TRANSPORT 1

CHEM 0915341

Summer Semester 21/22

CHAPTER 2

MOLECULAR TRANSPORT MECHANISM

GENERAL OBJECTIVE

- To be able to understand and relate the fundamental mechanisms of mass, heat, and momentum transport at the molecular and turbulent regime that would cover:

1. Evaluation of transport properties correlations;
2. Use of transport principles to interphase transfer;
3. Integration of rate equations for systems with variable concentration along the length of contacting path; and
4. Integration of transport phenomena to industrial equipment design.

PART ONE

- Introduction to Transport Phenomena
- Molecular Transport Mechanism
  - The General Molecular Transport Equation
    1. Mass Transport
    2. Heat Transport
    3. Momentum Transport

UNIT OPERATION & PROCESS

Q. Differentiate a chemical process from a unit operation. Give at least five examples for each.

CHEMICAL PROCESS (Foust et. al, 1980)

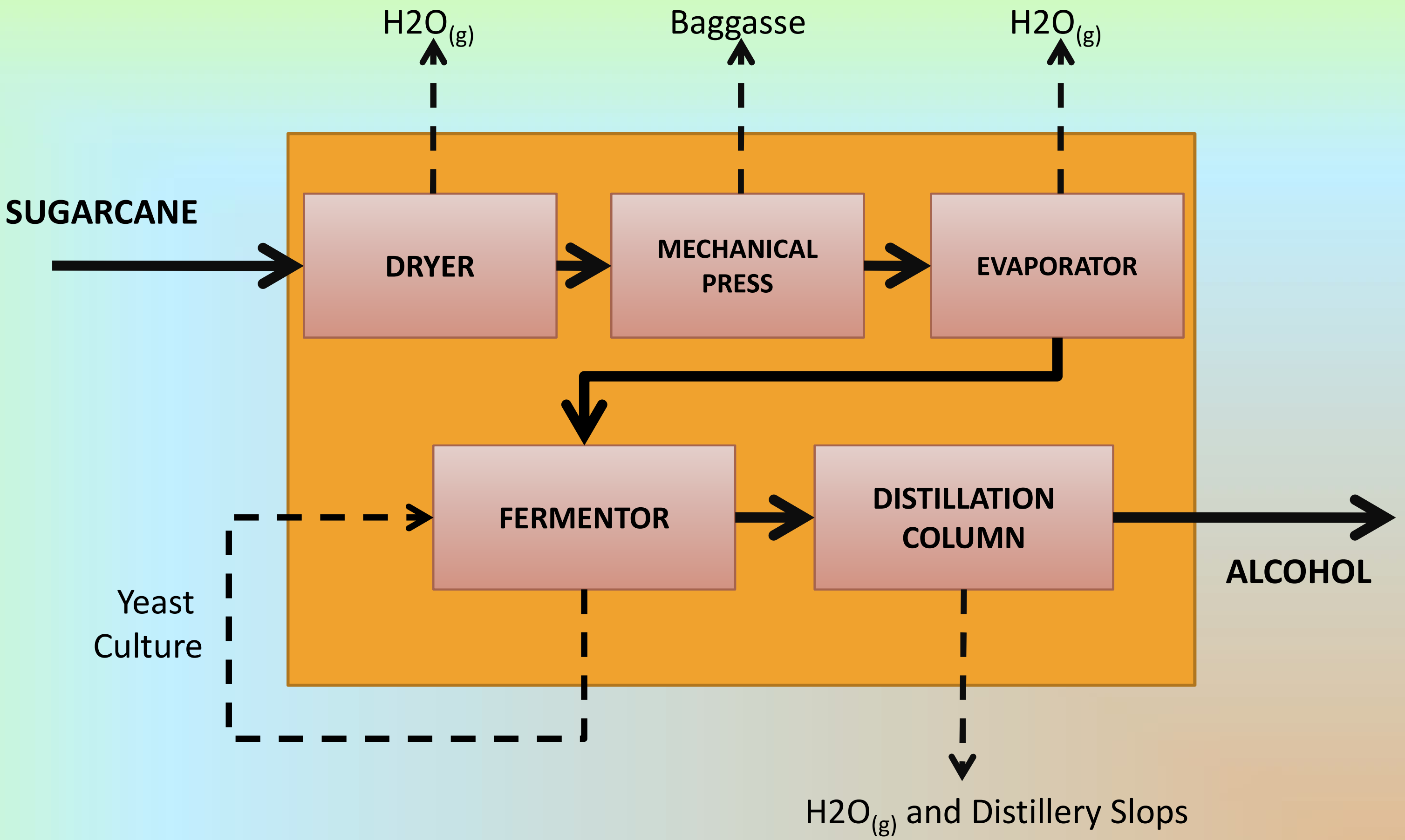
> "...may consist of widely varying sequence of steps, the principles of which are independent of the material being operated upon and of other characteristics of each particular system."

Examples: biodiesel production, sugar processing/refining, food processing, waste treatment

UNIT OPERATIONS (Foust et. al, 1980)

> "...individual steps that break up a complex process; which are identical in fundamentals regardless of the material being processed."

Examples: pulverizing, mixing, heating, roasting, crystallization, drying, screening, electrolysis, fluid flow, distillation, humidification, gas absorption

