2}{\frac{\dot{V}}{Q}} = \frac{58.48\frac{\mu g}{L} - 17.10\frac{\mu g}{L}}{10.998\frac{m^3}{m^3}} = 3.76\frac{\mu g}{L}$$

Eq. 21

The parameters required to find y_2 in Eq. 21 can be found as follows:

Parameter	Location
C_1	Eq. 16
C_2	Eq. 17
$\frac{\dot{V}}{Q}$	Eq. 3

(3)   Gas Phase Effluent Concentration from Tank Number 3

The gas phase effluent concentration tank number *3*, y_3, is calculated using Eq. 22:

$$y_3 = \frac{C_2 - C_3}{\frac{\dot{V}}{Q}} = \frac{17.10\frac{\mu g}{L} - 5\frac{\mu g}{L}}{10.998\frac{m^3}{m^3}} = 1.10\frac{\mu g}{L}$$

Eq. 22

The parameters required to find y_3 in Eq. 22 can be found as follows:

Parameter	Location
C_2	Eq. 17
C_3	Eq. 18
$\frac{\dot{V}}{Q}$	Eq. 3

d)   *Blower Brake Power*

The blower brake power in bubble aeration, P_{blower}, is determined from the following equation. Note that this is the blower brake power per tank. The total power requirement would simply be obtained by multiplying P_{blower} times the number of tanks, times the number of blowers per tank.

$$P_{blower} = \left[\frac{G_{me}\, R_g\, T_{air}}{1000\, n_a\, Eff_b}\right]\left[\left(\frac{P_{in,b}}{P_{out,b}}\right)^{n_a} - 1\right]$$

$$= \left[\frac{1.735\frac{kg}{s} \cdot 286.7\frac{J}{kg \cdot K} \cdot 283.15\,K}{1000\frac{W}{kW}\left(0.283\right)\left(0.35\right)}\right]\left[\left(\frac{140555\frac{N}{m^2}}{101325\frac{N}{m^2}}\right)^{0.283} - 1\right]\left(\frac{1W}{1\frac{J}{s}}\right) = 138\,kW$$

Eq. 23

The parameters required to determine P_{blower} in Eq. 22 can be found as follows:

Parameter	Location
G_{me}	Eq. 24
R_g	Universal gas constant
T_{air}	Typically assumed equal to water temperature
n_a	Constant (see nomenclature)
Eff_b	Given in problem statement
$P_{in,b}$	Eq. 26
$P_{out,b}$	Assumed equal to $P_{ambient}$

(1) Air Mass Flow Rate

The air mass flow rate, G_{me}, is calculated below:

$$G_{me} = \dot{V} \cdot \rho_g = 1.388 \, \tfrac{m^3}{s} \cdot 1.25 \, \tfrac{kg}{m^3} = 1.735 \, \tfrac{kg}{s}$$

Eq. 24

The parameters required to calculate G_{me} in Eq. 24 can be found as follows:

Parameter	Location
$\dot{V}$	Given in problem statement
ρ_g	Eq. 25

(a) Air Density

The air density, ρ_g, is determined from the ideal gas law:

$$\rho_g = \frac{M_a \cdot P_{ambient} \, [atm]}{R_g \left[\tfrac{L \cdot atm}{mol \cdot K}\right] \cdot T_{air}} = \frac{28.95 \, \tfrac{g}{mol} \cdot 1 \, atm}{\left[0.08205 \, \tfrac{L \cdot atm}{mol \cdot K}\right] \cdot 283.15 \, K} \times \frac{\tfrac{1 kg}{1000 g}}{\tfrac{1 m^3}{1000 L}} = 1.25 \, \tfrac{kg}{m^3}$$

Eq. 25

The parameters required to calculate ρ_g in Eq. 25 can be found as follows:

Parameter	Location
M_a	Known
$P_{ambient}$	Given
R_g	Universal Gas Constant
T_{air}	Assumed equal to T

(2)   Inlet Air Pressure to Bubble Aeration Tank

The term $P_{in,b}$ refers to the pressure at the top of the tank, which represents the sum of the ambient pressure and the head required to raise the water to the inlet of the tank. The equation used to find $P_{in,b}$ is:

$$P_{in,b} = P_{ambient} + \rho_l \, H_b \, g = 101325\,\tfrac{N}{m^2} + 999.75\,\tfrac{kg}{m^3}\,(4\,m)\,9.81\,\tfrac{m}{s^2} = 140555\,\tfrac{N}{m^2}$$

Eq. 26

The parameters required to calculate $P_{in,b}$ in Eq. 26 can be found as follows:

Parameter	Location
$P_{ambient}$	Given
ρ_l	Table 4
H_b	Assumed equal to water depth
g	Gravitational acceleration

3. Sample Program Run of ASAP™ to Verify Sample Calculations for Bubble Aeration in Design Mode

To start the ASAP™ program, double click on the ASAP™ icon in the *ETDOT Programs* group in windows. The screen shown in Figure 1 will appear.
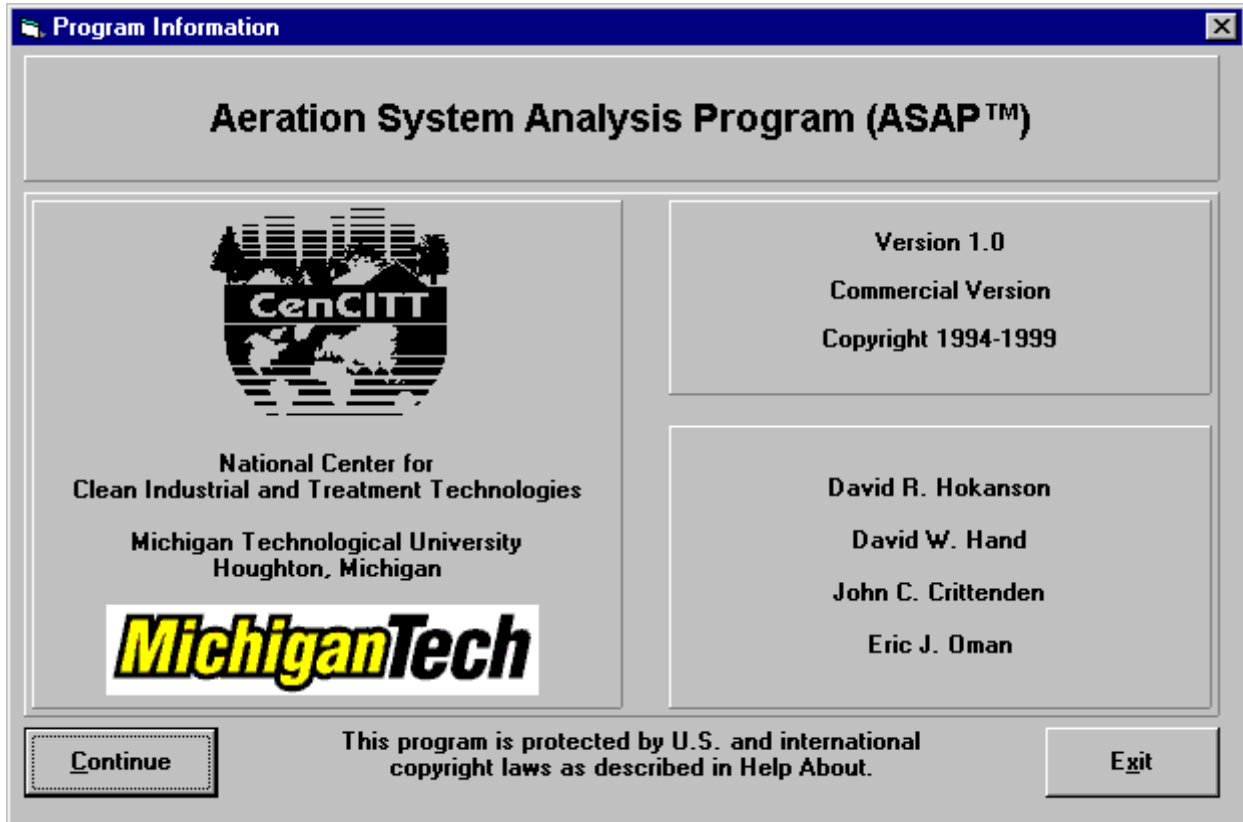
Figure 1 - ASAP™ Title Window

Click on the *Continue* button on the screen shown in Figure 1 and the menu shown in Figure 2 will appear.

Figure 2 - Main Menu Window in ASAP™

Click on the *Enter Design Mode* button for Bubble Aeration (option 3 in Figure 2) and the design mode screen for bubble aeration shown in Figure 3 will appear.

Figure 3 - Design Mode Window for Bubble Aeration

a) Physical Properties of Water

Specify pressure and temperature in the upper left-hand corner of the window shown in Figure 3. This portion of the bubble aeration design mode window is shown in Figure 4.

Figure 4 - Operating Conditions Portion of Design Mode Window

Click on the *Display Physical Properties of Water* button in Figure 3 (and highlighted in Figure 4) to show the properties of water at the specified temperature and

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pressure (101325 Pa and 10°C). Figure 5 shows the water properties window for this case.

Figure 5 - Water Properties Window

The properties shown in Figure 5 are by default calculated from correlations so the user should not have to change his values. In the rare case that the user would like to enter a value for any of these properties instead of using the correlations, it is possible to do so on the window shown in Figure 5. Click on the *OK* button shown in Figure 5 to close the window.

It can be seen that the water properties shown in Figure 5 agree with the properties shown in Table 4.

b) *Properties of Oxygen (reference compound)*

The mass transfer coefficient for the design contaminant is calculated using its relationship to the mass transfer coefficient of oxygen under similar conditions. The mass transfer coefficient of oxygen is estimated using clean water oxygen transfer test data. This portion of the design mode window is shown in Figure 6.

Figure 6 - Oxygen Section of Design Mode Window

Oxygen mass transfer coefficient at 10°C is determined as 2.89E-03 1/s. This agrees with the value from the sample calculations (see Eq. 5). To view additional information about calculation of oxygen mass transfer coefficient by this method, click on the ▼ button to display a choice between *CW O2 Transfer Test Data* and *User Input*. Click on *CW O2 Transfer Test Data* button to obtain the window shown in Figure 7.

Figure 7 - Mass Transfer Coefficient of O$_2$ from Clean Water Oxygen Transfer Test Data

The values shown in Figure 7 agree with values shown in sample calculations. Dissolved oxygen saturation concentration attained at infinite time was determined as 10.3, which agrees with sample calculations (see Eq. 10). Apparent K$_L$a at 20°C was calculated as 3.40E-03 1/s by the program and the sample calculations (see Eq. 9). The program found the oxygenation coefficient to be 0.0236 1/s as the sample calculations show (see Eq. 7). True K$_L$a at 20°C was determined to be 3.67E-03 1/s as calculated by the program and shown by the sample calculations (see Eq. 6). True K$_L$a at operating temperature is 2.89E-03 which agrees with the sample calculations (see Eq. 5).

Additional parameters shown in Figure 7 were either specified in the problem statement or chosen for the purposes of this design.

c) Chemical Properties

Chemical properties for each of the six components can be retrieved from StEPP™. When the screen shown in Figure 3 loads, the properties of the six contaminants load as a default design case. Before retrieving the chemical properties of the six chemicals required in the current design, it is necessary to delete the six default chemicals shown in the Design Contaminant list box on the bottom of the left-hand column shown in Figure 3. This portion of the design mode window is highlighted in Figure 8.

Figure 8 - Contaminant Selection Portion of Design Mode Window

It can be seen that the value for mass transfer coefficient of trichloroethylene calculated by the program as 1.58E-03 1/s agrees with sample calculations (see Eq. 4).

To delete each chemical click on the *Delete* button located between the *Add* and *Edit Properties* buttons shown in Figure 3 (and highlighted in Figure 8). Click the *Delete* button once for each chemical until all chemicals have been deleted.

(1) Transferring Properties from StEPP™ to ASAP™

ASAP™ has the capability of transferring the physical properties of contaminants from Software to Estimate Physical Properties (StEPP™). There are two choices available in the *Options* menu within StEPP for transferring data from StEPP into ASAP: (a) Create Export File for AdDesignS/ASAP and (b) Copy to Clipboard for AdDesignS/ASAP. The StEPP™ main window highlighting the *Options* menu is shown in Figure 9 (refer to StEPP manual for more information on selecting compounds within StEPP).

Figure 9 - StEPP™ Main Window for This Design

> *(a)   Transferring Chemical Properties from StEPPÔ to ASAPÔ Using the* Create Export File for AdDesignS/ASAP *Option*

To create an export file within StEPP™ for use in ASAP™, click on the *Create Export File for AdDesignS™/ASAP™* in the StEPP™ **Options** menu. This option is shown in Figure 9. After clicking this option, the *Save StEPP™ Export File* window shown in Figure 10 appears. Give the export file a *.exp* extension (the default), such as *bub10.exp*, and the file will be readily importable into ASAP™, as described below.

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Figure 10 - Save StEPP™ Export File Window

To import the StEPP™ export file described above (*bub10.exp*), click on the *Add* button shown on the bottom left-hand corner of the window shown in Figure 3 (and highlighted in Figure 8). Figure 11 shows the window that will appear.

Figure 11 - Contaminant Properties Input Window

Click on the *Import StEPP™ Export File* button shown in Figure 11. The window shown in Figure 12 will appear.

Figure 12 - Load StEPP™ Export File Window

Select the file *bub10.exp* that was created earlier and the chemicals selected in StEPP™ for the given design will be imported into ASAP™. Figure 13 appears after the import and shows a successful import was achieved.

Figure 13 - Successful StEPP™ Property Retrieval Indication Window

To copy selected StEPP™ data to the Windows clipboard for export into ASAP, select *Copy to Clipboard for AdDesignS/ASAP* from the <u>*Options*</u> menu within StEPP. The message box shown in Figure 14 will appear, verifying that all of the StEPP data is now stored in the Windows clipboard.

Figure 14 – Successful Copy to Clipboard from StEPP™ Message Box

To import the chemicals and their physical properties to ASAP™ from the data on the clipboard, click on the <u>*Add*</u> button in the *Component Properties* block of the ASAP™ main window. The Component Properties window shown in Figure 15 will appear.

Figure 15 - Component Properties window (adding new components)

To import the StEPP™ data from the Windows clipboard, click the *Import from Clipboard* button on the Component Properties window. The window shown in Figure 16 will appear, showing that the properties have been successfully transferred into ASAP.

Figure 16 – Successful Import from StEPP™ Window

(2)   Manipulation of Data Required after Transferring Properties from StEPP™ to ASAP™

Click on the *OK* button to continue. Figure 3 appears. As shown in Figure 13 or Figure 16, it is necessary to input influent concentrations and treatment objectives for each of the six components retrieved. To do so, select each contaminant one at a time in the Design Contaminant list box shown in the lower left-hand corner of Figure 3. Then click on the *Edit Properties* button. Figure 17 shows the window that appears for trichloroethylene.

Figure 17 - Specify Contaminant Properties Window for Trichloroethylene

The properties molecular weight, Henry's constant, molar volume, and liquid diffusivity are already correct since they were retrieved from StEPP™. The influent concentration and treatment objective shown at the bottom of the screen must be input since they will vary from case to case. These properties shown in Figure 17 already reflect the values for the current design case. It is seen that the properties shown in Figure 17 agree with the trichloroethylene properties shown in Tables 1 and 2.

Figure 18 shows the *Specify Contaminant Properties* window for tetrachloroethylene. It can be seen that the properties shown in Figure 18 agree with the properties of tetrachloroethylene shown in Tables 1 and 2.

Figure 18 - Specify Contaminant Properties Window for Tetrachloroethylene

Figure 19 shows the *Specify Contaminant Properties* window for vinyl chloride. It can be seen that the properties shown in Figure 19 agree with the properties of vinyl chloride shown in Tables 1 and 2.

Figure 19 - Specify Contaminant Properties Window for Vinyl Chloride

Figure 20 shows the *Specify Contaminant Properties* window for ethylbenzene. It can be seen that the properties shown in Figure 20 agree with the properties of ethylbenzene shown in Tables 1 and 2.

Figure 20 - Specify Contaminant Properties Window for Ethylbenzene

Figure 21 shows the *Specify Contaminant Properties* window for toluene. It can be seen that the properties shown in Figure 21 agree with the properties of toluene shown in Tables 1 and 2.

Figure 21 - Specify Contaminant Properties Window for Toluene

Figure 22 shows the *Specify Contaminant Properties* window for 1,1-dichloroethene. It can be seen that the properties shown in Figure 22 agree with the properties of 1,1-dichloroethene shown in Tables 1 and 2.

Figure 22 - Specify Contaminant Properties Window for 1,1-Dichloroethene

d)   *Flow Parameters*

Flow parameters are shown in the upper right-hand column of Figure 3. This portion of Figure 3 is reproduced here as Figure 23.

Figure 23 - Flow Parameters of Design Mode Window

Explanation of the origin of the values for the properties shown in Figure 23 is provided here. The water flow rate of 2000 gpm is given in the problem statement. The minimum air to water ratio of 10.5 was calculated by the program. An air to water ratio of 11 was chosen to satisfy this minimum. This value agrees with the value calculated in the sample calculations for this design case (see Eq. 3 in the sample calculations section). An air flow rate of 1.39 m^3/s was chosen for design purposes (see Eq. 2).

e)   Tank Parameters

The tank parameters are shown in the middle of the right-hand column of the design mode window shown in Figure 3, as shown in Figure 24.

Figure 24 - Tank Parameters Section of Design Mode Window

The values of the tank parameters shown in Figure 3 (and highlighted in Figure 24) agree with the sample calculations section. The number of tanks in the series is given in the problem statement. The retention time of 1.393 hr calculated by the program agrees with the sample calculations performed previously (see Eq. 12). The total retention time for the system determined by the program to be 4.179 hr corresponds to the value calculated in the sample calculations (see Eq. 13). The volume of 6.333E+02 m^3 calculated by the program agrees with the sample calculations performed previously (see Eq. 2). The volume of the entire system shown to be 1.899E+03 m^3 reflects the sample calculations provided (see Eq. 1).

f)   Stanton Number

The Stanton number used in the calculation of the liquid phase effluent concentrations is located beneath the tank parameters in the middle of the right-hand column as shown in Figure 3 (and highlighted in Figure 25).

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Figure 25 - Stanton Number Section of Design Mode Window

The Stanton number calculated by the program is 3.14 and can be seen in the sample calculations (see Eq. 15).

g) *Concentration Results*

The effluent concentrations of both the liquid phase and the gas phase of the contaminant as well as the achieved percent removal are found in the lower right-hand corner of the design mode window as shown in Figure 3 (and highlighted in Figure 26).

Figure 26 - Concentration Results Portion of Design Mode Window

Click on the *View Effluent Concentrations from All Tanks* button shown in Figure 3 (and highlighted in Figure 26) to see the effluent concentrations of both the liquid phase and the gas phase of the contaminant from each tank. The window that appears is shown in Figure 27.

Figure 27 - Effluent Concentrations from Each Tank

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It can be seen that the values calculated by the program for the liquid phase effluent concentrations; 58.5 µg/L from tank 1 (see Eq. 16), 17.1 µg/L from tank 2 (see Eq. 17), and 5.00 µg/L from tank 3 (see Eq. 18); and the gas phase concentrations; 12.9 µg/L from tank 1 (see Eq. 20), 3.76 µg/L from tank 2 (see Eq. 21), and 1.10 µg/L from tank 3 (see Eq. 22), match the values shown in the sample calculations.

Click the *OK* button shown in Figure 27 to return to the design mode window shown in Figure 3.

h)   *Power Parameters*

The power calculations window can be opened by selecting Perform Power Calculations from the Power menu. The resultant window is shown in Figure 28:

Figure 28 - Power Window

i) Viewing Effluent Concentration Results for Contaminants Other than the Design Contaminant

For a given design, it is useful to see what the effluent concentrations of contaminants other than the design contaminant would be. ASAP provides a convenient method for seeing these results without having to switch to rating mode. (of course, the user will have to switch to rating mode to investigate commercially available packed tower sizes).

By clicking on the **Concentration Results** button in the lower left-hand corner of the bubble aeration – design mode window shown in Figure 3, the user will see the concentration results for all contaminants using the given design.

View Concentration Results for All Contaminants

Concentration Results

CN	Cinf	Cto	D % R	Ceff	A % R
1	200	5.00	97.5	5.00	97.5
2	150	5.00	96.7	1.78	98.8
3	60.0	1.00	98.3	0.314	99.5
4	30.0	5.00	83.3	1.33	95.6
5	80.0	5.00	93.8	3.63	95.5
6	85.0	7.00	91.8	0.366	99.6

Contaminant Glossary:

CN	Contaminant Name
1	trichloroethylene
2	tetrachloroethylene
3	vinyl chloride
4	ethylbenzene
5	toluene
6	1,1-dichloroethylene

Glossary:

Label	Description
CN	Contaminant Number
Cinf	Influent Concentration (ug/L)
Cto	Treatment Objective (ug/L)
D % R	Desired Percent Removal
Ceff	Effluent Concentration (ug/L)
A % R	Achieved Percent Removal

OK

Figure 29 – View Concentration Results for All Contaminants Window

This window provides a quick method to see whether the given design will meet the treatment objectives for all contaminants.

j)   Switching to Rating Mode

Once the bubble aeration system has been specified in design mode, the user can take the established properties and switch to rating mode in order to examine the effect of modifications of various properties. The procedure for switching to rating mode is described here.

Figure 30 shows the **File** menu for bubble aeration, design mode.
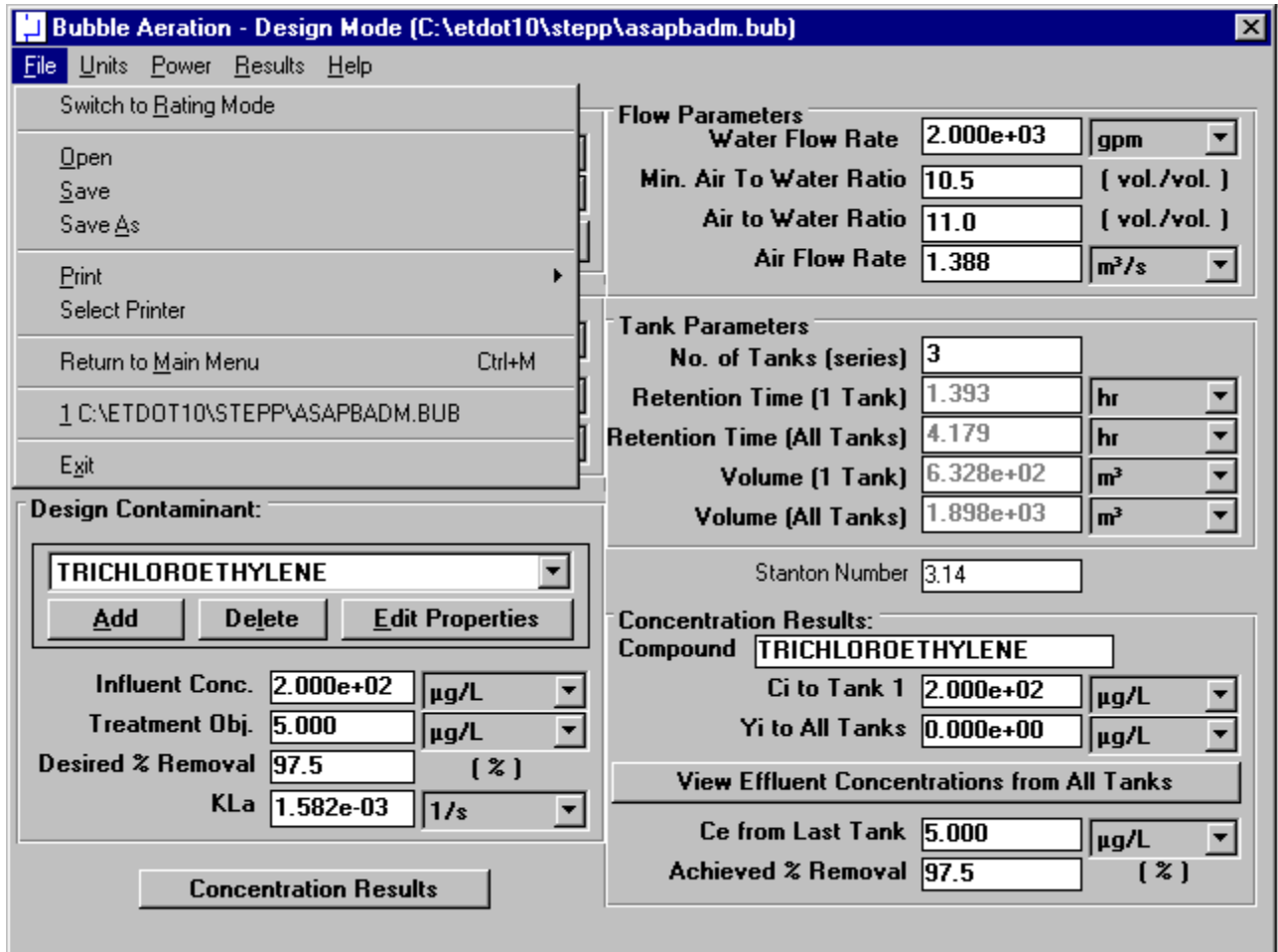

Figure 30 – File Menu for Bubble Aeration – Design Mode

Click on the menu option called *Switch to Rating Mode* in Figure 30. The bubble aeration – rating mode window will appear, as shown in Figure 31.

Figure 31 - – Bubble Aeration – Rating Mode Window

Use of *Bubble Aeration – Rating Mode* will be described in the next section.

E.   Bubble Aeration - Rating Mode

The following problem will be used to show sample calculations for bubble aeration in rating mode. In addition, a sample program run of ASAP™ will be used to verify that the program is correctly duplicating the results of the sample calculations.

1.   Problem Statement

The city of Anytown, USA recently discovered that one of its wells was contaminated with the compounds listed in Table 1. In order for them to continue using the well, they are required to remove these compounds below their MCLs, also shown in Table 1. During normal pumping operations, the well produces about 2000 gpm, the water temperature is 10°C, and the barometric pressure is 1 atm. An air to water ratio of 11 should be used. Tank volume for one tank is 600 m^3 and the system consists of three tanks in series. Will the system be able to remove all the components below their MCLs?

Show a sample calculation of effluent concentrations in each tank in both the liquid and gas phase for Trichloroethylene. Present a table showing the influent concentration, treatment objective, Stanton number, and effluent concentrations from each tank in each phase for all components. Show that the sample calculations match the results of using ASAP™ for bubble aeration in rating mode.

Power calculations and mass transfer coefficient calculations are the same as for the design mode case presented in Appendix B.4 and need not be shown again. Mass transfer coefficients obtained in design mode which are also applicable to this rating mode case are shown in Table 3.

Table 1 - Contaminant Influent Concentrations and Treatment Objectives (MCLs)

Compound	Concentration Discharged, C_0 (µg/L)	MCL, C_{TO} (µg/L)
Trichloroethylene (TCE)	200.0	5.0
Tetrachloroethylene (PCE)	150.0	5.0
Vinyl Chloride	60.0	1.0
Ethylbenzene	30.0	5.0
Toluene	80.0	5.0
1,1-Dichloroethene (1,1-DCE)	85.0	7.0

Properties Needed to Perform Sample Calculations and Program Run

Table 2 shows the Henry's constants retrieved from StEPP™ required for bubble aeration at 10°C and 1 atm.

Table 2 - Henry's Constants from StEPP™ at 10° C and 1 atm

Compound	H (-)
Trichloroethylene	0.230
Tetrachloroethylene	0.361
Vinyl Chloride	0.546
Ethylbenzene	0.170
Toluene	0.167
1,1-Dichloroethene	0.680

Table 3 - Mass Transfer Coefficients (KLa) from Design Mode Calculations

Compound	K_La (1/s)
Trichloroethylene	0.001582
Tetrachloroethylene	0.001518
Vinyl Chloride	0.001882
Ethylbenzene	0.001392
Toluene	0.001471
1,1-Dichloroethene	0.001739

b) *Note Regarding Comparison of Sample Calculation Values to Sample Program Run*

In certain cases, the numbers that appear in the sample calculations are slightly different from the values displayed in the sample program run. These variations can be attributed to rounding.

2. Sample Rating Mode Calculation of Effluent Concentration for Trichloroethylene as the Design Compound Including Supplementary Parameter Calculations

a) *Liquid Phase Effluent Concentration from Tank Number i*

The calculation of liquid phase effluent concentration from tank number i, C_i, of a bubble aeration system with tanks in series is shown in Eq. 1.

$$C_i = \frac{C_{i-1}}{1+\frac{\dot{V}}{Q}H\left(1-e^{-\phi}\right)} = \frac{C_0}{\left[1+\frac{\dot{V}}{Q}H\left(1-e^{-\phi}\right)\right]^i} = \frac{C_{i-1}}{1+\frac{\dot{V}}{Q}H\left(1-e^{-\phi}\right)} = \frac{C_0}{\left[1+\frac{\dot{V}}{Q}H\left(1-e^{-\phi}\right)\right]^i}$$

Eq. 1

The parameters required to calculate C_i in Eq. 1 can be found as follows:

Parameter	Location
C_{i-1}	Calculated value
$\frac{\dot{V}}{Q}$	User-specified
H	Table 2
ϕ	Eq. 2
C_0	Table 1
i	User-specified

(1) Stanton Number, ϕ

Stanton number, ϕ, is calculated using the following relationship:

$$\phi = \frac{K_L aV}{H\dot{V}} = \frac{0.0015823\frac{1}{s} \times 600\,\text{m}^3}{0.230 \times 1.3882\,\frac{\text{m}^3}{s}} = 2.97$$

Eq. 2

The parameters required to find ϕ in Eq. 2 can be found as follows:

Parameter	Location
$K_L a$	Table 3
V	Given
H	Table 2
$\dot{V}$	Eq. 3

(2) Liquid Phase Effluent Concentration from Tank Number 1

Calculation of C_1 from Eq. 1 is given in Eq. 3:

$$C_1 = \frac{C_0}{\left[1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)\right]^1} = \frac{200.0\frac{\mu g}{L}}{\left[1 + 11\frac{m^3}{m^3} \times 0.230\left(1 - e^{-2.97}\right)\right]^1} = 58.82\frac{\mu g}{L}$$

Eq. 3

The parameters required to find C_1 in Eq. 3 can be found as follows:

Parameter   Location

$\frac{\dot{V}}{Q}$ User-specified

H Table 2

ϕ Eq. 2

C_0 Table 1

(3) Liquid Phase Effluent Concentration from Tank Number 2

Calculation of the liquid phase effluent concentration from tank number *2* in the series of tanks forming the bubble aeration system, C_2 from Eq. 1 is given in Eq. 4:

$$C_2 = \frac{C_0}{\left[1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)\right]^2} = \frac{200.0\frac{\mu g}{L}}{\left[1 + 11\frac{m^3}{m^3} \times 0.230\left(1 - e^{-2.97}\right)\right]^2} = 17.30\frac{\mu g}{L}$$

Eq. 4

The parameters required to find C_2 in Eq. 4 can be found as follows:

Parameter   Location

$\frac{\dot{V}}{Q}$ User-specified

H Table 2

ϕ Eq. 2Eq. 2

C_0 Table 1

(4) Liquid Phase Effluent Concentration from Tank Number 3

The liquid phase effluent concentration from tank number 3 in the series, C_3 is calculated in Eq. 5:

$$C_3 = \frac{C_0}{\left[1 + \frac{\dot{V}}{Q} H \left(1 - e^{-\phi}\right)\right]^3} = \frac{200.0 \frac{\mu g}{L}}{\left[1 + 11 \frac{m^3}{m^3} \times 0.230 \left(1 - e^{-2.97}\right)\right]^3} = 5.088 \frac{\mu g}{L}$$

Eq. 5

The parameters required to find C_3 in Eq. 5 can be found as follows:

Parameter	Location
$\frac{\dot{V}}{Q}$	User-specified
H	Table 2
ϕ	Eq. 2
C_0	Table 1

b) Gas Phase Effluent Concentration from Tank Number i

The gas phase effluent concentration, y_i, corresponding to the liquid phase effluent concentrations for each tank calculated above can be found using Eq. 6:

$$y_i = \frac{C_{i-1} - C_i}{\frac{\dot{V}}{Q}} = \frac{C_{i-1} - C_i}{\frac{\dot{V}}{Q}}$$

Eq. 6

The parameters required to find y_i in Eq. 6 can be found as follows:

Parameter	Location
C_{i-1}	Eq. 1
C_i	Eq. 1
$\frac{\dot{V}}{Q}$	User-specified

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(1) Gas Phase Effluent Concentration from Tank Number 1

Gas phase effluent concentration, y_1, from tank *1* is calculated using Eq. 7:

$$y_1 = \frac{C_0 - C_1}{\frac{\dot{V}}{Q}} = \frac{200.0\frac{\mu g}{L} - 58.82\frac{\mu g}{L}}{11\frac{m^3}{m^3}} = 12.88 \frac{\mu g}{L}$$

Eq. 7

The parameters required to find y_1 in Eq. 7 can be found as follows:

Parameter	Location
C_0	Table 1
C_1	Eq. 3
$\frac{\dot{V}}{Q}$	User-specified

(2) Gas Phase Effluent Concentration from Tank Number 2

Gas phase effluent concentration, y_2, from tank *2* is calculated using Eq. 8:

$$y_2 = \frac{C_1 - C_2}{\frac{\dot{V}}{Q}} = \frac{58.82\frac{\mu g}{L} - 17.30\frac{\mu g}{L}}{11\frac{m^3}{m^3}} = 3.77 \frac{\mu g}{L}$$

Eq. 8

The parameters required to find y_2 in Eq. 8 can be found as follows:

Parameter	Location
C_1	Eq. 3
C_2	Eq. 4
$\frac{\dot{V}}{Q}$	User-specified

(3) Gas Phase Effluent Concentration from Tank Number 3

Gas phase effluent concentration, y_3, from tank *3* is calculated using Eq. 9:

$$y_3 = \frac{C_2 - C_3}{\frac{\dot{V}}{Q}} = \frac{17.30\frac{\mu g}{L} - 5.088\frac{\mu g}{L}}{11\frac{m^3}{m^3}} = 1.11 \frac{\mu g}{L}$$

Eq. 9

The parameters required to find y_3 in Eq. 9 can be found as follows:

Parameter	Location
C_2	Eq. 4
C_3	Eq. 5
$\frac{\dot{V}}{Q}$	User-specified

c) *Note Regarding Calculation of V, V_n, τ, and τ_n*

In rating a bubble aeration system, it is possible to specify one of the parameters listed above and then calculate the other three. Sample calculations for the four cases are presented here.

