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Chapter 11

VOC Incinerators

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11.1 Introduction



What are volatile organic compounds (VOCs) ?

- ❑ Volatile organic compounds (VOCs) *are emitted as gases from liquids or solids that contain organic carbon* (carbon bonded to carbon, hydrogen, nitrogen, or sulfur, but not carbonate carbon as in CaCO_3 , nor carbide carbon as in CaC_2 , CO , or CO_2), *which vaporize at significant rates.*
- ❑ US EPA: Volatile organic compounds (VOCs) means any compound of carbon, excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides or carbonates and ammonium carbonate, which participates in atmospheric photochemical reactions, except those designated by EPA as having negligible photochemical reactivity

11.1 Introduction



The properties of VOCs?

- ❑ volatile organic compounds (VOCs) make up a major class of air pollutants. This class includes not only **pure hydrocarbons** but also **partially oxidized hydrocarbons** (organic acids, aldehydes, ketones), as well as organics containing chlorine, sulfur, nitrogen, or other atoms in the molecule.
- ❑ Within this class there are hundreds of individual compounds, each with its own properties and characteristics.
- ❑ These VOCs are emitted from **combustion processes**, from many types of **industrial operations**, and from **solvent evaporation**, among other sources.

11.1 Introduction



One method of pollution control that can be applied broadly to VOCs is incineration.

- ❑ Note that vapor incinerators (also called thermal oxidizers or afterburners) can sometimes be used successfully for air polluted with small particles of combustible solids or liquids.
- ❑ Incineration can be used for odor control, to destroy a toxic compound, or to reduce the quantity of photochemically reactive VOCs released to the atmosphere.

11.1 Introduction



- ❑ The VOC vapors might be in a concentrated stream (such as emergency relief gases in a petroleum refinery), or might be a dilute mixture in air (such as from a paint-drying oven).
- ❑ For large volume, intermittent (but concentrated) VOC streams, elevated flares are usually used.
- ❑ In the case of a **dilute fume in air**, the two methods for incineration are **direct thermal oxidation and catalytic oxidation**.

11.1 Introduction



Aschematic diagram of an afterburner is presented in Figure 11.1.

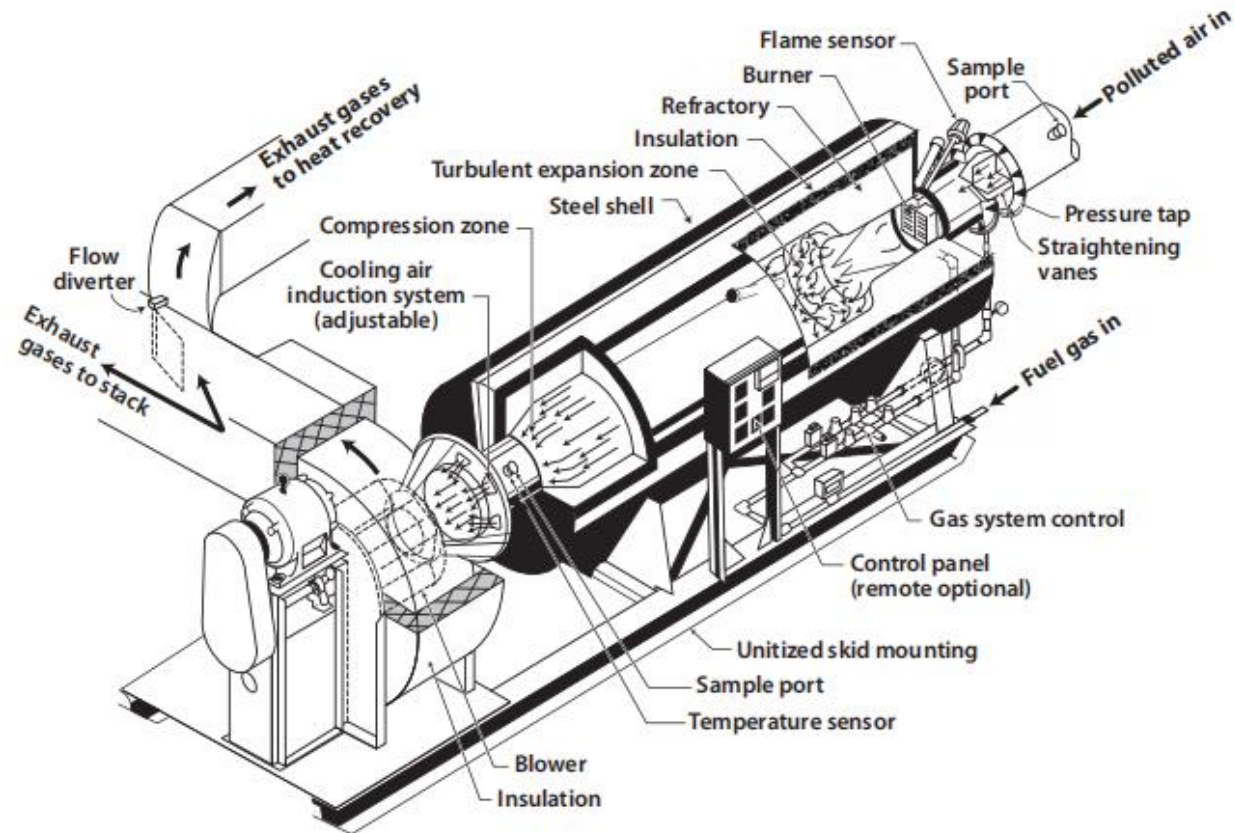


Figure 11.1
Sectional view of a direct-flame afterburner.
(Adapted from KTI Gas Processors, Inc., Santa Ana, CA.)

11.1 Introduction

- ❑ Quite often, there are several VOC sources within a manufacturing plant (such as printing presses or parts-painting stations), the emissions from which are gathered by several hoods and a common duct system and routed to a thermal oxidizer.
- ❑ It should be pointed out that the total reduction in VOC emissions from these sources depends not only on the **destruction efficiency** of the thermal oxidizer but also on the system's **capture efficiency**.
- ❑ **The capture efficiency** *is defined as the fraction of VOCs emitted from the processing point that is actually gathered by the side baffles, hoods or other capturing devices, and routed to the incinerator.*
- ❑ Emissions that are not captured are termed **fugitive emissions**.
- ❑ Under U.S. EPA (Environmental Protection Agency) rules, **the total VOC reduction efficiency is the product of the capture efficiency and the destruction efficiency.**

11.1 Introduction

■ Advantage of VOC Incinerators

- The main advantage of incineration is its potential for very **high efficiency**. If held for a sufficient length of time at a sufficiently high temperature, organics can be oxidized to any desired degree of completeness.