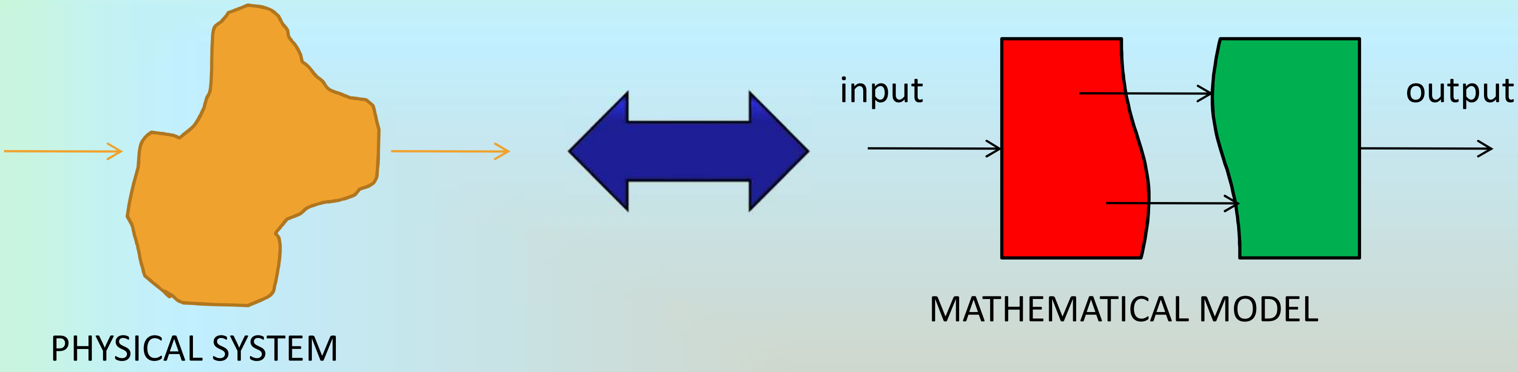


SIMPLIFIED BLOCK DIAGRIAM FOR ALCOHOL PROCESSING

“The complexity of chemical engineering results from the variety of conditions as to temperature, pressure, etc. under which the unit actions must be carried out in different processes along with other limitations of the operation.

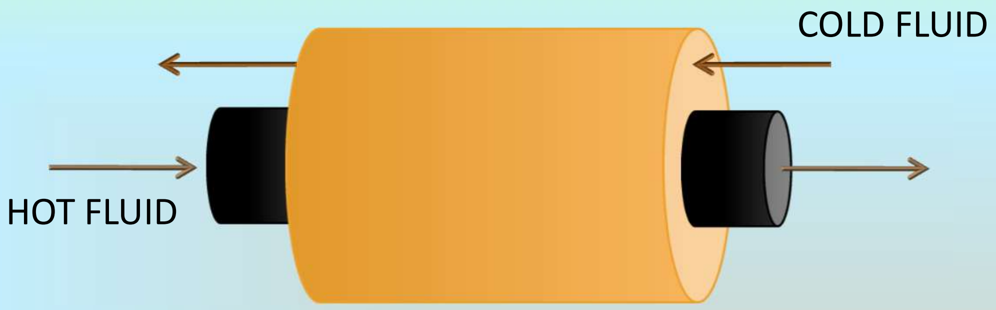
Foust et. al, 1980

TRANSPORT PHENOMENA



- When chemical rates and equilibria are known, chemical changes as well as physical changes may be mathematically modeled into unit operation calculations.

Three Major Properties Involved in Transport Phenomena



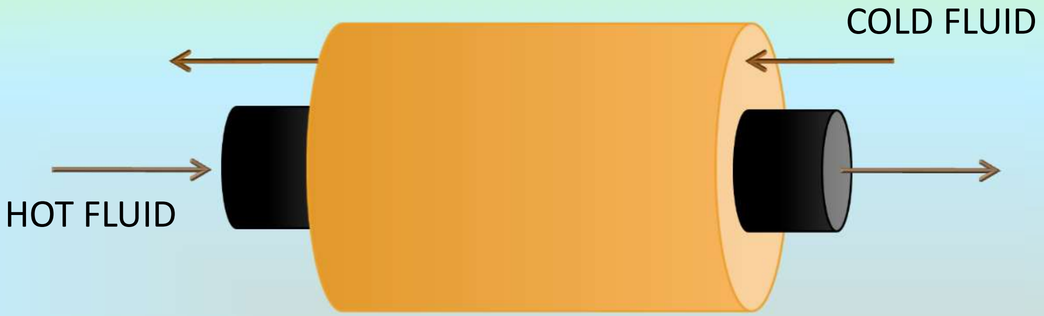
Transport Phenomena in a Heat Exchanger

Mass – the property of an object that is a measure of its inertia, the amount of matter it contains, and its influence in a gravitational field

Heat – energy perceived as temperature; a form of transferred energy (conduction, convection, radiation) that arises from the random motion of molecules

Momentum – measure of movement; quantity that expresses the motion of a body and its resistance to slowing down

Three Major Properties Involved in Transport Phenomena



Momentum Transport: fluid flowing through the heat exchanger

Heat Transport: exchange of heat between the cold and the hot fluids

Mass Transport: presence of phase change

Note: **TRANSPORT vs TRANSFER**

Transport → refers to the fundamental mechanism in a single phase

Transfer → refers to the overall process

Three Major Properties Involved in Transport Phenomena

<table>
<tr><th>MASS</th><th>HEAT</th><th>MOMENTUM</th></tr>
<tr><td>Leaching/Extraction
Gas Absorption
Distillation
Humidification
Crystallization</td><td>Heat exchanger</td><td>Piping system, agitation and mixing of fluids</td></tr>
<tr><td colspan="2">Evaporation</td><td></td></tr>
<tr><td colspan="2">Drying of solids</td><td></td></tr>
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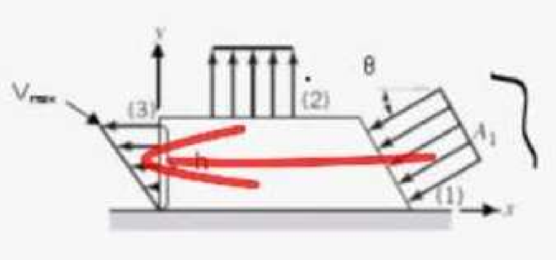
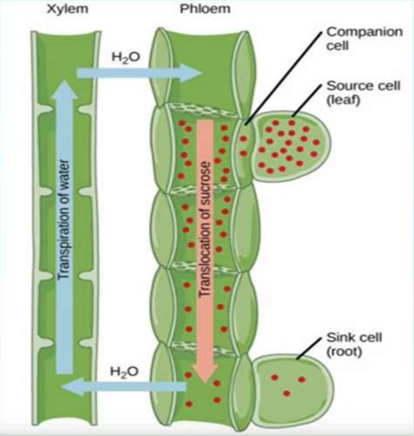
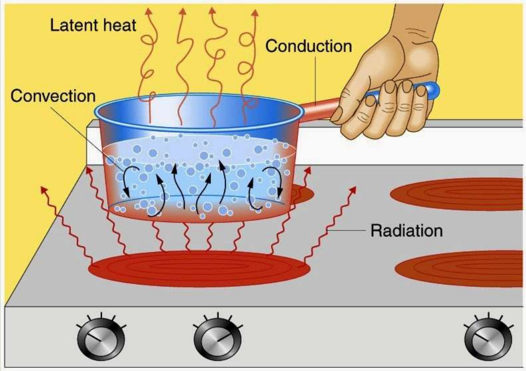
CONCERNS IN TRANSPORT PHENOMENA