(1) Case 1: Specify V, Calculate V_n, τ, and τ_n

(a) *Total Volume of System*

The total volume of all of the aeration tanks, V_n, can be calculated as follows:

$$V_n = V \cdot n = 600\,\text{m}^3 \cdot 3 = 1800\,\text{m}^3$$

Eq. 10

The parameters required to calculate V_n in Eq. 10 can be found as follows:

Parameter	Location
V	User-specified
n	Given in problem statement

(b) *Hydraulic Retention Time*

The hydraulic retention time for one of the aeration tanks, τ, is found as:

$$\tau = \frac{V}{Q} = \frac{600\,\text{m}^3}{0.1262\,\frac{\text{m}^3}{\text{s}} \times 3600\,\frac{\text{s}}{\text{hr}}} = 1.321\,\text{hr}$$

Eq. 11

The parameters required to calculate τ in Eq. 11 can be found as follows:

Parameter	Location
V	User-specified
Q	Given in problem statement

(c) *Total Hydraulic Retention Time*

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The total hydraulic retention time for the system, τ_n, can be found using Eq. 12:

$$\tau_n = \frac{V_n}{Q} = \frac{1800\,\text{m}^3}{0.1262\,\frac{\text{m}^3}{\text{s}} \times 3600\,\frac{\text{s}}{\text{hr}}} = 3.963\,\text{hr}$$

Eq. 12

The parameters required to calculate τ_n in Eq. 12 can be found as follows:

Parameter   Location

V_n Eq. 10

Q Given in problem statement

(2)   Case 2: Specify V_n, Calculate V, τ, and τ_n

(a)   Volume of One Aeration Tank

The volume of one of the aeration tanks, V, can be calculated as follows:

$$V = \frac{V_n}{n} = \frac{1800\,\text{m}^3}{3} = 600\,\text{m}^3$$

Eq. 13

The parameters required to calculate V in Eq. 13 can be found as follows:

Parameter   Location

V_n User-specified

n Given in problem statement

(b)   Hydraulic Retention Time

The hydraulic retention time, τ, can be calculated using the following relationship:

$$\tau = \frac{V}{Q} = \frac{600\,\text{m}^3}{0.1262\,\frac{\text{m}^3}{\text{s}} \times 3600\,\frac{\text{s}}{\text{hr}}} = 1.321\,\text{hr}$$

Eq. 14

The parameters required to calculate τ in Eq. 14 can be found as follows:

Parameter   Location

V Eq. 13

Q Given in problem statement

(c)   Total Hydraulic Retention Time

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The total hydraulic retention time for the system, τ_n, is calculated using the following relationship:

$$\tau_n = \frac{V_n}{Q} = \frac{1800 \, \text{m}^3}{0.1262 \, \frac{\text{m}^3}{\text{s}} \times 3600 \, \frac{\text{s}}{\text{hr}}} = 3.963 \, \text{hr}$$

Eq. 15

The parameters required to calculate τ_n in Eq. 15 can be found as follows:

Parameter	Location
V_n	User-specified
Q	Given in problem statement

(3) Case 3: Specify τ, Calculate V, V_n, and τ_n

(a) *Volume of One Aeration Tank*

The volume of one of the aeration tanks, V, can be calculated using the following:

$$V = \tau \cdot Q = 1.321 \, \text{hr} \cdot 0.1262 \, \frac{\text{m}^3}{\text{s}} \cdot 3600 \, \frac{\text{s}}{\text{hr}} = 600 \, \text{m}^3$$

Eq. 16

The parameters required to calculate V in Eq. 16 can be found as follows:

Parameter	Location
τ	User-specified
Q	Given in problem statement

(b) *Total Volume of System*

The total volume of all of the aeration tanks V_n can be calculated using Eq. 17:

$$V_n = V \cdot n = 600 \, \text{m}^3 \cdot 3 = 1800 \, \text{m}^3$$

Eq. 17

The parameters required to calculate V_n in Eq. 17 can be found as follows:

Parameter	Location
V	Eq. 16
n	Given in problem statement

(c)   Total Hydraulic Retention Time

The total hydraulic retention time for the system, τ_n, is calculated as follows:

$$\tau_n = \frac{V_n}{Q} = \frac{1800\,\text{m}^3}{0.1262\,\frac{\text{m}^3}{\text{s}} \cdot 3600\,\frac{\text{s}}{\text{hr}}} = 3.963\,\text{s}$$

Eq. 18

The parameters required to calculate τ_n in Eq. 18 can be found as follows:

Parameter	Location
V_n	Eq. 17
Q	Given in problem statement

(4)   Case 4: Specify τ_n, Calculate τ, V, and V_n

(a)   Hydraulic Retention Time

The hydraulic retention time, τ, is found using Eq. 19:

$$\tau = \frac{\tau_n}{n} = \frac{3.963\,\text{hr}}{3} = 1.321\,\text{hr}$$

Eq. 19

The parameters required to calculate τ in Eq. 19 can be found as follows:

Parameter	Location
τ_n	User-specified
n	Given in problem statement

(b)   Volume of One Aeration Tank

The volume of one of the aeration tanks, V, can be calculated using Eq. 20:

$$V = \tau \cdot Q = 1.321\,\text{hr} \cdot 1262\,\frac{\text{m}^3}{\text{s}} \cdot 3600\,\frac{\text{s}}{\text{hr}} = 600\,\text{m}^3$$

Eq. 20

The parameters required to calculate V in Eq. 20 can be found as follows:

Parameter	Location
τ	Eq. 19
Q	Given in problem statement

(c)   Total Volume of System

The total volume of all of the aeration tanks, V_n, can be calculated using the following relationship:

$$V_n = V \cdot n = 600\,\text{m}^3 \cdot 3 = 1800\,\text{m}^3$$

Eq. 21

The parameters required to calculate V_n in Eq. 21 can be found as follows:

Parameter	Location
V	Eq. 20
n	Given in problem statement

d)   Table Showing Effluent Results for All Components

Table 4 shows the effluent results for all components for this rating mode case. The calculation of the values for trichloroethylene (TCE) was shown earlier. Calculation of values for the other components follows exactly the same method and is thus not shown.

Table 4 - Effluent Results for All Components

Concentration	Compound					
	TCE	PCE	Vinyl Chloride	Ethylbenzene	Toluene	1,1-DCE
C_0 (µg/L)	200	150.0	60.0	30.0	80.0	85
C_{TO} (µg/L)	5.0	5.0	1.0	5.0	5.0	7.0
ϕ	2.97	1.82	1.49	3.54	3.81	1.11
C_1 (µg/L)	58.82	34.7	10.60	10.7	28.60	14.2
C_2 (µg/L)	17.30	8.02	1.88	3.78	10.20	2.36
C_3 (µg/L)	5.088	1.85	0.332	1.34	3.66	0.393
y_1 (µg/L)	12.88	10.5	4.49	1.76	4.67	6.44
y_2 (µg/L)	3.77	2.42	0.794	0.625	1.67	1.07
y_3 (µg/L)	1.11	0.560	0.141	0.222	0.597	0.179

3. Sample Program Run of ASAP™ to Verify Sample Calculations for Bubble Aeration in Rating Mode

To start the ASAP™ program, double click on the ASAP™ icon in the *ETDOT Programs* group in windows. The screen shown in Figure 1 will appear.
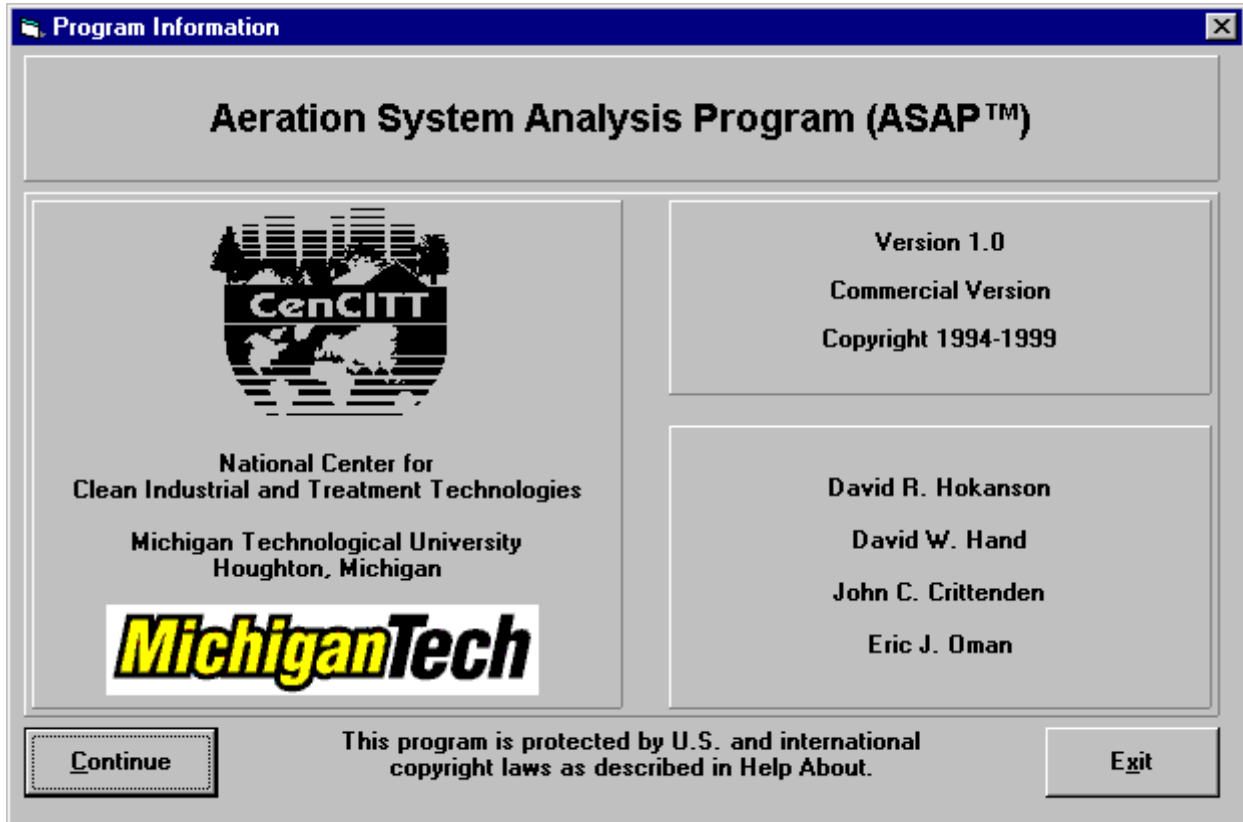
Figure 1 - ASAP™ Title Window

Click on the *Continue* button on the screen shown in Figure 1 and the menu shown in Figure 2 will appear.
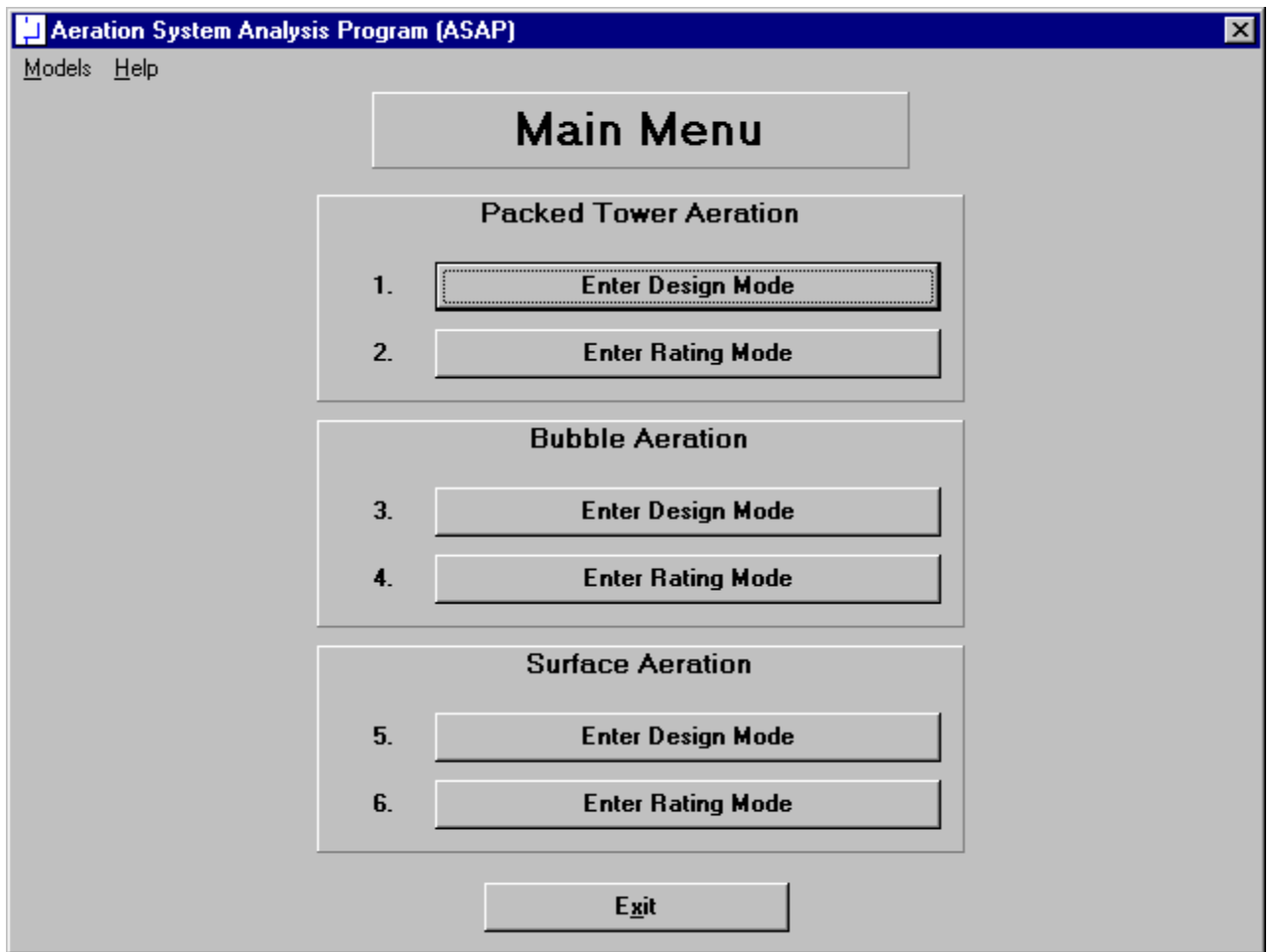
Figure 2 - Main Menu Window in ASAP™

Click on the *Enter Rating Mode* button for Bubble Aeration (option 4 in Figure 2) and the rating mode screen for bubble aeration shown in Figure 3 will appear.

Figure 3 - Rating Mode Window for Bubble Aeration

a) *Physical Properties of Water*

Specify pressure and temperature in the upper left-hand corner of the window shown in Figure 3. This portion of the bubble aeration rating mode window is shown in Figure 4.

Figure 4 - Operating Conditions Portion of Rating Mode Window

Click on the *Display Physical Properties of Water* button in Figure 3 (and highlighted in Figure 4) to show the properties of water at the specified temperature and

pressure (101325 Pa and 10°C). Figure 5 shows the water properties window for this case.

Figure 5 - Water Properties Window

The properties shown in Figure 5 are by default calculated from correlations so the user should not have to change his values. In the rare case that the user would like to enter a value for any of these properties instead of using the correlations, it is possible to do so on the window shown in Figure 5. Click on the *OK* button shown in Figure 5 to close the window.

b)   Oxygen (reference compound)

The mass transfer coefficient for the design contaminant is calculated using its relationship to the mass transfer coefficient of oxygen under similar conditions. The mass transfer coefficient of oxygen is estimated using clean water oxygen transfer test data. This portion of the rating mode window is shown in Figure 6.

Figure 6 - Oxygen Section of Rating Mode Window

The mass transfer coefficient of oxygen at 10°C is calculated by the program as 2.89E-03 1/s. This agrees with the value from the sample calculations of the design mode section. To view additional information regarding the calculation of the mass transfer coefficient of oxygen by this method, click on the ▼ button to display a choice between *CW O2 Transfer Test Data* and *User Input*. Click on *CW O2 Transfer Test Data* button to obtain the window shown in Figure 3 (and highlighted in Figure 7).

Find KLa, O2 from Clean Water Oxygen Transfer Test Data

Data Available:

⦿ SOTR vs. Qair Data Available

○ SOTE vs. Qair Data Available

○ No Data Available

OK

Clean Water Oxygen Transfer Test Data Parameters:

SOTE (%)	12.974691	C* (mg/L)	10.3
SOTR (kg O2/d)	1469.6	Apparent KLa,20 (1/s)	3.40E-03
Air Flow (std. m³/hr)	1699	Phi (1/s)	0.0237
Barometric Pres. (Pa)	101325	True KLa,20 (1/s)	3.67E-03
Water Depth (m)	4	Theta (-)	1.024
Water Volume (m³)	485.63655	KLa,O2 at Op. T (1/s)	2.89E-03

Figure 7 - Mass Transfer Coefficient of O_2 from Clean Water Oxygen Transfer Test Data

The dissolved oxygen surface saturation concentration, apparent K_La at 20°C, oxygenation coefficient, and true K_La at 20°C calculated by the program are shown by the sample calculations of the design mode section.

Additional parameters shown in Figure 7 were either specified in the problem statement of the design mode case or chosen for the purposes of the design.

<center>*c)*   ***Chemical Properties***</center>

Chemical properties for each of the six components can be retrieved from StEPP™. When the screen shown in Figure 3 loads, the properties of the six contaminants load as a default rating situation. Before retrieving the chemical properties of the six chemicals required in the current rating mode case, it is necessary to delete the six default chemicals shown in the Design Contaminant list box on the bottom of the left-hand column shown in Figure 3. This portion of the rating mode window is highlighted in Figure 8.

Figure 8 - Contaminant Selection Portion of Rating Mode Window

The value for the mass transfer coefficient of trichloroethylene calculated by the program, 1.58E-03 1/s, agrees with the sample calculations of the design mode section.

To delete each chemical click on the *Delete* button located in between the *Add* and *Edit Properties* buttons shown in Figure 3 (and highlighted in Figure 8). Click the *Delete* button once for each chemical until all chemicals have been deleted.

<center>(1)   Transferring Properties from StEPP™ to ASAP™</center>

ASAP™ has the capability of transferring the physical properties of contaminants from Software to Estimate Physical Properties (StEPP™). There are two choices available in the *Options* menu within StEPP for transferring data from StEPP into ASAP: (a) Create Export File for AdDesignS/ASAP and (b) Copy to Clipboard for AdDesignS/ASAP. The StEPP™ main window highlighting the *Options* menu is shown in Figure 9. Figure 9 shows the main StEPP™ window after the chemicals for this design have been selected at 10° C (see StEPP™ manual for how to get to this stage).

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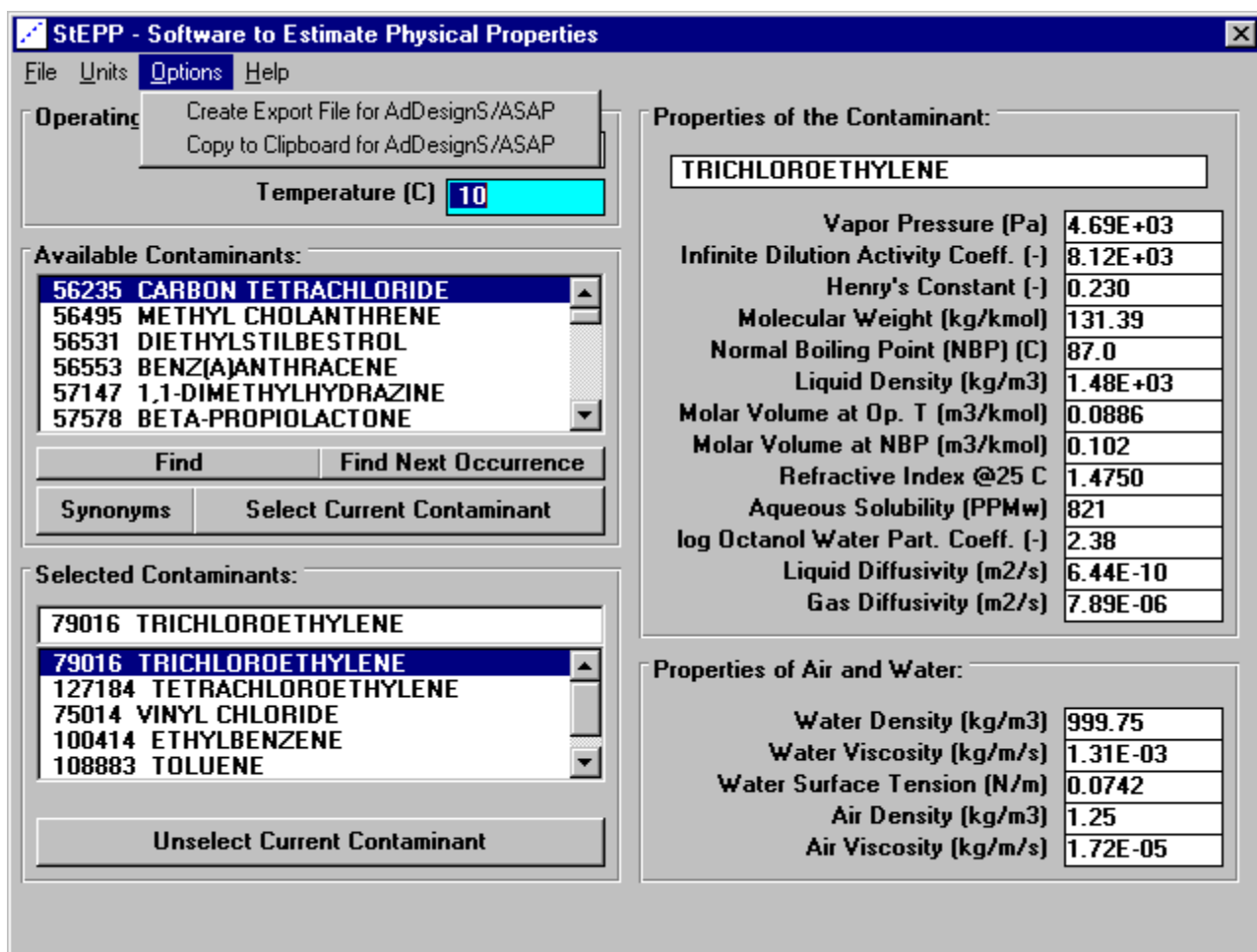
Figure 9 - StEPP™ Main Window for This Design

After the contaminants have been selected in StEPP™ and their properties calculated at the proper temperature and pressure, they can be transferred from StEPP to ASAP using either of two options, which are described below: (a) Create Export File for AdDesignS/ASAP and (b) Copy to Clipboard for AdDesignS/ASAP.

> *(a)   Transferring Chemical Properties from StEPPÔ to ASAPÔ Using the* Create Export File for AdDesignS/ASAP *Option*

To create an export file within StEPP™, for use in ASAP™, click on the *Create Export File for AdDesignS™/ASAP™* in the StEPP™ **Options** menu. This option is shown in Figure 9. After clicking this option, the *Save StEPP™ Export File* window shown in Figure 10 appears. Give the export file an *.exp* extension (the default), such as *bub10.exp*, and the file will be readily importable into ASAP™, as described below.

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Figure 10 - Save StEPP™ Export File Window

To import the StEPP™ export file described above (*bub10.exp*), click on the *Add* button shown on the bottom left-hand corner of the window shown in Figure 3 (and highlighted in Figure 8). Figure 11 shows the window that will appear.

Figure 11 - Contaminant Properties Input Window

Click on the *Import StEPP™ Export File* button shown in Figure 11. The window shown in Figure 12 will appear.

Figure 12 - Load StEPP™ Export File Window

Select the file *bub10.exp* that was created earlier and the chemicals selected in StEPP™ for the given design will be imported into ASAP™. Figure 13 appears after the import and shows a successful import was achieved.

Figure 13 - Successful StEPP™ Property Retrieval Indication Window

(b) *Transferring Chemical Properties from StEPPÔ to ASAPÔ Using the Copy to Clipboard for AdDesignS/ASAP Option*

To copy selected StEPP™ data to the Windows clipboard for export into ASAP, select *Copy to Clipboard for AdDesignS/ASAP* from the *Options* menu within StEPP. The message box shown in Figure 14 will appear, verifying that all of the StEPP data is now stored in the Windows clipboard.

Figure 14 – Successful Copy to Clipboard from StEPP™ Message Box

To import the chemicals and their physical properties to ASAP™ from the data on the clipboard, click on the *Add* button in the *Component Properties* block of the ASAP™ main window. The Component Properties window shown in Figure 15 will appear.

Figure 15 - Component Properties window (adding new components)

To import the StEPP™ data from the Windows clipboard, click the *Import from Clipboard* button on the Component Properties window. The window shown in Figure 16 will appear, showing that the properties have been successfully transferred into ASAP.

ASAP

Successfully imported 6 components from StEPP:
 TRICHLOROETHYLENE
 TETRACHLOROETHYLENE
 VINYL CHLORIDE
 ETHYLBENZENE
 TOLUENE
 1,1-DICHLOROETHYLENE
The properties are for a pressure of 101325 Pa and a temperature of 10 degrees Celcius.

Don't forget to set the correct values of influent concentration and treatment objective concentration for each of these components.

[OK]

Figure 16 – Successful Import from StEPP™ Window

> (2) Manipulation of Data Required after Transferring Properties from StEPP™ to ASAP™

Click on the *OK* button to continue. Figure 3 appears. As shown in Figure 13 or Figure 16, it is necessary to input influent concentrations and treatment objectives for each of the six components retrieved. To do so, select each contaminant, one at a time, in the Design Contaminant list box shown in the lower left-hand corner of Figure 3. Then click on the *Edit Properties* button. Figure 17 shows the window that appears for trichloroethylene.

Figure 17 - Specify Contaminant Properties Window for Trichloroethylene

The properties molecular weight, Henry's constant, molar volume, and liquid diffusivity are already correct since they were retrieved from StEPP™. The influent concentration and treatment objective shown at the bottom of the screen must be input since they will vary from case to case. These properties shown in Figure 17 already reflect the values for the current design case. It is seen that the properties shown in Figure 17 agree with the trichloroethylene properties shown in Tables 1 and 2.

Figure 18 shows the *Specify Contaminant Properties* window for tetrachloroethylene. It can be seen that the properties shown in Figure 18 agree with the properties of tetrachloroethylene shown in Tables 1 and 2.

Figure 18 - Specify Contaminant Properties Window for Tetrachloroethylene

Figure 19 shows the *Specify Contaminant Properties* window for vinyl chloride. It can be seen that the properties shown in Figure 19 agree with the properties of vinyl chloride shown in Tables 1 and 2.

Figure 19 - Specify Contaminant Properties Window for Vinyl Chloride

Figure 20 shows the *Specify Contaminant Properties* window for ethylbenzene. It can be seen that the properties shown in Figure 20 agree with the properties of ethylbenzene shown in Tables 1 and 2.

Figure 20 - Specify Contaminant Properties Window for Ethylbenzene

Figure 21 shows the *Specify Contaminant Properties* window for toluene. It can be seen that the properties shown in Figure 21 agree with the properties of toluene shown in Tables 1 and 2.

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Figure 21 - Specify Contaminant Properties Window for Toluene

Figure 22 shows the *Specify Contaminant Properties* window for 1,1-dichloroethene. It can be seen that the properties shown in Figure 22 agree with the properties of 1,1-dichloroethene shown in Tables 1 and 2.

Figure 22 - Specify Contaminant Properties Window for 1,1-Dichloroethene

d) *Flow Parameters*

Flow parameters are shown in the upper right-hand side of Figure 3. This portion of Figure 3 is reproduced here as Figure 23.

Figure 23 - Flow Parameters of Rating Mode Window

Explanation of the origin of the values for the properties shown in Figure 23 is provided here. The water flow rate of 2000 gpm is given in the problem statement. An air to water ratio of 11 is used as it was calculated by the program in the design mode for this case and agreed with the value calculated in the sample calculations for this design case (see Eq. 3 in the sample calculations section of the design mode). An air flow rate of 1.39 m^3/s was calculated as the product of $\frac{\dot{V}}{Q} \times Q$.

e) Tank Parameters

The tank parameters are shown in the middle of the right-hand column of the design mode window shown in Figure 3. This portion of the window is highlighted as Figure 24.
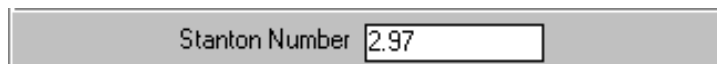
Tank Parameters		
No. of Tanks (series)	3	
Retention Time (1 Tank)	1.321	hr
Retention Time (All Tanks)	3.963	hr
Volume (1 Tank)	6.000e+02	m³
Volume (All Tanks)	1.800e+03	m³

Figure 24 - Tank Parameters Section of Design Mode Window

The values of the tank parameters shown in Figure 3 (and highlighted in Figure 24) were taken from the design calculations performed for the design mode run of this program and corresponding sample calculations. The number of tanks in series is given in the problem statement. In rating mode, one of the other parameters can be specified with the program calculating the remainder. Case 1 of the sample calculations shows the specification of the tank volume as 6.00E+02 m^3. The retention time of 1.32 hr calculated by the program agrees with the sample calculations (see Eq. 11). The total retention time for the system determined by the program to be 3.963 hr corresponds to the value calculated in the sample calculations (see Eq. 12). The volume of 1.800E+03 m^3 calculated by the program agrees with the sample calculations performed previously (see Eq. 10).

f)   *Stanton Number for Trichloroethylene*

The Stanton number used in the calculation of the liquid phase effluent concentrations is located beneath the tank parameters in the middle of the right-hand column as shown in Figure 3 (and highlighted in Figure 25).
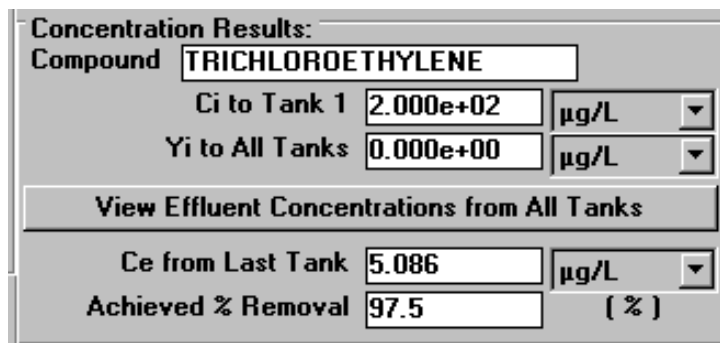
Figure 25 - Stanton Number Section of Rating Mode Window

The Stanton number calculated by the program is 2.97 and can be seen in the sample calculations (see Eq. 2).

g)   *Concentration Results for Trichloroethylene*

The effluent concentrations of both the liquid phase and the gas phase of the contaminant as well as the achieved percent removal are found in the lower right-hand corner of the rating mode window as shown in Figure 3 (and highlighted in Figure 26).

Figure 26 - Concentration Results Portion of Rating Mode Window

Click on the *View Effluent Concentrations from All Tanks* button shown in Figure 3 (and highlighted in Figure 26) to see the effluent concentrations of both the liquid phase and the gas phase of the contaminant from each tank. The window that appears is shown in Figure 27.

Figure 27 - Effluent Concentrations from Each Tank

It can be seen that the values calculated by the program for the liquid phase effluent concentrations; 58.82 µg/L from tank 1 (see Eq. 3), 17.30 µg/L from tank 2 (see Eq. 4), and 5.088 µg/L from tank 3 (see Eq. 5); and the gas phase concentrations; 12.9 µg/L from tank 1 (see Eq. 7), 3.77 µg/L from tank 2 (see Eq. 8), and 1.11 µg/L from tank 3 (see Eq. 9), match the values shown in the sample calculations.

Click the *OK* button shown in Figure 27 to return to the rating mode window shown in Figure 3.

h)   *Concentration Results for Other Components*

Figure 28 - Figure 32 show the main window with the effluent concentrations for each tank window for the other components. It is seen from the figures that the values calculated by the program match the results given in Table 4.

Figure 28 - Concentration Results for Tetrachloroethylene

Figure 29 - Concentration Results for Vinyl Chloride

Figure 30 - Concentration Results for Ethylbenzene

Figure 31 - Concentration Results for Toluene

Figure 32 - Concentration Results for 1,1-Dichloroethylene

i) *Power Results*

The power calculations for rating mode are identical to those for design mode. To view the power window for this rating mode case, click the *Perform Power Calculations* options in the *Power* menu shown in Figure 3. Then the power window will appear:

Figure 33 - Power Window

j) Viewing Effluent Concentration Results for All Contaminants

For the current design, it is useful to see what the effluent concentrations of all contaminants on the same window. ASAP provides a convenient method for seeing these results. By clicking on the *Concentration Results* button in the lower left-hand corner of the bubble aeration – rating mode window shown in Figure 3, the user will see the concentration results for all contaminants using the given design (see Figure 34).