■ Disadvantage

- The main disadvantage of incineration is the **high fuel cost**.
- Also, some of the products of combustion of certain pollutants are **themselves pollutants**. For example, when a chlorinated hydrocarbon is burned, HCl or Cl₂ or both will be emitted. Depending on the amounts of these by-product pollutants, additional controls might be required.



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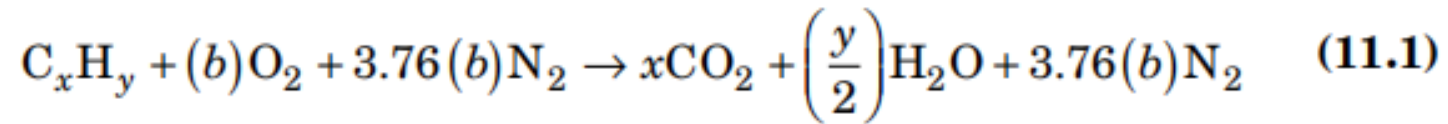


11.2 Theory



■ Oxidation Chemistry

For simplicity, consider only the case of a premixed dilute stream of a pure hydrocarbon (HC) in air. The stoichiometry of complete combustion in air is:



where

C_xH_y = the general formula for any hydrocarbon

$b = x + (y / 4)$, the stoichiometric number of
moles of oxygen required per mole of C_xH_y

3.76 = the number of moles of nitrogen present in air
for every mole of oxygen

11.2 Theory



- In Eq. (11.1), we have included the nitrogen as a reminder that when combustion occurs using air, much additional gas (the nitrogen) is always present.
- For simplicity, in future equations we will not include nitrogen explicitly.
- Note that the formation of nitrogen oxides is not accounted for in Eq. (11.1).
- Furthermore, if sulfur or chlorine (two common impurities) were present in the VOC, sulfur oxides or HCl gas, respectively, would be formed.

11.2 Theory



The Three Ts

- The importance of the three Ts of incineration—**temperature, time, and turbulence**—has been recognized for many years.
- In a mathematical sense, the three Ts are related to three characteristic times—**a chemical time, a residence time, and a mixing time**— given by the following equations:

where

τ_c, τ_r, τ_m = chemical, residence, and mixing times, respectively, s

$$\tau_c = 1 / k \quad (11.10)$$

$$\tau_r = V / Q = L / u \quad (11.11)$$

$$\tau_m = L^2 / D_e \quad (11.12)$$

V = volume of the reaction zone, m^3

Q = volumetric flow rate (at the temperature in the afterburner), m^3/s

L = length of the reaction zone, m

u = gas velocity in the afterburner, m/s

D_e = effective (turbulent) diffusion coefficient, m^2/s

11.2 Theory



Predicting VOC Kinetics

■ 1. Method of Ross

Ross (1977) summarized the older methods by suggesting that the design temperature be set “**several hundred degrees (°F) above the VOC autoignition temperature.**” *The autoignition temperature is the temperature at which combustible mixtures of the VOC in air will ignite without an external source (that is, without spark or flame).*

■ 2. Method of Lee et al.

Lee and coworkers, in two studies (Lee, Hansen, and Macauley 1979; Lee, Morgan, Hansen, and Whipple 1982), conducted experiments on several VOCs and proposed a **purely statistical model** to predict the temperatures required to give various levels of destruction in an isothermal plug flow afterburner.

11.2 Theory



- Model of Lee et al. depends on a number of properties of the VOC, the most important of which are the **autoignition temperature, the residence time, and the ratio of hydrogen to carbon atoms** in the molecule. Two of their equations are as follows:

$$\begin{aligned} T_{99.9} = & 594 - 12.2W_1 + 117.0W_2 + 71.6W_3 + 80.2W_4 \\ & + 0.592W_5 - 20.2W_6 - 420.3W_7 + 87.1W_8 \\ & - 66.8W_9 + 62.8W_{10} - 75.3W_{11} \end{aligned} \quad (11.13)$$

$$\begin{aligned} T_{99} = & 577 - 10.0W_1 + 110.2W_2 + 67.1W_3 + 72.6W_4 \\ & + 0.586W_5 - 23.4W_6 - 430.9W_7 + 85.2W_8 \\ & - 82.2W_9 + 65.5W_{10} - 76.1W_{11} \end{aligned} \quad (11.14)$$

(empirical equation)

where

$T_{99.9}$ = temperature for 99.9% destruction efficiency, °F

T_{99} = temperature for 99% destruction efficiency, °F

W_1 = number of carbon atoms

W_2 = aromatic compound flag (0 = no, 1 = yes)

W_3 = C=C (double bond) flag—not counting the aromatic ring—
(0 = no, 1 = yes)

W_4 = number of nitrogen atoms

W_5 = autoignition temperature, °F

W_6 = number of oxygen atoms

W_7 = number of sulfur atoms

W_8 = hydrogen/carbon ratio

W_9 = allyl (2-propenyl) compound flag (0 = no, 1 = yes)

W_{10} = carbon-double-bond – chlorine interaction (0 = no, 1 = yes)

W_{11} = natural logarithm of residence time (sec)

11.2 Theory



■ 3. Method of Cooper et al.