- **Mass Transport:** to describe the process
- **Energy Transport:** to predict heat exchange performance
- **Momentum Transport:** to yield prediction of pressure losses in a piping system







TWO MECHANISMS OF TRANSPORT

- **Molecular Transport**
  - ✓ Depends upon the motion of individual particles
  - ✓ Transport occurring due to aggregate group of molecules
- **Turbulent/Convective Transport**
  - ✓ Results from the motion of large groups or cluster of molecules

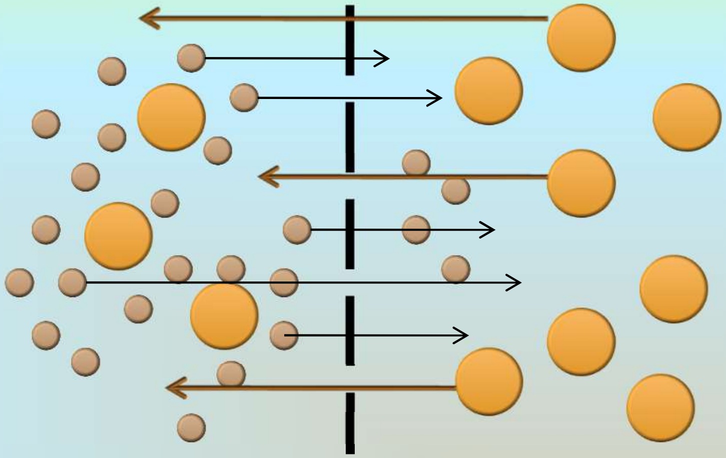
MOLECULAR TRANSPORT MECHANISM

Objectives:

1. To understand molecular transport mechanism from a study of the kinetic theory of gases and liquids or from a consideration of solid-state physics;
2. From a simplified physical model of a fluid, to be able to derive an expression for the rate of transport as a function of a concentration gradient, which will be extended to real gases, liquids, and solids; and
3. To predict transport properties of gases, liquids, and solids from a given correlation obtained from experimental data.

Molecular Transport

REGION A
-Mass
-Thermal Energy
-Momentum



REGION B
-Mass
-Thermal Energy
-Momentum

Due to concentration gradient, net transport occurs.

- Transport of mass, heat, and momentum occurs among solids, liquids, and gases.
- Due to the substantial differences in molecular structure, the actual mechanism of transport differs greatly

PHYSICAL STATE	CHARACTERISTICS	IMPLICATION
GAS	▪ Few molecules per unit volume ▪ Intermolecular Forces of Attraction (IMFA) relatively weak ▪ Molecules move at random motion	▪ Molecules move relatively freely for considerable distance before colliding
LIQUID	▪ Relatively contain higher concentration of molecules per unit volume than gases ▪ Relatively has higher IMFA than gases ▪ Molecular motion is much more restricted	▪ Migration of molecules from one region to another is at lower rate than in gases
SOLID	▪ Closely-packed/highly ordered structure ▪ IMFA are strong enough to form crystal lattice	▪ Freedom of movement is restricted to small vibrations in lattice sites ▪ Lattice molecular motion

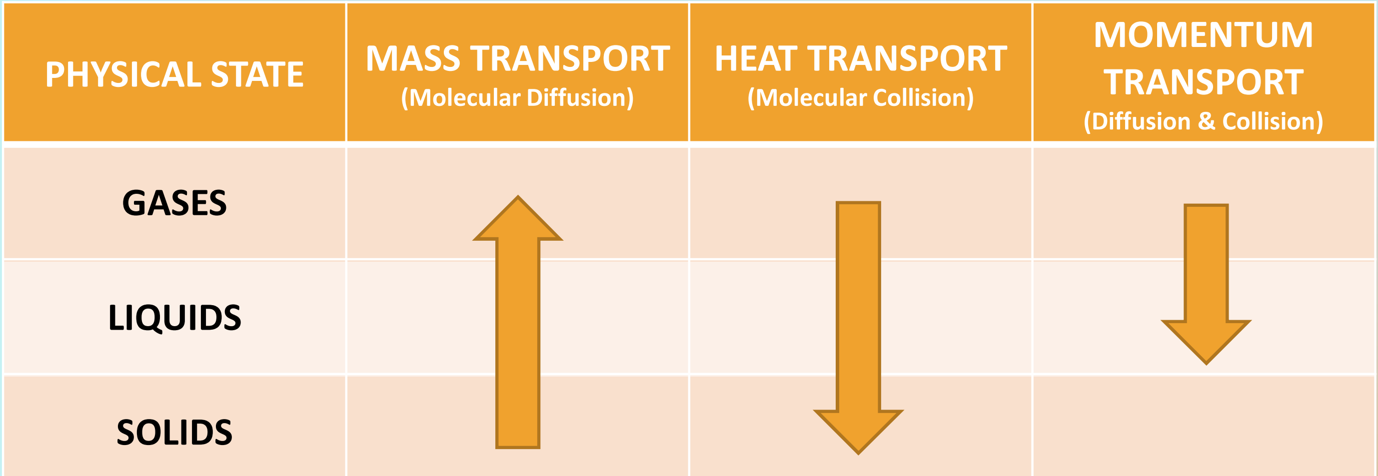
Molecular Transport

From the three physical states, two important factors were considered:

1. **Molecular Diffusion** – the flow of energy or matter from higher concentration to a lower concentration resulting in an even distribution (equilibrium)
2. **Molecular Collision** – collision of molecules vibrating at relatively fixed conditions in conduction

Molecular Transport

- In summary...



PHYSICAL STATE	MASS TRANSPORT (Molecular Diffusion)	HEAT TRANSPORT (Molecular Collision)	MOMENTUM TRANSPORT (Diffusion & Collision)
GASES			
LIQUIDS			
SOLIDS			

Review

1. What are the two molecular transport mechanism?

2. What are the respective driving force/s of heat, mass and momentum transport?

3. Differentiate transport and transfer.

4. Differentiate flux and gradient.

5. Differentiate molecular diffusion and molecular collision.

THE GENERAL MOLECULAR TRANSPORT EQUATION

- Influenced by the “simple model gas”, which was first derived by James Clerk Maxwell (1860)
- Derived from the assumptions in the model of “ultrasimplified kinetic theory of gases” which are based on the Ideal Gas and Kinetic Theory of Gases.