Figure 34 – View Concentration Results for All Contaminants Window

This window provides a quick method to see whether the given design will meet the treatment objectives for all contaminants.

F. *Bubble Aeration - Nomenclature*

C_0 — Liquid phase influent concentration of contaminant, (*mg/L*)

C_1 — Liquid phase effluent concentration of contaminant discharged from tank number *1*, (*mg/L*)

C_2 — Liquid phase effluent concentration of contaminant discharged from tank number *2*, (*mg/L*)

C_3 — Liquid phase effluent concentration of contaminant discharged from tank number *3*, (*mg/L*)

C_i — Liquid phase effluent concentration of contaminant discharged from tank number *i*, (μg/L)

C_s^* — Tabulated value of dissolved oxygen surface saturation concentration at 20°C, (*mg/L*)

C_{TO} — Treatment objective concentration of contaminant, (*mg/L*)

C_∞^* — Dissolved oxygen saturation concentration attained at infinite time, (*mg/L*)

d_e — Effective saturation depth, (*m*)

D — Tank water depth, (*m*)

$D_{l,i}$ — Liquid diffusivity of contaminant at 10°C, (*m^2/s*)

D_{l,O_2} — Diffusivity of Oxygen at 10°C, (*m^2/s*)

g — gravitational constant (*m/s^2*) = 9.81

H — Henry's constant, (dimensionless)

H_b — Water depth (*m*)

H_i — Henry's constant of the contaminant, (dimensionless)

H_{O_2} — Henry's constant of oxygen, (*mg/L*atm*)

i — Tank number, (dimensionless)

$K_L a$	Design mass transfer coefficient, ($1/s$)
$K_L a_i$	Design mass transfer coefficient of contaminant at 10°C, ($1/s$)
$K_L a_{O_2}$	Mass transfer coefficient of Oxygen at 10°C, ($1/s$)
$K_L a_T^*$	True mass transfer coefficient for oxygen at temperature, T, ($1/s$)
$K_L a_{20}^*$	True mass transfer coefficient for oxygen at 20°C, ($1/s$)
M_a	Molecular weight of air, (amu)
M_{O_2}	Molecular weight of oxygen, (amu)
n	Number of tanks operating in series, (dimensionless)
n_a	constant used in determining blower brake power = 0.283
$P_{ambient}$	ambient pressure (N/m^2)
P_b	Barometric pressure, (N/m^2)
P_{blower}	Blower brake power (kW)
$P_{in,b}$	Inlet air pressure to bubble aeration tank (N/m^2)
P_s	Barometric pressure under standard conditions, (N/m^2)
P_v	Vapor pressure of water at 20°C, (N/m^2)
Q	Water flowrate, (m^3/s)
Q_a	Volumetric air flow rate, (m^3/s)
R_g	Universal gas constant ($L*atm/(mol*K)$) = 0.08205
$SOTR$	Standardized oxygen transfer rate, (kg/d)
T	Operating temperature (K)
V	Volume of each tank in series, (m^3)
V_n	Total volume of system, (m^3)
V_{test}	Clear water oxygen test volume (m^3)
$\dot{V}$	Air flowrate, (m^3/s)

$\frac{\dot{V}}{Q}$	Air to water ratio, (dimensionless)
$\left(\frac{\dot{V}}{Q}\right)_{min}$	Minimum air to water ratio, (dimensionless)
W_{O_2}	Rate of oxygen supply by the diffuser, (kg/s)
y_1	Gas phase effluent concentration of contaminant discharged from tank number 1, (mg/L)
y_2	Gas phase effluent concentration of contaminant discharged from tank number 2, (mg/L)
y_3	Gas phase effluent concentration of contaminant discharged from tank number 3, (mg/L)
y_i	Gas phase effluent concentration of contaminant discharged from tank number i, (mg/L)

Greek Letters

γ_w	Weight density of water, (N/m^3)
θ	Parameter used for temperature correlation
ρ_a, ρ_g	Air density at 20°C, (kg/m^3)
τ	Hydraulic retention time of one tank in series, (hr)
τ_n	Total hydraulic retention time of system, (hr)
ϕ_o	Oxygenation coefficient, ($1/sec$)

G. *Surface Aeration - Design Mode*

The following problem will be used to show sample calculations for surface aeration. In addition, a sample program run of ASAP™ will be used to verify that the program is correctly duplicating the results of the sample calculations.

1. Problem Statement

The city of Anytown, USA recently discovered that one of its wells was contaminated with the compounds listed in Table 1. In order for them to continue using the well, they were required to remove these compounds below their MCLs, also shown in Table 1. During normal pumping operations, the well produces about 2000 gpm, the water temperature is 10°C, and the barometric pressure is 1 atm.

Design a surface aeration system consisting of three tanks in series using TCE as the design contaminant. Obtain physical and chemical properties for the design from StEPP™. The power input to the system is assumed to have 80 percent efficiency and a power input per unit volume of 65.0 W/m^3.

Present a sample calculation of the volume of an individual tank in the system. Also show sample calculations for total tank volume, hydraulic retention time of each tank, and the total hydraulic retention time for all tanks.

Table 1 – Contaminant Influent Concentrations and Treatment Objectives (MCLs)

Compound	Concentration Discharged, C_0 (µg/L)	MCL, C_{TO} (µg/L)
Trichloroethylene	200.0	5.0
Tetrachloroethylene	150.0	5.0
Vinyl Chloride	60.0	1.0
Ethylbenzene	30.0	5.0
Toluene	80.0	5.0
1,1-Dichloroethene	85.0	7.0

a) *Properties Needed to Perform Sample Calculations and Program Run*

Table 2 shows the chemical properties retrieved from StEPP™ and ASAP™ required for surface aeration at 10°C and 1 atm.

Table 2 - Chemical Properties from StEPP™ and ASAP™ at 10° C and 1 atm

Compound	MW (kg/kmol)	H (-)	V_b (m³/kmol)	T_{NBP} (°C)	D_l (m²/s)	D_g (m²/s)
Trichloroethylene	131.39	0.230	0.1020	87.0	6.44E-10	7.89E-06
Tetrachloroethylene	165.84	0.361	0.1190	121.0	5.86 E-10	7.13 E-06
Vinyl Chloride	62.50	0.546	0.0665	-13.9	8.26 E-10	1.08E-05
Ethylbenzene	106.17	0.170	0.1400	136.0	5.33 E-10	6.88 E-06
Toluene	92.15	0.167	0.1190	111.0	5.86 E-10	7.57 E-06
1,1-Dichloroethene	96.95	0.680	0.0840	31.6	7.20 E-10	9.05 E-06

b) Note Regarding Comparison of Sample Calculation Values to Sample Program Run

In certain cases, the numbers that appear in the sample calculations are slightly different from the values displayed in the sample program run. These variations can be attributed to rounding.

2. Sample Design Mode Calculation of Tank Volume for Trichloroethylene as the Design Compound Including Supplementary Parameter Calculations

a) Total Volume

The total volume of the system, V_n, is calculated using the following relationship:

$$V_n = V \times n = 353.29 \text{ m}^3 \times 3 = 1060 \text{m}^3$$

Eq. 1

The parameters required to calculate V_n in Eq. 1 can be found as follows:

Parameter   Location

V Eq. 2

n Given in problem statement

(1) Tank Volume

The calculation of the volume for each tank, V, in the series is shown in Eq. 2.

$$V = \frac{Q}{K_L a}\left[\left(\frac{C_0}{C_{TO}}\right)^{1/n} - 1\right] = \frac{0.1262 \frac{m^3}{s}}{0.00086445 \frac{1}{s}}\left[\left(\frac{200.0 \frac{\mu g}{L}}{5.0 \frac{\mu g}{L}}\right)^{1/3} - 1\right] = 353.29 \text{ m}^3$$

Eq. 2

The parameters required to calculate V in Eq. 2 can be found as follows:

Parameter	Location
$K_L a$	Eq. 3
C_0	Table 1
C_{TO}	Table 1
n	Given in problem statement
Q	Given in problem statement

(a)   Mass Transfer Coefficient

For surface aeration, it is difficult to determine the overall mass transfer coefficient, $K_L a$, for a compound with the method utilized in aeration pack tower design due to variations in each system. In order to determine the overall mass transfer coefficient of a compound for these systems, it is necessary to relate the mass transfer coefficient of a given compound, $K_L a_i$, to the mass transfer coefficient of a reference compound, $K_L a_{ref}$ as shown in Eq. 3. For the purposes of this design, oxygen will be used as the reference compound.

$$K_L a_i = K_L a_{O_2} \left[\left(\frac{D_{l,i}}{D_{l,O_2}} \right)^{0.5} \left(1 + \frac{1}{H_i \, 40} \right) \right]^{-1}$$

$$= 0.0015299 \tfrac{1}{s} \left[\left(\frac{6.44\text{E}-10 \, \frac{m^2}{s}}{1.64\text{E}-09 \, \frac{m^2}{s}} \right)^{0.5} \left(1 + \frac{1}{0.230 \, 40} \right) \right]^{-1} = 0.00086445$$

Eq. 3

The parameters required to calculate $K_L a_i$ in Eq. 3 can be found as follows:

Parameter	Location
$K_L a_{O_2}$	Eq. 4
$D_{l,i}$	Table 2
D_{l,O_2}	Eq. 5
H_i	Table 2

Mass Transfer Coefficient of Oxygen

The mass transfer coefficient of oxygen, $K_L a_{O_2}$, can be estimated using   Eq. 4.

$$K_L a_{O_2} = 2.9E-05 \left(P/V \right)^{0.95} = 2.9E-05 \left(65 \frac{W}{m^3} \right)^{0.95} = 0.0015299 \, \frac{1}{s}$$

Eq. 4

The parameters required to calculate $K_L a_{O_2}$ in   Eq. 4 can be found as follows:

Parameter	Location
$\frac{P}{V}$	Given in problem statement

Liquid Diffusivity of Oxygen

The liquid diffusivity of oxygen, $D_{l_{O_2}}$, is calculated in the following equation:

$$D_{l_{O_2}} = \left[10^{\left(A + B/T \right)} \right] \left(1.0 \times 10^{-9} \right) = \left[10^{\left(3.15 + -831.0/283 \right)} \right] \left(1.0 \times 10^{-9} \right) = 1.641E - 09 \, \frac{m^2}{s}$$

Eq. 5

The parameters required to calculate $D_{l_{O_2}}$ in Eq. 5 can be found as follows:

Parameter	Location
A	Table 3
B	Table 3
T	Given in problem statement

(b)   *Hydraulic Retention Time*

The hydraulic retention time, τ, can be calculated using the following relationship:

$$\tau = \frac{V}{Q} = \frac{353.29 \, m^3}{0.1262 \frac{m^3}{s} * 3600 \frac{s}{hr}} = 0.778 \, hr$$

Eq. 6

The parameters required to calculate τ in Eq. 6 can be found as follows:

Parameter	Location
V	Eq. 2
Q	Given in problem statement

Total Hydraulic Retention Time

The total hydraulic retention time of the system, τ_n, can be found using the following equation:

$$\tau_n = \tau \times n = 0.778\,hr \times 3 = 2.33\,hr$$

Eq. 7

The parameters required to calculate τ_n in Eq. 7 can be found as follows:

Parameter	Location
τ	Eq. 6
n	Given in problem statement

b) *Liquid Phase Effluent Concentration from Tank Number i*

The liquid phase effluent concentration from tank number i, C_i, can be calculated using the following relationships:

$$C_i = \frac{C_{i-1}}{1 + K_L a\left(\frac{V}{Q}\right)} = \frac{C_0}{\left[1 + K_L a\left(\frac{V}{Q}\right)\right]^i} = \frac{C_0}{\left[1 + K_L a\left(\tau\right)\right]^i} = \frac{C_0}{\left[1 + K_L a\left(\frac{V_n}{n \cdot Q}\right)\right]^i} = \frac{C_0}{\left[1 + K_L a\left(\frac{\tau_n}{n}\right)\right]^i}$$

Eq. 8

The parameters required to calculate C_i in Eq. 8 can be found as follows:

Parameter	Location
C_{i-1}	Calculated value
$K_L a$	Eq. 3
V	Eq. 2
Q	Given in problem statement
C_0	Table 1
i	User-specified
τ	Eq. 6
V_n	Eq. 1
n	Given in problem statement
τ_n	Eq. 7

(1) Liquid Phase Effluent Concentration from Tank Number 1

The liquid phase effluent concentration from tank number 1, C_1, can be found using Eq. 9.

$$C_1 = \frac{C_0}{\left[1 + K_L a \left(\frac{V}{Q}\right)\right]^1} = \frac{200.0 \frac{\mu g}{L}}{\left[1 + 0.00086445 \frac{1}{s} \left(\frac{353.29\,m^3}{0.1262 \frac{m^3}{s}}\right)\right]^1} = 58.48 \frac{\mu g}{L}$$

Eq. 9

The parameters required to calculate C_1 in Eq. 9 can be found as follows:

Parameter	Location
$K_L a$	Eq. 3
C_0	Table 1
Q	Given in problem statement
V	Eq. 3

(2) Liquid Phase Effluent Concentration from Tank Number 2

The liquid phase effluent concentration from tank number 2, C_2, can be found using Eq. 10:

$$C_2 = \frac{C_0}{\left[1 + K_L a \left(\frac{V}{Q}\right)\right]^2} = \frac{200.0 \frac{\mu g}{L}}{\left[1 + 0.00086445 \frac{1}{s} \left(\frac{353.29\,m^3}{0.1262 \frac{m^3}{s}}\right)\right]^2} = 17.10 \frac{\mu g}{L}$$

Eq. 10

The parameters required to calculate C_2 in Eq. 10 can be found as follows:

Parameter	Location
$K_L a$	Eq. 3
C_0	Table 1
Q	Given in problem statement
V	Eq. 2

(3) Liquid Phase Effluent Concentration from Tank Number 3

The liquid phase effluent concentration from tank number 3, C_3, can be found using Eq. 11:

$$C_3 = \frac{C_0}{\left[1 + K_L a \left(\frac{V}{Q}\right)\right]^3} = \frac{200.0 \, \frac{\mu g}{L}}{\left(1 + 0.00086445 \, \frac{1}{s} \left(\frac{353.29 \, m^3}{0.1262 \, \frac{m^3}{s}}\right)\right)^3} = 5.00 \, \frac{\mu g}{L}$$

Eq. 11

The parameters required to calculate C_3 in Eq. 11 can be found as follows:

Parameter	Location
$K_L a$	Eq. 3
C_0	Table 1
Q	Given in problem statement
V	Eq. 2

c) *Power Calculations*

(1) Total Power Input

The total power input to the system, P_n, can be found using the relationship shown in Eq. 12:

$$P_n = \left(\frac{P}{V}\right) \times \frac{V_n}{1000 \, \frac{W}{kW} \times Eff} = \left(65 \, \frac{W}{m^3}\right) \times \frac{1060 \, m^3}{1000 \, \frac{W}{kW} \times 0.8} = 86.1 \, kW$$

Eq. 12

The parameters required to calculate P_n in Eq. 12 can be found as follows:

Parameter	Location
$\left(\frac{P}{V}\right)$	Given in problem statement
V_n	Eq. 1
Eff	Given in problem statement

(a) Power Input per Tank

The power input per tank, P, is calculated by the following:

$$P = \left(\frac{P}{V}\right) \times \frac{V}{1000\frac{W}{kW} \times Eff} = \left(65\frac{W}{m^3}\right) \times \frac{353.29 \text{ m}^3}{1000\frac{W}{kW} \times 0.8} = 28.7 \text{ kW}$$

Eq. 13

The parameters required to calculate P in Eq. 13 can be found as follows:

Parameter	Location
$\left(\frac{P}{V}\right)$	Given in problem statement
V	Eq. 2
Eff	Given in problem statement

3. Sample Program Run of ASAP™ to Verify Sample Calculations for Surface Aeration in Design Mode

To start the ASAP™ program, double click on the ASAP™ icon in the *ETDOT Programs* group in windows. The screen shown in Figure 1 will appear.
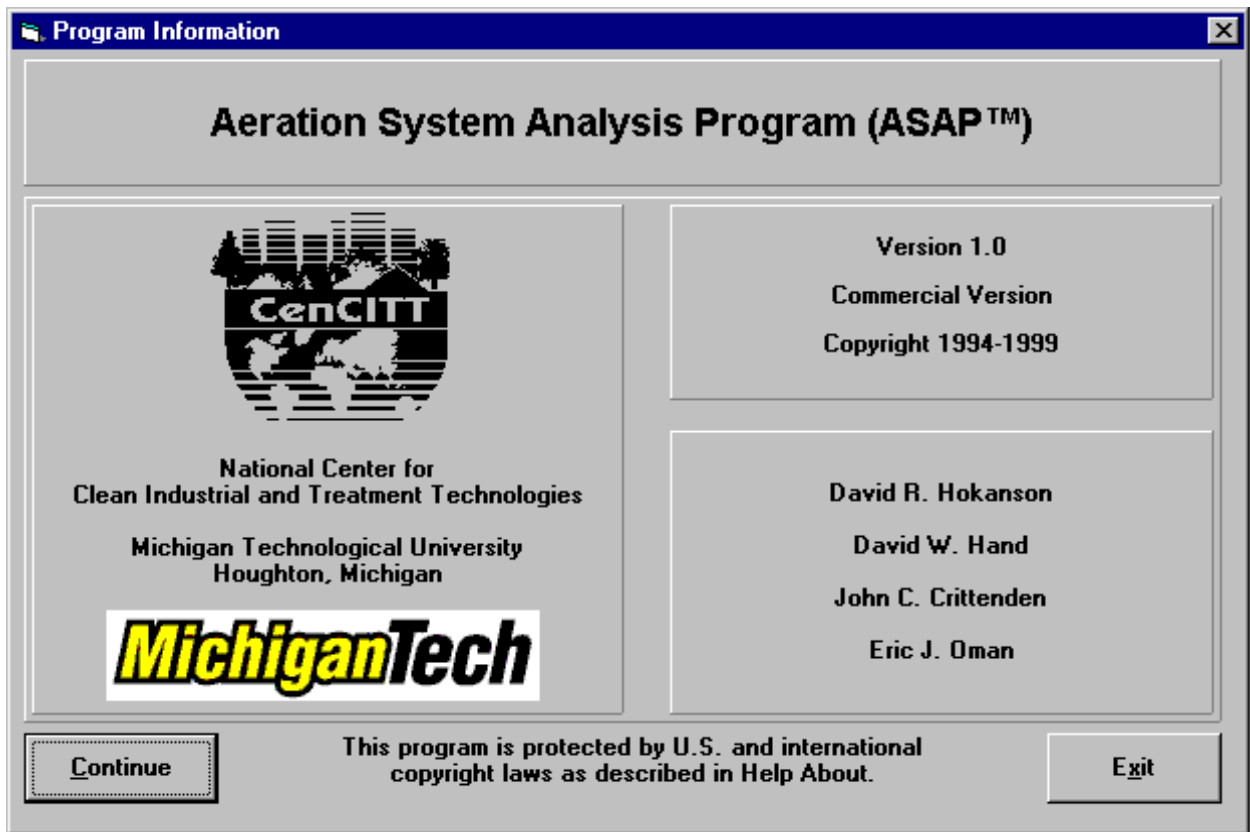
Figure 1 - ASAP™ Title Window

Click on the *Continue* button on the screen shown in Figure 1 and the menu shown in Figure 2 will appear.

Figure 2 - Main Menu Window in ASAP™

Click on the *Enter Design Mode* button for Surface Aeration (option 5 in Figure 2) and the design mode screen for surface aeration shown in Figure 3 will appear.

Figure 3 - Design Mode Window for Surface Aeration

a) *Physical Properties of Water*

Specify pressure and temperature in the upper left-hand corner of the window shown in Figure 3. This portion of the surface aeration design mode window is shown in Figure 4.

Figure 4 - Operating Conditions Portion of Design Mode Window

Click on the *Display Physical Properties of Water* button in Figure 3 (and highlighted in Figure 4) to show the properties of water at the specified temperature and

pressure (101325 Pa and 10°C). Figure 5 shows the water properties window for this case.

Figure 5 - Water Properties Window

The properties shown in Figure 5 are by default calculated from correlations so the user should not have to change his values. In the rare case that the user would like to enter a value for any of these properties instead of using the correlations, it is possible to do so on the window shown in Figure 5. Click on the *OK* button shown in Figure 5 to close the window.

b)   *Oxygen (reference compound)*

The mass transfer coefficient for the design contaminant is calculated using its relationship to the mass transfer coefficient of oxygen under similar conditions. The mass transfer coefficient of oxygen is estimated using the Roberts & Dandlike Correlation. This portion of the design mode window is shown in Figure 3 (and highlighted in Figure 6).

Figure 6 - Oxygen Section of Design Mode Window

The mass transfer coefficient of oxygen at 10°C is calculated by the program as 1.530E-03 1/s. This agrees with the value from the sample calculations section (see

Eq. 4).

c) *Chemical Properties*

Chemical properties for each of the six components can be retrieved from StEPP™. When the screen shown in Figure 3 loads, the properties of the six contaminants load as a default design case. Before retrieving the chemical properties of the six chemicals required in the current design, it is necessary to delete the six default chemicals shown in the Design Contaminant list box on the bottom of the left-hand column shown in Figure 3. This portion of the design mode window is in Figure 3 (and highlighted in Figure 7).

Figure 7 - Contaminant Selection Portion of Design Mode Window

It can be seen that the value for the mass transfer coefficient of trichloroethylene calculated by the program, 8.644E-04 1/s, agrees with the sample calculations (see Eq. 3).

To delete each chemical click on the *Delete* button located in between the *Add* and *Edit Properties* buttons shown in Figure 3 (and highlighted in Figure 7). Click the *Delete* button once for each chemical until all chemicals have been deleted.

(1) Transferring Properties from StEPP™ to ASAP™

ASAP™ has the capability of transferring the physical properties of contaminants from Software to Estimate Physical Properties (StEPP™). There are two choices available in the *Options* menu within StEPP for transferring data from StEPP into ASAP: (a) Create Export File for AdDesignS/ASAP and (b) Copy to Clipboard for AdDesignS/ASAP. The StEPP™ main window highlighting the *Options* menu is shown in Figure 8 (refer to StEPP manual for more information on selecting compounds within StEPP). Figure 8 shows the main StEPP™ window after the chemicals for this design have been selected at 10°C.

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Figure 8 - StEPP™ Main Window for This Design

(a)   *Transferring Chemical Properties from StEPPÔ to ASAPÔ Using the* Create Export File for AdDesignS/ASAP *Option*

To create an export file within StEPP™ for use in ASAP™, click on the *Create Export File for AdDesginS™/ASAP™* in the StEPP™ **Options** menu. This option is shown in Figure 8. After clicking this option, the *Save StEPP™ Export File* window shown in Figure 9 appears. Give the export file a *.exp* extension (the default), such as *surf10.exp*, and the file will be readily importable into ASAP™, as described below.

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Figure 9 - Save StEPP™ Export File Window

To import the StEPP™ export file described above (*surf10.exp*), click on the *Add* button shown on the bottom left-hand corner of the window shown in Figure 3 (and highlighted in Figure 7). Figure 10 shows the window that will appear.

Figure 10 - Contaminant Properties Input Window

Click on the *Import StEPP™ Export File* button shown in Figure 10. The window shown in Figure 11 will appear.

Figure 11 - Load StEPP™ Export File Window

Select the file *surf10.exp* that was created earlier and the chemicals selected in StEPP™ for the given design will be imported into ASAP™. Figure 12 appears after the import and shows a successful import was achieved.

Figure 12 - Successful StEPP™ Property Retrieval Indication Window

(b)   *Transferring Chemical Properties from StEPPÔ to ASAPÔ Using the Copy to Clipboard for AdDesignS/ASAP Option*

To copy selected StEPP™ data to the Windows clipboard for export into ASAP™, select *Copy to Clipboard for AdDesignS/ASAP* from the *Options* menu within StEPP™. The message box shown in Figure 13 will appear, verifying that all of the StEPP™ data is now stored in the Windows clipboard.

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Figure 13 – Successful Copy to Clipboard from StEPP™ Message Box

To import the chemicals and their physical properties to ASAP™ from the data on the clipboard, click on the *Add* button in the *Component Properties* block of the ASAP™ main window. The Component Properties window shown in Figure 14 will appear.

Figure 14 - Component Properties window (adding new components)

To import the StEPP™ data from the Windows clipboard, click the *Import from Clipboard* button on the Component Properties window. The window shown in Figure 15 will appear, showing that the properties have been successfully transferred into ASAP.

Figure 15 – Successful Import from StEPP™ Window

     (2)   Manipulation of Data Required after Transferring Properties from StEPP™ to ASAP™

Click on the *OK* button to continue. Figure 3 appears. As shown in Figure 12 or Figure 15, it is necessary to input influent concentrations and treatment objectives for each of the six components retrieved. To do so, select each contaminant one at a time in the Design Contaminant list box shown in the lower left-hand corner of Figure 3. Then click on the *Edit Properties* button. Figure 16 shows the window that appears for trichloroethylene.

Figure 16 - Specify Contaminant Properties Window for Trichloroethylene

The properties molecular weight, Henry's constant, molar volume, and liquid diffusivity are already correct since they were retrieved from StEPP™. The influent concentration and treatment objective shown at the bottom of the screen must be input since they will vary from case to case. These properties shown in Figure 16 already reflect the values for the current design case. It is seen that the properties shown in Figure 16 agree with the trichloroethylene properties shown in Tables 1 and 2.

Figure 17 shows the *Specify Contaminant Properties* window for tetrachloroethylene. It can be seen that the properties shown in Figure 17 agree with the properties of tetrachloroethylene shown in Tables 1 and 2.

Figure 17 - Specify Contaminant Properties Window for Tetrachloroethylene

Figure 18 shows the *Specify Contaminant Properties* window for vinyl chloride. It can be seen that the properties shown in Figure 18 agree with the properties of vinyl chloride shown in Tables 1 and 2.

Figure 18 - Specify Contaminant Properties Window for Vinyl Chloride

Figure 19 shows the *Specify Contaminant Properties* window for ethylbenzene. It can be seen that the properties shown in Figure 19 agree with the properties of ethylbenzene shown in Tables 1 and 2.

Figure 19 - Specify Contaminant Properties Window for Ethylbenzene

Figure 20 shows the *Specify Contaminant Properties* window for toluene. It can be seen that the properties shown in Figure 20 agree with the properties of toluene shown in Tables 1 and 2.

Figure 20 - Specify Contaminant Properties Window for Toluene

Figure 21 shows the *Specify Contaminant Properties* window for 1,1-dichloroethene. It can be seen that the properties shown in Figure 21 agree with the properties of 1,1-dichloroethene shown in Tables 1 and 2.

Figure 21 - Specify Contaminant Properties Window for 1,1-Dichloroethene

d)   *Flow Parameters*

The flow is shown in the upper right-hand side of Figure 3. This portion of Figure 3 is reproduced here as Figure 22.

Figure 22 - Flow Rate in Design Mode Window

The water flow rate of 2000 gpm is given in the problem statement.

e)   *Tank Parameters*

The tank parameters are shown in the middle of the right-hand column of the design mode window shown in Figure 3. This portion of the window is highlighted as Figure 23.

Figure 23 - Tank Parameters Section of Design Mode Window

The values of the tank parameters shown in Figure 3 (and highlighted in Figure 23) agree with the sample calculations section. The number of tanks in the series is given in the problem statement. The retention time of 0.778 hr calculated by the program agrees with the sample calculations performed previously (see Eq. 6). The total retention time for the system determined by the program to be 2.333 hr corresponds to the value calculated in the sample calculations (see Eq. 7). The volume of 353.3 m^3 calculated by the program agrees with the sample calculations performed previously (see Eq. 2). The volume of the entire system shown to be 1.060E+03 m^3 reflects the sample calculations provided (see Eq. 1).

f)   *Concentration Results*

The effluent concentrations of the liquid phase and the achieved percent removal are found in the lower right-hand corner of the design mode window as shown in Figure 3 (and highlighted in Figure 24).

Figure 24 - Concentration Results Portion of Design Mode Window

Click on the *View Effluent Concentrations from All Tanks* button shown in Figure 3 (and highlighted in Figure 24) to see the effluent concentrations of the liquid of the contaminant from each tank. The window that appears is shown in Figure 25.

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Figure 25 - Effluent Concentrations from Each Tank

It can be seen that the values calculated by the program for the liquid phase effluent concentrations; 58.5 µg/L from tank 1 (see Eq. 9), 17.1 µg/L from tank 2 (see Eq. 10), and 5.00 µg/L from tank 3 (see Eq. 11), match the values shown in the sample calculations.

Click the *OK* button shown in Figure 25 to return to the design mode window shown in Figure 3.

g)   Power Input

The power input to the system is displayed in middle of the left-hand column of the design mode window as shown in Figure 3 (and highlighted in Figure 26). This value is chosen to suit design purposes. Typical values range from 10 to 200 W/m^3.

Figure 26 - Power Input Portion of Design Mode Window

h)   Power Calculations

Other power parameters can be viewed in the lower right-hand corner of the design mode window as shown in Figure 3 (and highlighted in Figure 27). The value for the aerator motor efficiency is input by the user. The power required per tank is determined by the program to be 28.702 kW which agrees with the sample calculations (see Eq. 13). The total power required is calculated to be 86.105 kW which also agrees with the sample calculations (see Eq. 12).

Figure 27 - Power Calculation Section of Design Mode Window

> *i)*   *Viewing Effluent Concentration Results for*
> *Contaminants Other than the Design Contaminant*

For a given design, it is useful to see what the effluent concentrations of contaminants other than the design contaminant would be. ASAP provides a convenient method for seeing these results without having to switch to rating mode. (of course, the user will have to switch to rating mode to investigate commercially available packed tower sizes).

By clicking on the ***Concentration Results*** button in the lower left-hand corner of the surface aeration – design mode window shown in Figure 3, the user will see the concentration results for all contaminants using the given design.

Figure 28 – View Concentration Results for All Contaminants Window

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This window provides a quick method to see whether the given design will meet the treatment objectives for all contaminants.

j) Switching to Rating Mode

Once the surface aeration system has been specified in design mode, the user can take the established properties and switch to rating mode in order to examine the effect of modifications of various properties. The procedure for switching to rating mode is described here.

Figure 29 shows the **File** menu for surface aeration, design mode.
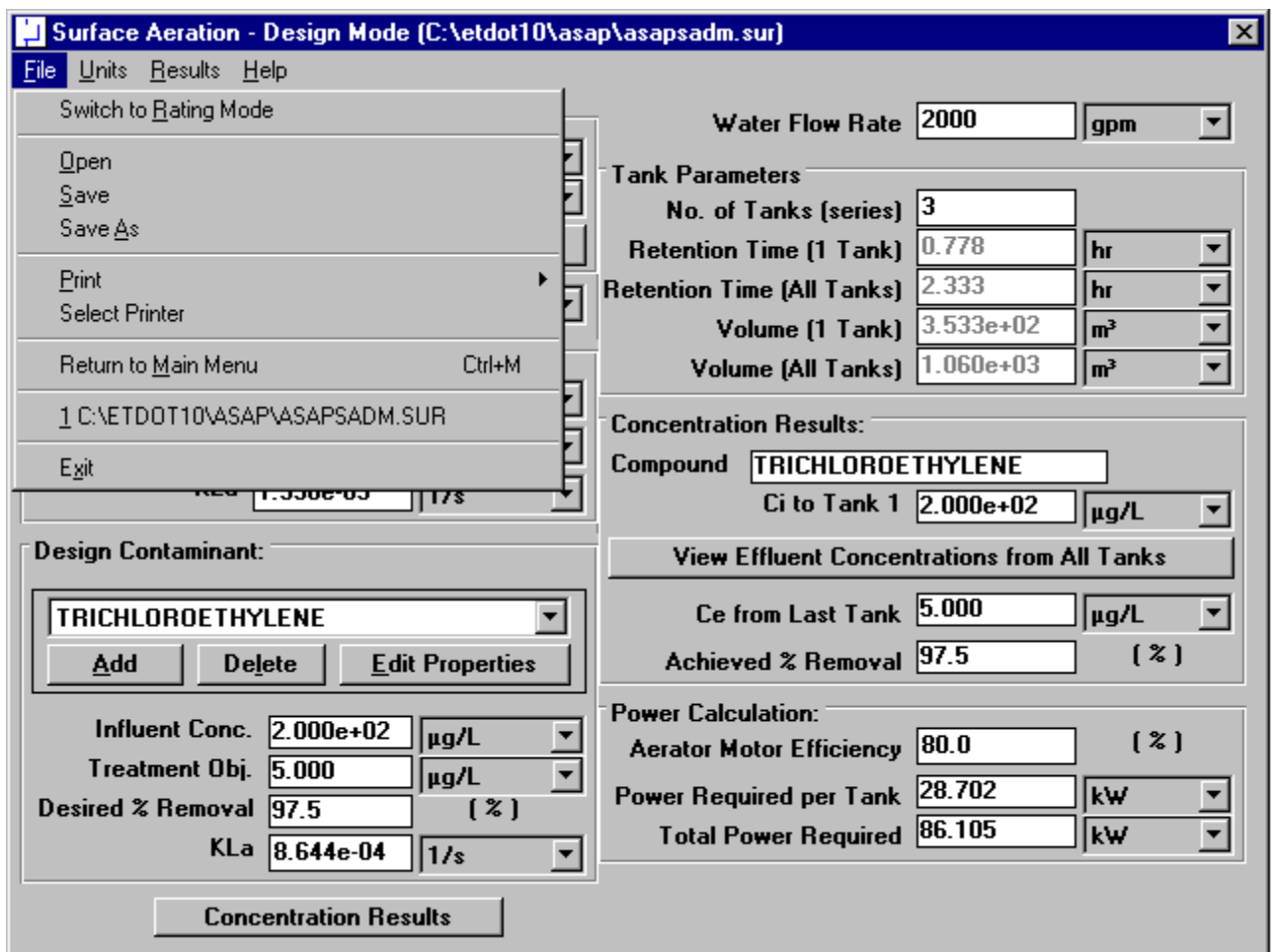
Figure 29 – File Menu for Surface Aeration – Design Mode

Click on the menu option called *Switch to Rating Mode* in Figure 29. The surface aeration – rating mode window will appear, as shown in Figure 30.

