



LOADING AND FLOODING

CHARACTERISTICS OF A PACKED

COLUMN

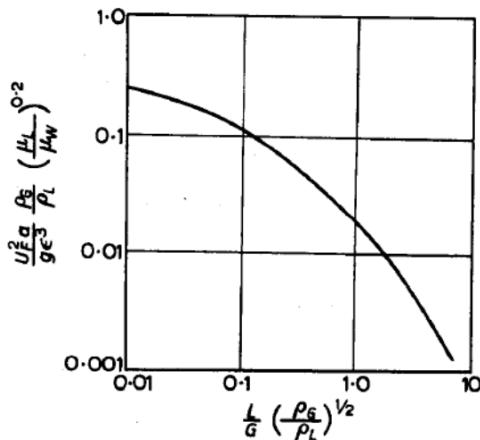
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Objective:

- To determine the loading and flooding velocities for the air-water system in a packed tower
- To plot $\log(\Delta P/L)$ vs $\log(G)$ where $(\Delta P/L)$ is the pressure gradient and G is the mass velocity of air
- To compare the experimental values of the flooding velocity with those obtained from Sherwood plot

Theory:

- Packed towers are used in vertical columns for continuous contact of liquid and gas. While trickling down through the packed bed, the liquid exposes a large surface area for contact with the gas. The pressure drop experienced by the gas in a randomly packed column is determined by the gas and liquid flow rates. The state can change from gas-continuous-liquid-dispersed to liquid continuous-gas-dispersed depending on the gas and liquid hold-up.
- Packed towers are used for continuous counter-current and co-current contact of liquid and gas. The towers are vertical columns filled with packings that provide a large interfacial area. For a constant liquid flow, at low to moderate gas velocity G ; the pressure drop characteristics is similar to that of dry packings. As the gas velocity is increased further, the pressure difference increases. When a certain point is reached, the quantity of liquid retained in the packed bed increases significantly.
- This is known as the loading point, as the liquid starts to accumulate (load) in the packings. From this point, there is a greater amount of liquid hold-up, and the column is slowly "drowned" in the liquid. At this point, the entire column is filled with liquid and the gas now has to bubble through the liquid in the packing voids. This is known as the flooding point and the gas velocity at this point is known as the flooding velocity (limiting velocity).
- Since it is difficult to identify the flooding and loading velocity visually, a conventional approach is to obtain the same from a log-log plot of $(\Delta P/L)$ vs G . Flooding is detected by an abrupt change in the nature of the curve. For random packings, Sherwood made a plot that can be used for theoretical estimation of the flooding velocity



In this correlation a log-log scale is used and the group $\frac{U_F^2 a}{g \epsilon^3} \frac{\rho_G}{\rho_L} \left(\frac{\mu_L}{\mu_W} \right)^{0.2}$ or $\frac{G_F^2 a}{g \epsilon^3 \rho_L \rho_G} \left(\frac{\mu_L}{\mu_W} \right)^{0.2}$ is plotted against $\frac{L}{G} \left(\frac{\rho_G}{\rho_L} \right)^{\frac{1}{2}}$, where

U_F = flooding velocity of the gas phase based on total column cross-section,

G_F = flooding rate expressed as mass flow of the gas phase per unit area of column,

a = surface area of packing per unit volume of column,

g = acceleration due to gravity,

ϵ = void fraction of the packing,

ρ_L = density of the liquid,

ρ_G = density of the gas,

μ_L = viscosity of the liquid,

μ_W = viscosity of water at 20°C (approx. 1 centipoise),

G = mass rate of flow of the gas phase,

L = mass rate of flow of the liquid phase.

Experimental Details:

EXPERIMENTAL SETUP



The set-up essentially consists of a Perspex column filled with Raschig rings (ID 1.25 cm), a compressor, centrifugal pump, an orifice meter for measuring gas flow rate, a rotameter for water flow rate and a manometer for pressure drop across the column.

Procedure

- Initially, the column is run in dry mode with only gas flow, and the pressure drop is measured for each airflow rate setting.
- The water flow rate in the packed tower is then started and held constant at a specific value while the air velocity is gradually increased until flooding occurs.
- This process is repeated for four different water flow rates, and flooding velocity is computed as a function of fluid flow rates.
- The loading and flooding points for each liquid flow rate should be calculated from the plot of $\log(P/L)$ vs $\log(G)$.
- Flooding velocities for various liquid flow r

Experimental Data and Observation Table

Liquid Flow Rate(LPH) = 0

Δh for calculating packed bed Pressure	Δh for calculating gas velocity	$\Delta P_{\text{orifice}}$	$\Delta P_{\text{packed bed}}$	G (mass velocity of air)	$\log(G)$	$\log(\Delta P_{\text{packed bed}} / L)$
67	14.5	1043.994	2259.39	32.38456701	1.510338095	3.891593204
73	15	1137.486	2337.3	33.80353536	1.528962124	3.906316461
81	15.4	1262.142	2399.628	35.60764102	1.551543203	3.917745923
85	15.5	1324.47	2415.21	36.47624771	1.562010156	3.9205569
95	16.4	1480.29	2555.448	38.56226157	1.586162496	3.94506905

Liquid Flow Rate(LPH) = 20

Δh for calculating packed bed Pressure	Δh for calculating gas velocity	$\Delta P_{\text{orifice}}$	$\Delta P_{\text{packed bed}}$	G (mass velocity of air)	$\log(G)$	$\log(\Delta P_{\text{packed bed}} / L)$
35	15	545.37	2337.3	23.40640502	1.369334716	3.906316461
38	15.5	592.116	2415.21	24.38891566	1.387192492	3.9205569
40	16	623.28	2493.12	25.02249949	1.398330689	3.934345185
44	16.5	685.608	2571.03	26.24381887	1.419027032	3.947709146
49	17.5	763.518	2726.85	27.6948319	1.442398734	3.973263251