- **Assumptions**
  1. The gas is made up of molecules, each which is a perfect sphere, $D = \sigma$
  2. Negligible attractive & repulsive forces between gas molecules
  3. Each molecule is in random motion at a mean speed, ć.

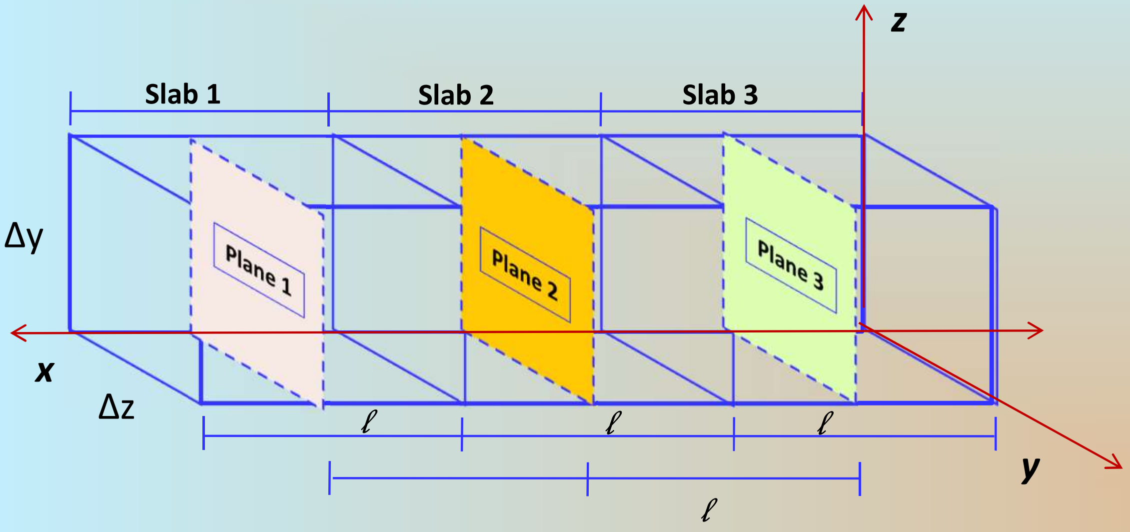
Assumptions

4. Actual volume of the molecules is negligible compared to the volume between molecules
5. Perfectly elastic collision between molecules
6. Each molecule moves a distance l between collisions with other molecules. The distance l is called "mean free path".
7. The time required for a molecule to travel a mean free path travelling at the mean speed is the mean time between collisions, θ.

$$\overline{\theta} = \frac{l}{\overline{c}}$$

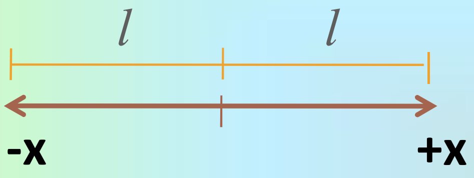
8. The number of molecules is large enough that statistically average values of properties can be used to describe the system.

- Consider the volume element of the model gas,
- Let:
  - ✓ Γ = transferent property; concentration of the property to be transferred
  - ✓ (dΓ/dx) = gradient; increase in concentration at a certain distance, l



Possible Movement of Molecule in a Volume Element

1. One-dimensional flow



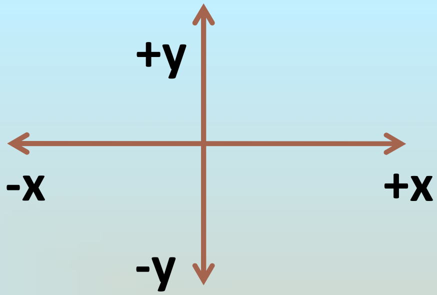
Two coordinate axes (+x,-x)

l - mean free path

θ- mean time

N = c = mean speed = l/θ

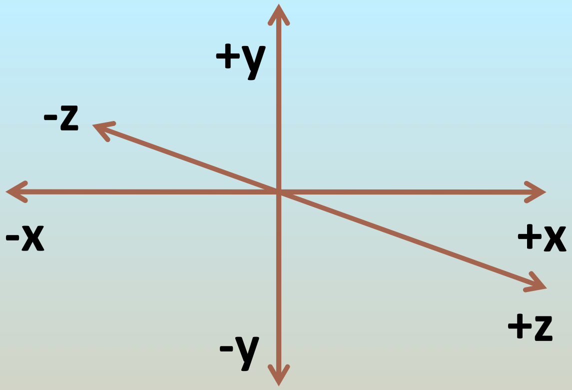
2. Two-dimensional flow



Four coordinate axes

(+x -x, +y -y)

3. Three-dimensional flow



Six coordinate axes

(+x -x, +y –y, +z -z)

DEFINITION OF TERMS (GRADIENT)