Figure 30 – Surface Aeration – Rating Mode Window

Use of *Surface Aeration – Rating Mode* will be described in the next section.

H. Surface Aeration - Rating Mode

The following problem will be used to show sample calculations for surface aeration. In addition, a sample program run of ASAP™ will be used to verify that the program is correctly duplicating the results of the sample calculations.

1. Problem Statement

The city of Anytown, USA recently discovered that one of its wells was contaminated with the compounds listed in Table 1. In order for them to continue using the well, they were required to remove these compounds below their MCLs, also shown in Table 1. During normal pumping operations, the well produces about 2000 gpm, the water temperature is 10°C, and the barometric pressure is 1 atm.

A surface aeration system consisting of three surface aeration tanks operating in series was designed to remove all the VOCs below their MCLs. The tanks each have a volume of 400 m^3. Physical and chemical properties for the design were retrieved from StEPP™.

Power input to the system has an efficiency of 80 percent. The power input per unit volume is 65.0 W/m^3.

Now that the system is under full operation, the performance of the system must be evaluated. This can be accomplished using the ASAP's™ program rating mode for surface aeration. Show a calculation of the effluent concentration for TCE from each tank. Present a table showing influent concentration, treatment objective, mass transfer coefficient, and effluent concentration from each tank for each component.

Table 1 - Influent Concentrations and Treatment Objectives (MCLs)

Compound	Concentration Discharged, C_0 (μg/L)	MCL, C_{TO} (μg/L)
Trichloroethylene (TCE)	200.0	5.0
Tetrachloroethylene (PCE)	150.0	5.0
Vinyl Chloride	60.0	1.0
Ethylbenzene	30.0	5.0
Toluene	80.0	5.0
1,1-Dichloroethene (1,1-DCE)	85.0	7.0

In certain cases, the numbers that appear in the sample calculations are slightly different from the values displayed in the sample program run. These variations can be attributed to rounding.

2. Sample Rating Mode Calculation of Effluent Concentration for Trichloroethylene as the Design Compound Including Supplementary Parameter Calculations

a) *Liquid Phase Effluent Concentration from Tank Number i*

The liquid phase effluent concentration from tank number i, C_i, can be calculated using the following relationships:

$$C_i = \frac{C_{i-1}}{1 + K_L a \left(\frac{V}{Q}\right)} = \frac{C_0}{\left[1 + K_L a \left(\frac{V}{Q}\right)\right]^i} = \frac{C_0}{\left[1 + K_L a (\tau)\right]^i} = \frac{C_0}{\left[1 + K_L a \left(\frac{V_n}{n \cdot Q}\right)\right]^i} = \frac{C_0}{\left[1 + K_L a \left(\frac{\tau_n}{n}\right)\right]^i}$$

Eq. 1

The parameters required to calculate C_i in Eq. 1 can be found as follows:

Parameter	Location
C_{i-1}	Calculated value
$K_L a$	See design mode calculations
V	See design mode calculations
Q	Given in problem statement
C_0	Table 1
i	User-specified
τ	See design mode calculations
V_n	Eq. 4
n	Given in problem statement
τ_n	Eq. 6

(1) Liquid Phase Effluent Concentration from Tank Number 1

The liquid phase effluent concentration from tank number 1, C_1, can be found using Eq. 2:

$$C_1 = \frac{C_0}{\left[1 + K_L a\left(\frac{V}{Q}\right)\right]^1} = \frac{200.0 \frac{\mu g}{L}}{\left(1 + 0.00086445 \frac{1}{s}\left(\frac{400\,\text{m}^3}{0.1262 \frac{m^3}{s}}\right)\right)^1} = 53.48 \frac{\mu g}{L}$$

Eq. 2

The parameters required to calculate C_1 in Eq. 2 can be found as follows:

Parameter	Location
$K_L a$	See design mode calculations
C_0	Table 1
Q	Given in problem statement
V	See design mode calculations

(2) Liquid Phase Effluent Concentration from Tank Number 2

Liquid phase effluent concentration from tank number 2 C_2, is found with Eq. 3

$$C_2 = \frac{C_0}{\left[1 + K_L a\left(\frac{V}{Q}\right)\right]^2} = \frac{200.0 \frac{\mu g}{L}}{\left(1 + 0.00086445 \frac{1}{s}\left(\frac{400\,\text{m}^3}{0.1262 \frac{m^3}{s}}\right)\right)^2} = 14.3 \frac{\mu g}{L}$$

Eq. 3

The parameters required to calculate C_2 in Eq. 3 can be found as follows:

Parameter	Location
$K_L a$	See design mode calculations
C_0	Table 1
Q	Given in problem statement
V	See design mode calculations

(3) Liquid Phase Effluent Concentration from Tank Number 3

Liquid phase effluent concentration from tank number 3, C_3, can be found using Eq. 4:

$$C_3 = \frac{C_0}{\left[1 + K_L a \left(\frac{V}{Q}\right)\right]^3} = \frac{200.0 \frac{\mu g}{L}}{\left[1 + 0.00086445 \frac{1}{s} \left(\frac{400 \, m^3}{0.1262 \frac{m^3}{s}}\right)\right]^3} = 3.82 \frac{\mu g}{L}$$

Eq. 4

The parameters required to calculate C_3 in Eq. 4 can be found as follows:

Parameter	Location
$K_L a$	See design mode calculations
C_0	Table 1
Q	Given in problem statement
V	See design mode calculations

b) Total Power Input

The total power input to the system, P_n, can be found using the following:

$$P_n = \left(\frac{P}{V}\right) \times \frac{V_n}{1000 \frac{W}{kW} \times Eff} = \left(65 \frac{W}{m^3}\right) \times \frac{1200 \, m^3}{1000 \frac{W}{kW} \times 0.8} = 97.5 \text{ kW}$$

Eq. 5

The parameters required to calculate P_n in Eq. 5 can be found as follows:

Parameter	Location
$\left(\frac{P}{V}\right)$	Given in problem statement
V_n	Eq. 7
Eff	Given in problem statement

(1) Power Input per Tank

The power input per tank, P, is calculated using Eq. 6 as follows:

$$P = \left[\frac{P}{V}\right] \times \frac{V}{1000\frac{W}{kW} \times Eff} = \left(65\frac{W}{m^3}\right) \times \frac{400\,m^3}{1000\frac{W}{kW} \times 0.8} = 32.5 \text{ kW}$$

Eq. 6

The parameters required to calculate P in Eq. 6 can be found as follows:

Parameter	Location
$\left[\frac{P}{V}\right]$	Given in problem statement
V	Given in problem statement
Eff	Given in problem statement

c) Note Regarding Calculation of V, V_n, τ, and τ_n

In rating a surface aeration system, one of the parameters listed above can be specified and then the other three calculated. Sample calculations are presented here.

(1) Case 1: Specify V, Calculate V_n, τ, and τ_n

(a) Total Volume of System

The total volume of all of the aeration tanks, V_n, can be calculated as follows:

$$V_n = V \cdot n = 400\,m^3 \cdot 3 = 1200m^3$$

Eq. 7

The parameters required to calculate V_n in Eq. 7 can be found as follows:

Parameter	Location
V	User-specified
n	Given in problem statement

(b) Hydraulic Retention Time

Hydraulic retention time for one aeration tank, τ, is calculated as follows:

$$\tau = \frac{V}{Q} = \frac{400\,m^3}{0.1262\frac{m^3}{s} * 3600\frac{s}{hr}} = 0.880\,hr$$

Eq. 8

The parameters required to calculate τ in Eq. 8 can be found as follows:

Parameter	Location
V	User-specified
Q	Given in problem statement

(c) Total Hydraulic Retention Time

The total hydraulic retention time for the system, τ_n, can be found using Eq. 9:

$$\tau_n = \frac{V_n}{Q} = \frac{1200\,\text{m}^3}{0.1262\,\frac{\text{m}^3}{s} * 3600\,\frac{s}{hr}} = 2.64\,hr$$

Eq. 9

The parameters required to calculate τ_n in Eq. 9 can be found as follows:

Parameter	Location
V_n	Eq. 7
Q	Given in problem statement

(2) Case 2: Specify V_n, Calculate V, τ, and τ_n

(a) Volume of One Aeration Tank

The volume of one of the aeration tanks, V, can be calculated as follows:

$$V = \frac{V_n}{n} = \frac{1200\,\text{m}^3}{3} = 400\,\text{m}^3$$

Eq. 10

The parameters required to calculate V in Eq. 10 can be found as follows:

Parameter	Location
V_n	User-specified
n	Given in problem statement

(b) Hydraulic Retention Time

The hydraulic retention time, τ, can be calculated using the following relationship:

$$\tau = \frac{V}{Q} = \frac{400\,\text{m}^3}{0.1262\,\frac{\text{m}^3}{s} * 3600\,\frac{s}{hr}} = 0.88\,hr$$

Eq. 11

The parameters required to calculate τ in Eq. 11 can be found as follows:

Parameter | Location

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V Eq. 10

Q Given in problem statement

(c)   *Total Hydraulic Retention Time*

The total hydraulic retention time for the system, τ_n, is calculated as follows:

$$\tau_n = \frac{V_n}{Q} = \frac{1200\,\text{m}^3}{0.1262\,\frac{\text{m}^3}{s} * 3600\,\frac{s}{hr}} = 2.64\,hr$$

Eq. 12

The parameters required to calculate τ_n in Eq. 12 can be found as follows:

Parameter   Location

V_n User-specified

Q Given in problem statement

(3)   **Case 3: Specify τ, Calculate V, V_n, and τ_n**

(a)   *Volume of One Aeration Tank*

The volume of one of the aeration tanks, V, can be calculated as follows:

$$V = \tau \cdot Q = 0.88\,hr \cdot 0.1262\,\frac{\text{m}^3}{s} * 3600\,\frac{s}{hr} = 400\,\text{m}^3$$

Eq. 13

The parameters required to calculate V in Eq. 13 can be found as follows:

Parameter   Location

τ User-specified

Q Given in problem statement

(b)   *Total Volume of System*

The total volume of all of the aeration tanks, V_n, can be calculated using Eq. 14:

$$V_n = V \cdot n = 400\,\text{m}^3 \cdot 3 = 1200\,\text{m}^3$$

Eq. 14

The parameters required to calculate V_n in Eq. 14 can be found as follows:

Parameter   Location

V Eq. 13

n Given in problem statement

(c)   Total Hydraulic Retention Time

The total hydraulic retention time for the system, τ_n, is calculated using the equation below:

$$\tau_n = \frac{V_n}{Q} = \frac{1200\,\text{m}^3}{0.1262\,\frac{\text{m}^3}{s} * 3600\,\frac{s}{hr}} = 2.64\,hr$$

Eq. 15

The parameters required to calculate τ_n in Eq. 15 can be found as follows:

Parameter   Location

V_n Eq. 14

Q Given in problem statement

(4)   Case 4: Specify τ_n, Calculate V, V_n, and τ

(a)   Hydraulic Retention Time

The hydraulic retention time, τ, is found using Eq. 16:

$$\tau = \frac{\tau_n}{n} = \frac{2.64\,hr}{3} = 0.88\,hr$$

Eq. 16

The parameters required to calculate τ in Eq. 16 can be found as follows:

Parameter   Location

τ_n User-specified

n Given in problem statement

(b)   Volume of One Aeration Tank

The volume of one of the aeration tanks, V, can be calculated using Eq. 17

$$V = \tau \cdot Q = 0.88\,hr \cdot 0.1262\,\frac{\text{m}^3}{s} * 3600\,\frac{s}{hr} = 400\,\text{m}^3$$

Eq. 17

The parameters required to calculate V in Eq. 17 can be found as follows:

Parameter	Location
τ	Eq. 16
Q	Given in problem statement

(c) Total Volume of System

The total volume of all of the aeration tanks, V_n, can be calculated as follows:

$$V_n = V \cdot n = 400\,\text{m}^3 \cdot 3 = 1200\,\text{m}^3$$

Eq. 18

The parameters required to calculate V_n in Eq. 18 can be found as follows:

Parameter	Location
V	Eq. 17
n	Given in problem statement

d) Effluent Results for All Components

Table 2 - Effluent Results for All Compounds

Concentration	Compound					
	TCE	PCE	Vinyl Chloride	Ethylbenzene	Toluene	1,1-DCE
C_0 (µg/L)	200	150.0	60.0	30.0	80.0	85
C_{TO} (µg/L)	5	5.0	1.0	5.0	5.0	7
$K_L a$ (1/s)	0.000864	0.000855	0.00104	0.000760	0.000795	0.000977
C_1 (µg/L)	53.48	40.43	13.99	8.8	22.72	20.74
C_2 (µg/L)	14.3	10.9	3.26	2.58	6.46	5.06
C_3 (µg/L)	3.82	2.94	0.76	0.757	1.83	1.24

3. Sample Program Run of ASAP™ to Verify Sample Calculations for Surface Aeration in Rating Mode

To start the ASAP™ program, double click on the ASAP™ icon in the *ETDOT Programs* group in windows. The screen shown in Figure 1 will appear.
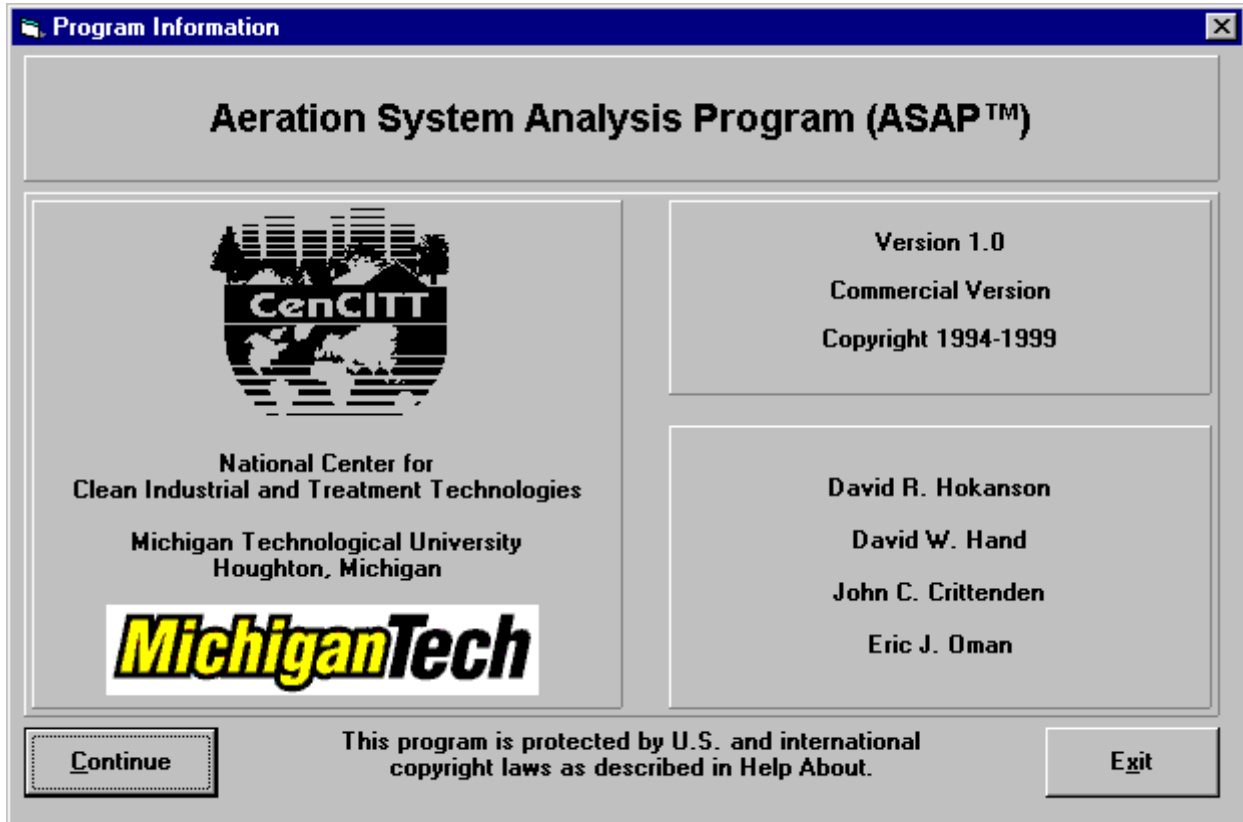
Figure 1 - ASAP™ Title Window

Click on the *Continue* button on the screen shown in Figure 1 and the menu shown in Figure 2 will appear.

Figure 2 - Main Menu Window in ASAP™

Click on the *Enter Rating Mode* button for Surface Aeration (option 6 in Figure 2) and the rating mode screen for surface aeration shown in Figure 3 will appear.

Figure 3 - Rating Mode Window for Surface Aeration

a) *Physical Properties of Water*

Specify pressure and temperature in the upper left-hand corner of the window shown in Figure 3. This portion of the surface aeration rating mode window is shown in Figure 4.

Figure 4 - Operating Conditions Portion of Rating Mode Window

Click on the *Display Physical Properties of Water* button in Figure 3 (and highlighted in Figure 4) to show the properties of water at the specified temperature and pressure (101325 Pa and 10°C). Figure 5 shows the water properties window for this case.

Figure 5 - Water Properties Window

The properties shown in Figure 5 are by default calculated from correlations so the user should not have to change his values. In the rare case that the user would like to enter a value for any of these properties instead of using the correlations, it is possible to do so on the window shown in Figure 5. Click on the *OK* button shown in Figure 5 to close the window.

b)   Oxygen (reference compound)

The mass transfer coefficient for the design contaminant is calculated using its relationship to the mass transfer coefficient of oxygen under similar conditions. The mass transfer coefficient of oxygen is estimated using the Roberts & Dandlike Correlation. This portion of the design mode window is shown in Figure 3 (and highlighted in Figure 6).

Figure 6 - Oxygen Section of Rating Mode Window

The mass transfer coefficient of oxygen at 10°C is calculated by the program as 1.530E-03 1/s. This agrees with the value from the sample calculations of the design mode section for surface aeration (see Eq. 4).

c) *Chemical Properties*

Chemical properties for each of the six components can be retrieved from StEPP™. When the screen shown in Figure 3 loads, the properties of the six contaminants load as a default rating situation. Before retrieving the chemical properties of the six chemicals required in the current rating situation, it is necessary to delete the six default chemicals shown in the Design Contaminant list box on the bottom of the left-hand column shown in Figure 3. This portion of the rating mode window is in Figure 3 (and highlighted in Figure 7).

Figure 7 - Contaminant Selection Portion of Rating Mode Window

It can be seen that the value for the mass transfer coefficient of trichloroethylene calculated by the program to be 8.644E-04 1/s agrees with the sample calculations of the design mode section (see Eq. 3).

To delete each chemical click on the *Delete* button located in between the *Add* and *Edit Properties* buttons shown in Figure 3 (and highlighted in Figure 7). Click the *Delete* button once for each chemical until all chemicals have been deleted from the *Design Contaminant* list box.

(1)   Transferring Properties from StEPP™ to
ASAP™

ASAP™ has the capability of transferring the physical properties of contaminants from Software to Estimate Physical Properties (StEPP™). There are two options for transferring data from StEPP™ into ASAP™: (a) Create Export File for AdDesignS/ASAP and (b) Copy to Clipboard for AdDesignS/ASAP. Both choices are available in the *Options* menu within StEPP™. The StEPP™ main window highlighting the *Options* menu is shown in Figure 8. Figure 8 shows the main StEPP™ window after the chemicals for this design have been selected at 10° C (see StEPP™ manual for how to get to this stage).

Figure 8 – StEPP™ Main Window

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After the contaminants have been selected in StEPP™ and their properties calculated at the proper temperature and pressure, they can be transferred from StEPP to ASAP using either of two options, which are described below: (a) Create Export File for AdDesignS/ASAP and (b) Copy to Clipboard for AdDesignS/ASAP.

(a)   *Transferring Chemical Properties from StEPPÔ to ASAPÔ Using the* Create Export File for AdDesignS/ASAP *Option*

To create an export file within StEPP™ for use in ASAP™, click on the *Create Export File for AdDesginS™/ASAP™* in the StEPP™ **Options** menu. This option is shown in Figure 8. After clicking this option, the *Save StEPP™ Export File* window shown in Figure 9 appears. Give the export file a *.exp* extension (the default), such as *surf10.exp*, and the file will be readily importable into ASAP™, as described below.

Figure 9 - Save StEPP™ Export File Window

To import the StEPP™ export file described above (*surf10.exp*), click on the *Add* button shown on the bottom left-hand corner of the window shown in Figure 3 (and highlighted in Figure 7). Figure 10 shows the window that will appear.

Figure 10 - Contaminant Properties Input Window

Click on the *Import StEPP™ Export File* button shown in Figure 10. The window shown in Figure 11 will appear.

Figure 11 - Load StEPP™ Export File Window

Select the file *surf10.exp* that was created earlier and the chemicals selected in StEPP™ for the given design will be imported into ASAP™. Figure 12 appears after the import and shows a successful import was achieved.

Figure 12 - Successful StEPP™ Property Retrieval Indication Window

(b)   Transferring Chemical Properties from StEPPÔ to ASAPÔ Using the Copy to Clipboard for AdDesignS/ASAP Option

To copy selected StEPP™ data to the Windows clipboard for export into ASAP™, select *Copy to Clipboard for AdDesignS/ASAP* from the *Options* menu within StEPP™. The message box shown in Figure 13 will appear, verifying that all of the StEPP™ data is now stored in the Windows clipboard.

Figure 13 – Successful Copy to Clipboard from StEPP™ Message Box

To import the chemicals and their physical properties to ASAP™ from the data on the clipboard, click on the *Add* button in the *Component Properties* block of the ASAP™ main window. The Component Properties window shown in Figure 14 will appear.

Figure 14 - Component Properties window (adding new components)

To import the StEPP™ data from the Windows clipboard, click the *Import from Clipboard* button on the Component Properties window. The window shown in Figure 15 will appear, showing that the properties have been successfully transferred into ASAP.

Figure 15 – Successful Import from StEPP™ Window

Click on the *OK* button to continue. Figure 3 appears. As shown in Figure 12 or Figure 15, it is necessary to input influent concentrations and treatment objectives for each of the six components retrieved. To do so, select each contaminant one at a time in the Design Contaminant list box shown in the lower left-hand corner of Figure 3. Then click on the *Edit Properties* button. Figure 16 shows the window that appears for trichloroethylene.

Figure 16 - Specify Contaminant Properties Window for Trichloroethylene

The properties molecular weight, Henry's constant, molar volume, and liquid diffusivity are already correct since they were retrieved from StEPP™. The influent concentration and treatment objective shown at the bottom of the screen must be input since they will vary from case to case. These properties shown in Figure 16 already reflect the values for the current design case. It is seen that the properties shown in Figure 16 agree with the trichloroethylene properties shown in Tables 1 and 2.

Figure 17 shows the *Specify Contaminant Properties* window for tetrachloroethylene. It can be seen that the properties shown in Figure 17 agree with the properties of tetrachloroethylene shown in Tables 1 and 2.

Figure 17 - Specify Contaminant Properties Window for Tetrachloroethylene

Figure 18 shows the *Specify Contaminant Properties* window for vinyl chloride. It can be seen that the properties shown in Figure 18 agree with the properties of vinyl chloride shown in Tables 1 and 2.

Figure 18 - Specify Contaminant Properties Window for Vinyl Chloride

Figure 19 shows the *Specify Contaminant Properties* window for ethylbenzene. It can be seen that the properties shown in Figure 19 agree with the properties of ethylbenzene shown in Tables 1 and 2.

Figure 19 - Specify Contaminant Properties Window for Ethylbenzene

Figure 20 shows the *Specify Contaminant Properties* window for toluene. It can be seen that the properties shown in Figure 20 agree with the properties of toluene shown in Tables 1 and 2.

Figure 20 - Specify Contaminant Properties Window for Toluene

Figure 21 shows the *Specify Contaminant Properties* window for 1,1-dichloroethene. It can be seen that the properties shown in Figure 21 agree with the properties of 1,1-dichloroethene shown in Tables 1 and 2.

Figure 21 - Specify Contaminant Properties Window for 1,1-Dichloroethene

d) *Flow Parameters*

The flow is shown in the upper right-hand side of Figure 3. This portion of Figure 3 is reproduced here as Figure 22.

Figure 22 - Flow Rate in Rating Mode Window

The water flow rate of 2000 gpm is given in the problem statement.

4. Tank Parameters

The tank parameters are shown at the top of the right-hand column of the rating mode window shown in Figure 3. This portion of the window is highlighted as Figure 23.

Figure 23 - Tank Parameters Section of Rating Mode Window

The values of the tank parameters shown in Figure 3 (and highlighted in Figure 23) agree with the sample calculations of the design mode section. The number of tanks in the series is given in the problem statement. Any one of the other parameters in this section may be specified and the program will calculate the remainder. Case 1 of the sample calculations allows for specification of the volume of one tank. The retention time of 0.88 hr calculated by the program agrees with the sample calculations performed in this case (see Eq. 8). The total retention time for the system determined by the program to be 2.64 hr corresponds to the value calculated in the sample calculations (see Eq. 9). The volume of the entire system calculated as 1200 m^3 by the program agrees with the sample calculations performed previously (see Eq. 5).

a)   *Concentration Results for Trichloroethylene*

The effluent concentrations of the liquid phase and the achieved percent removal are found in the middle of the right-hand column of the rating mode window as shown in Figure 3 (and highlighted in Figure 24).

Figure 24 - Concentration Results Portion of Rating Mode Window

Click on the *View Effluent Concentrations from All Tanks* button shown in Figure 3 (and highlighted in Figure 24) to see the effluent concentrations of the liquid of the contaminant from each tank. The window that appears is shown in Figure 25.

Figure 25 - Effluent Concentrations from Each Tank

It can be seen that the values calculated by the program for the liquid phase effluent concentrations; 53.5 µg/L from tank 1 (see Eq. 2), 14.3 µg/L from tank 2 (see Eq. 3), and 3.82 µg/L from tank 3 (see Eq. 4), match the values shown in the sample calculations.

Click the *OK* button shown in Figure 25 to return to the rating mode window shown in Figure 3.

b)   *Concentration Results for Other Compounds*

Figure 26 - Figure 30 shows the ASAP™ main window with the effluent concentrations for each tank window for the other components. It is seen from the figures that the values calculated by the program match the results given in Table 2.

Figure 26 - Concentration Results for Tetrachloroethylene

Figure 27 - Concentration Results for Vinyl Chloride

Figure 28 - Concentration Results for Ethylbenzene

Figure 29 - Concentration Results for Toluene

Figure 30 - Concentration Results for 1,1-Dichloroethene

c)   *Power Input*

The power input to the system is displayed in middle of the left-hand column of the rating mode window as shown in Figure 3 (and highlighted in Figure 31). This value is specified by the user.

Figure 31 - Power Input Portion of Rating Mode Window

d) **Power Calculations**

Other power parameters can be viewed in the lower right-hand corner of the rating mode window as shown in Figure 3 (and highlighted in Figure 32). A value is chosen for the aerator motor efficiency by the user. The power required per tank is calculated by the program as 32.5 kW which agrees with the sample calculations (see Eq. 6). The total power required is also calculated by the program and found to be 97.5 kW which again agrees with the sample calculations (see Eq. 5).

Figure 32 - Power Calculation Section of Rating Mode Window

e) **Viewing Effluent Concentration Results for All Contaminants**

For the current design, it is useful to see what the effluent concentrations of all contaminants on the same window. ASAP provides a convenient method for seeing these results.

By clicking on the ***Concentration Results*** button in the lower left-hand corner of the surface aeration – rating mode window shown in Figure 3, the user will see the concentration results for all contaminants using the given design (see Figure 33).

Figure 33 – View Concentration Results for All Contaminants Window

This window provides a quick method to see whether the given design will meet the treatment objectives for all contaminants.

I.   Surface Aeration - Nomenclature

C_0 Liquid phase influent concentration of contaminant, ($\mathbf{T}g/L$)

C_1 Liquid phase effluent concentration from tank number *1*, ($\mathbf{T}g/L$)

C_2 Liquid phase effluent concentration from tank number *2*, ($\mathbf{T}g/L$)

C_3 Liquid phase effluent concentration from tank number *3*, ($\mathbf{T}g/L$)

C_i Liquid phase effluent concentration from tank number *i*, ($\mathbf{T}g/L$)

C_{TO} Treatment objective concentration of contaminant, ($\mathbf{T}g/L$)

$D_{l,i}$ Liquid diffusivity of contaminant at 10°C, (m^2/s)

D_{l,O_2} Diffusivity of Oxygen at 10°C, (m^2/s)

Eff   Motor efficiency (dimensionless)

H   Henry's constant, (dimensionless)

H_i Henry's constant of the contaminant, (dimensionless)

$K_L a$ Design mass transfer coefficient, (*1/s*)

$K_L a_{O_2}$ Mass transfer coefficient of Oxygen at 10°C, (*1/s*)

n   Number of tanks operating in series, (dimensionless)

P   Power input per tank, (W/m^3)

P_n Total power input to the system, (W/m^3)

Q   Water flowrate, (m^3/s)

V   Volume of each tank in series, (m^3)

V_n Total volume of system, (m^3)

Greek Letters

τ Hydraulic retention time, (*hr*)

τ_n Hydraulic retention time, (*hr*)

IV. Theoretical Development of ASAP

A. *Estimating the Mass Transfer Coefficient in Air Stripping Processes*

1. Development

Mass transfer between the air and liquid phases can be described using two film theory (Lewis and Whitman, 1924). Figure 1 shows a diagram illustrating the equilibrium between the air and water phases for two film theory.

| Bulk Air Phase | Air Film | Water Film | Bulk Water Phase |
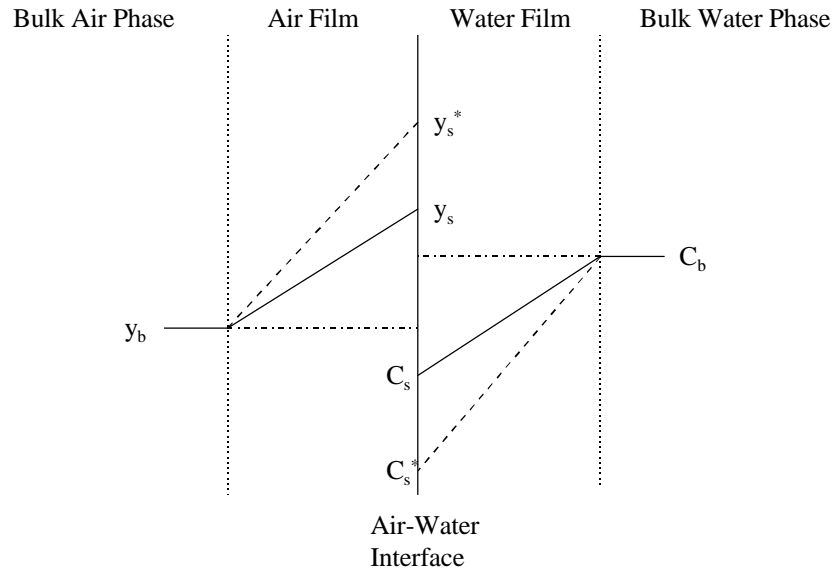
Figure 1 - Diagram Describing Equilibrium between Air and Liquid Phases Using Two Film Theory

Definitions of variables shown in Figure 1 are provided here:

C_b — Aqueous phase concentration in the bulk solution (M/L^3)

C_s — Aqueous phase concentration at air-water interface (M/L^3)

C_s^* — Equilibrium aqueous phase concentration assuming no concentration gradient in the air phase (M/L^3)

y_b — Gas phase concentration in the bulk (M/L^3)

y_s — Gas phase concentration at air-water interface (M/L^3)

y_s^* — Equilibrium gas phase concentration assuming no concentration gradient in the liquid phase (M/L^3)

Equilibrium between the air and water phases can be described using Henry's Law. At the air-water interface, local equilibrium exists. Because of this, the following relationships hold true:

$$y_s = H C_s$$

Eq. 1

$$y_b = H C_s^*$$

Eq. 2

$$y_s^* = H C_b$$

Eq. 3

Fick's Law states that the flux across the air-water interface, N_A, is proportional to concentration gradient. Mathematically, N_A, is described by:

$$N_A = k_l \left(C_b - C_s \right) = k_g \left(y_s - y_b \right)$$

Eq. 4

Assuming all resistance to mass transfer is on the liquid side allows for the calculation of an overall mass transfer coefficient, K_L, based on a liquid phase driving force. It should be noted that this development accounts for both liquid and gas phase resistance to mass transfer. An expression for the flux based on a liquid phase driving force is given as:

$$N_A = K_L \left(C_b - C_s^* \right)$$

Eq. 5

Equating Eq. 4 and Eq. 5 results in:

$$N_A = k_l \left(C_b - C_s \right) = k_g \left(y_s - y_b \right) = K_L \left(C_b - C_s^* \right)$$

Eq. 6

Noting the following relationship:

$$\left(C_b - C_s^* \right) = \left(C_b - C_s \right) + \left(C_s - C_s^* \right)$$

Eq. 7

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Substituting $C_s = \frac{y_s}{H}$ and $C_s^* = \frac{y_b}{H}$ into Eq. 7:

$$\left(C_b - C_s^* \right) = \left(C_b - C_s \right) + \frac{1}{H}\left(y_s - y_b \right)$$

Eq. 8

Combining Eq. 6 and Eq. 8:

$$\frac{N_A}{K_L} = \frac{N_A}{k_l} + \frac{N_A}{H k_g} \Rightarrow$$

Eq. 9

$$\frac{1}{K_L} = \frac{1}{k_l} + \frac{1}{H k_g}$$

Eq. 10

Eq. 10 can also be written as:

$$R_T = R_L + R_G$$

Eq. 11

where: $R_T = \frac{1}{K_L} =$ Overall resistance to mass transfer (T/L)

$R_L = \frac{1}{k_l} =$ Liquid side resistance to mass transfer (T/L)

$R_G = \frac{1}{H k_g} =$ Gas side resistance to mass transfer (T/L)

It is clear from Eq. 11 that the expression for overall mass transfer coefficient based on a liquid phase driving force, K_L, accounts for both liquid phase and gas phase resistance to mass transfer, as stated above.