Liquid Flow Rate(LPH) = 35

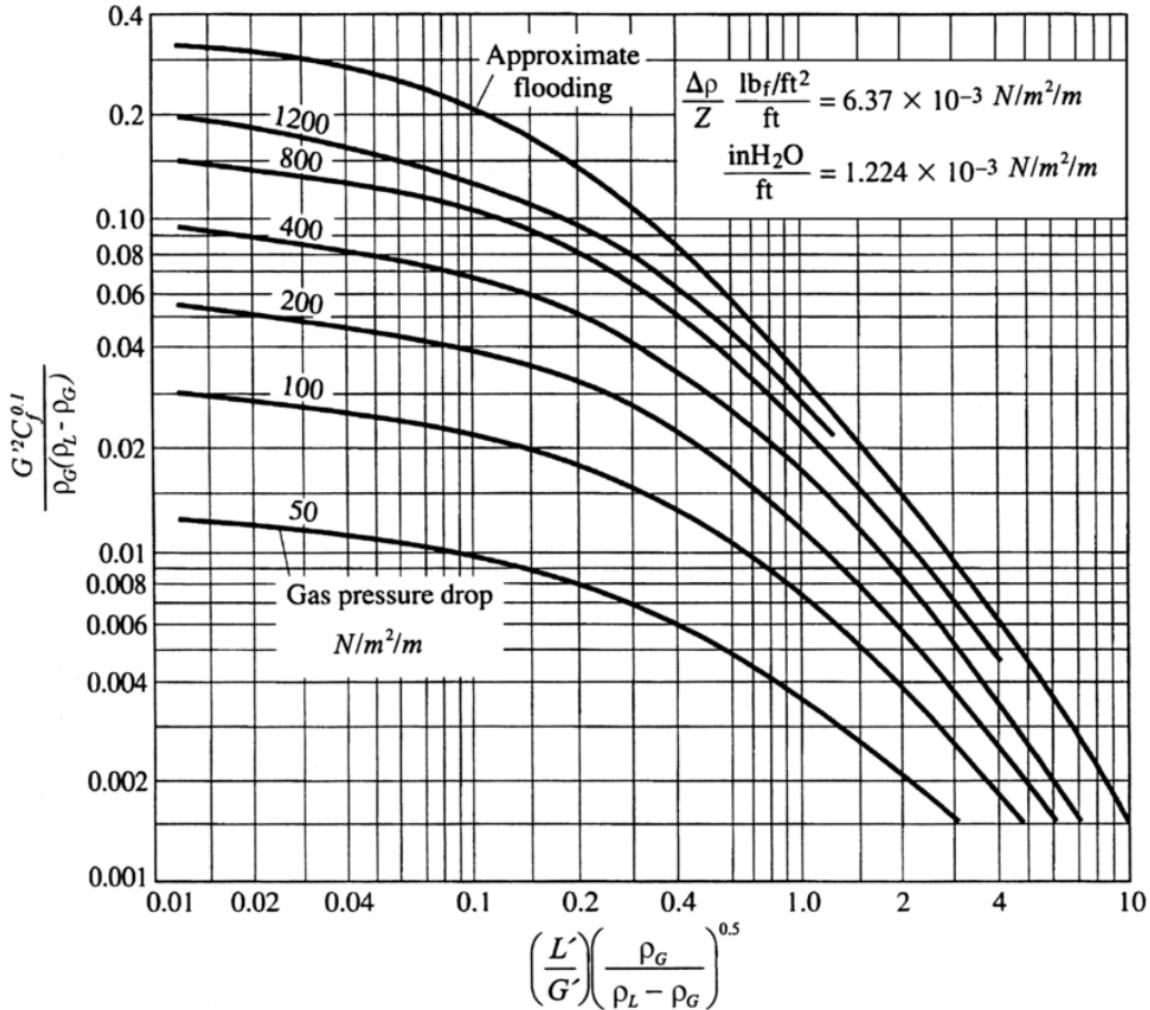
Δh for calculating packed bed Pressure	Δh for calculating gas velocity	$\Delta P_{\text{orifice}}$	$\Delta P_{\text{packed bed}}$	G (mass velocity of air)	$\log(G)$	$\log(\Delta P_{\text{packed bed}} / L)$
25	16	389.55	2337.3	19.78202279	1.296270698	3.906316461
28	16.6	436.296	2415.21	20.93532509	1.320879709	3.9205569
35	17	545.37	2493.12	23.40640502	1.369334716	3.934345185
38	18	592.116	2571.03	24.38891566	1.387192492	3.947709146
43	19.5	670.026	2726.85	25.94387966	1.414034921	3.973263251

Liquid Flow Rate(LPH) = 50

Δh for calculating packed bed Pressure	Δh for calculating gas velocity	$\Delta P_{\text{orifice}}$	$\Delta P_{\text{packed bed}}$	G (mass velocity of air)	$\log(G)$	$\log(\Delta P_{\text{packed bed}} / L)$
15	19	233.73	2493.12	15.32308896	1.185346323	3.934345185
20	19.2	311.64	2586.612	17.69357907	1.247815691	3.95033329
23	19.5	358.386	2648.94	18.9742497	1.278164611	3.960674123
25	21.5	389.55	2804.76	19.78202279	1.296270698	3.985497707
28	24	436.296	3038.49	20.93532509	1.320879709	4.020259813