Γ - concentration of transferent property

- amount of transferent property/volume

P - amount of transferent property

V - volume of the element

Γ_1- concentration of transferent property in slab 1

Γ_2- concentration of transferent property in slab 2

Γ_3- concentration of transferent property in slab 3

- For the amount of gas

$$P_1 = \Gamma_1 V$$

$$P_2 = \Gamma_2 V$$

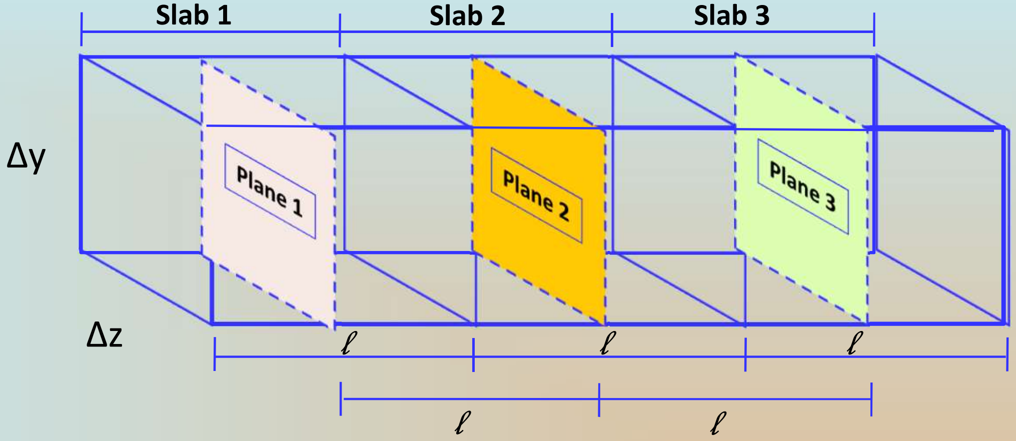
$$P_3 = \Gamma_3 V$$

But $V = l\Delta y \Delta z$

Then $P_1 = \Gamma_1 l\Delta y \Delta z$

$$P_2 = \Gamma_2 l\Delta y \Delta z$$

$$P_3 = \Gamma_3 l\Delta y \Delta z$$



- Consider the movement of molecule from plane to plane

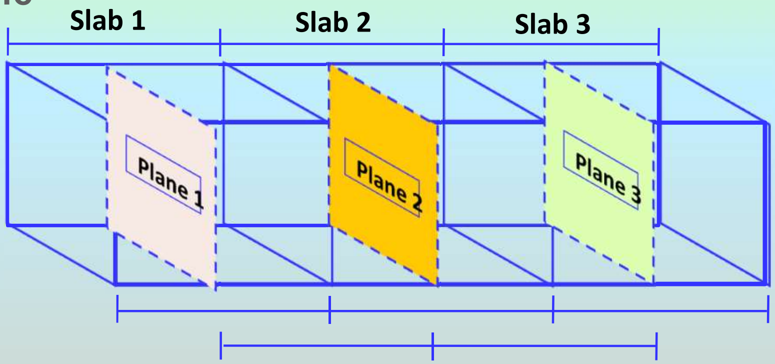
Slope:

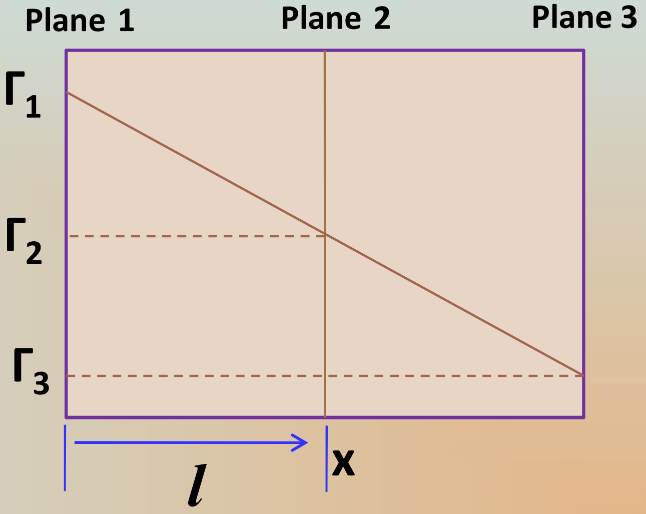
$$-\frac{d\Gamma}{dx} = \frac{\Gamma_2 - \Gamma_1}{-l}$$

$$\Gamma_1 = \Gamma_2 - \frac{l d\Gamma}{dx}$$

$$\Gamma_2 = \Gamma_3 - \frac{l d\Gamma}{dx}$$

$$\Gamma_3 = \Gamma_2 + \frac{l d\Gamma}{dx}$$





FLUX

Ψ = Φ = F = flux of transferent property

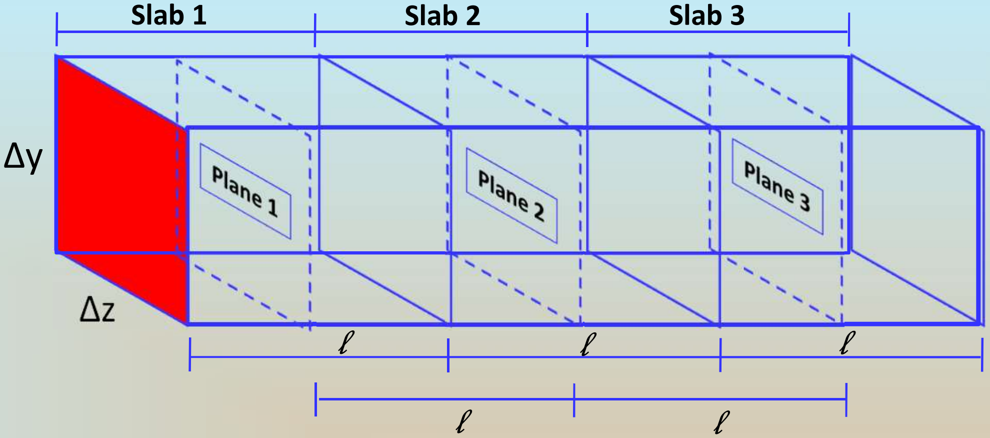
$$\frac{flow\ of\ transferent/time}{transferent\ area}$$

$$\Psi = \frac{P/\theta}{A}$$

$$\Psi = \frac{rate\ of\ transferent\ property}{transferent\ area}$$

$$\Psi = \frac{dP/dt}{A}$$

$$A = \Delta y \Delta z$$



- Assuming that 1/6 of the total amount of the transferent property migrates along the +x axis

$$P_1 = \frac{\Gamma_1 l \Delta y \Delta z}{6} \qquad P_2 = \frac{\Gamma_2 l \Delta y \Delta z}{6} \qquad P_3 = \frac{\Gamma_3 l \Delta y \Delta z}{6}$$