Introducing a new variable, a, which is constant for all compounds and defined as the area available for mass transfer divided by the vessel volume, it is possible to rewrite Eq. 10 as:

$$\frac{1}{K_L a} = \frac{1}{k_l a} + \frac{1}{H k_g a}$$

Eq. 12

Eq. 12 represents the general equation for determining the mass transfer coefficient in an aeration process, such as packed tower aeration, bubble aeration, or surface aeration.

2. Nomenclature

a Area available for mass transfer divided by the vessel volume (L^2/L^3)

A Name of compound

C_b Aqueous phase concentration of A in the bulk solution (M/L^3)

C_s Aqueous phase concentration of A at air-water interface (M/L^3)

C_s^* Equilibrium aqueous phase concentration of A assuming no concentration

         gradient in the air phase (M/L^3)

H Henry's Law constant describing equilibrium between the air and water

         phases (dimensionless)

k_g Gas phase mass transfer coefficient (L/T)

$k_g a$ Gas phase mass transfer coefficient for compound i (1/T)

k_l Liquid phase mass transfer coefficient (L/T)

$k_l a$ Liquid phase mass transfer coefficient for compound i (1/T)

K_L Overall mass transfer coefficient based on a liquid phase driving force (L/T)

$K_L a$ Overall mass transfer coefficient for compound i (1/T)

N_A Flux across the air-water interface ($M/L^2/T$)

R_G Gas side resistance to mass transfer (T/L)

R_L Liquid side resistance to mass transfer (T/L)

R_T Overall resistance to mass transfer (T/L)

y_b Gas phase concentration of A in the bulk (M/L^3)

y_s Gas phase concentration of A at air-water interface (M/L^3)

y_s^* Equilibrium gas phase concentration of A assuming no concentration

         gradient in the liquid phase (M/L^3)

3. References

Lewis, W. K. and W. E. Whitman, "Principles of Gas Absorption," *Ind. Engng. Chem.*, **16**, 1215-1220 (1924).

B. Development of Process Design Equations for Packed Tower Aeration

1. Development

This development is for a single compound in packed tower aeration. All liquid phase concentrations, gas phase concentrations, and mass transfer coefficients specified in the development are relevant to a specific generic compound. The development presented is for a single tower. The model development for the countercurrent packed tower aeration process is well established in the literature (Ball, et al, 1981; Roberts, et al, 1985; Singley, et al, 1981; Kavanaugh and Trussell, 1981; Gross and TerMaath, 1985; Sherwood and Hollaway, 1940; Umphres, et al, 1983; McKinnon and Dyksen, 1984; Cummins and Westrick, 1983; Roberts and Levy, 1985; Treybal, 1980; Hand, et al, 1986; Hand and Crittenden, 1986; Ball and Edwards, 1992; Dzombak, et al, 1993).

a) Operating Line Equation

The first step is to develop the operating line equation for packed tower aeration. Assumptions incorporated into the development of the operating line equation include: (1) steady state conditions prevail in the tower, (2) air flow rate and water flow rate are constant along the column, (3) concentration of organics in both streams is small, and (4) no reaction occurs. Figure 1 shows a schematic of a packed tower.
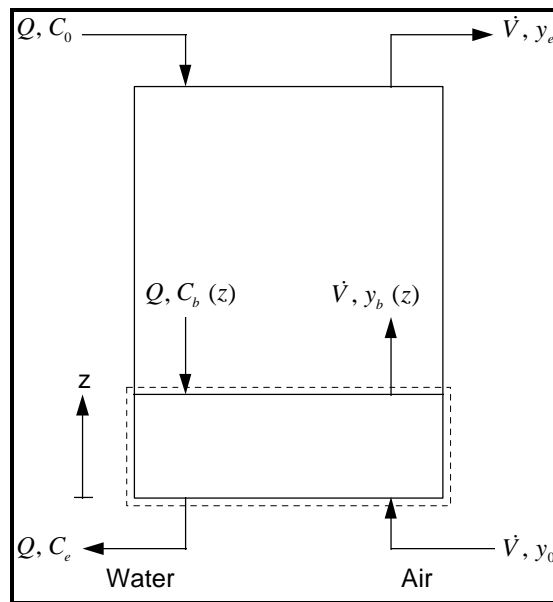

Figure 1 - Schematic of a Packed Tower

Taking a mass balance around the lower part of the column, which is surrounded by a dashed box in Figure 1, results in:

$$\begin{Bmatrix} \text{Mass of} \\ \text{Organic} \\ \text{Entering} \\ \text{Per} \\ \text{Unit Time} \end{Bmatrix} - \begin{Bmatrix} \text{Mass of} \\ \text{Organic} \\ \text{Leaving} \\ \text{Per} \\ \text{Unit Time} \end{Bmatrix} + \begin{Bmatrix} \text{Mass of} \\ \text{Organic} \\ \text{Generated} \\ \text{Per} \\ \text{Unit Time} \end{Bmatrix} - \begin{Bmatrix} \text{Mass of} \\ \text{Organic} \\ \text{Lost} \\ \text{Per} \\ \text{Unit Time} \end{Bmatrix} = \begin{Bmatrix} \text{Mass of} \\ \text{Organic} \\ \text{Accumulated} \\ \text{Per} \\ \text{Unit Time} \end{Bmatrix} \Rightarrow$$

$$\left[Q\,C_b\,dz \right] + \dot{V}\,y_0 \rceil - \left[Q\,C_e\,dz \right] + \dot{V}\,y_b\,dz \rceil + \left| N_A\,a\,A\,z \right] - \left| N_A\,a\,A\,z \right] = 0$$

Eq. 1

After some rearrangement, Eq. 1 can be written as:

$$y_b\,dz\rceil - y_0 = \frac{Q}{\dot{V}}\left[C_b\,dz\rceil - C_e \right]$$

Eq. 2

This is the operating line equation for packed tower aeration. A plot showing the operating line for packed tower aeration is given in Figure 2.
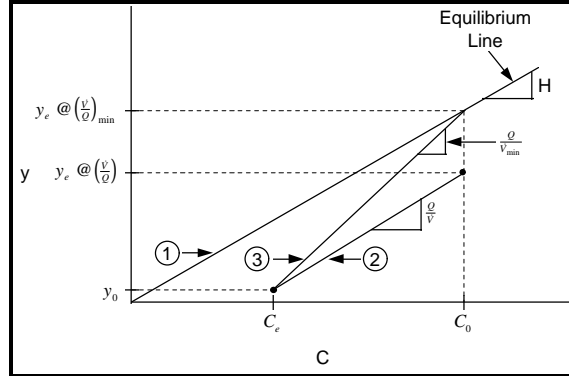

Figure 2 - Operating Line Diagram for a Packed Tower

Equilibrium between the air and water phases in packed tower aeration is governed by Henry's Law. Line 1 in Figure 2 is the equilibrium line for packed tower aeration. The equation of the equilibrium line is given below:

$$y = H\,C$$

Eq. 3

Line 2 in Figure 2 is the operating line equation for packed tower aeration that was derived above and shown in Eq. 2. Using the operating line (Line 2) in Figure 2, it is possible to determine the effluent concentration in the gas phase, y_e, that will be achieved for a given air to water ratio, $\frac{\dot{V}}{Q}$, gas phase influent concentration, y_0 (which is typically assumed to be zero for packed tower aeration), and treatment objective, C_e. Line 3 in Figure 2 represents a special case of the operating line equation. For Line 3, the influent water is in equilibrium with the exiting air (i.e. $y_e = H C_0$). The slope of Line 3 represents the inverse of the minimum air to water ratio that can be used to meet the treatment objective. Rearranging Eq. 2 to describe this situation results in:

$$y_e - y_0 = \frac{1}{\left(\frac{\dot{V}}{Q}\right)_{min}}[C_0 - C_e]$$

Eq. 4

Substituting $y_e = H C_0$ and applying the assumption that y_0 equals zero for pure influent air, Eq. 4 can be written as follows after solving for $\left(\frac{\dot{V}}{Q}\right)_{min}$:

$$\left(\frac{\dot{V}}{Q}\right)_{min} = \frac{C_0 - C_e}{H C_0}$$

Eq. 5

The minimum air to water ratio, $\left(\frac{\dot{V}}{Q}\right)_{min}$, represents the minimum air to water ratio that can be applied for a packed tower to meet its treatment objective, C_e. If the air to water ratio applied is less than the minimum air to water ratio, it will not be possible to design a packed tower capable of meeting the treatment objective. Hand, et al (1986) determined that operating at an air to water ratio approximately 3.5 times the minimum air to water ratio minimized both the volume and power requirements for a full-scale packed tower.

b) Design Equation

The next step is to develop the design equation used to calculate the tower length for packed tower aeration. Assumptions incorporated into the development of the design equation include: (1) steady state conditions prevail in the tower, (2) air flow rate and water flow rate are constant along the column, and (3) no reaction occurs.

Figure 3 shows a schematic of a packed tower that is used to develop the design equation for packed tower aeration.
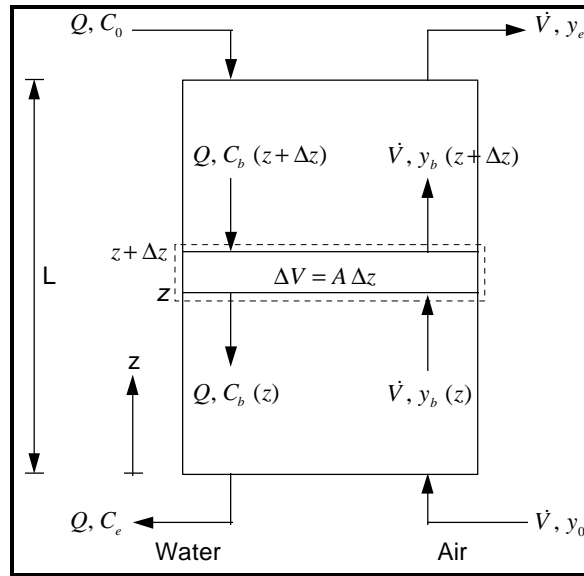

Figure 3 - Schematic of a Packed Tower Used in Development of Design Equation

It is necessary to take a liquid phase mass balance around the differential element surrounded by a dashed box in Figure 3. Figure 4 shows a schematic of the differential element applicable to the case of a liquid side mass balance.
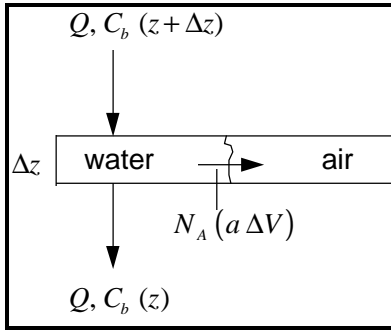
Figure 4 - Schematic of Differential Element in Packed Tower Used for Liquid Phase Mass Balance

The liquid phase mass balance around the differential element is written below:

$$\left\{\begin{array}{c}\text{Mass of}\\\text{Organic}\\\text{Entering}\\\text{Per}\\\text{Unit Time}\end{array}\right\} - \left\{\begin{array}{c}\text{Mass of}\\\text{Organic}\\\text{Leaving}\\\text{Per}\\\text{Unit Time}\end{array}\right\} + \left\{\begin{array}{c}\text{Mass of}\\\text{Organic}\\\text{Generated}\\\text{Per}\\\text{Unit Time}\end{array}\right\} - \left\{\begin{array}{c}\text{Mass of}\\\text{Organic}\\\text{Lost}\\\text{Per}\\\text{Unit Time}\end{array}\right\} = \left\{\begin{array}{c}\text{Mass of}\\\text{Organic}\\\text{Accumulated}\\\text{Per}\\\text{Unit Time}\end{array}\right\} \Rightarrow$$

$$\left[QC_b(z+\Delta z)\right] - \left[QC_b(z)\right] - \left[N_A(a\,\Delta V)\right] = 0$$

Eq. 6

The term N_A in Eq. 6 represents the mass flux lost from the liquid phase (and entering the air phase). N_A is proportional to a concentration driving force for mass transfer. The proportionality constant is referred to as the mass transfer coefficient and is denoted by K_L. The concentration driving force for packed tower aeration is the difference between the bulk liquid phase concentration, C_b, and the liquid phase concentration at the air-water interface, C_s^*. The equation for mass flux can be represented as:

$$\left\{\begin{array}{c}\text{Mass Flux}\\\text{Out of}\\\text{Liquid Phase}\end{array}\right\} = \left\{\begin{array}{c}\text{Mass}\\\text{Transfer}\\\text{Coefficient}\end{array}\right\} \times \left\{\begin{array}{c}\text{Concentration}\\\text{Driving}\\\text{Force}\end{array}\right\} \Rightarrow$$

$$N_A = K_L \times \left[C_b(z) - C_s^*(z)\right]$$

Eq. 7

Applying this relationship and the fact that the volume of the differential element is equal to the cross-sectional area of the tower times the height of the differential element ($\Delta V = A\,\Delta z$) to Eq. 6 results in:

$$\left[Q\,C_b\big|_{z+\Delta z}\right] - \left[Q\,C_b\big|_z\right] - \left[K_L\left[C_b\big|_z - C_s^*\big|_z\right]a\,A\,\Delta z\right] = 0$$

Eq. 8

The term a in Eq. 6 and Eq. 8 is defined as the area available for mass transfer divided by the vessel volume. The term does not vary with contaminant in packed tower aeration. Therefore, the a term is typically lumped together with the liquid phase mass transfer coefficient term, K_L, and the combined term is referred to as the overall liquid phase mass transfer coefficient, $K_L a$. Eq. 8 can be written in terms of $K_L a$ as:

$$\left[Q\,C_b\big|_{z+\Delta z}\right] - \left[Q\,C_b\big|_z\right] - \left[K_L a\left[C_b\big|_z - C_s^*\big|_z\right]A\,\Delta z\right] = 0 \Rightarrow$$

Eq. 9

$$\left[Q\,C_b\big|_{z+\Delta z}\right] - \left[Q\,C_b\big|_z\right] = \left[K_L a\left[C_b\big|_z - C_s^*\big|_z\right]A\,\Delta z\right] \Rightarrow$$

Eq. 10

$$\frac{Q}{A\,K_L a}\left\{\frac{C_b\big|_{z+\Delta z} - C_b\big|_z}{\Delta z}\right\} = \left[C_b\big|_z - C_s^*\big|_z\right]$$

Eq. 11

Taking the limit as Δz approaches zero results in:

$$\frac{Q}{A\,K_L a}\lim_{\Delta z \to 0}\left\{\frac{C_b\big|_{z+\Delta z} - C_b\big|_z}{\Delta z}\right\} = \left[C_b\big|_z - C_s^*\big|_z\right] \Rightarrow$$

Eq. 12

$$\frac{Q}{A\,K_L a}\frac{dC_b}{dz} = C_b - C_s^*$$

Eq. 13

Integrating Eq. 13 results in:

$$\int_0^L dz = \frac{Q}{A \, K_L a} \int_{C_e}^{C_0} \frac{dC_b}{C_b - C_s^*} \Rightarrow$$

Eq. 14

$$L = \frac{Q}{A \, K_L a} \int_{C_e}^{C_0} \frac{dC_b}{C_b - C_s^*}$$

Eq. 15

In order to solve the integral on the right-hand side of Eq. 15, it is useful to examine the operating line diagram for packed tower aeration, which is shown below in Figure 5.
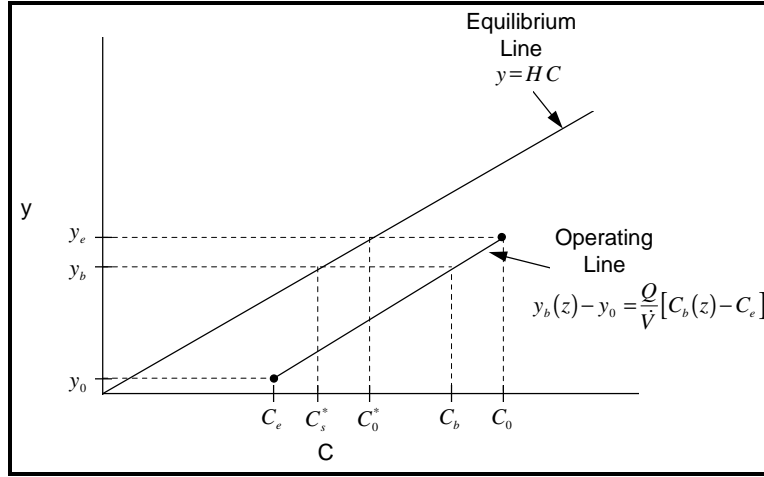

Figure 5 - Operating Line Diagram Used in Development of Design Equation for Packed Tower Aeration

From Figure 5, it is clear that the liquid phase concentration at the air-water interface, C_s^*, that is in equilibrium with the bulk air phase concentration, y_b, can be represented by the following relationship:

$$C_s^* = \frac{y_b}{H} = \frac{y_b(z)}{H}$$

Eq. 16

Substituting in the equation for the operating line that was developed earlier (Eq. 2) and that is shown in Figure 5 results in:

$$C_s^* = \frac{Q}{\dot{V} H}\left[C_b - C_e\right] + \frac{y_0}{H}$$

Substituting Eq. 17 into Eq. 15 results in the following:

$$L = \frac{Q}{A K_L a} \int_{C_e}^{C_0} \frac{dC_b}{\left(C_b - \frac{Q}{\dot{V} H}\left[C_b - C_e\right] - \frac{y_0}{H}\right)} \Rightarrow$$

$$L = \frac{Q}{A K_L a} \int_{C_e}^{C_0} \frac{dC_b}{\left(C_b\left[1 - \frac{Q}{\dot{V} H}\right] + \frac{Q}{\dot{V} H} C_e - \frac{y_0}{H}\right)} \Rightarrow$$

$$L = \frac{Q}{A K_L a} \frac{1}{\left[1 - \frac{Q}{\dot{V} H}\right]} \left\{\ln\left(C_b\left[1 - \frac{Q}{\dot{V} H}\right] + \frac{Q}{\dot{V} H} C_e - \frac{y_0}{H}\right)\right\}\Big|_{C_0}^{C_e} \Rightarrow$$

$$L = \frac{Q}{A K_L a} \frac{1}{\left[1 - \frac{Q}{\dot{V} H}\right]} \ln\left(\frac{\frac{Q}{\dot{V} H}\left(C_e - C_0\right) + \left(C_0 - \frac{y_0}{H}\right)}{C_e - \frac{y_0}{H}}\right)$$

Eq. 21 can be further simplified after examining the operating line diagram and equation shown in Figure 5. Solving the operating line equation (Eq. 2) for $\frac{Q}{\dot{V}}$ at the point where $y_b = y_e$ and $C_b = C_0$ then dividing both sides of the resultant equation by H results in:

$$\frac{Q}{\dot{V} H} = \frac{1}{H}\left(\frac{y_e - y_0}{C_o - C_e}\right) = \left(\frac{\frac{y_e}{H} - \frac{y_0}{H}}{C_o - C_e}\right)$$

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By looking at the operating line diagram in Figure 5, it is clear that the variable C_0^* is defined as the liquid phase concentration that is in equilibrium with the exiting gas phase concentration, y_e. That is, $y_e = H C_0^*$. Substituting into Eq. 22 results in:

$$\frac{Q}{\dot{V} H} = \left| \frac{C_0^* - \frac{y_0}{H}}{C_o - C_e} \right|$$

Eq. 23

By rearranging Eq. 23, it is possible to show that the following relationship holds true:

$$\frac{Q}{\dot{V} H} \left(C_e - C_0 \right) - \frac{y_0}{H} = -C_0^*$$

Eq. 24

Subtracting Eq. 23 from 1 results in the following:

$$1 - \frac{Q}{\dot{V} H} = 1 - \left| \frac{C_0^* - \frac{y_0}{H}}{C_o - C_e} \right| = \left| \frac{C_o - C_e - C_0^* + \frac{y_0}{H}}{C_o - C_e} \right|$$

Eq. 25

Substituting Eq. 24 and Eq. 25 into Eq. 21 results in an expression for tower length, L:

$$L = \frac{Q}{A K_L a} \left| \frac{C_o - C_e}{C_o - C_e - C_0^* + \frac{y_0}{H}} \right| \ln \left| \frac{C_0 - C_0^*}{C_e - \frac{y_0}{H}} \right|$$

Eq. 26

For a packed tower, it is typically assumed that the incoming air phase concentration is approximately equal to zero ($y_0 \approx 0$). Making this assumption, Eq. 26 simplifies to:

$$L = \frac{Q}{A K_L a} \left| \frac{C_o - C_e}{C_o - C_e - C_0^*} \right| \ln \left| \frac{C_0 - C_0^*}{C_e} \right|$$

Eq. 27

In packed tower aeration, the tower length is often defined as the product of the height of a transfer unit (or *HTU*) and the number of transfer units (or *NTU*). The following two equations define *HTU* and *NTU*:

$$HTU = \frac{Q}{A\,K_L a}$$

Eq. 28

$$NTU = \left[\left|\frac{C_o - C_e}{C_o - C_e - C_0^*}\right|\right] \ln\left[\left|\frac{C_0 - C_0^*}{C_e}\right|\right]$$

Eq. 29

Substituting Eq. 28 and Eq. 29 into Eq. 27 results in:

$$L = HTU \times NTU$$

Eq. 30

The parameters required to determine tower height using Eq. 27 are described below:

Q Water flow rate (L^3/T). This parameter is user-specified.

A Cross-sectional area of the packed tower (L^2). This parameter is calculated based on the desired pressure drop in the tower. The method is shown later.

$K_L a$ Overall liquid phase mass transfer coefficient ($1/T$). This parameter is calculated based on the Onda correlation, which is described in detail later.

C_0 Influent liquid phase concentration (M/L^3). This parameter is user-specified.

C_e Effluent liquid phase concentration (M/L^3). In Eq. 27, this parameter represents the treatment objective, which is user-specified.

C_0^* Liquid phase concentration in equilibrium with the exiting gas phase concentration, y_e (M/L^3). This parameter can be found by rearranging Eq. 24 with the assumption that $y_0 \approx 0$: $C_0^* = \frac{Q}{\dot{V}H}\left[C_0 - C_e\right]$.

H Henry's Law constant which describes the equilibrium between the air and water phases in a packed tower (dimensionless). This value is available from Software to Estimate Physical Properties (StEPP™) and from various literature sources (Ashworth, et. al., 1988; Gossett, 1987).

$\frac{Q}{\dot{V}}$ Inverse of air to water ratio, $\frac{\dot{V}}{Q}$, which is user-specified.

c)   *Design Mode*

In design mode, it is desired to size a packed tower in order to exactly meet the treatment objective, C_{TO}. Substituting $C_{TO} = C_e$ into Eq. 27 results in the design equation for packed tower aeration:

$$L = \frac{Q}{A\,K_L a}\left[\frac{C_o - C_{TO}}{C_o - C_{TO} - C_0^*}\right]\ln\left[\frac{C_0 - C_0^*}{C_{TO}}\right]$$

Eq. 31

Substituting $C_0^* = \frac{Q}{\dot{V}H}\left[C_0 - C_{TO}\right]$ into Eq. 31 and introducing the stripping factor, $R = \frac{\dot{V}}{Q}H$, results in a way that the design mode equation is often written:

$$L = \frac{Q}{A\,K_L a}\left[\frac{C_o - C_{TO}}{C_o - C_{TO} - \frac{Q}{\dot{V}H}\left[C_0 - C_{TO}\right]}\right]\ln\left[\frac{C_0 - \frac{Q}{\dot{V}H}\left[C_0 - C_{TO}\right]}{C_{TO}}\right] \Rightarrow$$

Eq. 32

$$L = \frac{Q}{A\,K_L a}\left[\frac{1}{1 - \frac{Q}{\dot{V}H}}\right]\ln\left[\frac{C_0\left(1 - \frac{Q}{\dot{V}H}\right) + C_{TO}}{C_{TO}}\right] \Rightarrow$$

Eq. 33

$$L = \frac{Q}{A\,K_L a}\left[\frac{\frac{\dot{V}}{Q}H}{\frac{\dot{V}}{Q}H - 1}\right]\ln\left[\frac{\frac{C_0}{C_{TO}}\left(\frac{\dot{V}}{Q}H - 1\right) + 1}{\frac{\dot{V}}{Q}H}\right] \Rightarrow$$

Eq. 34

$$L = \frac{Q}{A\,K_L a}\left[\frac{R}{R - 1}\right]\ln\left[\frac{\frac{C_0}{C_{TO}}\left(R - 1\right) + 1}{R}\right]$$

Eq. 35

Estimation of mass transfer coefficient, $K_L a$ and cross-sectional area, A, for packed tower aeration are described in detail later.

d) Rating Mode

In rating mode, it is possible to determine effluent concentration of various compounds for an existing tower. In rating mode, the following variables are specified: (1) tower height, (2) tower diameter, (3) type of packing, (4) water flow rate, (5) air flow rate, (6) pressure, (7) temperature, (8) influent concentration, and (9) mass transfer coefficient. Knowing these variables, it is possible to determine effluent concentration and gas pressure drop for the tower. The effluent concentration is found by rearranging Eq. 27 and solving for effluent concentration, C_e (recalling that $C_0^* = \frac{Q}{VH}[C_0 - C_e]$):

$$L = \frac{Q}{AK_La}\left[\frac{C_o - C_e}{C_o - C_e - C_0^*}\right]\ln\left[\frac{C_0 - C_0^*}{C_e}\right] \Rightarrow$$

Eq. 36

$$\frac{LAK_La}{Q} = \left[\frac{C_o - C_e}{C_o - C_e - \frac{Q}{VH}[C_0 - C_e]}\right]\ln\left[\frac{C_0 - \frac{Q}{VH}[C_0 - C_e]}{C_e}\right] \Rightarrow$$

Eq. 37

$$\frac{LAK_La}{Q} = \left[\frac{[C_o - C_e]}{[C_o - C_e]\left[1 - \frac{Q}{VH}\right]}\right]\ln\left[\frac{C_0\left[1 - \frac{Q}{VH}\right] + \frac{Q}{VH}C_e}{C_e}\right] \Rightarrow$$

Eq. 38

$$\frac{LAK_La\left[1 - \frac{Q}{VH}\right]}{Q} = \ln\left[\frac{C_0\left[1 - \frac{Q}{VH}\right] + \frac{Q}{VH}C_e}{C_e}\right] \Rightarrow$$

Eq. 39

$$\frac{LAK_La\left[1 - \frac{Q}{VH}\right]}{Q} = \ln\left[\frac{C_0\left[1 - \frac{Q}{VH}\right] + \frac{Q}{VH}C_e}{C_e}\right] \Rightarrow$$

Eq. 40

$$\exp\left[\frac{LAK_La\left(1-\frac{Q}{\dot{V}H}\right)}{Q}\right]=\frac{C_0\left(1-\frac{Q}{\dot{V}H}\right)+\frac{Q}{\dot{V}H}C_e}{C_e}\Rightarrow$$

Eq. 41

$$C_e\exp\left[\frac{LAK_La\left(1-\frac{Q}{\dot{V}H}\right)}{Q}\right]-\frac{Q}{\dot{V}H}C_e=C_0\left(1-\frac{Q}{\dot{V}H}\right)\Rightarrow$$

Eq. 42

$$C_e\left(\exp\left[\frac{LAK_La\left(1-\frac{Q}{\dot{V}H}\right)}{Q}\right]-\frac{Q}{\dot{V}H}\right)=C_0\left(1-\frac{Q}{\dot{V}H}\right)\Rightarrow$$

Eq. 43

$$C_e=\frac{C_0\left(1-\frac{Q}{\dot{V}H}\right)}{\left(\exp\left[\frac{LAK_La\left(1-\frac{Q}{\dot{V}H}\right)}{Q}\right]-\frac{Q}{\dot{V}H}\right)}\Rightarrow\qquad\text{Divide top and bottom by }\frac{\dot{V}}{Q}H$$

Eq. 44

$$C_e=\frac{C_0\left(\frac{\dot{V}}{Q}H-1\right)}{\left(\frac{\dot{V}}{Q}H\exp\left[\frac{LK_La\left(\frac{\dot{V}}{Q}H-1\right)}{\frac{Q}{A}\left(\frac{\dot{V}}{Q}H\right)}\right]-1\right)}\Rightarrow$$

Eq. 45

The term $\frac{\dot{V}}{Q}H$ in Eq. 45 is stripping factor, R. Substituting into Eq. 45 results in:

$$C_e=\frac{C_0\left(R-1\right)}{\left(R\exp\left[\frac{LK_La\left(R-1\right)}{\frac{Q}{A}R}\right]-1\right)}$$

Eq. 46

In rating mode, the pressure drop for the tower can be calculated using an iterative method based on the Eckert pressure drop curves. This process is described in detail later.

2. Nomenclature

a — Area available for mass transfer divided by vessel volume (L^2/L^3)

A — Cross-sectional area of the packed tower (L^2)

$C_b, C_b|_z$ — Bulk liquid phase concentration at axial position z along tower (M/L^3)

C_e — Effluent liquid phase concentration (M/L^3)

C_0 — Influent liquid phase concentration (M/L^3)

C_0^* — Liquid phase concentration in equilibrium with exiting gas phase concentration, y_e (M/L^3)

$C_s^*, C_s^*|_z$ — Liquid phase concentration at air-water interface, which is in equilibrium with bulk air (M/L^3)

C_{TO} — Treatment objective (M/L^3)

H — Henry's Law constant (dimensionless)

HTU — Height of a transfer unit (L)

K_L — Liquid phase mass transfer coefficient (L/T)

$K_L a$ — Overall liquid phase mass transfer coefficient ($1/T$)

L — Packed tower height (L)

N_A — Mass flux leaving the liquid phase and entering the gas phase ($M/L^2/T$)

NTU — Number of transfer units (dimensionless)

Q — Water flow rate (L^3/T)

R — Stripping factor (L^3/L^3)

V — Volume of packed tower (L^3)

ΔV — Volume of a differential element in a packed tower (L^3)

$\dot{V}$ — Air flowrate (L^3/T)

$\frac{\dot{V}}{Q}$ — Air to water ratio (L^3/L^3)

$\left(\frac{\dot{V}}{Q}\right)_{min}$ — Minimum air to water ratio that will allow a packed tower to meet the treatment objective for a contaminant (L^3/L^3)

$y_b, y_b|_z$ — Bulk gas phase concentration at axial position z along tower (M/L^3)

y_e — Effluent gas phase concentration (M/L^3)

y_0 — Influent gas phase concentration (M/L^3)

z — Axial position in the tower (L)

Δz — Width of a differential element in packed tower aeration (L)

3.   References

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C. *Estimation of the Cross-Sectional Area of a Packed Tower (Design Mode)*

1. Development

In design mode, the cross-sectional area of a packed tower is estimated based on the generalized pressure drop curves developed by Eckert (1961), which are shown in Treybal (1980) and reprinted by permission in Hand, et al (1986). Once the packing factor for the media, the air to water ratio, and the gas pressure drop per packing height have been specified, it is possible to determine the gas loading rate and the tower diameter from the Eckert curves. The Eckert pressure drop curves were fit by Cummins and Westrick (1983) in order to develop correlations capable of predicting gas loading rate and tower area. The correlations developed by Cummins and Westrick are shown below:

$$G_m = \sqrt{\frac{M \rho_g \left(\rho_l - \rho_g\right)}{C_f \left(\mu_l\right)^{0.1}}}$$

Eq. 1

The empirical parameter M is defined by the following relationship:

$$\log_{10}\left(M\right) = a_0 + a_1 E + a_2 E^2$$

Eq. 2

The parameter E is defined as follows:

$$E = -\log_{10}\left(\left(\frac{\dot{V}}{Q}\right)\sqrt{\left(\rho_g / \rho_l\right) - \left(\rho_g / \rho_l\right)^2}\right)$$

Eq. 3

The parameters a_0, a_1, and a_2 are given in the following relationships:

$$a_0 = -6.6599 + 4.3077\,F - 1.3503\,F^2 + 0.15931\,F^3$$

Eq. 4

$$a_1 = 3.0945 - 4.3512\,F + 1.6240\,F^2 - 0.20855\,F^3$$

Eq. 5

$$a_2 = 1.7611 - 2.3394\,F + 0.89914\,F^2 - 0.11597\,F^3$$

Eq. 6

The parameter F that appears in Eq. 4 - Eq. 6 is defined as:

$$F = \log_{10}\left|\Delta P / L\right|$$

Eq. 7

Validity ranges for the equations presented above include:

Pressure Drop Gradient, $\Delta P / L$ (N/m^2/m) $\qquad 50 \leq \Delta P / L \leq 1200$

Empirical Parameter, M $\qquad M > 0.0015$

Parameter, $\left(\frac{\dot{V}}{Q}\right)\sqrt{\left(\rho_g / \rho_l\right)\left(1 - \left(\rho_g / \rho_l\right)\right)^2}$ $\qquad \left(\frac{\dot{V}}{Q}\right)\sqrt{\left(\rho_g / \rho_l\right)\left(1 - \left(\rho_g / \rho_l\right)\right)^2} < 33$

The correlations used to estimate gas loading rate presented in Eq. 1 - Eq. 6 were fit for a particular set of units. When applying this method, it must be assured that values are supplied in the appropriate set of units. A summary of the parameters required and proper units needed to apply the correlations of Cummins and Westrick is provided below (note that for calculated empirical parameters, units are not applicable):

G_m $\qquad$ Gas mass loading rate ($kg/m^2/s$)

M $\qquad$ Calculated empirical parameter

ρ_g $\qquad$ Air density (kg/m^3)

ρ_l $\qquad$ Water density (kg/m^3)

C_f $\qquad$ Packing factor (dimensionless)

μ_l $\qquad$ Liquid viscosity ($kg/m/s$)

a_0 $\qquad$ Calculated empirical parameter

a_1 $\qquad$ Calculated empirical parameter

a_2 $\qquad$ Calculated empirical parameter

E $\qquad$ Calculated empirical parameter

$\frac{\dot{V}}{Q}$ $\qquad$ Air to water ratio on a volumetric basis (m^3/m^3)

F $\qquad$ Calculated empirical parameter

$\Delta P / L$ $\qquad$ Pressure drop gradient ($N/m^2/m$)

Once gas loading rate is known from Eq. 1, it is possible to determine the cross-sectional area of the tower. First, it is necessary to calculate liquid loading rate:

$$L_m = \frac{G_m}{\left(\frac{\dot{v}}{Q}\right)\left(\frac{\rho_g}{\rho_l}\right)}$$

Eq. 8

Once liquid loading rate is known from Eq. 8, the cross-sectional area of the tower, A, can be found from the relationship:

$$A = \frac{Q\rho_l}{L_m}$$

Eq. 9

Once tower area is known, it is a simple matter to calculate the diameter of the tower, D:

$$D = \sqrt{\frac{4A}{\pi}}$$

Eq. 10

2.   Nomenclature

a_0, a_1, a_2	Calculated empirical parameters
A	Cross-sectional area of the tower (L^2)
C_f	Packing factor (dimensionless)
D	Diameter of the tower (L^2)
E	Calculated empirical parameter
F	Calculated empirical parameter
G_m	Gas mass loading rate ($M/L^2/T$)
L_m	Liquid mass loading rate ($M/L^2/T$)
M	Calculated empirical parameter
$\Delta P / L$	Pressure drop gradient ($F/L^2/L$)
Q	Water flow rate (L^3/T)
$\frac{\dot{v}}{Q}$	Air to water ratio (L^3/L^3)

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Greek Letters

μ_l Liquid viscosity (*M/L/T*)

ρ_l Liquid density (*M/L³*)

ρ_g Gas density (*M/L³*)

3. References

Cummins, M. D. and J. J. Westrick, *Proc. ASCE Envir. Engrg. Conf.*, Boulder, Colorado (July 1983).