Liquid Flow Rate(LPH) = 65

Δh for calculating packed bed Pressure	Δh for calculating gas velocity	$\Delta P_{\text{orifice}}$	$\Delta P_{\text{packed bed}}$	G (mass velocity of air)	$\log(G)$	$\log(\Delta P_{\text{packed bed}} / L)$
10	19.5	155.82	2960.58	12.51124975	1.097300693	4.008978803
14	20.7	218.148	2991.744	14.80351034	1.170364711	4.013526431
15	22.6	233.73	3038.49	15.32308896	1.185346323	4.020259813
18	23.5	280.476	3350.13	16.78560295	1.224936946	4.062663662
20	25.5	311.64	3739.68	17.69357907	1.247815691	4.110436444



Sherwood Correlation plot on Flooding Capacity

We use the following Sherwood correlation to get the theoretical flooding capacity

Sherwood et al. ²	$\log(Y) = -0.2866 \log^2(X) - 1.0997 \log(X) - 1.6784 *$ $X = \frac{U_L}{U_{G,fl}} \sqrt{\frac{\rho_L}{\rho_G}} \quad Y = \frac{U_{G,fl}^2}{g} \left(\frac{\rho_G}{\rho_L} \right) \left(\frac{a_T}{\varepsilon^3} \right) \mu_L^{0.2}$	$0.01 \leq X \leq 200$ $\mu_L [cp]$
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Using the following data, we observe the median flooding velocity of the packed column for a water-air system (according to the experimental setup conditions) to be close to the experimentally obtained values at different liquid flow rates

packing & bed properties	nominal diameter, d_N (mm)	15.0
	bed porosity, ϵ (%)	72.5
	bed-specific surface area, a_T (m^{-1})	303
	tower diameter, D_C (m)	0.16
	bed height, Z (m)	1.22
liquid properties	density, ρ_L (kg/m^3)	997.1
	viscosity, μ_L ($Pa\ s$)	1.07×10^{-3}
	surface tension, σ_L (N/m)	7.30×10^{-2}
	superficial velocity, U_L (mm/s)	6.600
gas properties	density, ρ_G (kg/m^3)	1.190
	viscosity, μ_G ($Pa\ s$)	1.75×10^{-5}
	superficial velocity, $U_{G,FL}$ (m/s)	0.503

Sample Calculation

Density of manometric liquid (ρ_l) = 1590 kg/m³

Density of gas (ρ_g) = 1.225 kg/m³

Length of packed bed = 0.29 m

For first reading of dry run:

$$G = \frac{C_o}{\sqrt{1-\beta^4}} \sqrt{2 \Delta P \rho_{air}} \text{ where } \Delta P = \rho_l g \Delta h \text{ (orifice)}$$

$$C_0 = 0.62, \beta = 0.5$$

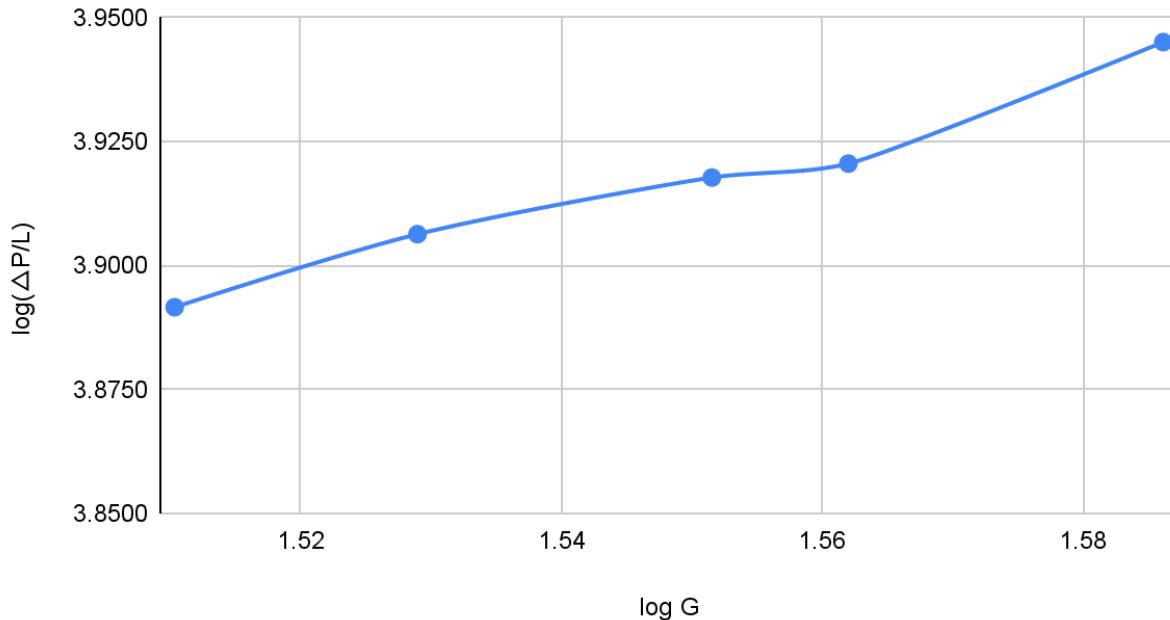
$$G = \frac{0.62}{\sqrt{1-0.5^4}} \sqrt{2 \times 1590 \times 9.8 \times 0.067 \times 1.225} = 32.38 \text{ kg/m}^2 \text{ s}$$

Pressure drop across the bed, $\Delta P = \rho_l g \Delta h$ (bed) = $1590 \times 9.8 \times 0.145 = 2259.4 \text{ N/m}^2$