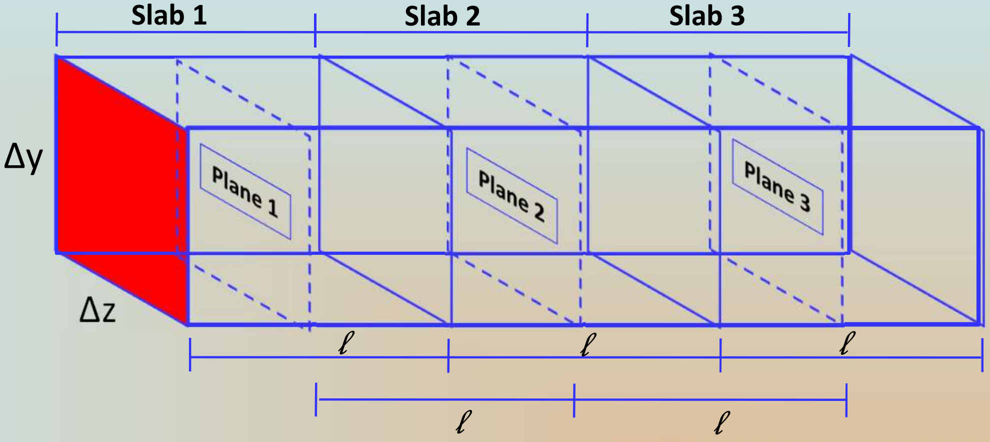
- Flux from plane 1-2:

$$\Psi_{1-2} = \frac{\Gamma_1 l \Delta y \Delta z/(6\theta)}{\Delta y \Delta z} = \frac{\Gamma_1 l}{6\theta}$$

$$\Psi_{2-1} = \frac{-\Gamma_2 l}{6\theta}$$

$$\Psi_{2-3} = \frac{\Gamma_2 l}{6\theta}$$

$$\Psi_{3-2} = \frac{-\Gamma_3 l}{6\theta}$$



- Net Flux from plane 1-2

$$\Psi_{net\ 1-2} = \Psi_{1-2} + \Psi_{2-1} = \frac{\Gamma_1 l}{6\theta} - \frac{\Gamma_2 l}{6\theta}$$

$$\Psi_{net\ 1-2} = \frac{l}{6\theta}(\Gamma_1 - \Gamma_2) = \frac{\Gamma_1 l}{6\theta} - \frac{\Gamma_2 l}{6\theta}$$

- But $\Gamma_1 = \Gamma_2 - \frac{ld}{dx}$

$$\therefore \Psi_{net\ 1-2} = \frac{l}{6\theta}\left(\Gamma_2 - \frac{ld\Gamma}{dx} - \Gamma_2\right)$$

$$\Psi_{net\ 1-2} = \frac{-l^2}{6\theta}\left(\frac{d\Gamma}{dx}\right)$$

- And $c = v = \frac{l}{\theta}; \theta = \frac{l}{c}$

$$\Psi_{net\ 1-2} = \frac{-lc}{6}\left(\frac{d\Gamma}{dx}\right)$$

The General Molecular Transport Equation

- For steady state processes,

$$\Psi = -\frac{1}{6} l \bar{c} \left(\frac{d\Gamma}{dx} \right)$$

Generalized molecular transport equation

SEATWORK

Derivation of the Net Flux from plane 2-3

- Net Flux from plane 2-3

$$\Psi_{net\ 2-3} = \Psi_{2-3} + \Psi_{3-2} = \frac{\Gamma_2 l}{6\theta} - \frac{\Gamma_3 l}{6\theta}$$

$$\Psi_{net\ 2-3} = \frac{l}{6\theta}(\Gamma_2 - \Gamma_3) = \frac{\Gamma_1 l}{6\theta} - \frac{\Gamma_2 l}{6\theta}$$

- But $\Gamma_2 = \Gamma_3 - \frac{ld\Gamma}{dx}$

$$\therefore \Psi_{net\ 2-3} = \frac{l}{6\theta}\left(\Gamma_3 - \frac{ld\Gamma}{dx} - \Gamma_3\right)$$

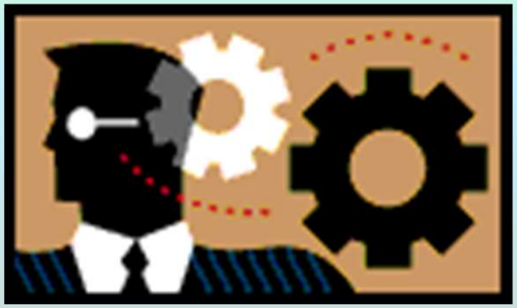
$$\Psi_{net\ 2-3} = \frac{-l^2}{6\theta}\left(\frac{d\Gamma}{dx}\right)$$

- And $c = V = \frac{l}{\theta}; l = c\theta$

$$\Psi_{net\ 2-3} = \frac{-lc}{6}\left(\frac{d\Gamma}{dx}\right)$$

Heat, Mass, and Momentum Transport

Phenomenological Laws



- Mathematical expressions which describe how matter undergoes heat, mass, and momentum transport on a molecular level
- These are based on the observations of the natural phenomena

> *"The practical applications of mass, heat, and momentum transport developed before the basic mechanisms were understood. The engineers who applied the principles of the three types of transport were not primarily interested in the similarities among the mechanisms of transport."*
>
> *Foust et. al, 1980*

Heat, Mass, and Momentum Transport

Phenomenological Laws

- **Fourier’s Law of Heat Conduction** (Heat Transport)
- **Fick’s Law of Molecular Diffusion** (Mass Transport)
- **Newton’s Law of Viscosity** (Momentum Transport)

Heat, Mass, and Momentum Transport

Fourier’s Law of Heat Conduction

$$Q = \frac{q}{A} = -k\frac{dT}{dx}$$

Where: Q = heat flux (W/m^2)

q = heat transfer rate (W or J/sec)

A = area

k = thermal conductivity

$\frac{dT}{dx}$ = temperature gradient along x

Heat, Mass, and Momentum Transport

Fick's Law of Molecular Diffusion

$$\overline{N_a} = \frac{N_a}{A} = -D\,\frac{dC_a}{dx}$$

Where:			
	$\overline{N_a}$	=	mass flux
	N_a	=	mass transfer rate
	A	=	area
	D	=	mass diffusivity
	$\frac{dC_a}{dx}$	=	concentration gradient along x

Heat, Mass, and Momentum Transport

Newton's Law of Viscosity

$$\tau_{yx} = \frac{F_y}{A} g_c = -\mu \frac{dV_y}{dx}$$

Where:

τ_{yx} = momentum flux

y = direction of flow (velocity)

x = momentum flux

μ = absolute viscosity

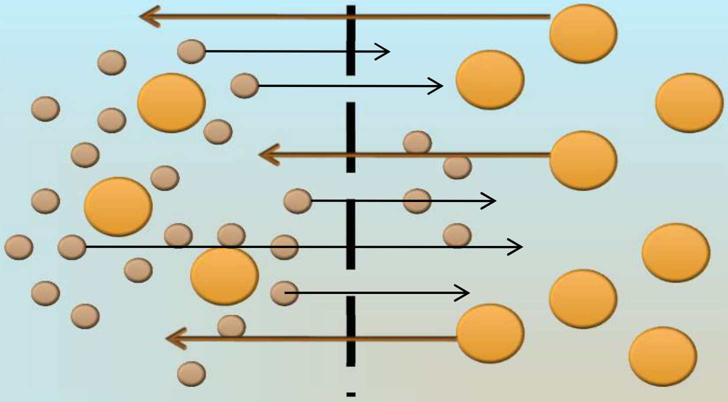
$\frac{dV_y}{dx}$ = velocity gradient along x

$\frac{F_y}{A}$ = shear stress

g_c = gravitational constant

Heat, Mass, and Momentum Transport

Heat/Thermal Energy Transport



REGION A

-Thermal Energy

REGION B

-Thermal Energy

Generalizations:

- Temperature is conceived from the movement of the molecules
- The higher the temperature of the system, the greater is the concentration of thermal energy.

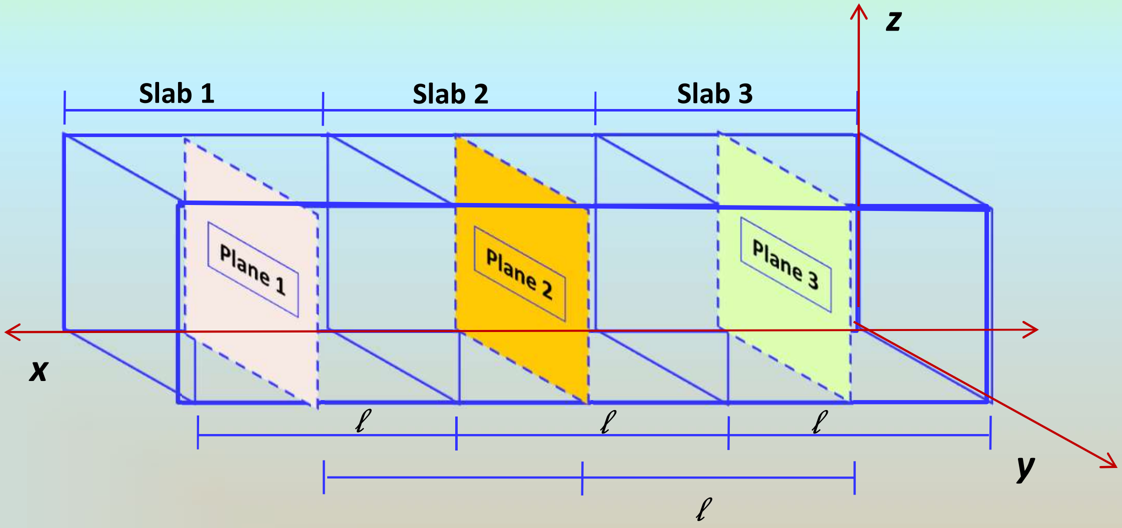
Heat, Mass, and Momentum Transport

Heat/Thermal Energy Transport

- Extended Molecular Heat Transport Equation

$$Q = \frac{q}{A} = -\alpha \frac{d(\rho C_p T)}{dx} = -k\frac{dT}{dx}$$

where: α = thermal diffusivity



Sample Problem1:

Calculate the heat flux across a copper block 10 cm thick, one side of which is maintained at 0°C and the other at 100°C. The k can be assumed constant at 380 W/m-K.

Solution:

$$\frac{q}{A} = -k\frac{dT}{dx}$$

Integration:

$$\int_{x_1}^{x_2}\left(\frac{q}{A}\right).dx = -k\int_{T_1}^{T_2} dT$$

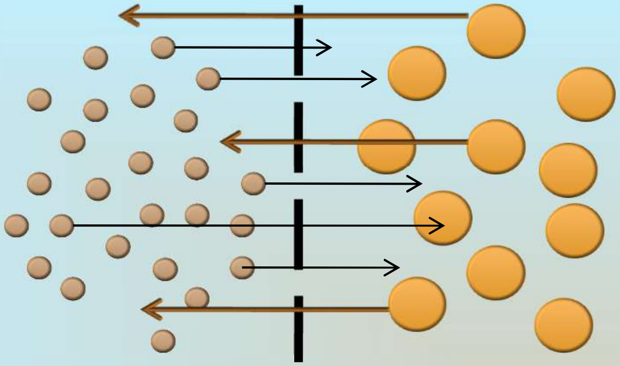
The integration will become:

$$\left(\frac{q}{A}\right).(x_2 - x_1) = -k[T_2 - T_1]$$

Substituting the given information:

$$\left(\frac{q}{A}\right) = -3.8 \times 10^5 J.m^{-2}s^{-1}$$

MASS TRANSPORT: Equimolar Counter Diffusion (ECD)



REGION A

-Mass
(species A)

REGION B

-Mass
(species B)

$$\overline{N_a} = -D\frac{dC_a}{dx}$$

$$\overline{N_b} = -D\frac{dC_b}{dx}$$

Generalizations:

The boundaries of the system are permeable to both components.

At constant T & P, both A and B will diffuse because of concentration gradient.

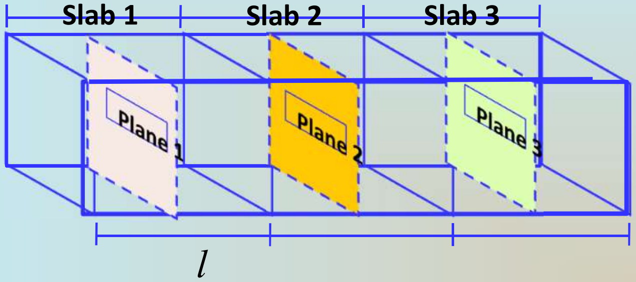
For system containing A&B species:

Assume $C_{a1}>C_{a2}>C_{a3}$ and $C_{b1}<C_{b2}<C_{b3}$

Gradient

$$\frac{d\Gamma}{dx} = \frac{(\Gamma_2 - \Gamma_1)}{l}$$

$$\Gamma_1 = \Gamma_2 - \frac{l d\Gamma}{dx}$$



Flux

$$\Psi_{1-2} = \frac{\Gamma_1 l}{6\theta} \quad \text{and} \quad \Psi_{2-1} = \frac{-\Gamma_2 l}{6\theta}$$