Cooper, Alley, and Overcamp (1982) combined collision theory with empirical data and proposed a method for predicting an “effective” first-order rate constant k for hydrocarbon incineration over the range from 940 to 1140 K . Their method depends on the molecular weight and the type of the HC. Once k is found, the design temperature can be obtained. Recall that the rate constant k can be written as:

$$k = Ae^{-E/RT} \quad (11.15)$$

where

E = activation energy, cal/mol

A = pre-exponential factor, s^{-1}

R = ideal gas law constant, 1.987 cal/mol-K

T = absolute temperature, K

11.2 Theory



□ The **pre-exponential factor A** was given by

$$A = \frac{Z'Sy_{O_2}P}{R'} \quad (11.16)$$

where

Z' = collision rate factor

S = steric factor

y_{O_2} = mole fraction oxygen in the afterburner

P = absolute pressure, atm

R' = gas constant, 0.08206 L-atm/mol-K

The **collision rate factor Z'** can be estimated from Figure 11.5 for three classes of compounds. The pre-exponential factor A can then be calculated for an estimated mole fraction of oxygen in the afterburner.

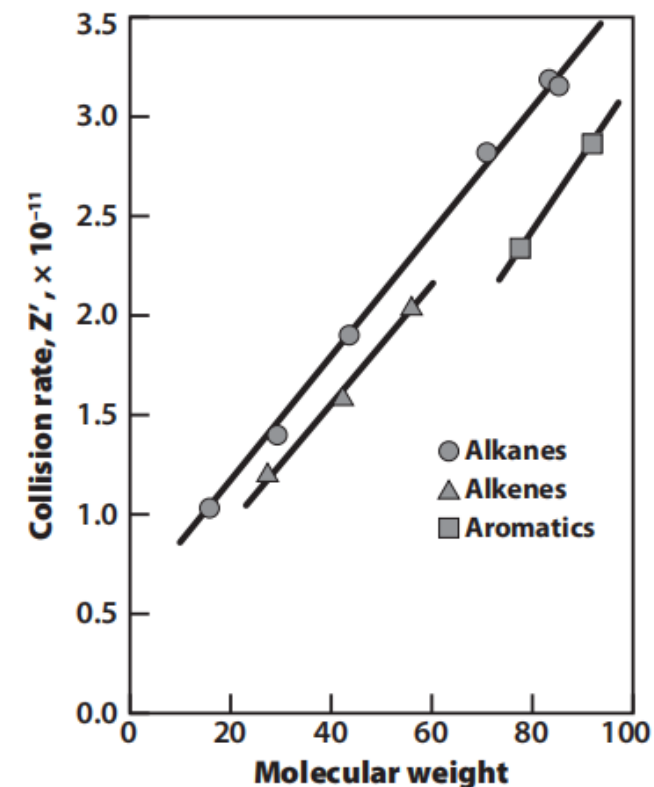


Figure 11.5
Collision rate factor for various hydrocarbons.

11.2 Theory



□ The **steric factor S** in Eq. (11.16) was calculated from

$$S = \frac{16}{MW} \quad (11.17)$$

where MW = molecular weight of the HC

□ The **activation energy E** (in kcal/mol) was correlated with molecular weight as shown in Figure 11.6, the equation for which is:

$$E = -0.00966(MW) + 46.1 \quad (11.18)$$

11.2 Theory



- Once A and E have been estimated, **kinetics k** can be calculated for any desired temperature. In an isothermal plug flow reactor (PFR), the HC destruction efficiency, the rate constant, and the residence time are interdependent, and are related as

$$\eta = 1 - \frac{[\text{HC}]_{\text{out}}}{[\text{HC}]_{\text{in}}} = 1 - e^{-k\tau_r} \quad (11.19)$$

where η = HC destruction efficiency

Thus, in addition to being useful for the ideal case of an **isothermal PFR**, the approach described in the preceding discussion can also be used in the design of a **nonisothermal afterburner**, which is more representative of actual conditions.

11.2 Theory



Example 11.1

Estimate the temperature required in an isothermal plug flow incinerator with a residence time of 0.5 sec to give 99.5% destruction of toluene. Use the three methods discussed in this section.

Solution

(a) autoignition temp + 300 °F = 1026 + 300 = 1326 °F

(b) Method of Lee et al.:

From Eqs. (11.13) and (11.14),

$$\begin{aligned} T_{99.9} &= 594 - 12.2(7) + 117 + 0 + 0 \\ &\quad + 0.592(1026) - 0 - 0 + 87.1(1.14) \\ &\quad - 0 + 0 - 75.3(\ln 0.5) \\ &= 1386 \text{ °F} \end{aligned}$$

$$\begin{aligned} T_{99} &= 577 - 10.0(7) + 110.2 + 0 + 0 \\ &\quad + 0.586(1026) - 0 - 0 + 85.2(1.14) \\ &\quad - 0 + 0 - 76.1(\ln 0.5) \\ &= 1369 \text{ °F} \end{aligned}$$

$T_{99.5}$ will be between T_{99} and $T_{99.9}$. Since this method is approximate, a linear average is satisfactory. Thus,

$$T_{99.5} = 1378 \text{ °F}$$

(c) Method of Cooper et al.

First, we rearrange Eq. (11.19) and calculate the required value of k .

$$k = \frac{-\ln(1 - 0.995)}{0.5} = 10.6 \text{ s}^{-1}$$

From Eq. (11.18), we calculate E as

$$E = -0.00966(92) + 46.1 = 45.2 \text{ kcal/mol}$$

We calculate S from Eq. (11.17), and estimate Z' from Figure 11.5. Thus,

$$S = \frac{16}{92} = 0.174$$

$$Z' = 2.85(10)^{11}$$

For an assumed oxygen mole fraction of 0.15 and a pressure of 1 atm, we calculate A from Eq. (11.16) as

$$A = \frac{2.85(10)^{11} (0.174)(0.15)(1.0)}{0.08205} = 9.07(10)^{10} \text{ s}^{-1}$$

Finally, we rearrange Eq. (11.15) to solve for T , knowing k , A , and E . Thus,

$$\begin{aligned} T &= \frac{-E}{R} \frac{1}{\ln(k/A)} \\ &= \frac{-45,200}{1.987} \frac{1}{\ln[10.6/9.07(10)^{10}]} \\ &= 995 \text{ K} = 1331 \text{ °F} \end{aligned}$$

11.2 Theory



Catalytic Oxidation

- ❑ A **catalyst** *is an element or a compound that speeds up a reaction without undergoing permanent change itself.*
- ❑ Typically, gaseous molecules diffuse to and adsorb onto the surface of the catalyst, which is where the reaction takes place. Product gases desorb and diffuse back into the bulk gas stream.
- ❑ The detailed mechanisms of the reaction are not known. Perhaps the catalyst weakens the internal VOC bond energies, or perhaps it alters the VOC molecular geometry.
- ❑ However, because the mechanism of the reaction is changed by the catalyst, the reaction proceeds **much faster and/or at much lower temperatures** with the use of a catalyst than with direct thermal incineration.