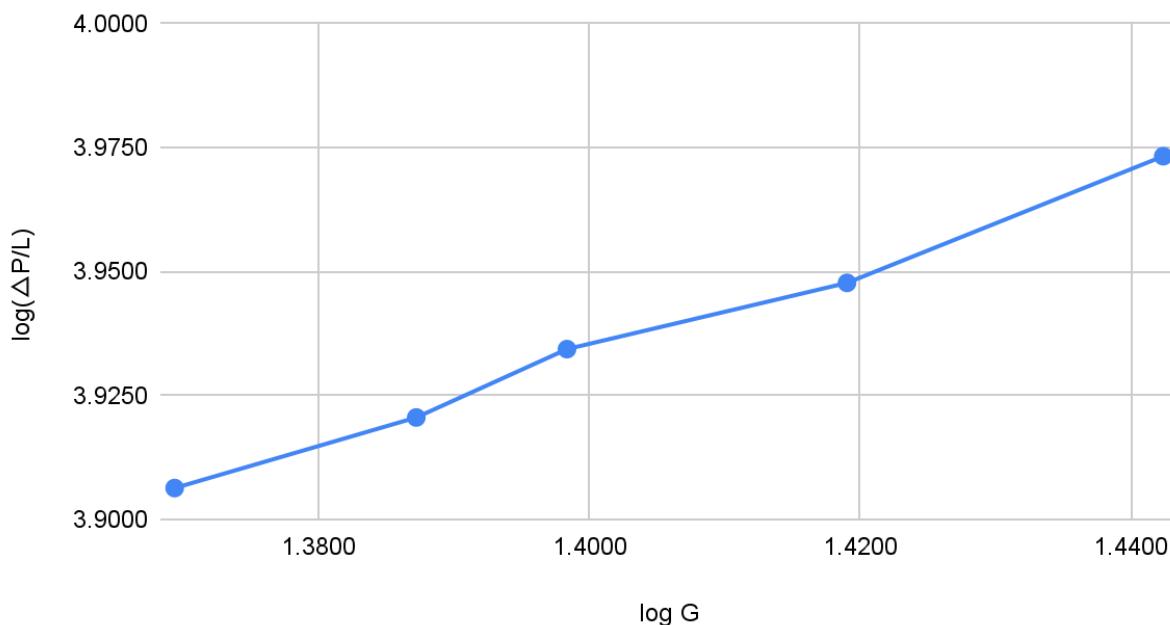
$$\Delta P/L = 2259.4/0.29 = 7791 \text{ N/m}^3$$

Graphs:

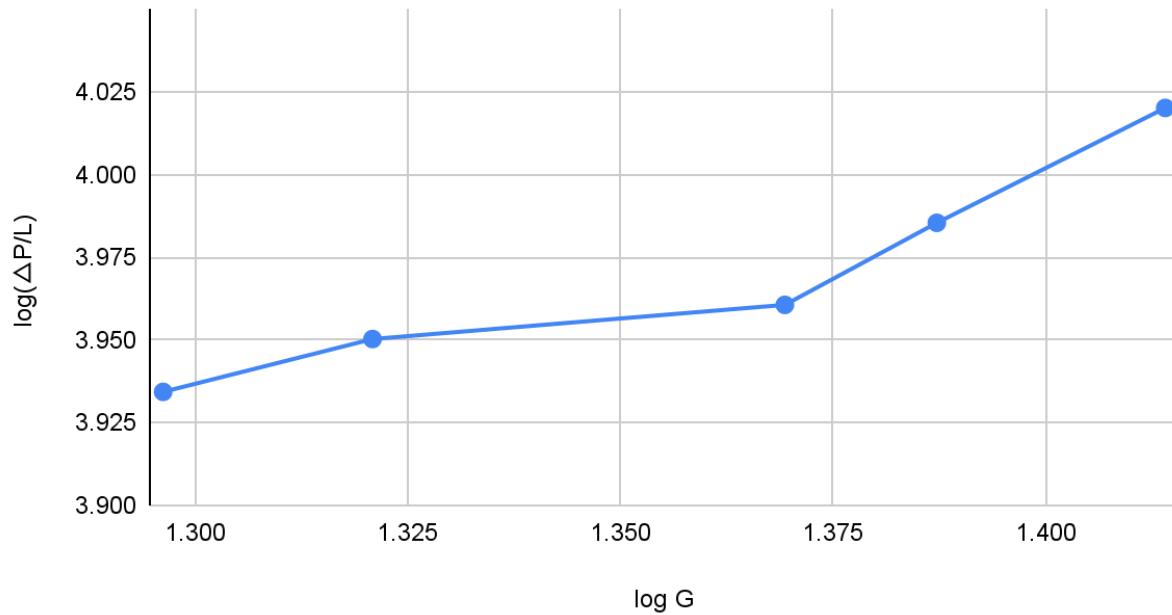
log($\Delta P/L$) vs. log G for dry run



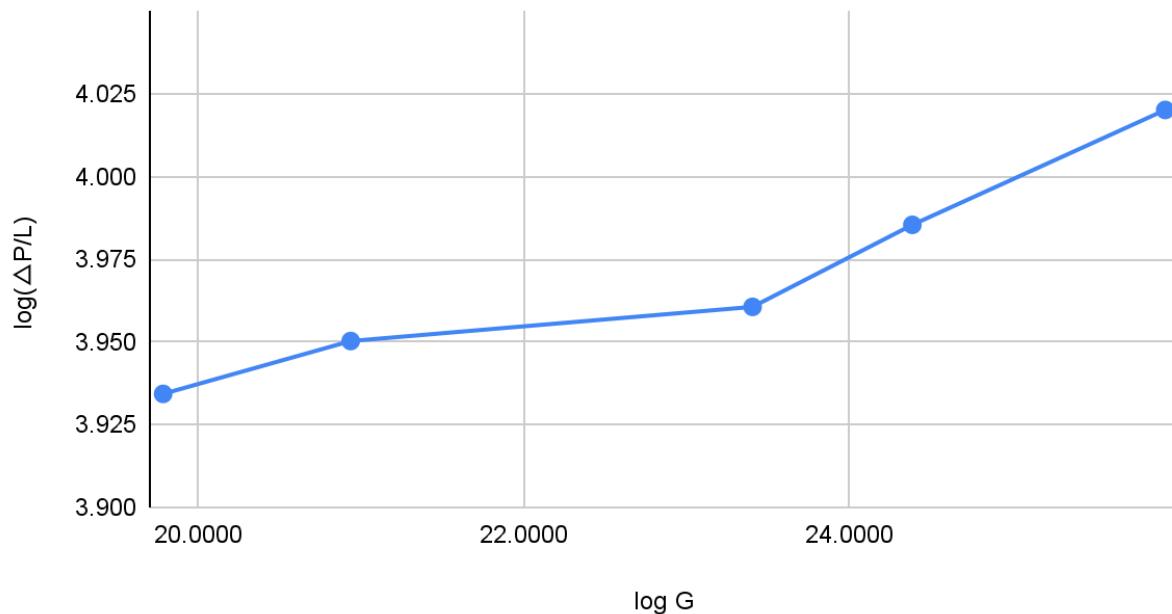
log($\Delta P/L$) vs. log G for 20 cm³/s



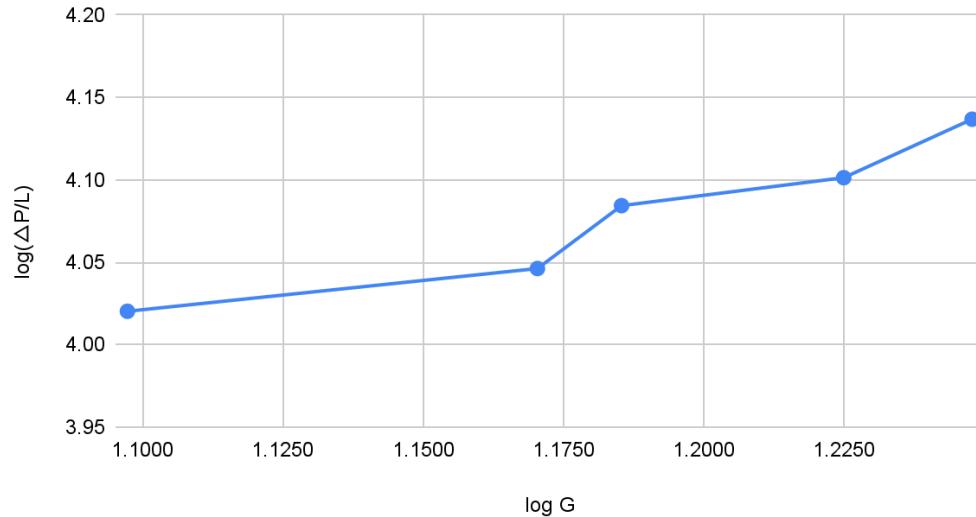
$\log(\Delta P/L)$ vs. $\log G$ for $35 \text{ cm}^3/\text{s}$



$\log(\Delta P/L)$ vs. $\log G$ for $50 \text{ cm}^3/\text{s}$



$\log(\Delta P/L)$ vs. $\log G$ for 65 cm³/s



Results:

Flow rate (cm ³ /s)	Loading Velocity (m/s)	Flooding velocity (m/s)
20	20.43	21.42
35	17.09	19.11
50	17.09	19.11
65	12.08	13.70

DISCUSSIONS

- Up to a certain point, there is an orderly trickling of the liquid down the packings. There is no observable liquid being trapped among the packings (no liquid hold-up).
- As the gas velocity is increased further, the pressure difference increases. There is a change in slope of the line at this point as pressure drop increases more rapidly with G. This is known as the loading point.
- From this point, there is a sharp increase in pressure drop at higher G, and the column is slowly "drowned" in the liquid.
- Then there is another sharp change in the slope. The gas pressure drop at the point is very high. This is known as the flooding point and the gas velocity at this point is known as the flooding velocity (limiting velocity).

CONCLUSION

RELEVANT POINTS

- We observe that for a packed bed column:
 - at a constant liquid rate, the gas pressure difference increases with gas velocity.
 - at constant gas velocity, the gas pressure drop is higher at a larger liquid rate.
 - each liquid rate has its own loading and flooding points.
 - at a higher liquid rate, the loading and flooding points occur at lower gas pressure drops.
- Operation of a gas absorption column is not practical above the loading point. For optimum design, the recommended gas velocity is half of the flooding velocity. Alternatively, some designs can be based on a specified pressure drop condition, usually well below the pressure drop at which flooding would occur.
- The theoretical Sherwood correlation and the experimental log graph are quite in similar nature which further solidify its practical viability

PRECAUTIONS

- The flowmeter must be installed vertically, the fluid flows through the flowmeter from bottom to top, and the perpendicular $< 2^\circ$.
- Do not apply pressure higher than the rated withstand pressure. Applying a pressure higher than this may cause damage.
- Pressure drop should not be invariably high and the gas flow rate should be increased gradually in order to avoid damage of the packing column/material.

SOURCES OF ERROR

- Parallax error should be avoided in taking U-tube manometer readings and the rotameter height difference which may result in error in the calculations.
- The gas velocity should be increased gradually to obtain a clear visual demarcation for the flooding and loading points in the packed column to avoid human error.