Eckert, J. S., "Design Techniques for Sizing Packed Towers," *Chem. Eng. Prog.*, **57**, 9 (1961).

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D. *Optimization Routine for Packed Tower Aeration (Design Mode)*

1. Development

In design mode for packed tower aeration, there is a feature called *Optimize with All Contaminants* that uses an iterative technique to determine which contaminant should be chosen as a basis for design such that all contaminants will meet their treatment objectives. Knowing influent concentration and treatment objective for each compound allows the optimization routine to pick out the design compound (note: in some cases, the optimization routine may fail to converge on an appropriate design compound).

As a first estimate, the compound with the highest minimum air to water ratio is selected as the design compound. Hand, et al (1986) determined that operating at an air to water ratio approximately 3.5 times the minimum air to water ratio minimized both the volume and power requirements for a full-scale packed tower. Therefore, the air to water ratio is initially set as 3.5 times the minimum air to water ratio. The following procedure is then used to determine which compound should be the design compound:

(1) Air to water ratio is calculated as the product of minimum air to water ratio and multiple of minimum air to water ratio.

(2) A tower diameter and packing height are determined for the specified compound, making use of the Eckert curve and the Onda mass-transfer correlation.

(3) Once a tower diameter and packing height have been determined, it is necessary to calculate the effluent concentrations of the other compounds in the system given this design. This is done for each of the other compounds using the rating mode equation for C_e.

(4) If all compounds meet their treatment objectives with the current design compound, then the process is complete and the limiting compound has been found. If any compounds fail to meet their treatment objectives with the current design, the compound that misses its treatment objective by the greatest amount is chosen as the new design compound.

(5)   If the number of iterations attempting to find the limiting compound at the current air to water ratio is less than the number of compounds in the system, then the iteration process returns to step (1). Otherwise, the multiple of minimum air to water ratio is increased by 0.5. If the total number of multiples tried to this point is less than or equal to 20 then the iteration process returns to step (1). Otherwise, the iteration process is terminated, having failed to converge on an appropriate design compound.

2.   Reference

Hand, D. W., J. C. Crittenden, J. L. Gehin, and Benjamin W. Lykins, Jr., "Design and Evaluation of an Air-Stripping Tower for Removing VOCs from Groundwater," *Journal AWWA*, **78**, 9, 87-97 (1986).

E. *Determination of Flows and Loadings for Packed Tower Aeration (Rating Mode)*

1. Development

In rating mode, the user has three flow and loading specification options:

(1) Specify water flow rate and air flow rate

Calculate air to water ratio, water loading rate, and air loading rate

(2) Specify water flow rate and air to water ratio

Calculate air flow rate, water loading rate, and air loading rate

(3) Specify water loading rate and air loading rate

Calculate water flow rate, air flow rate, and air to water ratio

The equations used for the calculations in each of the three cases are given below.

Case (1) Specify water flow rate and air flow rate

Calculate air to water ratio, water loading rate, and air loading rate

$$\frac{\dot{V}}{Q} = \frac{\dot{V}}{Q}$$

Eq. 1

$$L_m = \frac{Q \rho_l}{A}$$

Eq. 2

$$G_m = \frac{\dot{V} \rho_g}{A}$$

Eq. 3

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Case (2)   Specify water flow rate and air to water ratio

Calculate air flow rate, water loading rate, and air loading rate

$$\dot{V} = \left(\frac{\dot{V}}{Q}\right) Q$$

$$L_m = \frac{Q \rho_l}{A}$$

$$G_m = \frac{\dot{V} \rho_g}{A}$$

Case (3)   Specify water loading rate and air loading rate

Calculate water flow rate, air flow rate, and air to water ratio

$$Q = \frac{A L_m}{\rho_l}$$

$$\dot{V} = \frac{A G_m}{\rho_g}$$

$$\frac{\dot{V}}{Q} = \frac{\dot{V}}{Q}$$

2. Nomenclature

A — Cross-sectional area of tower (L^2)

G_m — Air mass loading rate ($M/L^2/T$)

L_m — Water mass loading rate ($M/L^2/T$)

Q — Water flow rate (L^3/T)

$\dot{V}$ — Air flow rate (L^3/T)

$\frac{\dot{V}}{Q}$ — Air to water ratio (L^3/L^3)

Greek Letters

ρ_l — Water density (M/L^3)

ρ_g — Air density (M/L^3)

F. Estimation of the Pressure Drop across a Packed Tower (Rating Mode)

1. Development

In rating mode, the pressure drop across a packed tower is estimated based on the generalized pressure drop curves developed by Eckert (1961), which are shown in Treybal (1980) and reprinted with permission in Hand, et al (1986). The Eckert pressure drop curves were fit by Cummins and Westrick (1983) in order to develop correlations capable of predicting gas loading rate and tower area. The process to estimate pressure drop for rating mode based on the Eckert curves is described below. Note that in some cases it is not possible to attain convergence.

In rating mode, all the parameters necessary to calculate the value of the y-axis on the Eckert curves are known. The value of the y-axis on the Eckert curves, y_{actual}, can be calculated from the following equation:

$$y_{actual} = \frac{\left(G_m\right)^2 C_f \left(\mu_l\right)^{0.1}}{\rho_g \left(\rho_l - \rho_g\right)}$$

Eq. 1

Once y_{actual} is known, it is necessary to iterate the value of pressure drop using the process shown below until the calculated value of the y-axis on the Eckert curve, $y_{calculated}$, matches the actual value, y_{actual}. Pressure drop per packing height is usually iterated between the values of 50 and 1200 N/m^2/m since that is the region for which the correlations were developed.

a) Iteration Process to Calculate Pressure Drop

(1) Calculate the parameter, E:

$$E = -\log_{10}\left\{\left(\frac{\dot{v}}{Q}\right)\sqrt{\left(\rho_g / \rho_l\right) - \left(\rho_g / \rho_l\right)^2}\right\}$$

Eq. 2

(2) Specify a pressure drop, $\Delta P / L$, in N/m^2/m.

(3) Calculate the parameter, F:

$$F = \log_{10}|\Delta P / L|$$

Eq. 3

(4) Calculate the parameters, a_0, a_1, and a_2:

$$a_0 = -6.6599 + 4.3077\,F - 1.3503\,F^2 + 0.15931\,F^3$$

Eq. 4

$$a_1 = 3.0945 - 4.3512\,F + 1.6240\,F^2 - 0.20855\,F^3$$

Eq. 5

$$a_2 = 1.7611 - 2.3394\,F + 0.89914\,F^2 - 0.11597\,F^3$$

Eq. 6

(5) Determine the value of $y_{calculated}$ from the following equation:

$$y_{calculated} = 10^{|a_0 + a_1 E + a_2 E^2|}$$

Eq. 7

(6) If   is within 1 % of   then pressure drop is set equal to the value specified in step (2) above and the iterative process is complete. Otherwise, return to step (2) and perform the iterative process again, remembering that pressure drop is generally iterated between 50 and 1200 N/m²/m.

2.   Nomenclature

   ,   ,   Calculated empirical parameters

E, F Calculated empirical parameter

G_m Gas mass loading rate ($M/L^2/T$)

M Calculated empirical parameter

$\Delta P / L$ Pressure drop gradient ($F/L^2/L$)

Q Water flow rate (L^3/T)

$\frac{\dot{V}}{Q}$ Air to water ratio (L^3/L^3)

<u>Greek Letters</u>

μ_l Liquid viscosity (*M/L/T*)

ρ_l Liquid density (*M/L³*)

ρ_g Gas density (*M/L³*)

3.   References

Cummins, M. D. and J. J. Westrick, *Proc. ASCE Envir. Engrg. Conf.*, Boulder, Colorado (July 1983).

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G. Estimation of the Mass Transfer Coefficient in Packed Tower Aeration

1.

K_L

aeration processes was derived earlier based on the two-film theory of mass transfer:

$$\frac{1}{K_L a} = \frac{1}{k_l a} + \frac{1}{H k_g a}$$

Eq. 1

It should be noted that Eq. 1 accounts for both liquid- and gas-phase resistances to mass transfer. For packed tower aeration, the liquid phase mass transfer coefficient (k_l), gas phase coefficient (k_g), and specific interfacial area (a) are determined based on the following correlations, which were developed by Onda, et al (1968).

The specific interfacial area, a, is equivalent to the wetted surface area of the packing, a_w, which is calculated as follows:

$$a_w = a_t \left\{ 1 - \exp\left[-1.45 \left(\frac{\sigma_c}{\sigma} \right)^{0.75} (\text{Re})^{0.1} (\text{Fr})^{-0.05} (\text{We})^{0.2} \right] \right\}$$

Eq. 2

The parameter a_t refers to the specific surface area of the packing. The parameters σ_c and σ refer to the critical surface tension of the packing and the surface tension of water, respectively. The parameters *Re*, *Fr*, and *We* refer to the Reynolds number, Froude number, and Weber number, respectively, which are defined by the following equations:

$$\text{Re} = \frac{L_m}{a_t \mu_l}$$

Eq. 3

$$\text{Fr} = \frac{\left(L_m \right)^2 a_t}{\left(\rho_l \right)^2 g}$$

Eq. 4

$$We = \frac{\left(L_m\right)^2}{\rho_l \, a_t \, \sigma}$$

<div align="right">**Eq. 5**</div>

The liquid phase mass transfer coefficient, k_l, can be calculated as follows:

$$k_l = 0.0051 \left(\frac{L_m}{a_w \, \mu_l}\right)^{2/3} \left(\frac{\mu_l}{\rho_l \, D_l}\right)^{-0.5} \left(a_t \, d_p\right)^{0.4} \left(\frac{\rho_l}{\mu_l \, g}\right)^{-1/3}$$

<div align="right">**Eq. 6**</div>

Eq. 6 is valid for liquid loading rates between 1.1 and 63 gpm/ft^2 (0.8 and 43 kg/m^2/s).

The gas phase mass transfer coefficient, k_g, can be calculated as follows:

$$k_g = 5.23 \left(a_t \, D_g\right) \left(\frac{G_m}{a_t \, \mu_g}\right)^{0.7} \left(\frac{\mu_g}{\rho_g \, D_g}\right)^{1/3} \left(a_t \, d_p\right)^{-2}$$

<div align="right">**Eq. 7**</div>

Eq. 7 is valid for gas loading rates between 2.206 and 267.9 cfm (0.014 and 1.7 kg/m^2/s).
Eq. 2, Eq. 6, and Eq. 7 were correlated for nominal packing sizes up to 2 in. (0.0508 m).

a)   Applicability and Limitations of the Onda Model

Roberts, et. al. (1985) and Cummins and Westrick (1983) showed that for several VOCs, $K_L a$ obtained from the Onda correlations compared favorably to pilot plant data. Lamarche and Droste (1989) evaluated available mass transfer models for packed tower aeration (Onda, 1968; Sherwood and Holloway, 1940; and Shuman, et al, 1955) and determined that the Onda model gives the best predictions of mass transfer coefficient. Recent studies (Staudinger, et al, 1990; Lenzo, et al, 1990; Thom and Byers, 1993; Djebbar and Narbaitz, 1995) have identified some considerations that must be addressed when applying the Onda mass transfer model in packed tower aeration. Staudinger, et al (1990) evaluated the Onda model using 10 literature studies consisting of 11 VOCs and 4 packing materials for the following areas of concern: interactions and concentrations of compounds, prediction of gas-phase resistance, variations of performance between packing materials, extreme column operating conditions and temperature effects. The packing materials studied were both small ($\leq$ 1 in.) and large ($>$ 1 in.). While the study

<div align="center">279</div>

concluded that the Onda correlation provides an acceptable method for predicting the mass transfer coefficient in packed tower aeration, it also pointed out that the Onda correlation tended to underestimate performance for larger packings (2 in. nominal size). Lenzo, et al (1990) took mass transfer data from over 90 pilot- and full-scale air stripping tower studies and compared the experimental data to the mass transfer coefficients predicted by the Onda correlation. The study consisted of both large and small packings. The evaluation (which was limited to 596 data points collected for three different compounds) found that the Onda correlation overestimated $K_L a$ in 75 % of the situations examined by an average of 37 %. It should be noted that Staudinger's study was included in Lenzo's evaluation. The overestimation of $K_L a$ would result in an undersized tower failing to remove contaminants to the desired levels. Based on these findings, the study recommends a safety factor be applied on $K_L a$ to reduce its value and increase the size of the tower. The evaluation found that a safety factor of 0.75 (Actual $K_L a$ / Onda $K_L a$) would account for 99 % of the data evaluated.

Application of such a safety factor in all cases will be costly for designers since the degree of overestimation will differ from case to case. Djebbar and Narbaitz (1995) seek to address this issue by correlating the mass transfer coefficient predicted by the Onda model to nominal packing size. The Onda model was developed by correlating nominal packing sizes up to 2 in. Current packing sizes used in the field often are higher, in the range from 2 in. through 6 in. It is for these larger nominal packing sizes that the Onda model tends to produce the most error. The Djebber study accounts for larger packing sizes (up to 6 in.) than any of the previous studies. Based on data for these larger packings used in full-scale operations, Djebbar and Narbaitz concluded that the average overestimation in $K_L a$ was 40 % and that a safety factor of 0.68 (Actual $K_L a$ / Onda $K_L a$) would be required to account for 68 % of the data. Because the error in the Onda $K_L a$ tends to increase with nominal packing size, Djebbar and Narbaitz developed a correlation to predict the actual $K_L a$ achieved as a function of Onda $K_L a$ and nominal packing size, d_p. The correlation was created by regressing the full-scale data and is presented below:

$$\text{Actual } K_L a = \frac{\text{Onda } K_L a}{0.834 + 0.293 \ln(d_p)}$$

<div align="right">**Eq. 8**</div>

The correlation presented in Eq. 8 is applicable to nominal packing sizes greater than 1 inch. The error in $K_L a$ was reduced to ± 22 %, with the application of Eq. 8 to the studies of three different researchers for nominal sizes of 1.5",2", and 2". The greatest source of error in the Onda model appears to be in the equation for wetted surface area of the packing, a_w. It should be noted that Djebbar and Narbaitz's evaluation considered both the Lenzo and Staudinger studies. Djebbar and Narbaitz also found that $K_L a$ may vary along the packed column, which would contradict the previous assumptions that $K_L a$ is constant with depth.

Thom and Byers (1993) point out that there are additional concerns besides the ones described above that can result in an inappropriate estimation of $K_L a$. In pilot-scale tests where conditions are carefully controlled by researchers, predictions of $K_L a$ by the Onda correlation tend to closely match operating data. In the field, variation in design and construction details may lead to significantly different results between model predictions and packed tower performance. Important design and construction details include liquid distribution, packing materials, and adherence to the limitations and restrictions of the air stripping model used. Less likely to cause performance problems are factors such as Henry's Law data, fouling, chemical reactions, and end effects. Paying close attention to design and construction details is essential in designing a packed tower that will match predicted results.

Based on the above discussion, it is recognized that the Onda correlation tends to overestimate mass transfer coefficients for larger packings. Researchers are in the process of developing correlations to account for the deviations. At the present time, there is no correlation that will correct the $K_L a$ to an error of ± 10 % for larger packings. For this reason, based on the literature cited above, it is recommended that a safety factor of 0.6 (Actual $K_L a$ / Onda $K_L a$) be applied for nominal packing sizes > 1" in order to provide a conservative estimate of packing height required.

2. Nomenclature

a Specific interfacial area, which is the area available for mass transfer divided by the vessel volume (L^2/L^3)

a_t Total specific surface area of the packing material (L^2/L^3)

a_w Wetted surface area of the packing, which is equal to a (L^2/L^3)

d_p Nominal diameter of the packing material (L)

D_g Gas diffusivity (L^2/T)

D_l Liquid diffusivity (L^2/T)

Fr   Froude number (dimensionless)

g Gravitational Constant (L/T^2)

G_m Gas mass loading rate ($M/L^2/T$)

H Henry's Law constant (dimensionless)

k_g Gas phase mass transfer coefficient (L/T)

k_l Liquid phase mass transfer coefficient (L/T)

$K_L a$ Overall liquid phase mass transfer coefficient ($1/T$)

L_m Liquid mass loading rate ($M/L^2/T$)

Re   Reynolds number (dimensionless)

We   Weber number (dimensionless)

Greek Letters

μ_l Liquid viscosity ($M/L/T$)

μ_g Gas viscosity ($M/L/T$)

ρ_l Liquid density (M/L^3)

ρ_g Gas density (M/L^3)

σ Surface tension of liquid water (M/T^2)

σ_c Critical surface tension of the packing material (M/T^2)

3.   References

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H.   Power Requirements in Packed Tower Aeration

1.   Development

The total operating power for packed tower aeration is the sum of the blower and pump brake power requirements. The blower brake power was found from the following relationship (Metcalf & Eddy, 1991):

$$P_{blower} = \left[\frac{G_{me} \, R_g \, T_{air}}{1000 \, n_a \, Eff_b} \right] \left[\left[\frac{P_{in}}{P_{out}} \right]^{n_a} - 1 \right]$$

Eq. 1

Hand, et al (1986) discussed the application of Eq. 1 in packed tower aeration. The term P_{in} refers to the pressure at the bottom of the tower, which is the inlet for the gas stream. P_{in} is calculated as the sum of the ambient pressure and the pressure drop caused by the packing media, demister, packing support plate, duct work, inlet and outlet of the tower.

The equation used to find P_{in} is:

$$P_{in} = P_{ambient} + \left[\left[\tfrac{\Delta P}{L} \right] L \right] + \Delta P_{losses}$$

Eq. 2

ΔP_{losses} is found from the following:

$$\Delta P_{losses} = \left[\frac{\dot{V}}{A} \right]^2 k_p$$

Eq. 3

Note that Eq. 3 represents the pressure drop through the demister, packing support plate, duct work, inlet and outlet of the tower. It is assumed that turbulent flow conditions prevail and most of the losses occur in the tower (i.e. in the packing support plate and the demister).

The pump brake power for packed tower aeration is given by (note that this expression only accounts for the pressure loss resulting from the head required to pump the water to the top of the tower):

$$P_{pump} = \frac{\rho_l \, Q \, L \, g}{1000 \, Eff_p}$$

<div align="right">**Eq. 4**</div>

2. Nomenclature

A	Tower cross-sectional area (L^2)
Eff_b	Blower efficiency (expressed as decimal), which is a net efficiency accounting for both the fan and motor on the blower
Eff_p	Pump efficiency (expressed as decimal)
g	Gravitational constant (L/T^2)
G_{me}	Mass flow rate of air (M/T) = $\dot{V} \cdot \rho_g$
k_p	Constant used to estimate gas pressure drop in tower for losses other than that in the tower packing (M/L^3) = $275 \, N \, s^2 / m^4$ (Hand, et al, 1986)
L	Packing height (L)
n_a	Constant used in determining blower brake power = 0.283 for air
$P_{ambient}$	Ambient air pressure ($M \, L/T^2/L^2$)
P_{Blower}	Blower brake power ($M \, L^2 / T^2 / T$)
P_{in}	Inlet air pressure to packed tower (bottom of tower) ($M \, L/T^2/L^2$)
P_{out}	Outlet air pressure from packed tower (top of tower) ($M \, L/T^2/L^2$) = $P_{ambient}$
P_{Pump}	Pump brake power ($M \, L^2 / T^2 / T$)
$\Delta P / L$	Gas pressure drop per unit length of packing ($M \, L/T^2/L^2/L$)
ΔP_{losses}	Pressure drop through the demister, packing support plate, duct work, inlet and outlet of the tower ($M \, L/T^2/L^2$)
Q	Water flow rate (L^3/T)
R_g	Universal gas constant
T	Absolute water temperature
T_{air}	Absolute air temperature, which is typically assumed equal to T
$\dot{V}$	Air volumetric flow rate (L^3/T)

<u>Greek Letters</u>

ρ_l Liquid density (M/L^3)

ρ_g Gas density (M/L^3)

3. References

Hand, D.W., J.C. Crittenden, J.L. Gehin, and B.W. Lykins, Jr., "Design and Evaluation of an Air-Stripping Tower for Removing VOCs from Groundwater," *Journal AWWA*, **78**, 9, 87-97 (1986).

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I.   Determination of Mass Transfer Coefficient in Bubble and Surface Aeration

1.   Development

The general equation for estimating mass transfer coefficient, $K_L a$, for an aeration process was derived earlier as:

$$\frac{1}{K_L a} = \frac{1}{k_l a} + \frac{1}{H k_g a}$$

Eq. 1

For bubble and surface aeration, it is difficult to determine the overall mass transfer coefficient for a compound from Eq. 1 because the quantities k_l and k_g vary greatly from system to system and are difficult to measure. In order to determine the overall mass transfer coefficient of a compound for these systems, it is necessary to relate the mass transfer coefficient of a given compound, $K_L a_i$, to the mass transfer coefficient of a reference compound, $K_L a_{ref}$. The procedure for doing so is shown below.

Eq. 1 can be written for compound i as:

$$\frac{1}{K_L a_i} = \frac{1}{k_l a_i} + \frac{1}{H_i k_g a_i} \Rightarrow$$

Eq. 2

$$\frac{1}{K_L a_i} = \frac{1}{k_l a_i}\left[1 + \frac{1}{H_i \left(\frac{k_g a_i}{k_l a_i}\right)}\right] \Rightarrow$$

Eq. 3

$$K_L a_i = k_l a_i \left[1 + \frac{1}{H_i \left(\frac{k_g a_i}{k_l a_i}\right)}\right]^{-1}$$

Eq. 4

It should be noted that the term $\frac{k_g a_i}{k_l a_i}$ is relatively constant for a given device and does not depend on the compound, i. The following simplification can be made:

$$\frac{k_g a_i}{k_l a_i} = \frac{k_g}{k_l}$$

Substituting Eq. 5 into Eq. 4 results in:

$$K_L a_i = k_l a_i \left[1 + \frac{1}{H_i \left(\frac{k_g}{k_l} \right)} \right]^{-1}$$

Eq. 6 can be written for a reference compound as:

$$\frac{1}{K_L a_{ref}} = \frac{1}{k_l a_{ref}} + \frac{1}{H_i \, k_g a_{ref}}$$

A good choice for reference compound is a compound that has all resistance to mass transfer on the liquid side. Such a compound is oxygen since the liquid side controls mass transfer. For oxygen, the gas phase mass transfer resistance is negligible and Eq. 7 simplifies to:

$$\frac{1}{K_L a_{O_2}} = \frac{1}{k_l a_{O_2}} + \frac{1}{H_{O_2} \, k_g a_{O_2}} = \frac{1}{k_l a_{O_2}} \Rightarrow$$

$$K_L a_{O_2} = k_l a_{O_2}$$

Relating mass transfer coefficient of a given compound, i, to the mass transfer coefficient for oxygen as a reference compound results from dividing Eq. 6 by Eq. 9:

$$\frac{K_L a_i}{K_L a_{O_2}} = \frac{k_l a_i}{k_l a_{O_2}} \left[1 + \frac{1}{H_i \left(\frac{k_g}{k_l} \right)} \right]^{-1}$$

The quantity $\frac{k_l a_i}{k_l a_{O_2}}$ in Eq. 10 can be determined using the Sherwood number, Sh, which is defined by the following equation:

$$Sh = a_c + b\,\text{Re}^{m1}\,Sc^{m2}$$

Eq. 11

The constant a_c in Eq. 11 is a term accounting for natural convection. This term is negligible in most engineered systems compared to the term, $b\,\text{Re}^{m1}\,Sc^{m2}$, which is a term accounting for flow. Making this assumption, Eq. 11 can be rewritten as:

$$Sh = b\,\text{Re}^{m1}\,Sc^{m2}$$

Eq. 12

Taking the ratio of the Sherwood number of a given compound, i, to the Sherwood number for oxygen results in:

$$\frac{Sh_i}{Sh_{O_2}} = \frac{b\,\text{Re}^{m1}\,Sc_i^{m2}}{b\,\text{Re}^{m1}\,Sc_{O_2}^{m2}}$$

Eq. 13

The values for the constants b and $m1$ and the Reynolds number, Re, in Eq. 13, are dependent only on the system and not on the compound. Knowing this, Eq. 13 can be simplified to:

$$\frac{Sh_i}{Sh_{O_2}} = \frac{b\,\text{Re}^{m1}\,Sc_i^{m2}}{b\,\text{Re}^{m1}\,Sc_{O_2}^{m2}} = \frac{Sc_i^{m2}}{Sc_{O_2}^{m2}}$$

Eq. 14

The Sherwood number of a compound i is defined as:

$$Sh_i = \frac{k_{l,i}\,L}{D_{l,i}}$$

Eq. 15

Likewise, the Sherwood number for oxygen can be represented by:

$$Sh_{O_2} = \frac{k_{l,O_2}\, L}{D_{l,O_2}}$$

The Schmidt numbers for a compound i and for oxygen are defined as:

$$Sc_i = \frac{\mu_l}{\rho_l\, D_{l,i}}$$

$$Sc_{O_2} = \frac{\mu_l}{\rho_l\, D_{l,O_2}}$$

Substituting the definitions given in Eq. 15 - Eq. 18 into Eq. 14 results in:

$$\frac{\left(\dfrac{k_{l,i}\, L}{D_{l,i}}\right)}{\left(\dfrac{k_{l,O_2}\, L}{D_{l,O_2}}\right)} = \left(\frac{\left(\dfrac{\mu_l}{\rho_l\, D_{l,i}}\right)}{\left(\dfrac{\mu_l}{\rho_l\, D_{l,O_2}}\right)}\right)^{m2} \Rightarrow \text{ Multiplying top and bottom of left side by } a$$

$$\frac{\left(\dfrac{k_l a_i}{D_{l,i}}\right)}{\left(\dfrac{k_l a_{O_2}}{D_{l,O_2}}\right)} = \left(\frac{\left(\dfrac{1}{D_{l,i}}\right)}{\left(\dfrac{1}{D_{l,O_2}}\right)}\right)^{m2} \Rightarrow$$

$$\frac{k_l a_i}{k_l a_{O_2}} = \frac{D_{l,i}\left(\dfrac{1}{D_{l,i}}\right)^{m2}}{D_{l,O_2}\left(\dfrac{1}{D_{l,O_2}}\right)^{m2}} \Rightarrow$$

$$\frac{k_l a_i}{k_l a_{O_2}} = \frac{\left(D_{l,i}\right)^{1-m2}}{\left(D_{l,O_2}\right)^{1-m2}} \Rightarrow$$

Noting that $m2$ is a constant depending on the type of boundary in the range $\frac{1}{3} \le m2 \le \frac{1}{2}$, a variable $n = 1 - m2$ can be substituted into Eq. 22, where n is in the range $\frac{1}{2} \le n \le \frac{2}{3}$:

$$\frac{k_l a_i}{k_l a_{O_2}} = \frac{\left(D_{l,i}\right)^{1-m2}}{\left(D_{l,O_2}\right)^{1-m2}} = \frac{\left(D_{l,i}\right)^{n}}{\left(D_{l,O_2}\right)^{n}} = \left(\frac{D_{l,i}}{D_{l,O_2}}\right)^{n}$$

Substituting Eq. 23 into Eq. 10 results in the equation for determining the mass transfer coefficient of any compound, i, using oxygen as a reference compound:

$$K_L a_i = K_L a_{O_2} \left(\frac{D_{l,i}}{D_{l,O_2}}\right)^{n} \left(1 + \frac{1}{H_i \left(\frac{k_g}{k_l}\right)}\right)^{-1}$$

Eq. 24 represents the general formula for estimating the mass transfer coefficient of a compound in bubble and surface aeration. A few comments on each of the variables needed to calculate the mass transfer coefficient of a compound i:

$K_L a_{O_2}$ Overall mass transfer coefficient for oxygen ($1/T$).

$D_{l,i}$ Liquid diffusivity of compound i (L^2/T). This parameter is available in StEPP™.

D_{l,O_2} Diffusivity of oxygen (L^2/T). This parameter can be determined from a correlation presented by Holmén and Liss (1984). The correlation was obtained from a best fit of literature values and is described in detail below.

n Constant depending on the type of boundary. In water, there is typically a boundary layer and n is closer to 1/2. In air, there is typically no boundary layer and n is closer to 2/3.

H_i Henry's Law constant for component i

$\frac{k_g}{k_l}$ This ratio tends to be relatively constant for a given device. The range of values for this parameter is approximately $40 \leq \frac{k_g}{k_l} \leq 200$, depending on the device. This parameter does not depend on the compound of interest.

a)   *Estimating the Diffusivity of Oxygen*

This parameter can be determined from a correlation presented by Holmén and Liss in 1984. The correlation was obtained from a best fit of literature values:

$$D_{l,O_2} = \left[10^{[A+B/T]} \right] \left(1.0 \times 10^{-9} \right)$$

Eq. 25

Parameters used in the correlation are:

D_{l,O_2} Diffusivity of oxygen (m^2/s)

A Fitting parameter = 3.15

B Fitting parameter = -831.0

T Absolute temperature (K)

2.   Nomenclature

a Area available for mass transfer divided by the vessel volume (L^2/L^3)

a_c Constant accounting for natural convection in the equation for Sherwood number

A Fitting parameter in diffusivity of oxygen equation

b Constant in the equation for Sherwood number that depends on the system

B Fitting parameter in diffusivity of oxygen equation

$D_{l,i}$ Liquid diffusivity of compound i (L^2/T)

D_{l,O_2} Liquid diffusivity of oxygen (L^2/T)

H Henry's Law constant describing equilibrium between the air and water phases (dimensionless)

H_i Henry's Law constant for compound i (dimensionless)

H_{O_2} Henry's Law constant for oxygen (dimensionless)

i Name of compound of interest

k_g Gas phase mass transfer coefficient (L/T)

$k_g a_i$ Gas phase mass transfer coefficient for compound i $(1/T)$

$k_g a_{O_2}$	Gas phase mass transfer coefficient for oxygen ($1/T$)
$k_g a_{ref}$	Gas phase mass transfer coefficient for a reference compound ($1/T$)
$\frac{k_g}{k_l}$	This ratio tends to be relatively constant for a given device. The range of values for this parameter is approximately $40 \leq \frac{k_g}{k_l} \leq 200$, depending on the device. This parameter does not depend on the compound of interest.
k_l	Liquid phase mass transfer coefficient (L/T)
$k_{l,i}$	Liquid phase mass transfer coefficient for compound i (L/T)
k_{l,O_2}	Liquid phase mass transfer coefficient for oxygen (L/T)
$k_l a_i$	Liquid phase mass transfer coefficient for compound i ($1/T$)
$k_l a_{O_2}$	Liquid phase mass transfer coefficient for oxygen ($1/T$)
$k_l a_{ref}$	Liquid phase mass transfer coefficient for a reference compound ($1/T$)
K_L	Overall mass transfer coefficient based on a liquid phase driving force (L/T)
$K_L a_i$	Overall mass transfer coefficient for compound i ($1/T$)
$K_L a_{O_2}$	Overall mass transfer coefficient for oxygen ($1/T$)
$K_L a_{ref}$	Overall mass transfer coefficient for a reference compound ($1/T$)
L	Length term (L)
$m1$	Constant in the equation for Sherwood number that depends on the type of flow
$m2$	Constant in the equation for Sherwood number that depends on the type of boundary
n	Constant depending on the type of boundary in the range $\frac{1}{2} \leq n \leq \frac{2}{3}$. In water, there is typically a boundary layer and n is closer to 1/2. In air, there is typically no boundary layer and n is closer to 2/3.
Re	Reynolds number (dimensionless)
Sc	Schmidt number (dimensionless)
Sc_i	Schmidt number for compound i (dimensionless)
Sc_{O_2}	Schmidt number for oxygen (dimensionless)
Sh	Sherwood number (dimensionless)
Sh_i	Sherwood number for compound i (dimensionless)
Sh_{O_2}	Sherwood number for oxygen (dimensionless)
T	Absolute temperature (K)

<u>Greek Letters</u>

μ_l Viscosity of liquid water ($M/L/T$)

ρ_l Density of liquid water (M/L^3)

3.   Reference

Holmén, Kim, and Peter Liss, "Models for Air-Water Gas Transfer: An Experimental Investigation," *Tellus*, **36B**, 92-100 (1984).