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11.3 Design Considerations

Thermal Oxidizers

- ❑ The process design of a VOC thermal oxidizer or afterburner involves **specifying a temperature** of operation along with a **desired residence time**, and then sizing the device to achieve the desired residence time and temperature with the **proper flow velocity**.
- ❑ Selection of the proper piece of equipment depends on such factors as **mode of operation** (continuous or intermittent), **oxygen content**, and **the concentration of the VOC** (Hemsath and Susey 1972).
- ❑ Proper selection and sizing are very important when trying to minimize the overall cost of the incineration option. Thus, it is desirable to keep the volume of the stream to be treated as low as possible. Effectively, this means trying not to dilute a VOC-in-air waste stream with too much air. However, most insurance regulations limit the maximum VOC concentration in such streams to 25% of the lower explosive limit (LEL) of the VOC.

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The minimum effective temperature in a thermal oxidizer is a function of the POHC that is the most difficult to destroy. Dellinger and others have developed for the U.S. EPA a ranking of gas-phase thermal stability of numerous POHCs. The ranking order is related to, but is not identical with, the order of the compounds' heats of combustion per unit mass (Taylor et al. 1990). Selection of the critical POHC in a mixed waste should be based on this ranking. A partial listing is given in Table 11.3.

Table 11.3 Thermal Stability Ranking for Selected POHCs

POHC	T_{99} , °F	ΔH_c , kcal/g
Benzene	1150	10.03
Naphthalene	1070	9.62
Chlorobenzene	990	6.60
Acrylonitrile	985	5.57
Chloromethane	950	3.25
Toluene	895	10.14
Trichloroethene	865	1.74
Pyridine	785	7.83
Ethyl Cyanide	770	4.57
Acetyl Chloride	765	2.77
Isobutyl Alcohol	715	7.62
1,1,2,2-Tetrachloroethane	690	1.39
Methyl Ethyl Ketone	650	8.07
Tetrachloromethane	645	0.24
Trichloromethane	625	0.75

Notes: Higher thermal stabilities indicated by higher temperatures for 99% destruction (T_{99} 's). All T_{99} 's reported in this table were experimentally determined. ΔH_c = heat of combustion.

Adapted from Taylor et al., 1990.

11.3 Design Considerations

Material and Energy Balances

The steady-state overall **material balance** reduces to

$$0 = \dot{M}_G + \dot{M}_{PA} + \dot{M}_{BA} - \dot{M}_E \quad (11.21)$$

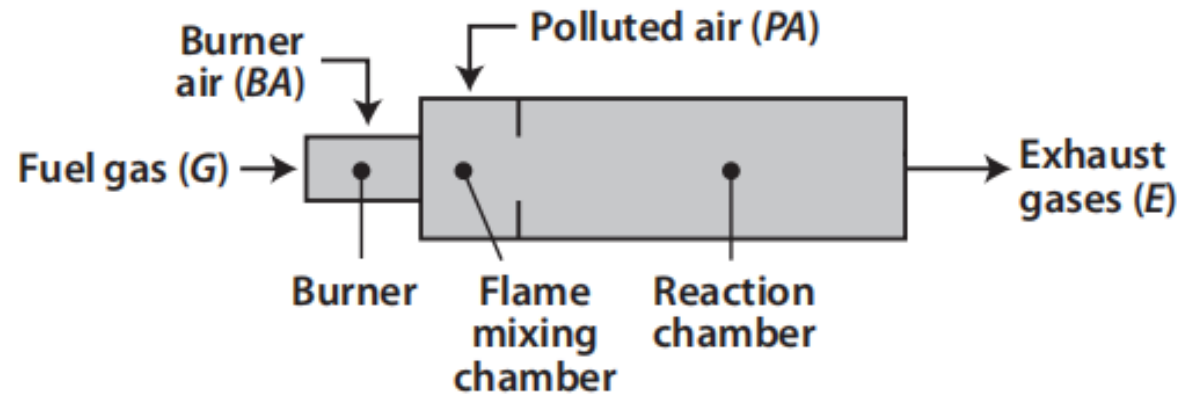


Figure 11.7
Schematic diagram of a vapor incinerator.

where \dot{M} denotes the mass flow rates (in kg/min or lb_m/min), and the subscripts refer to the streams identified in Figure 11.7. The

11.3 Design Considerations

Material and Energy Balances

The steady-state **enthalpy balance** (other forms of energy are insignificant) is as follows:

$$0 = \dot{M}_{PA} h_{PA} + \dot{M}_G h_G + \dot{M}_{BA} h_{BA} - \dot{M}_E h_E + \dot{M}_G (\Delta H_c)_G \quad (11.22) \\ + \sum \dot{M}_{VOC_i} (\Delta H_c)_{VOC_i} X_i - q_L$$

where

h = specific enthalpy, kJ/kg or Btu/lb_m

ΔH_c = net heat of combustion (lower heating value), kJ/kg or Btu/lb_m

X_i = fractional conversion of VOC_{*i*}

q_L = rate of heat loss from the incinerator, kJ/min or Btu/min

11.3 Design Considerations

Material and Energy Balances

If we assume that the enthalpy functions of all streams are similar to those for **pure air**, the steady-state **enthalpy balance** (other forms of energy are insignificant) is as follows:

$$\begin{aligned} 0 = & \dot{M}_{PA} h_{T_{PA}} + \dot{M}_G h_{T_G} + \dot{M}_{BA} h_{T_{BA}} - \dot{M}_E h_{T_E} + \dot{M}_G \\ & \times (\Delta H_c)_G (1 - f_L) + \sum \dot{M}_{VOC_i} (\Delta H_c)_{VOC_i} X_i (1 - f_L) \end{aligned} \quad (11.23)$$

where

f_L = fractional heat loss

h_{T_i} = enthalpy of air at temperature T_i , kJ/kg or Btu/lb_m

ΔH_c = net heat of combustion (lower heating value), kJ/kg or Btu/lb_m

X_i = fractional conversion of VOC_{*i*}

q_L = rate of heat loss from the incinerator, kJ/min or Btu/min

11.3 Design Considerations

- Substituting enthalpy balance and solving for the **mass flow rate** of the fuel gas, we obtain

$$\dot{M}_G = \frac{\dot{M}_{PA} (h_{TE} - h_{TPA}) + \dot{M}_{BA} (h_{TE} - h_{TBA}) - \sum \dot{M}_{VOC_i} (\Delta H_c)_{VOC_i} X_i (1 - f_L)}{(\Delta H_c)_G (1 - f_L) - (h_{TE} - h_{TG})} \quad (11.24)$$