LOADING AND FLOODING CHARACTERISTICS OF A PACKED COLUMN

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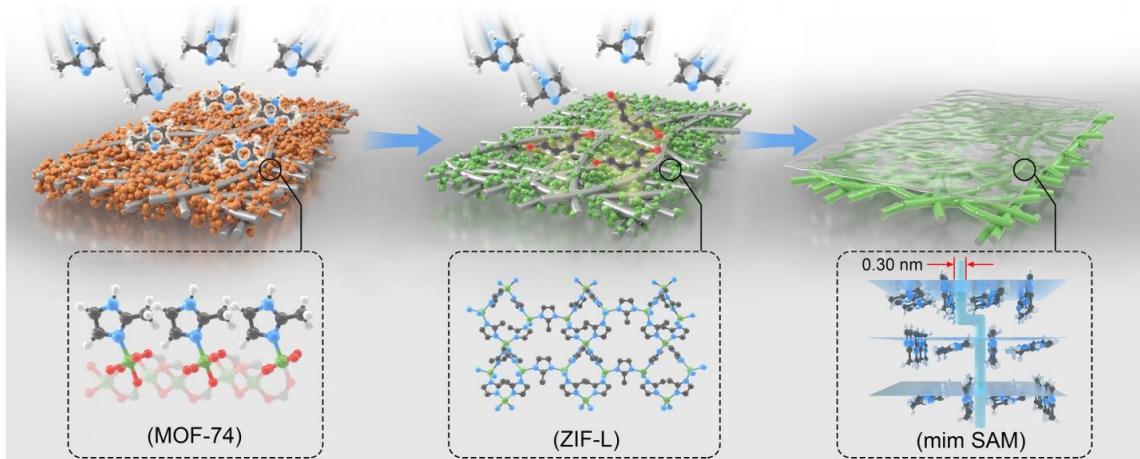
Objective:

- To study the flow circuit of the adsorption column.
- To determine the performance of the adsorption column for adsorption of carbon dioxide

from a mixture of air and carbon dioxide

Theory:

The components of a gaseous (or liquid) solution when contacted to certain solids, preferentially specific components get concentrated onto the solid surface. This method of separation is useful in the dehumidification of gases, removal of odour and impurities, and recovery of valuable solvent vapours from gas streams. The rigidity and immobility of a bed of solid make possible the operation under semi-continuous mode. In adsorption operation, a solute from a solution is preferentially adsorbed on the surface of a solid (adsorbent). Molecular sieves are such solids that can entrap adsorbed matter in the “cages” of the crystals and the diameter of the passageways (controlled by the crystal composition) regulates the size of the molecules which can enter. These solids can separate the components according to molecular size and hence the



name molecular sieves. The pore diameters of the molecular sieves range from 3 to 10 Å (Angstrom). As a mixture of molecules migrate through the stationary bed of porous, semi-solid substance referred to as a sieve (or matrix), the components of the highest molecular weight (which are unable to pass into the molecular pores) leave the bed first, followed by successively smaller molecules. Some molecular sieves are used in size-exclusion chromatography, a separation technique that sorts molecules based on their size. Other molecular sieves are used as desiccants (some examples include activated charcoal and silica gel).[1]

The pore diameter of a molecular sieve is measured in ångströms (Å) or nanometres (nm). According to IUPAC notation, microporous materials have pore diameters of less than 2 nm (20 Å) and macroporous materials have pore diameters of greater than 50 nm (500 Å), the mesoporous category thus lies in the middle with pore diameters between 2 and 50 nm.

Experimental set-up:

The experimental set-up consists of an adsorption column of diameter 8.0 cm and height 80 cm packed with 5A molecular sieve pellets. A carbon dioxide cylinder, compressed air line, surge tank and rotameter are connected in the circuit. A heater after the rotameter is also installed to study the effect of temperature on adsorption.



Experimental Set-Up

Procedure:

- Measure the flow rate of air from the compressor by the rotameter provided before the surge tank where carbon dioxide also enters from the CO₂ cylinder.
- Measure the total gas flow rate by the rotameter provided after the surge tank.
- Send the gas mixture to the top of the adsorption column.
- Collect gas samples from the bottom of the column in gas sampling bottles by liquid\ displacement technique at a regular time interval.
- Collect one gas sample from the inlet to the column.

- Determine the concentration of carbon dioxide in the collected gas samples by Orsat Apparatus.
- Note the flow rates of carbon dioxide, air and gas mixture as well as the surge tank pressure.
- The experiments are repeated for different compositions of the inlet gas mixture
-

Experimental data and Observation Table:

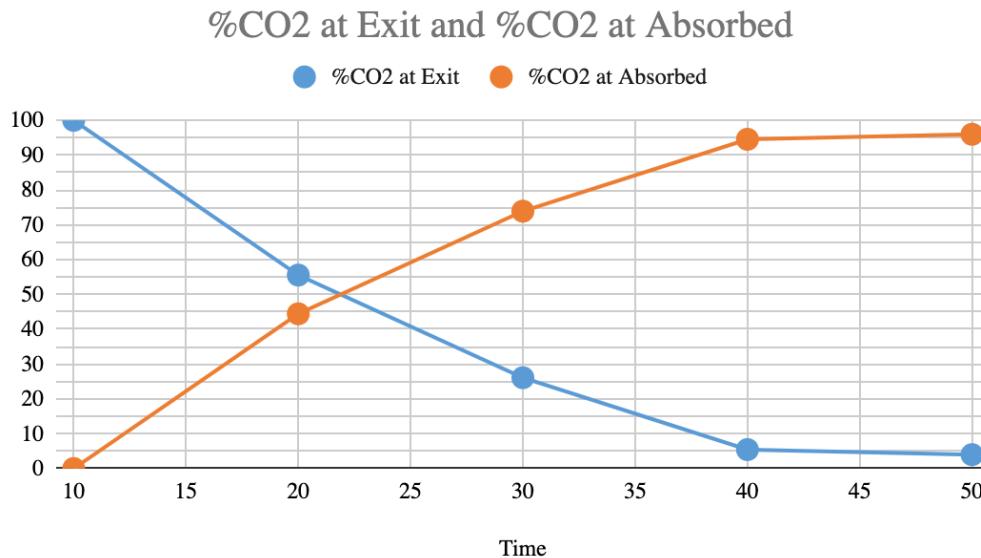
The experimental setup consists of an adsorption column of diameter 8 cm and height 80 cm, packed with 5 Angstrom molecular sieve pellets