J. Development of Process Design Equations for Bubble Aeration

1. Development

This development is for a single compound in bubble aeration. All liquid phase concentrations, gas phase concentrations, and mass transfer coefficients specified in the development are relevant to a specific generic compound, which could be anything.

a) Single Tank

Figure 1 shows a schematic of a bubble aeration system for a single tank. Model development for bubble aeration has been described in the literature (Matter-Müller, et al, 1981; Munz and Roberts, 1982; Roberts, et al, 1984). The development of the process design equations for bubble aeration incorporates the following assumptions: (1) completely mixed liquid phase, (2) plug flow gas phase, (3) the process is at steady state, and (4) the inlet gas concentration is zero.
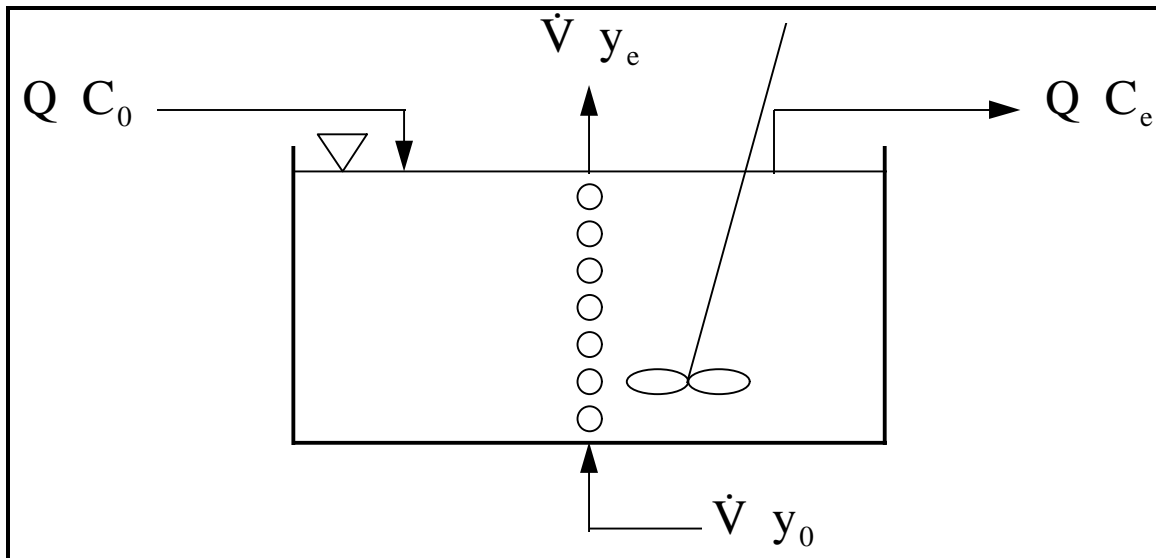
Figure 1 - Schematic of Bubble Aeration Configuration

1. Find minimum air to water ratio needed to achieve an effluent concentration of C_e in the tank.

Mass Balance around the tank:

$$\left\{\begin{matrix}\text{Mass of}\\ \text{Organic}\\ \text{Entering}\end{matrix}\right\} - \left\{\begin{matrix}\text{Mass of}\\ \text{Organic}\\ \text{Leaving}\end{matrix}\right\} + \left\{\begin{matrix}\text{Mass of}\\ \text{Organic}\\ \text{Generated}\end{matrix}\right\} - \left\{\begin{matrix}\text{Mass of}\\ \text{Organic}\\ \text{Lost}\end{matrix}\right\} = \left\{\begin{matrix}\text{Mass of}\\ \text{Organic}\\ \text{Accumulated}\end{matrix}\right\} \Rightarrow$$

$$\left\{\begin{matrix}\text{Mass of}\\ \text{Organic}\\ \text{Entering}\end{matrix}\right\} - \left\{\begin{matrix}\text{Mass of}\\ \text{Organic}\\ \text{Leaving}\end{matrix}\right\} + 0 - 0 = 0 \Rightarrow$$

$$Q\,C_0 - Q\,C_e - \dot{V}\,y_e = 0$$

Eq. 1

Assume: Exiting air in equilibrium with bulk liquid $\rightarrow$

$$y_e = H\,C_e$$

Eq. 2

Substituting Eq. 2 into Eq. 1 yields the following:

$$Q\,C_0 - Q\,C_e - \dot{V}\,H\,C_e = 0 \Rightarrow$$

Eq. 3

$$C_0 - C_e - \frac{\dot{V}}{Q}H\,C_e = 0 \Rightarrow$$

Eq. 4

$$\left(\frac{\dot{V}}{Q}\right)_{min} = \frac{C_0 - C_e}{H\,C_e}$$

Eq. 5

Note that for air to water ratio values, $\frac{\dot{V}}{Q}$, less than the minimum air to water ratio, $\left(\frac{\dot{V}}{Q}\right)_{min}$, it will not be possible to achieve the desired effluent concentration from the tank, C_e.

Now the derivation will be continued by eliminating the assumption made above that the exiting air is in equilibrium with the bulk liquid. Plug flow conditions will be assumed for the gas bubble. Figure 2 shows a schematic of a gas bubble in the tank.
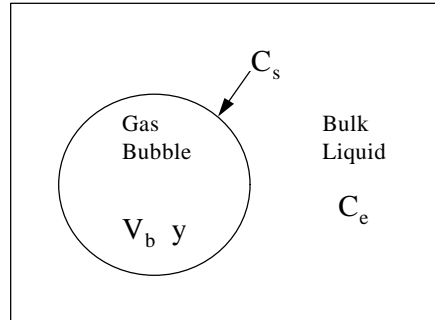
Figure 2 - Schematic of a Gas Bubble

Mass balance around a gas bubble:

$$\left\{\begin{array}{l}\text{Mass Transferred Across}\\ \text{Air / Water Interface}\\ \text{of Gas Bubble}\end{array}\right\} = \left\{\begin{array}{l}\text{Mass}\\ \text{Accumulated}\\ \text{within Gas Bubble}\end{array}\right\} \Rightarrow$$

$$\Delta t \left(K_L \, a\right)\left(C_e - C_s\right)V_b = V_b \left[y(t + \Delta t) - y(t)\right] \Rightarrow$$

Eq. 6

$$\left(K_L \, a\right)\left(C_e - C_s\right) = \lim_{\Delta t \to 0} \frac{\left[y(t + \Delta t) - y(t)\right]}{\Delta t} \Rightarrow$$

Eq. 7

$$\frac{dy}{dt} = \left(K_L \, a\right)\left(C_e - C_s\right)$$

Eq. 8

Based on Henry's Law, the equilibrium between the gas and liquid phases can be described using Henry's constant as follows:

$$y^* = H \, C_e$$

Eq. 9

$$y = H \, C_s$$

Eq. 10

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Substituting Eq. 9 and Eq. 10 into Eq. 8 results in the following:

$$\frac{dy}{dt} = \left(K_L a \right) \left(\frac{y^*}{H} - \frac{y}{H} \right) \Rightarrow$$

Eq. 11

$$\int_0^y \frac{dy}{y^* - y} = \frac{K_L a}{H} \int_0^t dt \Rightarrow$$

Eq. 12

$$- \ln \left(\frac{y^* - y}{y^*} \right) = \frac{K_L a}{H} t \Rightarrow$$

Eq. 13

$$\left(\frac{y^* - y}{y^*} \right) = \exp \left(- \frac{K_L a}{H} t \right)$$

Eq. 14

Note that for the case of plug flow gas, t is equal to the bubble retention time in the tank, as defined by:

$$t = \frac{V}{\dot{V}}$$

Eq. 15

Substituting Eq. 15 into Eq. 14 results in the following:

$$\left(\frac{y^* - y}{y^*} \right) = \exp \left(- \frac{K_L a V}{H \dot{V}} \right)$$

Eq. 16

In order to simplify the equation, a new term called the Stanton number, ϕ, will be defined as:

$$\phi = \frac{K_L a V}{H \dot{V}}$$

Eq. 17

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Substituting Eq. 17 into Eq. 16 yields:

$$\left\{1 - \frac{y}{y^*}\right\} = e^{-\phi} \Rightarrow$$

Eq. 18

$$y = y^* \left(1 - e^{-\phi}\right) \Rightarrow$$

Eq. 19

Substituting Eq. 9 into Eq. 19 results in the following:

$$y = H C_e \left(1 - e^{-\phi}\right) \Rightarrow$$

Eq. 20

Noting that $y = y_e$ and substituting Eq. 20 into Eq. 1 allows for the solution of the design and rating mode cases for bubble aeration:

$$Q C_0 - Q C_e - \dot{V} H C_e \left(1 - e^{-\phi}\right) = 0 \Rightarrow$$

Eq. 21

(1)   Design Mode

In design mode, it is desirable to size the bubble aeration system (i.e., determine the minimum tank volume that will allow for meeting the treatment objective). This is done by solving Eq. 21 for the volume, V, that appears in the f term. For design mode, the achieved effluent concentration, C_e, is the treatment objective, C_{TO}, so the substitution, $C_e = C_{TO}$ is made.

$$Q C_0 - Q C_{TO} - \dot{V} H C_{TO} \left(1 - e^{-\frac{K_L a V}{H \dot{V}}}\right) = 0 \Rightarrow$$

Eq. 22

$$C_0 - C_{TO} = \frac{\dot{V}}{Q} H C_{TO} \left(1 - e^{-\frac{K_L a V}{H \dot{V}}}\right) \Rightarrow$$

Eq. 23

$$\frac{C_0 - C_{TO}}{\frac{\dot{V}}{Q} H C_{TO}} = \left[1 - e^{-\frac{K_L a V}{H \dot{V}}}\right] \Rightarrow$$

Eq. 24

$$e^{-\frac{K_L a V}{H \dot{V}}} = \left[1 - \frac{C_0 - C_{TO}}{\frac{\dot{V}}{Q} H C_{TO}}\right] \Rightarrow$$

Eq. 25

$$e^{-\frac{K_L a V}{H \dot{V}}} = \left\{1 - \left[\left(\frac{C_0}{C_{TO}} - 1\right)\left(\frac{1}{\frac{\dot{V}}{Q} H}\right)\right]\right\} \Rightarrow$$

Eq. 26

$$-\frac{K_L a V}{H \dot{V}} = \ln\left\{1 - \left[\left(\frac{C_0}{C_{TO}} - 1\right)\left(\frac{1}{\frac{\dot{V}}{Q} H}\right)\right]\right\} \Rightarrow$$

Eq. 27

$$V = -\frac{H \dot{V}}{K_L a} \ln\left\{1 - \left[\left(\frac{C_0}{C_{TO}} - 1\right)\left(\frac{1}{\frac{\dot{V}}{Q} H}\right)\right]\right\} \Rightarrow$$

Eq. 28

In order for the bubble aeration tank to meet the treatment objective, the air to water ratio specified, $\frac{\dot{V}}{Q}$, must be greater than or equal to the minimum air to water ratio that was defined in Eq. 5:

$$\frac{\dot{V}}{Q} \geq \left(\frac{\dot{V}}{Q}\right)_{min} = \frac{C_0 - C_{TO}}{H C_{TO}}$$

Eq. 29

The gas phase concentration out of the tank can be calculated by solving Eq. 1 for y_e and substituting $C_e = C_{TO}$. The gas phase effluent concentration, y_e, is given as:

$$y_e = \frac{C_0 - C_{TO}}{\frac{\dot{V}}{Q}}$$

Eq. 30

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(2)   Rating Mode

The purpose of rating mode is to predict the removal of a given contaminant for an existing tank (i.e., V is known and it is desired to find C_e. This is accomplished by solving Eq. 21 for C_e, as shown below:

$$C_e = \frac{C_0}{1 + \dfrac{\dot{V}}{Q} H \left(1 - e^{-\phi}\right)}$$

Eq. 31

The equation for gas phase concentration of a contaminant out of a bubble aeration tank is the same as Eq. 30, except that for rating mode, C_e, is the actual effluent concentration achieved out of the tank, as opposed to the treatment objective that was achieved in design mode:

$$y_e = \frac{C_0 - C_e}{\dfrac{\dot{V}}{Q}}$$

Eq. 32

b)   Tanks in Series

Process performance can often be improved significantly (i.e., less total volume requirements) by configuring the bubble aeration system as tanks in series. Figure 3 shows a schematic of a bubble aeration system operated with a tanks in series configuration. The derivation of process design equations provided below is for the general case of n tanks in series. Assumptions in the development of the tanks in series equations for bubble aeration include: (1) liquid phase behaves as a completely mixed flow reactor, (2) plug flow conditions prevail in the gas phase, (3) the process is at steady state, (4) the volumetric gas flow rate to each tank is the same, $\dot{V}$, (5) each tank will be equally sized with volume, V, and (6) the inlet gas concentration to each tank is equal to zero.

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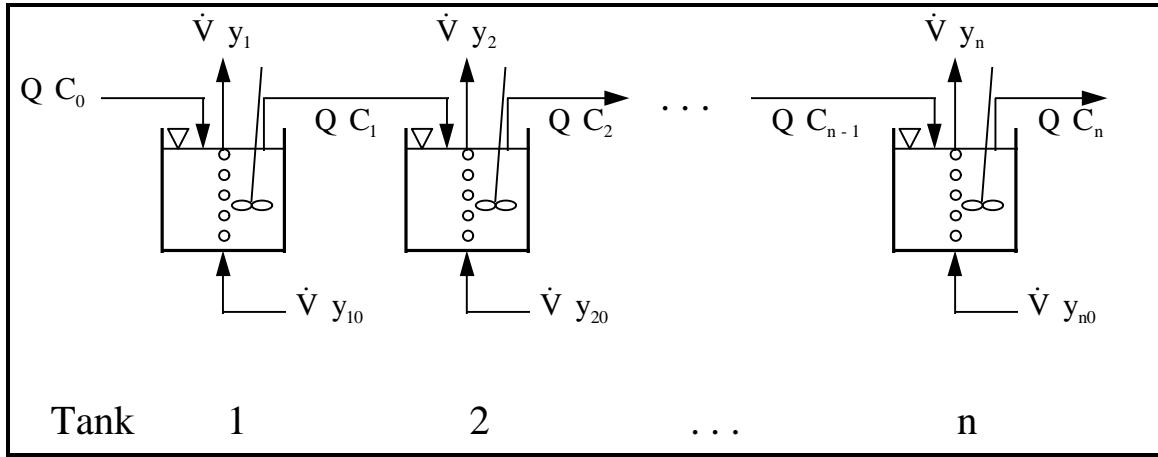
Figure 3 - Schematic of Bubble Aeration Tanks in Series Configuration

Mass Balance on Tank 1:

$$Q\,C_0 - Q\,C_1 - \dot{V}\,y_1 = 0$$

Eq. 33

By the same method shown above for a single tank, it is found that:

$$y_1 = H\,C_1\left(1 - e^{-\phi}\right) \Rightarrow$$

Eq. 34

$$Q\,C_0 - Q\,C_1 - \dot{V}\,H\,C_1\left(1 - e^{-\phi}\right) = 0 \Rightarrow$$

Eq. 35

$$C_1 = \frac{C_0}{1 + \frac{\dot{V}}{Q}\,H\left(1 - e^{-\phi}\right)}$$

Eq. 36

A mass balance around tank *2* produces a similar result:

$$C_2 = \frac{C_1}{1 + \frac{\dot{V}}{Q}\,H\left(1 - e^{-\phi}\right)} = \frac{C_0}{\left[1 + \frac{\dot{V}}{Q}\,H\left(1 - e^{-\phi}\right)\right]^2}$$

Eq. 37

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From mass balances around tanks *3, n-1*, and *n*, respectively:

$$C_3 = \frac{C_2}{1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)} = \frac{C_0}{\left[1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)\right]^3}$$

Eq. 38

$$C_{n-1} = \frac{C_{n-2}}{1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)} = \frac{C_0}{\left[1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)\right]^{n-1}}$$

Eq. 39

$$C_n = \frac{C_{n-1}}{1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)} = \frac{C_0}{\left[1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)\right]^{n}}$$

Eq. 40

Taking a closer look at Eq. 36 - Eq. 40, it is possible to write a general expression for Tank *i* as:

$$C_i = \frac{C_{i-1}}{1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)} = \frac{C_0}{\left[1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)\right]^{i}}$$

Eq. 41

(1)   Design Mode

To solve for the volume of each tank required to meet a specified treatment objective, C_{TO}, given *n* tanks, it is necessary to set $C_n = C_{TO}$ in Eq. 40 and solve for V:

$$C_{TO} = \frac{C_0}{\left[1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)\right]^{n}} \Rightarrow$$

Eq. 42

$$\left[1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)\right]^{n} = \frac{C_0}{C_{TO}} \Rightarrow$$

Eq. 43

$$\left[1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)\right] = \left(\frac{C_0}{C_{TO}}\right)^{1/n} \Rightarrow$$

Eq. 44

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$$e^{-\phi} = \left\{1 - \left[\left(\frac{C_0}{C_{TO}}\right)^{1/n} - 1\right]\left[\frac{1}{\frac{\dot{V}}{Q}H}\right]\right\} \Rightarrow$$

$$-\phi = \ln\left\{1 - \left[\left(\frac{C_0}{C_{TO}}\right)^{1/n} - 1\right]\left[\frac{1}{\frac{\dot{V}}{Q}H}\right]\right\} \Rightarrow$$

$$-\frac{K_L a V}{H \dot{V}} = \ln\left\{1 - \left[\left(\frac{C_0}{C_{TO}}\right)^{1/n} - 1\right]\left[\frac{1}{\frac{\dot{V}}{Q}H}\right]\right\} \Rightarrow$$

$$V = -\frac{H \dot{V}}{K_L a} \ln\left\{1 - \left[\left(\frac{C_0}{C_{TO}}\right)^{1/n} - 1\right]\left[\frac{1}{\frac{\dot{V}}{Q}H}\right]\right\} \Rightarrow$$

As for the case of the single tank, the air to water ratio for the tanks in series configuration must exceed the minimum air to water ratio for tanks in series in order to achieve the treatment objective. The minimum air to water ratio for tanks in series is found by assuming the exiting gas in equilibrium with the bulk liquid for each tank, or equivalently, that $y_i = H C_i \left(1 - e^{-\phi}\right) = H C_i$, where i denotes any tank. Making this assumption, Eq. 42 simplifies to:

$$C_{TO} = \frac{C_0}{\left[1 + \left(\frac{\dot{V}}{Q}\right)_{min} H\right]^n} \Rightarrow$$

Solving this equation for $\left(\frac{\dot{V}}{Q}\right)_{min}$ results in the minimum air to ratio for tanks in series:

$$\left(\frac{\dot{V}}{Q}\right)_{min} = \left[\left(\frac{C_0}{C_{TO}}\right)^{1/n} - 1\right]\frac{1}{H}$$

In order for V to achieve the treatment objective in Eq. 48, the following condition must hold true:

$$\frac{\dot{V}}{Q} \geq \left(\frac{\dot{V}}{Q}\right)_{min} = \left[\left(\frac{C_0}{C_{TO}}\right)^{1/n} - 1\right]\frac{1}{H}$$

Eq. 51

(2)   Rating Mode

The equation to predict the liquid phase effluent concentration for an existing tank in a tanks in series configuration has already been specified above in Eq. 41, which is repeated here. Note that C_i represents the liquid phase effluent concentration from tank number i.

$$C_i = \frac{C_{i-1}}{1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)} = \frac{C_0}{\left[1 + \frac{\dot{V}}{Q}H\left(1 - e^{-\phi}\right)\right]^i}$$

Eq. 52

Once the liquid phase effluent concentration from each tank has been calculated from Eq. 52, it is possible to calculate the gas phase effluent concentration. The gas phase effluent concentration from any tank i is specified by the following equation, which is analogous to the single tank case (see Eq. 32):

$$y_i = \frac{C_{i-1} - C_i}{\frac{\dot{V}}{Q}}$$

Eq. 53

2.   Nomenclature

Q Water flowrate (L^3/T)

C_0 Influent liquid phase concentration to the first bubble aeration tank (M/L^3)

C_1 Effluent liquid phase concentration from tank number 1 for a tanks in series configuration for bubble aeration (M/L^3)

C_2 Effluent liquid phase concentration from tank number 2 for a tanks in series configuration for bubble aeration (M/L^3)

C_3 Effluent liquid phase concentration from tank number 3 for a tanks in series configuration for bubble aeration (M/L^3)

C_e Effluent liquid phase concentration from a single bubble aeration tank (M/L^3)

C_{i-1} Effluent liquid phase concentration from tank number i-1 for a tanks in series configuration for bubble aeration (M/L^3)

C_i Effluent liquid phase concentration from tank number i for a tanks in series configuration for bubble aeration (M/L^3)

C_{n-1} Effluent liquid phase concentration from tank number n-1 for a tanks in series configuration for bubble aeration (M/L^3)

C_n Effluent liquid phase concentration from tank number n for a tanks in series configuration for bubble aeration (M/L^3)

C_s Liquid phase concentration at the air-water interface in bubble aeration (M/L^3)

C_{TO} Treatment objective (M/L^3)

H Henry's Law constant (dimensionless)

i Number of a given tank in a tanks in series configuration in bubble aeration

$K_L a$ Overall mass transfer coefficient $(1/T)$

n Total number of tanks in series used in a bubble aeration configuration

t Bubble retention time in the tank (T)

V Volume of a bubble aeration tank (L^3)

V_b Volume of a single gas bubble in a bubble aeration tank (L^3)

$\dot{V}$ Air flowrate (L^3/T)

$\frac{\dot{V}}{Q}$ Air to water ratio (L^3/L^3)

$\left(\frac{\dot{V}}{Q}\right)_{min}$ Minimum air to water ratio (L^3/L^3)

y_0 Inlet gas phase concentration to a single bubble aeration tank (M/L^3), a quantity whose value is assumed equal to zero

y_{10} Inlet gas phase concentration to tank number 1 in a tanks in series configuration for bubble aeration (M/L^3), a quantity whose value is assumed equal to zero

y_{20} Inlet gas phase concentration to tank number 2 in a tanks in series configuration for bubble aeration (M/L^3), a quantity whose value is assumed equal to zero

y_{i0} Inlet gas phase concentration to tank number i in a tanks in series configuration for bubble aeration (M/L^3), a quantity whose value is assumed equal to zero

y_{n0} Inlet gas phase concentration to tank number n in a tanks in series configuration for bubble aeration (M/L^3), a quantity whose value is assumed equal to zero

y_1 Outlet gas phase concentration from tank number 1 for a tanks in series configuration for bubble aeration (M/L^3)

y_2 Outlet gas phase concentration from tank number 2 for a tanks in series configuration for bubble aeration (M/L^3)

y_i Outlet gas phase concentration from tank number i for a tanks in series configuration for bubble aeration (M/L^3)

y_n Outlet gas phase concentration from tank number n for a tanks in series configuration for bubble aeration (M/L^3)

y_e Outlet gas phase concentration from a single bubble aeration tank (M/L^3)

y Gas phase concentration in a gas bubble, which is assumed to be in equilibrium with the liquid phase concentration at the air-water interface, C_s (M/L^3)

y^* Gas phase concentration in equilibrium with the liquid phase effluent concentration, C_e (M/L^3)

Greek Letters

ϕ Stanton number (dimensionless)

3. References

Matter-Müller, C., W. Gujer, and W. Giger, "Transfer of Volatile Substances from Water to the Atmosphere," *Water Research*, **15**, 1271-1279 (1981).

Munz, C. and P. V. Roberts, "Mass Transfer and Phase Equilibria in a Bubble Column," *Proc. AWWA Annual Conference*, 633-640 (1982).

Roberts, P. V., C. Munz, and P. Dändliker, "Modeling Volatile Organic Solute Removal by Surface and Bubble Aeration," *Journal WPCF*, **56**, 2, 157-163 (1984).

K. *Estimating the Mass Transfer Coefficient for Bubble Aeration*

1. Development

It was shown previously that the general formula for estimating the mass transfer coefficient of a compound in an air stripping process is:

$$K_L a_i = K_L a_{O_2} \left[\left(\frac{D_{l,i}}{D_{l,O_2}} \right)^n \right] \left[1 + \frac{1}{H_i \left(\frac{k_g}{k_l} \right)} \right]^{-1}$$

Eq. 1

Methods for obtaining each of the parameters in Eq. 1 are described below:

$K_L a_{O_2}$ For bubble aeration, the overall mass transfer coefficient for oxygen can be estimated using clean water oxygen transfer test data. The procedure for doing so is described in detail below.

$D_{l,i}$ Liquid diffusivity of compound i (L^2/T). This parameter can be calculated by the Hayduk & Laudie correlation (1974) for small molecules in water.

D_{l,O_2} Diffusivity of oxygen (L^2/T). This parameter can be determined from a correlation presented by Holmén and Liss (1984). The correlation was obtained from a best fit of literature values.

n Diffusivity exponent (dimensionless). For bubble aeration, this value will be set equal to 0.6. This is based on an evaluation of literature values performed by Holmén and Liss (1984) in which the mean value of n was found to be approximately 0.6 for air-water gas transfer. It should be noted that the range of n values shown in the various literature studies was $0.1 < n < 0.8$.

H_i Henry's constant of compound, i (dimensionless). This value is available from StEPP™ and from various literature sources (Ashworth, et al, 1988; Gossett, 1987)

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$\frac{k_g}{k_l}$ Munz and Roberts (1989) point out that a constant value of $\frac{k_g}{k_l} \approx 100 - 150$ has become widely used in air-water mass transfer. For this reason, a constant value of $\frac{k_g}{k_l} = 100$ will be used as a conservative estimate in bubble aeration. Munz and Roberts also point out that the assumption of a constant $\frac{k_g}{k_l}$ may over-simplify matters since $\frac{k_g}{k_l}$ could depend on operating conditions and/or temperature.

Therefore, the equation used to estimate the mass transfer coefficient of a compound, i, in bubble aeration is given below:

$$K_L a_i = K_L a_{O_2} \left[\left(\frac{D_{l,i}}{D_{l,O_2}} \right)^{0.6} \left(1 + \frac{1}{H_i} \left(\frac{1}{100} \right) \right)^{-1} \right]$$

Eq. 2

a) *Estimating the Mass Transfer Coefficient for Oxygen for Bubble Aeration*

For bubble aeration, the mass transfer coefficient for oxygen can be estimated using clean water oxygen transfer test data (Brown and Baillod, 1982; Baillod, et al, 1986). The procedure to find $K_L a_{O_2}^*$ is as follows:

True mass transfer coefficient for oxygen at 20 °C, $K_L a_{20}^*$, is calculated based on the observed mass transfer coefficient for oxygen at 20 °C, $K_L a_{20}$, and a parameter, ϕ :

$$K_L a_{20}^* = \frac{K_L a_{20}}{1 - \frac{K_L a_{20}}{2\phi}}$$

Eq. 3

The observed mass transfer coefficient for oxygen at 20 °C, $K_L a_{20}$, can be determined from the standardized oxygen transfer rate, $SOTR$, the water volume in the tank, V, and the dissolved oxygen saturation concentration attained at infinite time, C_∞^*. Further explanation on finding the $SOTR$ will be provided in the next section.

$$K_L a_{20} = \frac{SOTR}{V C_\infty^*}$$

Eq. 4

The dissolved oxygen saturation concentration attained at infinite time can be found from the following relationship:

$$C_\infty^* = C_s^* \left[\frac{P_b - P_v + \gamma_w d_e}{P_s - P_v} \right]$$

Eq. 5

The parameter, ϕ, needed to solve Eq. 3 is defined by the following expression:

$$\phi = \frac{M_{O_2} \, \rho_a \, Q_a}{M_a \, H_{O_2} \left(P_b + \gamma_w d_e \right)}$$

Eq. 6

Once the mass transfer coefficient for oxygen at 20 °C, $K_L a_{20}^*$, is known, it is possible to estimate the mass transfer coefficient at other temperatures using the relationship:

$$K_L a_T^* = K_L a_{20}^* \, \theta^{T-20} = K_L a_{20}^* \left(1.024 \right)^{T-20}$$

Eq. 7

This value, $K_L a_T^*$, is the mass transfer coefficient for oxygen, $K_L a_{O_2}$, referred to in the calculation of the mass transfer coefficient of a given compound, $K_L a$, in bubble aeration.

(1)   Determination of the Standardized Oxygen Transfer Rate

SOTR is defined as the rate of oxygen transfer in clean water at zero dissolved oxygen and a specified temperature, usually 20°C (68°F). One possible method for retrieving a value for *SOTR* for an aeration tank at a given sidewall depth, is by obtaining a rating curve showing SOTR versus air flow rate in SCFM. Such information should be available from operating data for a given tank. An example of such a curve is shown in Figure 1.
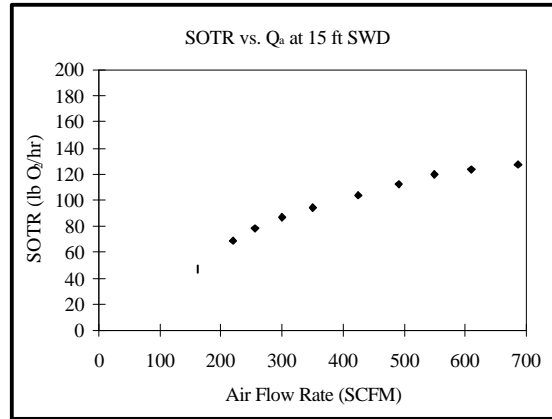
Figure 1 - Rating Curve Showing SOTR vs. Air Flow

Rate in SCFM for a Given Aeration Tank

At times, oxygen transfer data will be reported in terms of standardized oxygen transfer efficiency, *SOTE*, rather than in terms of *SOTR*. Given a value for *SOTE* in %, *SOTR* can be calculated from the following relationships:

SI Units

$$SOTR(kg\,O_2\,/\,d) = \frac{Q_a\,(std.\,m^3\,/\,hr)}{0.15} \times \frac{SOTE}{100}$$

Eq. 8

English Units

$$SOTR(lb\,O_2\,/\,d) = \frac{Q_a\,(scfm)}{0.0402} \times \frac{SOTE}{100}$$

Eq. 9

It should be noted that the *SOTR* and *SOTE* are by definition reported at 20°C (68°F), 1 atm pressure, and 36% relative humidity.

For completeness, derivations of Eq. 8 and Eq. 9 are provided.

Derivation to Calculate SOTR in terms of SOTE for SI Units

Problem: Find relationship between Q_a (std. m^3 / hr) and *SOTR* (kg/d).

Solution:

Standard Conditions →   20°C, 1 atm Pressure, 36% Relative Humidity (r.h.)