- All items on the right side of Eqs. (11.24) and (11.25) are known or can be found in tables or charts of data (see Appendix B), because the outlet temperature is set at the start of the design.

11.3 Design Considerations

Example 11.2

Calculate the mass flow rate of methane required for an afterburner to treat 2465 acfm of polluted air. The air enters at 200 °F, and the desired exhaust temperature is 1350 °F. It is estimated that the burner will bring in 200 scfm of outside air. The fuel gas enters at 80 °F, and the burner air enters at 80 °F. The lower heating value (LHV) of methane is 21,560 Btu/lbm. Assume 10% overall heat loss. Also, ignore any heat gained by the oxidation of the pollutants.

Solution

From Table B.2 in Appendix B, the densities of the inlet polluted air and burner air are 0.060 and 0.074 lb_m/ft³, respectively. Therefore,

$$\dot{M}_{PA} = 2465 \text{ acfm} \frac{0.060 \text{ lb}_m}{\text{acf}} = 148 \frac{\text{lb}_m}{\text{min}}$$
$$\dot{M}_{BA} = 200 \text{ scfm} (0.074) \frac{\text{lb}_m}{\text{scf}} = 14.8 \frac{\text{lb}_m}{\text{min}}$$

From Table B.7 in Appendix B, the enthalpies (all in Btu/lb_m) are as follows:

$$h_{TE} = 328 \quad h_{TBA} = 4.8 \quad h_{TPA} = 33.6 \quad h_{TG} = 4.8$$

Substituting these data into Eq. (11.24) and solving for \dot{M}_G , we obtain

$$\dot{M}_G = \frac{148(328 - 33.6) + 14.8(328 - 4.8)}{21,560(0.9) - (328 - 4.8)} = 2.53 \frac{\text{lb}_m}{\text{min}}$$