Air flow rate: 75 cm³/sec

CO₂ flow rate: 25 cm³/sec

Time	Initial Volume (cc)	CO ₂ in Initial Volume	Final Volume (cc)	CO ₂ absorbed (cc)	%CO ₂ at Exit	%CO ₂ Adsorbed
10	48	12	48	0	100	0
20	45	11.25	40	5	55.56	44.44
30	46	11.5	37.5	8.5	26.09	73.91
40	55	13.75	42	13	5.45	94.55
50	50	12.5	38	12	4	96

Plot of Carbon dioxide concentration at the exit against time:



Discussions:

- Functionality of flow circuit of Adsorption Column is studied and performance of the column for Air-Carbon Dioxide Mixture is tested and analyzed.
- Both the Absorbed and Exits Concentration curves reach close to their saturation and get flattened when time = 40min.
- Integration of the area above the entire breakthrough curve gives the maximum loading of the adsorptive material. The duration of the breakthrough experiment, until it reaches threshold concentration at the exit, can be measured, giving us the calculation of a technically usable sorption capacity. Product Quality of stream can be maintained till that span of time.

Precautions and sources of errors:

- The reagents in the bulbs are brought to the marked etched levels one by one by opening their valves and then the valves are closed.
- Plotting an inadequate number of points also causes the error as it doesn't give a very nice estimation of the true experiment conditions. The issue can be easily mitigated by taking more data points.
- Human error in identifying the concentrations is considerable since a slight increase in the volumetric measurements will create a difference in the visual results.
- All the air in the apparatus is released to the atmosphere
- The order of adsorption should be properly taken into consideration.



PERFORMANCE ANALYSIS OF A BENCH-TOP COOLING TOWER

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Objective:

- To determine the performance of the cooling tower
- To determine the number and height of the transfer units
- To calculate the theoretical evaporation rate.

Theory:

Over all mass balance:

Input = output

$$L_2 - L_1 = G_2 - G_1$$

Where L_2 water inlet, L_1 water outlet, G_1 air inlet, G_2 air outlet

Water mass balance:

$$L_2 - L_1 = G_2 Y'_2 - G_1 Y'_1$$

,For very high air rate

$$G_2 = G_1 = G_s = G$$

$$L_2 - L_1 = G(Y'_2 - Y'_1)$$

Where Y'_2 humidity of outlet air, Y'_1 humidity of inlet air

Energy balance:

$$H'_G = C_s(T_G - T_{G1}) + Y' \lambda_o$$

$$C_s = 1.005 + 1.884 Y'$$

$$\dot{Q} = G(H'_{G2} - H'_{G1})$$

Where, λ_o is latent heat, H'_G is enthalpy of air, C_s is heat capacity of air

Determination of number of transfer unit:

$$N_{tOG} = \int_{H'_{G1}}^{H'_{G2}} \frac{dH'_G}{H'^*_G - H'_G} = \frac{H'_{G2} - H'_{G1}}{\Delta H'^*_G}$$

Where N_{tOG} is number of transfer unit (dimensionless)

To calculate mean driving force :

$$\Delta H'^*_G = \frac{H'_{G2} - H'_{G1}}{\ln[(H'^*_G - H'_{G1})/(H'^*_G - H'_{G2})]}$$

To calculate height of the tower:

$$Z = N_{tOG} \times H_{tOG}$$

$$H_{tOG} = \frac{G}{M_B * P * K_G \alpha}$$

Where H_{tOG} is height of transfer unit (m), M_B is molecular weight of air, P is the pressure, and $K_G \alpha$ is mass transfer coefficient.

To calculate theoretical evaporation rate:

$$\text{Theoretical evaporation rate, TER} = L_2 - L_1 = G_z (Y'_2 - Y'_1)$$

$$G_z = V / v_H$$

Where, V is the volumetric flow rate of humid air and v_H is the humid volume

$$v_H = (0.00283 + 0.00456 Y') (t_G + 273)$$

To calculate Cooling Tower Effectiveness:

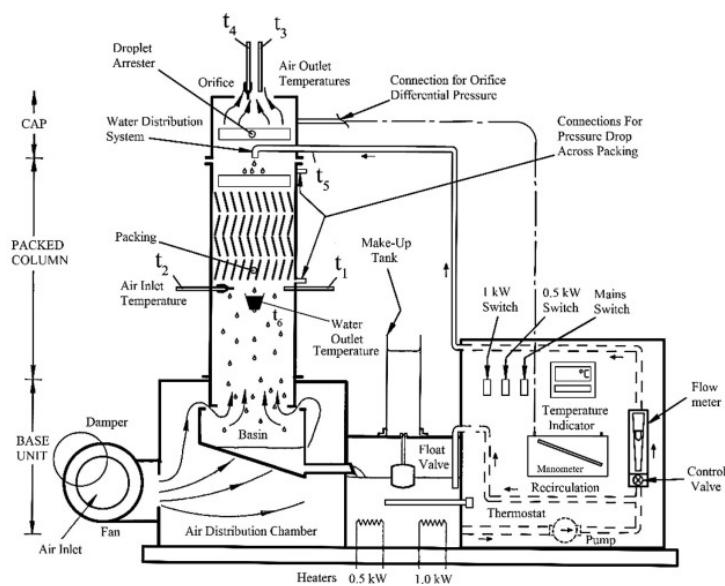
Effectiveness (%)

$$= 100 \times \text{Range} / (\text{Range} + \text{Approach})$$

$$= 100 \times (\text{Water inlet temp} - \text{Water outlet temp}) / (\text{Water inlet temp} - \text{Inlet air wet-bulb temp})$$

$$= 100 \times (t_{L2} - t_{L1}) / (t_{L2} - t_{W1})$$

Experimental Setup:





Experimental Procedure:

1. After the conditions have stabilized, introduce water and record its flow rate.
2. Put the heaters on so that water is heated to the required temperature.
3. Introduce air and record its flow rate.
4. Record the dry and wet bulb temperature of the entering and exit air
5. At regular intervals over a measured period of time, say 5 minutes, all temperatures and flow rates should be noted and the mean values entered on the observation chart.
6. While keeping the water and air flows constant, the cooling load should be increased to 0.5 kW. When the conditions have stabilized the observations should be repeated. Similar tests should be made with cooling loads of 1.0 and 1.5 kW.

Observation Table:

i. Load Power(0.5 KW)

Flow Rate (g/s)	Velocity (m/s)	Hot Air		Cold Air		Inlet water temp. (°C)	Outlet water temp. (°C)
		DB(°C)	WB(°C)	DB(°C)	WB(°C)		
10	4.10	29	24.0	25	22	38.0	28.8
14	3.35	28	23.5	26	24	38.5	30.8
20	3.30	28	25.0	25	24	38.5	31.8

ii. Load Power(1 KW)

Flow Rate (g/s)	Velocity (m/s)	Hot Air		Cold Air		Inlet water temp. (°C)	Outlet water temp. (°C)
		DB(°C)	WB(°C)	DB(°C)	WB(°C)		
10	3.55	35.5	32	26	24	51.5	29.8
14	3.59	38.0	32	26	24	55.0	37.0
22	3.49	40.0	33	26	24	52.0	38.4

Calculations

(i) Load Power (0.5 KW)

Hot Air DB(°C)	WB(°C)	Cold air DB(°C)	WB(°C)	Inlet water temp (°C)	Outlet water temp (°C)	Hs1'	Hs2
29	24	25	22	38	28.8	71.39	63.84
28	23.5	26	24	38.5	30.8	69.44	71.51
28	25	25	24	38.5	31.8	75.54	71.56

(ii) Load Power (1 KW)

Hot Air DB(°C)	WB(°C)	Cold air DB(°C)	WB(°C)	Inlet water temp (°C)	Outlet water temp (°C)	Hs1'	Hs2
35.5	32	26	24	51.5	29.8	109.61	71.52
38	32	26	24	55	37	109.46	71.52
40	33	26	24	52	38	115.2	71.52

Calculations

Over all mass balance:

Input = output

$$L_2 - L_1 = G_2 - G_1$$

Where L_2 water inlet, L_1 water outlet, G_1 air inlet, G_2 air outlet

Water mass balance:

$$L_2 - L_1 = G_s Y'_2 - G_s Y'_1$$

,For very high air rate

$$G_2 = G_1 = G_s = G$$

$$L_2 - L_1 = G(Y'_2 - Y'_1)$$

Where Y'_2 humidity of outlet air, Y'_1 humidity of inlet air

Energy balance:

$$H'_G = C_s (T_G - T_O) + Y' \lambda_o$$

$$C_s = 1.005 + 1.884 Y'$$

$$Q = G(H'_{G2} - H'_{G1})$$

Where, λ_o is latent heat, H'_G is enthalpy of air, C_s is heat capacity of air

Results, Discussion and Conclusions:

When using a distillation column, the column design should allow for effective separation without it being liable to flooding. An undersized column will be liable to flooding, which may result in high pressures and therefore higher temperature in the still. Flooding will also affect separation and can result in delayed problems (e.g. water/solvent separation in reactive distillations). Compatibility of materials of construction is particularly important as there is an increased surface area in column packing. Thermal stability screening can be carried out on materials doped with relevant materials of construction. Corrosion products from the column/packing may catalyse decompositions or reactions on the column (e.g. fires have been known in packing due to reaction with e.g. NO_x gases; anhydrous ammonia recovery distillations can be susceptible to corrosion due to acidic ammonium carbamate sublimation and solidification in the column).

Precautions:

- Special care should be taken when handling methanol. As neglecting to do so can have harmful effects. It is flammable and reactive. Health hazards are as follows:
- Inhalation (cough, dizziness, headache, nausea), Eyes (redness, pain), Skin (may be absorbed, redness, dryness), Ingestion (abdominal pain, shortness of breath, unconsciousness, vomiting, blindness, death) Long-term or repeated exposure: affects the respiratory tract and central nervous system (recurring headaches, impaired vision), may cause dermatitis.
- Distillation columns are widely used in many chemical process industries, especially in oil and gas processing. Accidents in the distillation columns have resulted in enormous loss of human lives and assets so all safety measures and protocols inside the plant have to be taken seriously.

Note: The area of cross-section isn't mentioned hence further calculations couldn't be performed