Composition of Dry Air →   21.0% O_2, 78.0% N_2, 1.0% Ar

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Using the Ideal Gas Law:

$$PV = nRT \Rightarrow$$

$$\frac{V_{mix}}{n} = \frac{RT}{P} = \frac{\left(0.08206 \frac{m^3\,atm}{kg-mol\,K}\right)(293\,K)}{1\,atm} = 24.044 \frac{m^3}{kg-mol}$$

$$r.h. = \frac{P_{H_2O}}{P_{v,H_2O}} \times 100 \Rightarrow$$

At 20°C, 100% r.h., vapor pressure of water, $P_{v,H_2O} = 17.53\,mm\,Hg$

At 20°C, 36% r.h., partial pressure of water, $P_{H_2O} = 0.36(17.53\,mm) = 6.31\,mm$

At 760 mm total pressure and $P_{H_2O} = 6.31\,mm\,H_2O$, the pressure at the dry air is:

$$753.69\,mm\,D.A. \Rightarrow \begin{cases} 0.21 \frac{mm\,O_2}{mm\,D.A.} \times 753.69\,mm\,D.A. = 158.27\,mm\,O_2 \\ 0.78 \frac{mm\,N_2}{mm\,D.A.} \times 753.69\,mm\,D.A. = 587.88\,mm\,N_2 \\ 0.01 \frac{mm\,Ar}{mm\,D.A.} \times 753.69\,mm\,D.A. = 7.54\,mm\,Ar \end{cases}$$

Assume 1 kg-mol mixture:

Wet Air Mixture	Mol Fraction, MF $(\frac{kg-mol}{kg-mol\,mix})$	Mol. Wt., MW $(\frac{kg}{kg-mol})$	# of $\frac{kg}{kg-mol\,mix}$ $(MF \times MW)$
H$_2$O	$\frac{6.31}{760} = 0.0083$	18.0	0.1494
O$_2$	$\frac{158.27}{760} = 0.2083$	32.0	6.6656
N$_2$	$\frac{587.88}{760} = 0.7735$	28.0	21.6580
Ar	$\frac{7.54}{760} = 0.0099$	40.0	0.3960

Average Molecular Weight = $28.87 \frac{kg}{kg-mol}$

$$W_{O_2} \left(\frac{kg\,O_2}{d}\right) \times \left[\frac{1\,kg-mol\,O_2}{32.0\,kg\,O_2} \times \frac{1\,kg-mol\,wet\,air}{0.2083\,kg-mol\,O_2} \times 24.044 \frac{m^3}{kg-mol\,wet\,air} \times \frac{1\,d}{24\,hr}\right] = Q_a\,(std.m^3/hr) \Rightarrow$$

$$W_{O_2} \left(\frac{kg\,O_2}{d}\right) \times [0.1503] = Q_a\,(std.m^3/hr)$$

Eq. 10

By definition:

$$SOTR = \frac{SOTE}{100} \times W_{O_2}$$

Eq. 11

Solving Eq. 10 for W_{O_2} and substituting into Eq. 11 results in:

$$SOTR = \frac{SOTE}{100} \times \frac{Q_a\left(std.m^3/hr\right)}{0.15}$$

Eq. 12

Eq. 12 matches Eq. 8, meaning the derivation of Eq. 8 is complete.

Derivation to Calculate SOTR in terms of SOTE for English Units

Problem: Find relationship between Q_a (scfm) and *SOTR* (lb/d).

Solution:

   Standard Conditions → 68°F, 1 atm Pressure, 36% Relative Humidity (r.h.)

   Composition of Dry Air → 21.0% O_2, 78.0% N_2, 1.0% Ar

Using the Ideal Gas Law:

$$PV = nRT \Rightarrow$$

$$\frac{V_{mix}}{n} = \frac{RT}{P} = \frac{\left(0.7302\,\frac{ft^3\,atm}{lb-mol\,°R}\right)\left(528\,°R\right)}{1atm} = 385.5\,\frac{ft^3}{lb-mol}$$

$$r.h. = \frac{P_{H_2O}}{P_{v,H_2O}} \times 100 \Rightarrow$$

At 20°C, 100% r.h., vapor pressure of water, $P_{v,H_2O} = 17.53\,mm\,Hg$

At 20°C, 36% r.h., partial pressure of water, $P_{H_2O} = 0.36\left(17.53\,mm\right) = 6.31\,mm$

At 760 mm total pressure and $P_{H_2O} = 6.31\,mm\,H_2O$, the pressure at the dry air is:

$$\left(753.69\,mm\,D.A.\right) \Rightarrow \begin{cases} 0.21\,\frac{mm\,O_2}{mm\,D.A.} \times 753.69\,mm\,D.A. = 158.27\,mm\,O_2 \\ 0.78\,\frac{mm\,N_2}{mm\,D.A.} \times 753.69\,mm\,D.A. = 587.88\,mm\,N_2 \\ 0.01\,\frac{mm\,Ar}{mm\,D.A.} \times 753.69\,mm\,D.A. = 7.54\,mm\,Ar \end{cases}$$

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Assume 1 lb-mol mixture:

Wet Air Mixture	Mol Fraction, MF $(\frac{lb-mol}{lb-mol\,mix})$	Mol. Wt., MW $(\frac{lb}{lb-mol})$	# of $\frac{lb}{lb-mol\,mix}$ $(MF \times MW)$
H_2O	$\frac{6.31}{760} = 0.0083$	18.0	0.1494
O_2	$\frac{158.27}{760} = 0.2083$	32.0	6.6656
N_2	$\frac{587.88}{760} = 0.7735$	28.0	21.6580
Ar	$\frac{7.54}{760} = 0.0099$	40.0	0.3960

$$\text{Average Molecular Weight} = 28.87 \frac{lb}{lb-mol}$$

$$W_{O_2}\left(\frac{lb\,O_2}{d}\right) \times \left[\frac{1\,lb-mol\,O_2}{32.0\,lb\,O_2} \times \frac{1\,lb-mol\,wet\,air}{0.2083\,lb-mol\,O_2} \times 385.5 \frac{ft^3}{lb-mol\,wet\,air} \times \frac{1\,d}{1440\,min}\right] = Q_a\,(scfm) \Rightarrow$$

$$W_{O_2}\left(\frac{lb\,O_2}{d}\right) \times [0.04016] = Q_a\,(scfm)$$

Eq. 13

By definition:

$$SOTR = \frac{SOTE}{100} \times W_{O_2}$$

Eq. 14

Solving Eq. 13 for W_{O_2} and substituting into Eq. 14 results in:

$$SOTR = \frac{SOTE}{100} \times \frac{Q_a\,(scfm)}{0.0402}$$

Eq. 15

Eq. 15 matches Eq. 9, meaning the derivation of Eq. 9 is complete.

2. **Nomenclature**

C_∞^* Dissolved oxygen saturation concentration attained at infinite time (M/L^3)

C_s^* Tabulated value of dissolved oxygen surface saturation concentration at 20°C (M/L^3) = $9.09 \frac{mg}{L}$ (Metcalf & Eddy, 1991)

d_e Effective saturation depth (L) = $\frac{1}{3} \times$ Water Depth

H_{O_2} Henry's constant for oxygen (M/L^3)/($M\,L/T^2/L^2$) = $50 \frac{mg}{L \cdot atm}$

$K_L a_{20}^*$ True mass transfer coefficient for oxygen at 20°C ($1/T$)

$K_L a_T^*$ True mass transfer coefficient for oxygen at temperature, T ($1/T$)

$K_L a_{20}$ Apparent observed mass transfer coefficient for oxygen at 20°C ($1/T$)

$K_L a_{O_2}$ Mass transfer coefficient for oxygen at temperature, T ($1/T$) = $K_L a_T^*$

M_a Molecular weight of air (amu) = 28.0

M_{O_2} Molecular weight of oxygen (amu) = 32.0

n Number of moles of gas in ideal gas law

P_b Barometric pressure ($M\,L/T^2/L^2$)

P_s Barometric pressure under standard conditions ($M\,L/T^2/L^2$) = 1 atm

P_v Vapor pressure of water at 20°C ($M\,L/T^2/L^2$) = $2.34 \frac{kN}{m^2}$ (Metcalf & Eddy, 1991)

Q_a Volumetric air flow rate (L^3/T)

R Universal gas constant

$r.h.$ Relative humidity (%)

$SOTE$ Standardized oxygen transfer efficiency (%)

$SOTR$ Standardized oxygen transfer rate (M/T)

T Absolute temperature

V Water volume (L^3)

V_{mix} Volume of wet air mixture (L^3)

W_{O_2} Rate of oxygen supply by the diffuser (M/T)

Greek Letters

γ_w Weight density of water $= 62.4 \frac{lb}{ft^3}$

ϕ Oxygenation coefficient (*1/T*)

ρ_a Density of air at 20°C $= 1240 \frac{mg}{L}$

θ Parameter used for temperature correlation $= 1.024$

3. References

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L. Power Requirements in Bubble Aeration

1. Development

The total operating power for bubble aeration is equal to the blower brake power requirement for each tank times the number of tanks times the number of blowers per tank. The blower brake power was found from the following relationship (Metcalf & Eddy, 1991):

$$P_{blower} = \left[\frac{G_{me} \, R_g \, T_{air}}{1000 \, n_a \, Eff_b} \right] \left[\left(\frac{P_{in,b}}{P_{out,b}} \right)^{n_a} - 1 \right]$$

Eq. 1

The term $P_{in,b}$ refers to the pressure at the top of the tank, which represents the sum of the ambient pressure and the head required to raise the water to the inlet of the tank. The equation used to find $P_{in,b}$ is:

$$P_{in,b} = P_{ambient} + \rho_l \, H_b \, g$$

Eq. 2

The pressure head, H_b, is assumed equal to the water depth in the tank, d_b.

2. Nomenclature

d_b	Water depth in bubble aeration tank (L)
Eff_b	Blower efficiency (%)
g	Gravitational constant (L/T^2)
G_{me}	Mass flow rate of air (M/T)
H_b	Pressure head required to raise water to top of tank (L) = d_b
L	Packing height (L)
n_a	Constant used in determining blower brake power = 0.283 for air
$P_{ambient}$	Ambient air pressure ($M \, L/T^2/L^2$)
$P_{in,b}$	Inlet air pressure to bubble aeration tank (bottom of tower) ($M \, L/T^2/L^2$)
$P_{out,b}$	Outlet air pressure from bubble aeration tank (top of tower) ($M \, L/T^2/L^2$) = $P_{ambient}$

R_g Universal gas constant

T Absolute water temperature

T_{air} Absolute air temperature, which is typically assumed equal to absolute water temperature

    <u>Greek Letters</u>

ρ_l Liquid density (M/L^3)

3. Reference

Metcalf and Eddy Inc., *Wastewater Engineering*, 3rd Ed., New York: McGraw-Hill (1991).

M.   *Development of Process Design Equations for Surface Aeration*

1.   Development

This development is for a single compound in surface aeration. All liquid phase concentrations, gas phase concentrations, and mass transfer coefficients specified in the development are relevant to a specific generic compound, which could be anything.

a)   Single Tank

Figure 1 shows a schematic of a surface aeration system for a single tank. Model development for surface aeration has been described in the literature (Matter-Müller, et al, 1981; Roberts and Dändliker, 1983; Roberts, et al, 1984; Roberts and Levy, 1985; Munz and Roberts, 1989). This development of process design equations for surface aeration incorporates the following assumptions: (1) completely mixed liquid phase, (2) the gas phase concentration in the tank equals zero, and (3) the process is at steady state.

$$Q\ C_0 \longrightarrow \hspace{4cm} \longrightarrow Q\ C_e$$
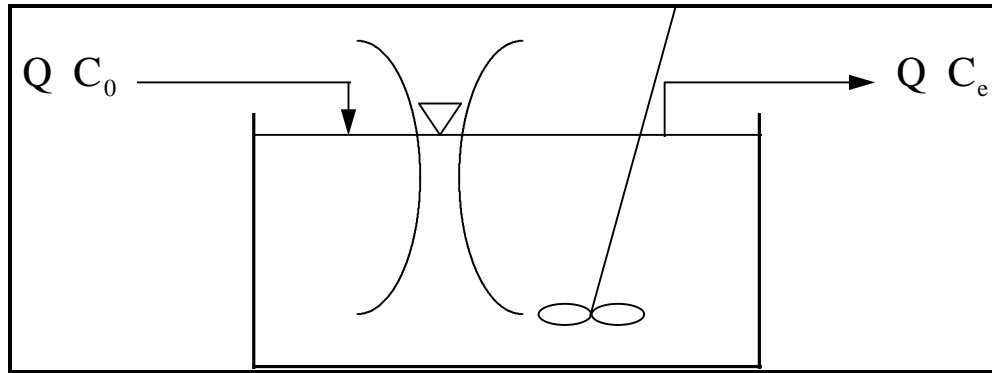
Figure 1 - Schematic of Surface Aeration Configuration

An overall mass balance around the tank is given below:

$$\begin{Bmatrix} \text{Mass of} \\ \text{Organic} \\ \text{Entering} \\ \text{Per} \\ \text{Unit Time} \end{Bmatrix} - \begin{Bmatrix} \text{Mass of} \\ \text{Organic} \\ \text{Leaving} \\ \text{Per} \\ \text{Unit Time} \end{Bmatrix} + \begin{Bmatrix} \text{Mass of} \\ \text{Organic} \\ \text{Generated} \\ \text{Per} \\ \text{Unit Time} \end{Bmatrix} - \begin{Bmatrix} \text{Mass of} \\ \text{Organic} \\ \text{Lost} \\ \text{Per} \\ \text{Unit Time} \end{Bmatrix} = \begin{Bmatrix} \text{Mass of} \\ \text{Organic} \\ \text{Accumulated} \\ \text{Per} \\ \text{Unit Time} \end{Bmatrix}$$

$$\left[Q\,C_0 \right] - \left[Q\,C_e \right] + \left[0 \right] - \left[\left(K_L a \right) \left(C_e - C_s \right) V \right] = \left\{ V \frac{dC}{dt} \right\}$$

Eq. 1

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With the assumption of steady-state conditions, Eq.1 simplifies to:

$$Q C_0 - Q C_e - K_L a (C_e - C_s) V = 0$$

Eq. 2

In surface aeration, it is assumed that the gas phase concentration in the tank, y_b, is equal to zero. As a result of this assumption, it is shown that the liquid phase concentration at the air-water interface, C_s, is also equal to zero based on the following relationship:

$$C_s = \frac{y_b}{H} = 0$$

Eq. 3

Substituting Eq. 3 into Eq. 2 results in:

$$Q C_0 - Q C_e - K_L a C_e V = 0$$

Eq. 4

(1) Design Mode

In design mode, it is desirable to size the surface aeration system (i.e., determine the minimum tank volume that will allow for meeting the treatment objective). This is done by solving Eq. 4 for the volume, V. For design mode, the achieved effluent concentration, C_e, is the treatment objective, C_{TO}, so the substitution, $C_e = C_{TO}$ is made into Eq. 4.

$$Q C_0 - Q C_{TO} - K_L a C_{TO} V = 0$$

Eq. 5

Solving Eq. 5 for V results in the minimum tank volume, V, required for a single tank in order to meet the treatment objective in surface aeration:

$$V = \frac{Q (C_0 - C_{TO})}{K_L a C_{TO}}$$

Eq. 6

The design equation for a single surface aeration tank may alternatively be written in terms of the hydraulic retention time of the tank, τ , where $\tau = V/Q$. Substituting this relationship into Eq. 6 results in the following expression:

$$\tau = \frac{\left[C_0 - C_{TO} \right]}{K_L a \, C_{TO}}$$

Eq. 7

(2)   Rating Mode

The purpose of rating mode is to predict the removal of a given contaminant for an existing tank (i.e. V is known and it is desired to find C_e). This is accomplished by solving Eq. 4 for C_e, as shown below:

$$C_e = \frac{C_0}{1 + K_L a \left(\frac{V}{Q} \right)} = \frac{C_0}{1 + K_L a \tau}$$

Eq. 8

b)   Tanks in Series

Process performance can often be improved significantly (i.e., less total volume requirements) by configuring the surface aeration system as tanks in series. Figure 2 shows a schematic of a surface aeration system operated with a tanks in series configuration. The derivation of process design equations provided below is for the general case of n tanks in series. Assumptions in the development of the tanks in series equations for surface aeration include: (1) liquid phase behaves as a completely mixed flow reactor, (2) the gas phase concentration of the contaminant in the tank equals zero, (3) the process is at steady state, and (4) each tank will be equally sized with volume, V.
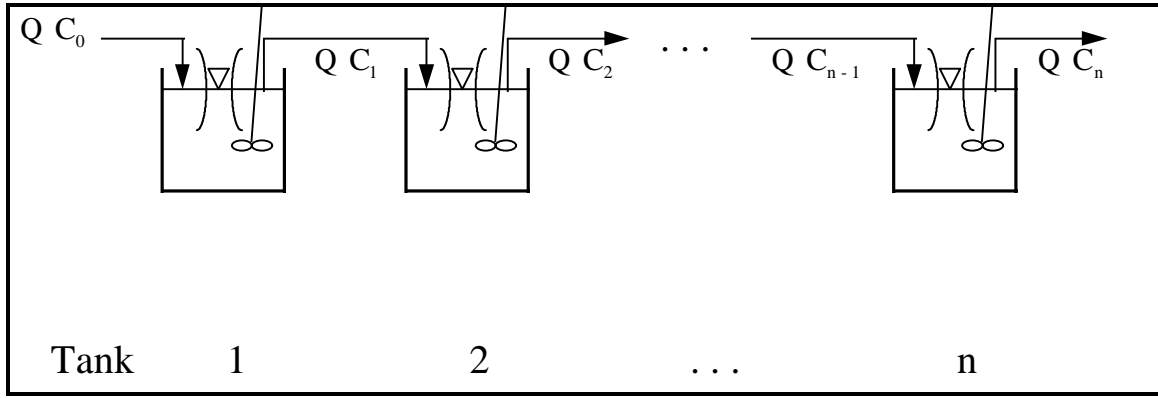
Figure 2 - Schematic of Surface Aeration Tanks in Series Configuration

Mass Balance on Tank 1:

$$Q C_0 - Q C_1 - K_L a C_1 V = 0$$

Eq. 9

Solving for the effluent concentration from tank 1, C_1:

$$C_1 = \frac{C_0}{1 + K_L a \left(\frac{V}{Q}\right)}$$

Eq. 10

Similarly, a mass balance around Tank 2 results in:

$$C_2 = \frac{C_1}{1 + K_L a \left(\frac{V}{Q}\right)} = \frac{C_0}{\left[1 + K_L a \left(\frac{V}{Q}\right)\right]^2}$$

Eq. 11

A mass balance around tank n results in:

$$C_n = \frac{C_{n-1}}{1 + K_L a \left(\frac{V}{Q}\right)} = \frac{C_0}{\left[1 + K_L a \left(\frac{V}{Q}\right)\right]^n}$$

Eq. 12

Taking a closer look at Eq. 10 - Eq. 12, it is possible to write a general formula for the effluent concentration from tank number i in surface aeration:

$$C_i = \frac{C_{i-1}}{1 + K_L a \left(\frac{V}{Q}\right)} = \frac{C_0}{\left[1 + K_L a \left(\frac{V}{Q}\right)\right]^i}$$

Eq. 13

(1) Design Mode

To solve for the volume of each tank required to meet a specified treatment objective, C_{TO}, given n tanks, it is necessary to set $C_n = C_{TO}$ in Eq. 12 and solve for V:

$$C_{TO} = \frac{C_0}{\left[1 + K_L a \left(\frac{V}{Q}\right)\right]^n} \Rightarrow$$

Eq. 14

$$\left[1 + K_L a \left(\frac{V}{Q}\right)\right]^n = \frac{C_0}{C_{TO}} \Rightarrow$$

Eq. 15

$$\left[1 + K_L a \left(\frac{V}{Q}\right)\right] = \left[\frac{C_0}{C_{TO}}\right]^{1/n} \Rightarrow$$

Eq. 16

$$K_L a \left(\frac{V}{Q}\right) = \left[\frac{C_0}{C_{TO}}\right]^{1/n} - 1 \Rightarrow$$

Eq. 17

$$V = \frac{Q}{K_L a} \left[\left(\frac{C_0}{C_{TO}}\right)^{1/n} - 1\right]$$

Eq. 18

It is also possible to solve for the hydraulic retention time of each individual tank, τ, by making the substitution $\tau = V / Q$ in Eq. 18. The resultant equation is:

$$\tau = \frac{1}{K_L a}\left[\left(\frac{C_0}{C_{TO}}\right)^{1/n} - 1\right]$$

<div align="right">**Eq. 19**</div>

The volume of all tanks required for a tanks in series configuration consisting of n tanks, V_n, is found by multiplying V in Eq. 18 by the number of tanks, n. The result is:

$$V_n = V \cdot n = \frac{n \cdot Q}{K_L a}\left[\left(\frac{C_0}{C_{TO}}\right)^{1/n} - 1\right]$$

<div align="right">**Eq. 20**</div>

Likewise, the total hydraulic retention time required for a tanks in series configuration consisting of n tanks, τ_n, is obtained by multiplying τ in Eq. 19 by n:

$$\tau_n = \tau \cdot n = \frac{n}{K_L a}\left[\left(\frac{C_0}{C_{TO}}\right)^{1/n} - 1\right]$$

<div align="right">**Eq. 21**</div>

Examination of Eq. 19 and Eq. 20 reveals that the following relationship holds true:

$$\tau_n = \tau \cdot n = \frac{n}{K_L a}\left[\left(\frac{C_0}{C_{TO}}\right)^{1/n} - 1\right] = \left\{\frac{n \cdot Q}{K_L a}\left[\left(\frac{C_0}{C_{TO}}\right)^{1/n} - 1\right]\right\} / Q = \frac{V_n}{Q}$$

<div align="right">**Eq. 22**</div>

It should be noted that for surface aeration in design mode, the quantities $V, V_n, \tau, \text{and} \tau_n$ are not independent variables. Calculation of one value allows for determination of the other three parameters using Eq. 18 - Eq. 22. The procedure is to find $V, V_n, \tau, \text{or} \tau_n$ using Eq. 18, Eq. 19, Eq. 20, or Eq. 21, respectively. Once any one quantity is known, it is possible to find the other three quantities using the relationships:

$$V_n = V \cdot n$$

<div align="right">**Eq. 23**</div>

$$\tau_n = V_n / Q$$

<div align="right">**Eq. 24**</div>

$$\tau = V / Q$$

<div align="right">**Eq. 25**</div>

(2) Rating Mode

The equation to predict the liquid phase effluent concentration for an existing tank in a tanks in series configuration has already been specified above in Eq. 13, which is repeated here. Note that C_i represents the liquid phase effluent concentration from tank number i.

$$C_i = \frac{C_{i-1}}{1 + K_L a\left(\frac{V}{Q}\right)} = \frac{C_0}{\left[1 + K_L a\left(\frac{V}{Q}\right)\right]^i} = \frac{C_0}{\left[1 + K_L a(\tau)\right]^i} = \frac{C_0}{\left[1 + K_L a\left(\frac{V_n}{n \cdot Q}\right)\right]^i} = \frac{C_0}{\left[1 + K_L a\left(\frac{\tau_n}{n}\right)\right]^i}$$

<div align="right">**Eq. 26**</div>

For surface aeration in rating mode, the user may specify any of the following properties: $V, V_n, \tau, \text{and} \tau_n$. Calculation of each of the other properties for each of the four cases will be explained below:

Case 1 - Specify V

Calculate V_n, τ , and τ_n using the following relationships:

$$V_n = V \cdot n$$

<div align="right">**Eq. 27**</div>

$$\tau = V / Q$$

<div align="right">**Eq. 28**</div>

$$\tau_n = V_n / Q$$

<div align="right">**Eq. 29**</div>

Case 2 - Specify V_n

Calculate V, τ, and τ_n using the following relationships:

$$V = V_n / n$$

Eq. 30

$$\tau = V / Q$$

Eq. 31

$$\tau_n = V_n / Q$$

Eq. 32

Case 3 - Specify **t**

Calculate V, V_n, and τ_n using the following relationships:

$$V = \tau \cdot Q$$

Eq. 33

$$V_n = V \cdot n$$

Eq. 34

$$\tau_n = V_n / Q$$

Eq. 35

Case 4 - Specify τ_n

Calculate V, V_n, and τ using the following relationships:

$$\tau = \tau_n / n$$

Eq. 36

$$V = \tau \cdot Q$$

Eq. 37

$$V_n = V \cdot n$$

Eq. 38

2.   Nomenclature

C_0 — Influent liquid phase concentration to the first surface aeration tank (M/L^3)

C_1 — Effluent liquid phase concentration from tank number *1* for a tanks in series configuration for surface aeration (M/L^3)

C_2 — Effluent liquid phase concentration from tank number *2* for a tanks in series configuration for surface aeration (M/L^3)

C_e — Effluent liquid phase concentration from one surface aeration tank (M/L^3)

C_{i-1} — Effluent liquid phase concentration from tank number *i-1* for a tanks in series configuration for surface aeration (M/L^3)

C_i — Effluent liquid phase concentration from tank number *i* for a tanks in series configuration for surface aeration (M/L^3)

C_{n-1} — Effluent liquid phase concentration from tank number *n-1* for a tanks in series configuration for surface aeration (M/L^3)

C_n — Effluent liquid phase concentration from tank number *n* for a tanks in series configuration for surface aeration (M/L^3)

C_s — Liquid phase concentration at the air-water interface in surface aeration (M/L^3), which is equal to zero

C_{TO} — Treatment objective (M/L^3)

H — Henry's Law constant (dimensionless)

i — Number of a given tank in a tanks in series configuration in surface aeration

$K_L a$ — Overall mass transfer coefficient ($1/T$)

n — Total number of tanks in series used in a surface aeration configuration

Q — Water flowrate (L^3/T)

V — Volume of an individual surface aeration tank (L^3)

V_n — Total volume of all surface aeration tanks in a tanks in series configuration (L^3)

y_b — Concentration in the bulk gas phase, which is assumed to be in equilibrium with the liquid phase concentration at the air-water interface, C_s (M/L^3).

Greek Letters

ϕ — Stanton number (dimensionless)

τ — Hydraulic retention time of an individual surface aeration tank (T)

τ_n — Total hydraulic retention time of all surface aeration tanks in a tanks in series configuration (T)

3. References

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Roberts, P. V. and J. A. Levy, "Energy Requirements for Air Stripping Trihalomethanes," *Journal AWWA*, **77**, 138-146 (1985).

N. *Estimating the Mass Transfer Coefficient for Surface Aeration*

1. Development

It was shown previously that the general formula for estimating the mass transfer coefficient of a compound in an air stripping process is:

$$K_L a_i = K_L a_{O_2} \left[\left(\frac{D_{l,i}}{D_{l,O_2}} \right)^n \left(1 + \frac{1}{H_i \left(\frac{k_g}{k_l} \right)} \right) \right]^{-1}$$

Eq. 1

Methods for obtaining each of the parameters in Eq. 1 are described below:

$K_L a_{O_2}$ For surface aeration, the overall mass transfer coefficient for oxygen can be estimated using a correlation developed by Roberts and Dändliker (1983): $K_L a_{O_2} = 2.9 \times 10^{-5} (P/V)^{0.95}$, where P/V, the power input, is in the range $10 \le P/V \le 200 \ W/m^3$.

$D_{l,i}$ Liquid diffusivity of compound i (L^2/T). This parameter can be calculated by the Hayduk & Laudie correlation (1974) for small molecules in water.

D_{l,O_2} Diffusivity of oxygen (L^2/T). This parameter can be determined from a correlation presented by Holmén and Liss (1984). The correlation was obtained from a best fit of literature values.

n Munz and Roberts (1989) report that n should be set equal to 0.5 for mechanical surface aeration.

H_i Henry's constant of compound, i (dimensionless). This value is available from StEPP™ and from various literature sources (Ashworth, et al, 1988; Gossett, 1987)

$\frac{k_g}{k_l}$ Munz and Roberts (1989) recommend a value of $\frac{k_g}{k_l}$ equal to 40 in mechanical surface aeration.

Therefore, the equation used to estimate the mass transfer coefficient of a compound, i, in surface aeration is given below:

$$K_L a_i = K_L a_{O_2} \left[\frac{D_{l,i}}{D_{l,O_2}} \right]^{0.5} \left[1 + \frac{1}{H_i (40)} \right]^{-1}$$

Eq. 2

2.   Nomenclature

$D_{l,i}$ — Liquid diffusivity of compound i (L^2/T)

D_{l,O_2} — Liquid diffusivity of oxygen (L^2/T)

H_i — Henry's constant for component i (dimensionless)

$\frac{k_g}{k_l}$ — Ratio that tends to be relatively constant for a surface aeration system and is not compound dependent. It is set equal to 40 for surface aeration.

$K_L a_i$ — Overall mass transfer coefficient of compound i in surface aeration ($1/T$)

$K_L a_{O_2}$ — Overall mass transfer coefficient of compound i in surface aeration ($1/T$)

n — Diffusivity exponent (dimensionless)

P/V — Power input per unit volume (W/m^3)

3.   References

Ashworth, R. A., G. B. Howe, M. E. Mullins, and T. N. Rogers, "Air--Water Partitioning Coefficients of Organics in Dilute Aqueous Solutions," *Journal of Hazardous Materials*, **18**, 25-36 (1988).

Gossett, J. M., "Measurement of Henry's Law Constants for C_1 and C_2 Chlorinated Hydrocarbons," *Environ. Sci. Technol.*, **21**, 202-208 (1987).

Hayduk, W. and H. Laudie, "Prediction of Diffusion Coefficients for Non-electrolytes in Dilute Aqueous Solutions," *Jour. AIChE*, **28**, 611 (1974).

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Munz, C. and P. V. Roberts, "Gas- and Liquid-Phase Mass Transfer Resistances of Organic Compounds during Mechanical Surface Aeration," *Water Research*, **23**, 5, 589-601 (1989).

Roberts, P. V. and P. G. Dändliker, "Mass Transfer of Volatile Organic Contaminants from Aqueous Solution to the Atmosphere during Surface Aeration," Environ. Sci. Technol., **17**, 8, 484-489 (1983).

O. *Power Requirements in Surface Aeration*

1. Development

The total operating power for surface aeration is equal to the power requirement for each tank times the number of tanks. The power requirement for each tank is determined from the following relationship:

$$P_s = \left[\left(\frac{P}{V} \right) \left(\frac{V_s}{Eff_s} \right) \right]$$

Eq. 1

2. Nomenclature

Eff_s Surface aerator motor efficiency (expressed as decimal)

P_s Power input required for each surface aeration tank ($M\,L^2\,/\,T^3$)

$\frac{P}{V}$ Power input per unit volume in surface aeration ($M\,L^2\,/\,T^3/L^3$)

V_s Volume of a surface aeration tank (L^3)

Appendix A – Explanation of Default Data Files

On the main menu, the user has the choice of six options:

1. Packed Tower Aeration – Design Mode
2. Packed Tower Aeration – Rating Mode
3. Bubble Aeration – Design Mode
4. Bubble Aeration – Rating Mode
5. Surface Aeration – Design Mode
6. Surface Aeration – Rating Mode

When the user selects an option and enters that particular mode, a default data file is loaded. This appendix provides a few words of explanation of the default data files. All default data files are stored in the **..\asap\dbase** directory and should not be deleted. If the default data files are deleted then the program will not function properly and it will be necessary to reinstall the software to regain proper functionality.

1. Packed Tower Aeration – Design Mode

The name of the default data file for this case is:

DEFAULT.DES

2. Packed Tower Aeration – Rating Mode

The name of the default data file for this case is:

DEFAULT.RAT

3. Bubble Aeration – Design Mode

The name of the default data file for this case is:

DEFLTDES.BUB

4. Bubble Aeration – Rating Mode

The name of the default data file for this case is:

DEFLTRAT.BUB

5. Surface Aeration – Design Mode

The name of the default data file for this case is:

DEFLTDES.SUR

6. Surface Aeration – Rating Mode

The name of the default data file for this case is:

DEFLTRAT.SUR

Note that the user may save any particular design case of interest to be the default. It is recommended that the user back up the original default files before making any changes in order to avoid having to reinstall the software if a mistake is made.

Appendix B – Complete Table of Contents, including Lists of Figures and Tables and Explanation of Word Documents that Comprise this ASAP Manual

A Few Words of Explanation about the ASAP Manual

The ASAP manual consists of 26 Microsoft Word® 97 files named *asap_01.doc*, *asap_02.doc*, *asap_03.doc … asap_26.doc*. These 26 files were used to create a single PDF file containing the entire ASAP manual, which is available through the **Help** menu in the ASAP software. Note that low print quality is observed when printing the PDF version of this manual for the screen captures that comprise many of the figures. For this reason, the 26 word files are also installed with the software and should produce considerably higher print quality than the PDF version of the manual. The procedure for printing the 26 Word files is explained in the **Help** menu. However, the authors have observed formatting changes when printing these Word files on different computers. It is not unexpected that a user printing the 26 Word files may not achieve a printed version of the manual that agrees completely with the page numbering shown in the Table of Contents.

CenCITT will send licensed users of the software a printed copy of the manual for a fee. To request information about obtaining a printed copy of the manual, please contact:

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> 1400 Townsend Drive
> Houghton, Michigan 49931
> Phone: (906) 487-2777
> Email: dwhand@mtu.edu

Complete Table of Contents for ASAP Manual

Please note that the equation numbering, table numbering and figure numbering are not continuous throughout the entire ASAP manual, but rather restart at the number 1 in each word file. This appendix presents a complete table of contents, divided up according to each word file, and including a list of figures and tables for each word file.

List of Tables in asap_02.doc

List of Figures in asap_02.doc

File Name = asap_03.doc

List of Tables in asap_03.doc

List of Figures in asap_03.doc

File Name = asap_04.doc

File Name = asap_05.doc

List of Tables in asap_04.doc

List of Figures in asap_04.doc

File Name = asap_06.doc

List of Tables in asap_06.doc

List of Figures in asap_06.doc

List of Tables in asap_08.doc

List of Figures in asap_08.doc

File Name = asap_09.doc

List of Tables in asap_09.doc

List of Figures in asap_09.doc

File Name = asap_10.doc

File Name = asap_11.doc

List of Figures in asap_11.doc

File Name = asap_12.doc

List of Figures in asap_12.doc

File Name = asap_13.doc

File Name = asap_14.doc

File Name = asap_15.doc

File Name = asap_16.doc

File Name = asap_17.doc

File Name = asap_18.doc

File Name = asap_21.doc

List of Figures in asap_21.doc

File Name = asap_22.doc

File Name = asap_23.doc

List of Figures in asap_23.doc

File Name = asap_24.doc

File Name = asap_25.doc

File Name = asap_26.doc