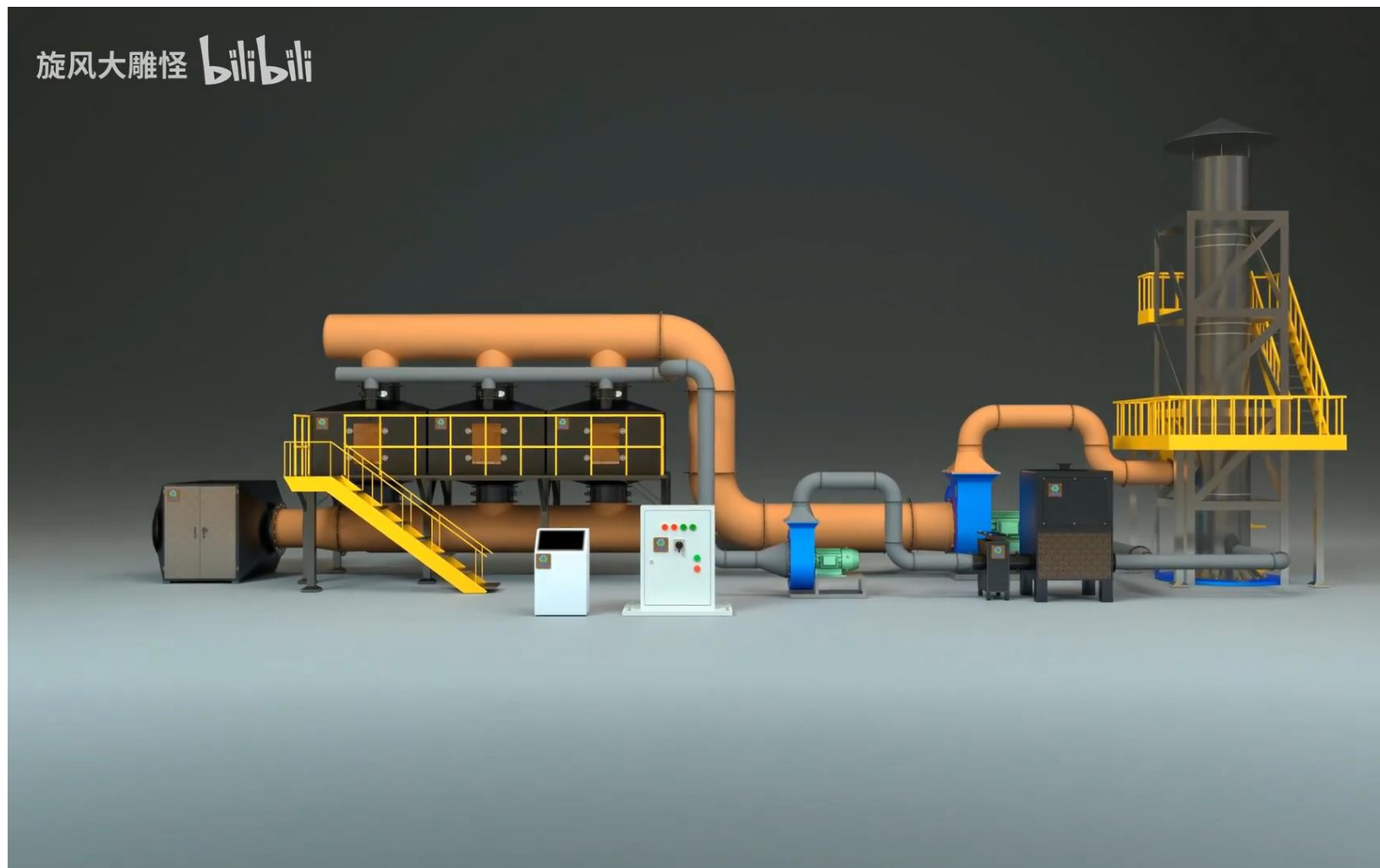
11.3 Design Considerations

Catalytic Oxidizers

- ❑ Catalytic oxidizers can **reduce the required temperature** by hundreds of degrees and can **save considerable amounts of space** for equipment as compared with thermal oxidizers.
- ❑ In most cases, the gases are heated by a small burner (as with a thermal oxidizer but to a much lower temperature). The gases are then passed directly through the catalyst bed, which is contained in the same unit as the burner.
- ❑ In air pollution control work, the catalyst is usually a **noble metal** (such as palladium or platinum, other metals are used, including Cr, Mn, Cu, Co, and Ni) deposited on an alumina support in a configuration to give minimum pressure drop.
- ❑ The pressure drop consideration is often critical for incinerator designs. A **honeycomb arrangement** (see Figure 11.10) typically results in a **lower pressure drop** (0.05–0.5 in. H₂O/inch of bed depth, whereas a packed bed of 1/8-inch diameter pellets results in pressure drops of 1.0–10 in. H₂O/inch of bed (Snape 1977)).

11.1 Introduction

Adsorption-catalytic oxidation device



11.3 Design Considerations

Catalyst

- ❑ In addition to exhibiting good reactivity and low pressure drop, the catalyst must be able to **resist attrition** (crumbling, breakage, or other mechanical wear), **withstand high temperature excursions, and last a reasonable length of time in service.**
- ❑ The overall rate of catalytic oxidation depends on **both the rate of mass transfer** (diffusion of the VOC to the surface of the catalyst) and the rate of the **chemical oxidation reactions** on the catalyst.
- ❑ **Catalyst activity** refers to the degree to which a chemical reaction rate is increased compared with the same reaction without the catalyst.
- ❑ Catalysts can also be very **selective** (more active for some compounds, less active for others)..

11.3 Design Considerations

Catalytic Oxidizers

- ❑ Catalytic incinerators require that the gas stream to be treated must be relatively **clean and free of PM**.
- ❑ Furthermore, it should not contain appreciable concentrations of any compounds that contain elements that can **poison the catalyst** (such as copper, nickel, lead, arsenic, zinc, chromium, silicon, sulfur, or phosphorus (Lewandowski 2000).)
- ❑ In addition to poisoning or plugging with PM, operating problems include **catalyst attrition** (the mechanical wearing of the surface), **thermal aging** (deactivation of surface sites by constant exposure to normal high temperatures), **thermal sintering** (destruction of catalytic sites by a sudden excursion of temperature well above normal), and **masking** (either by PM carried in with the gas or by soot particles that are formed on the surface during the oxidation of heavy hydrocarbons).
- ❑ Thus, all catalysts eventually must be **replaced** (usually every 3 to 5 years), even if the inlet gas is clean.

11.3 Design Considerations

Heat Recovery

- A very common method of recovering some of the energy in an incinerator's exhaust is by installing a **heat exchanger**. Heat exchangers that are used to preheat the incoming waste gas (as shown in Figure 11.12(a) (primary heat recovery)) are called **recuperators**.
- In recuperators, energy recoveries of 40–60% are common, and recoveries of 80% are often practical (Mueller 1977). When the hot exhaust gases are used to preheat the incoming VOC-in-air stream, the thermodynamic properties of the two streams are so similar that the energy recovery can be approximated by a simple equation, as follows:

$$\begin{aligned} E &= \frac{\Delta T_{\text{recovered}}}{\Delta T_{\text{available}}} \times 100 \\ &= \frac{T_2 - T_1}{T_3 - T_1} \times 100 \end{aligned} \quad (11.32)$$

where

E = percent heat recovery

T_1 = temperature of the VOC-in-air stream prior to preheat

T_2 = temperature of the stream after preheat but before incineration

T_3 = temperature of the hot afterburner exhaust

11.3 Design Considerations

Heat Recovery

- ❑ Preheating the waste gas results in direct savings by **reducing the fuel gas flow rate**.
- ❑ If there are other process needs for heat, more effective use of the hot exhaust is possible. For example, the exhaust gas can be routed to a waste heat boiler to **generate process steam, used to preheat a liquid process stream, or blended with fresh air to provide a hot air drying stream**. Figure 11.12 depicts these applications.

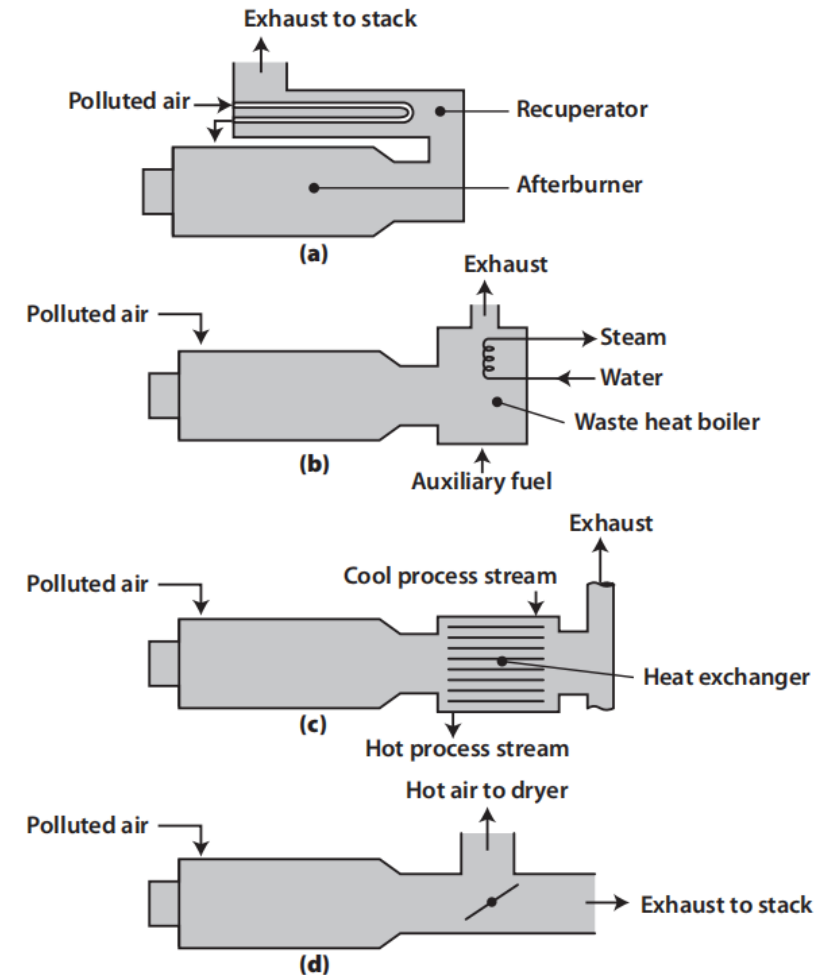


Figure 11.12
Various processing schemes for heat recovery from an afterburner.

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- ❑ In the past 30 years, an alternative to the traditional thermal oxidizer has evolved. Known as the **regenerative thermal oxidizer (RTO)**, this device can recover up to 97% (Lewandowski 2000) of the thermal energy of the final exhaust.
- ❑ RTO technology utilizes two chambers packed with (ceramic) heat transfer media. The two chambers are joined by an (insulated) duct with a small burner installed in it. The duct serves as the thermal oxidizer, and the burner is small, because so much of the heat is recovered, that very little additional fuel must be burned, to achieve the desired operating temperature.

11.3 Design Considerations



- Figure 11.13 shows the schematic flow diagram of an RTO and Figure 11.14 is a photograph of a small RTO.

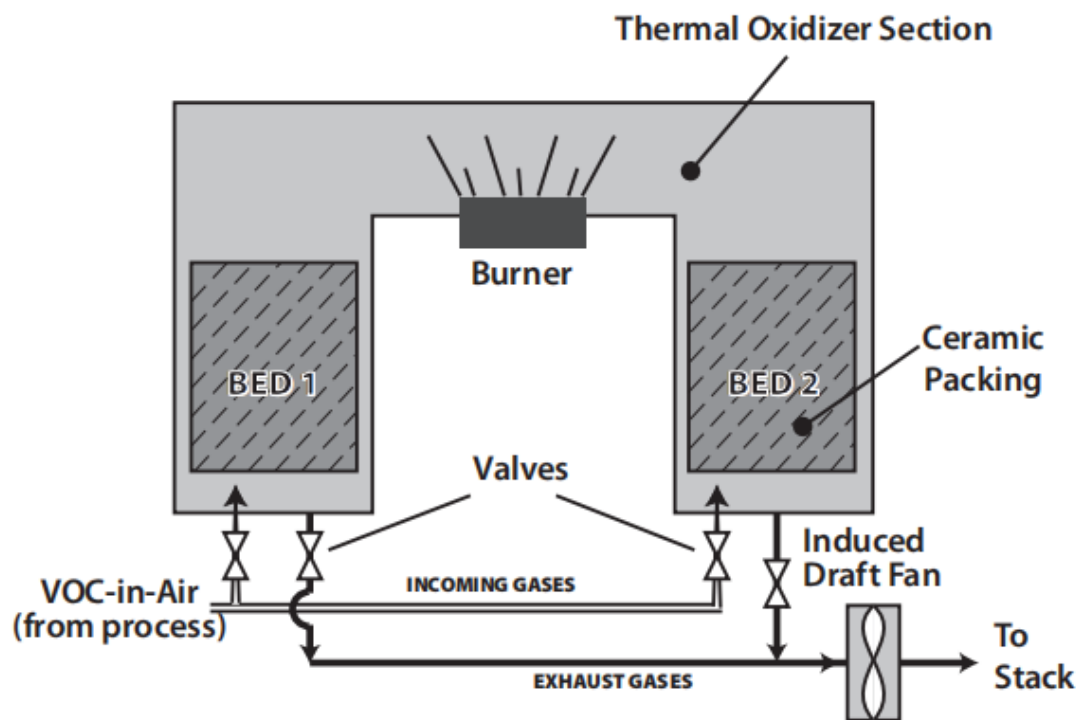


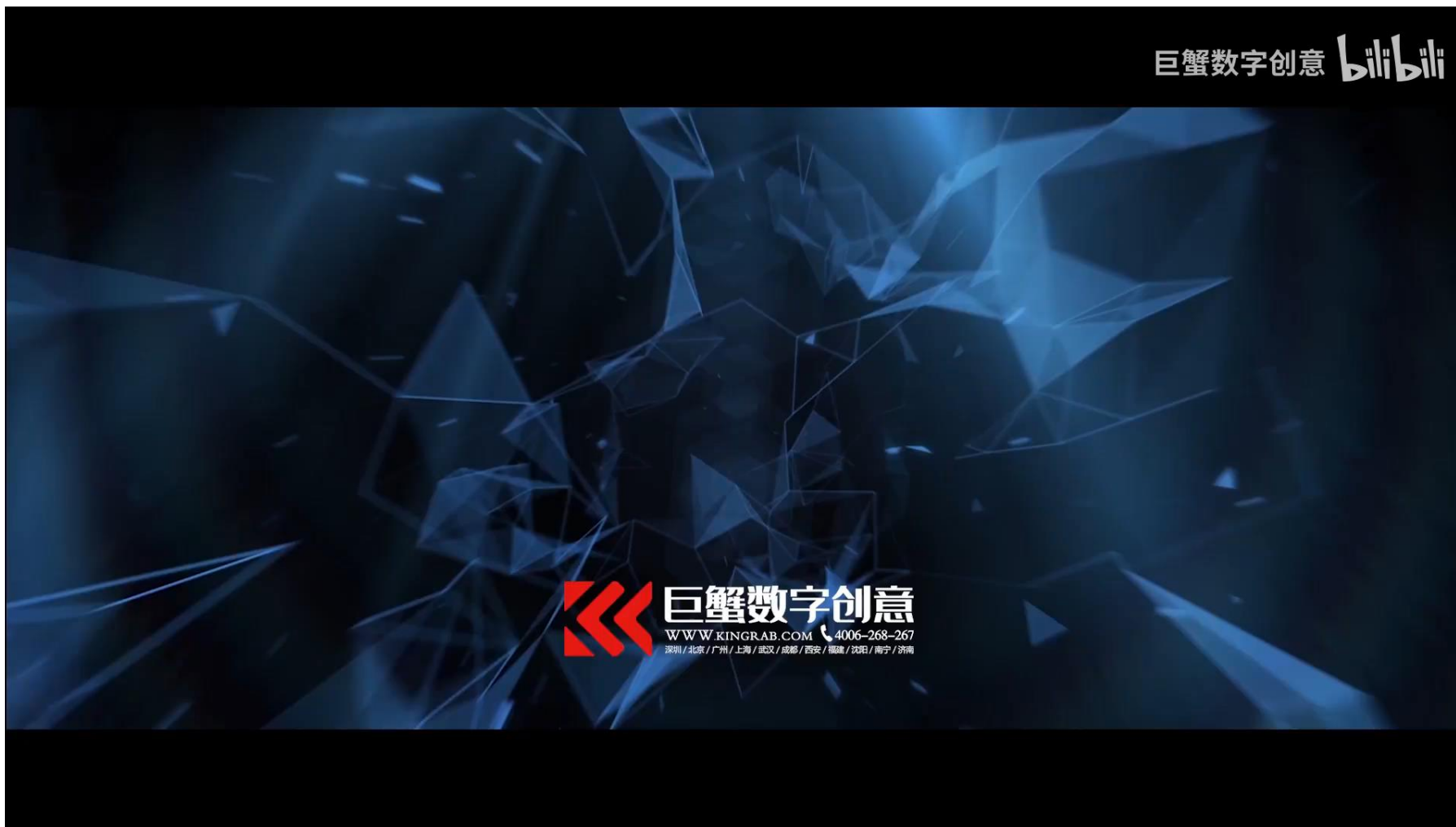
Figure 11.13
Schematic flow diagram of a regenerative thermal oxidizer (RTO).

- The flow through the packed beds is alternated as follows. First, the polluted air comes in through Bed 1, which is hot. As the cool air flows through the hot bed, the air becomes heated and the bed cools off.
- Meanwhile, the hot exhaust gases are flowing out through Bed 2, which is cool. Again the gases exchange heat with the (ceramic) media, this time heating the media and cooling the gases.
- After a period of time, when Bed 1 has become cool and Bed 2 hot, the valves are switched and the direction of flow is reversed. The cycle repeats itself.

11.3 Design Considerations



RTO



11.3 Design Considerations

- ❑ RTOs are capable of 80–97% heat recovery.
- ❑ Both random packing (e.g., ceramic saddles) and structured (monolith) packing have been used, but the structured packing is favored, due to lower pressure drop and less breakage.
- ❑ As reported by Lewandowski (2000), a new type of packing—**multi-layer media** (MLM)—was introduced to the market (in the late 1990s). This structured packing has a higher density than monolith structured packing and gives more heat recovery with less volume of packing.
- ❑ However, its pressure drop is about 50% higher (though still well below that of random packing) at the same gas flow rate (Lewandowski 2000).



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11.4 Costs



- ❑ The (capital) costs for vapor incinerators can be **very high** because of the high temperatures they must be able to withstand.
- ❑ However, the major contributor to annual operating cost is the **fuel cost**. Heat recovery can reduce the net fuel cost considerably;
- ❑ However, in most cases, even with good heat recovery and integration into an existing process plant, incinerators will represent a net cost, addition to the annual cost, of operating the plant.

□ Estimate the temperature required in an isothermal plug flow incinerator with a residence time of 0.5 sec to give 99.5% destruction of benzene (C_6H_6). Use the three methods discussed in this section. $Z' = 2.35 \times 10^{11}$

□ Solution

(a) autoignition temp + 300 °F = 1075 + 300 = 1375 °F

(b) Method of Lee et al.:

From Eqs. (11.13) and (11.14),

$$T_{99.9} = 594 - 12.2(6) + 117 + 0 + 0 + 0.592(1075) - 0 - 0 + 87.1(1) - 0 + 0 - 75.3(\ln 0.5) = 1413 \text{ °F}$$

$$T_{99} = 577 - 10.0(6) + 110.2 + 0 + 0 + 0.586(1075) - 0 - 0 + 85.2(1) - 0 + 0 - 76.1(\ln 0.5) = 1395 \text{ °F}$$

T_{99.5} will be between T₉₉ and T_{99.9}. Since this method is approximate, a linear average is satisfactory. Thus,

$$T_{99.5} = 1404 \text{ °F}$$

□ Solution

(c) Method of Cooper et al.

First, we rearrange Eq. (11.19) and calculate the required value of k.

$$k = \frac{-\ln(1 - 0.995)}{0.5} = 10.6 \text{ s}^{-1}$$

From Eq. (11.18), we calculate E as

$$E = -0.00966(78) + 46.1 = 45.3 \text{ kcal/mol}$$

We calculate S from Eq. (11.17), and estimate Z' from Figure 11.5.

$$\text{Thus, } S = 16/78 = 0.205, Z' = 2.35 \times 10^{11}$$

□ Solution

(c) Method of Cooper et al.

For an assumed oxygen mole fraction of 0.15 and a pressure of 1atm, we calculate A from Eq. (11.16) as

$$A = \frac{2.35(10)^{11}(0.205)(0.15)(1)}{0.08205} = 8.81(10)^{10} \text{ S}^{-1}$$

Finally, we rearrange Eq. (11.15) to solve for T, knowing k, A, and E.

Thus,

$$T = \frac{-E}{R} \frac{1}{\ln(k/A)} = \frac{-45300}{1.987} \frac{1}{\ln(10.6/8.81(10)^{10})} = 998 \text{ K}$$

$$F = 32 + 1.8 \times (k - 273.15) = 1337 \text{ }^{\circ}\text{F}$$

After-school assignment



- ❑ Q1: What are physical adsorption and chemistry? What's the difference?
- ❑ Q2: What is the reaction rate constant ? What formula can be used to calculate the reaction rate constant ? What do the parameters in the formula represent ?
- ❑ Q3: Solve Problems 11.4 and 11.5 on page 379.