Then $\Psi_{net\ 1-2} = \frac{-l}{6}\left(\frac{d\Gamma}{dx}\right)$

$$\frac{dC_a}{dx} = \frac{C_{a2} - C_{a1}}{l}$$

$$C_{a1} = C_{a2} - \frac{l dC_a}{dx}$$

Similarly

$$C_{a2} = C_{a3} - \frac{l dC_a}{dx}$$

$$\Psi_{1-2} = \frac{C_{a1} l}{6\theta}$$

$$\Psi_{2-1} = \frac{-C_{a2} l}{6\theta}$$

$$\Psi_{net\ 1-2} = \frac{-lc}{\theta}\left(\frac{dC_a}{dx}\right)$$

N_a ⟶ mass rate of component a

A ⟶ transfer area

$$\left(\frac{N_a}{A}\right)_{net} = \frac{-lc}{6}\frac{dC_a}{dx}$$

$$\frac{lc}{6} \rightarrow D\ is\ mass\ diffusivity$$

$$\delta\ is\ transport\ diffusivity$$

For substance B

$$\left(\frac{N_b}{A}\right)_{net} = \frac{-lc}{6}\frac{dC_b}{dx}$$

For ideal gas

$$D = \frac{lc}{6}$$

For real gases or liquids,

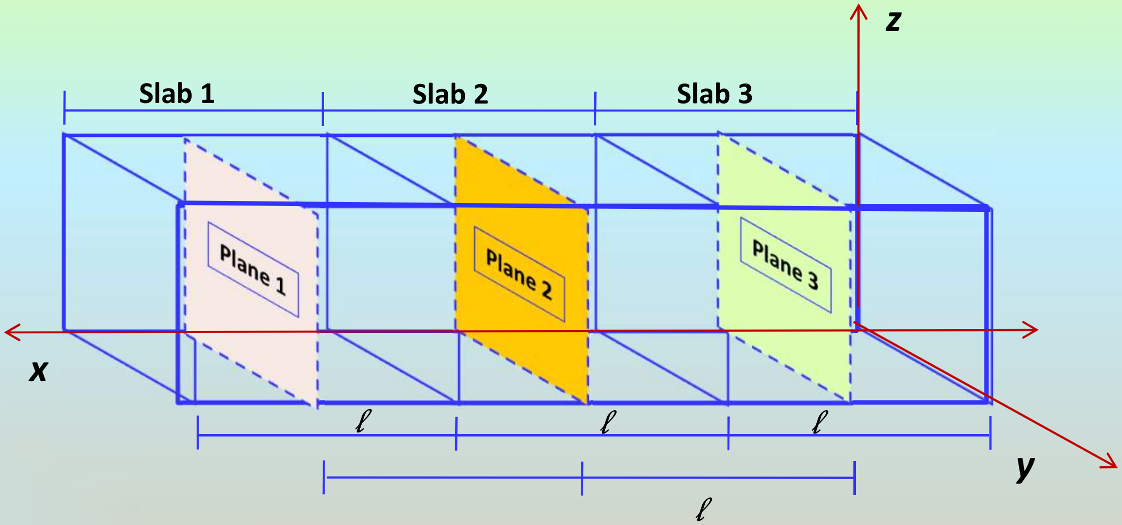
$$D\ is\ determined\ experimentally$$

$$\left(\frac{N_a}{A}\right)_{net} = -D\frac{dC_a}{dx}$$

$$\left(\frac{N_b}{A}\right)_{net} = -D\frac{dC_b}{dx}$$

What is the relation between these two equations?

These equations are Fick's Law of Diffusion



V_t - total volume of mixture/ container

V_a - volume of component a

V_b - volume of component b

At constant T and P, V is constant

$$V_a = V_t = V_b$$

m_t - total mass of the mixture

$$m_t = m_a + m_b$$

The diffusion rate of A and B are interrelated by the total concentration

$V_tC_t = V_aC_a + V_bC_b$ and since V is constant, then $C_t = C_a + C_b$

Differentiate the last equation with respect to x:

$$0 = \frac{dC_a}{dx} + \frac{dC_b}{dx} \quad \text{and} \quad \frac{dC_a}{dx} = -\frac{dC_b}{dx} \qquad (1)$$

The gradient of B is equal to but opposite sign to that of gas A.

$$\left(\frac{N_a}{A}\right)_{net} = -D\frac{dC_a}{dx}$$

$$\frac{dC_a}{dx} = -\frac{\left(\frac{N_a}{A}\right)_{net}}{D} \qquad (2)$$

$$\left(\frac{N_b}{A}\right)_{net} = -D\frac{dC_b}{dx}$$

$$\frac{dC_b}{dx} = -\frac{\left(\frac{N_b}{A}\right)_{net}}{D} \qquad (3)$$

Substitute (2) and (3) into (1)

$$\frac{dC_a}{dx} = -\frac{dC_b}{dx}$$

$$-\frac{\left(\frac{N_a}{A}\right)_{net}}{D} =- -\frac{\left(\frac{N_b}{A}\right)_{net}}{D}$$

$$-N_a = N_b \; or \; N_a = -N_b$$

Equimolar Counter Diffusion

$$\left(\frac{N_a}{A}\right)_{net} = -D\,\frac{dC_a}{dx}$$

In terms of partial pressure, assume that the model gas behaves ideally

$$PV = nRT; \quad P_t V_t = nRT$$

For substance a: $P_a = \frac{n_a RT}{V}$

$$\frac{P_a}{RT} = C_a; \quad P_a = C_a RT$$

$$dP_a = RT\,dC_a$$

$\therefore \quad dC_a = \frac{dP_a}{RT}$ Substitute this equation into $\left(\frac{N_a}{A}\right)_{net} = -D\,\frac{dC_a}{dx}$

Then $\left(\frac{N_a}{A}\right)_{net} = -D\,\frac{dP_a/_{RT}}{dx} = -D\,\frac{dP_a}{RT\,dx}$

For substance b: $P_b = \frac{n_b RT}{V}$

Following the same procedure

One can easily obtain:

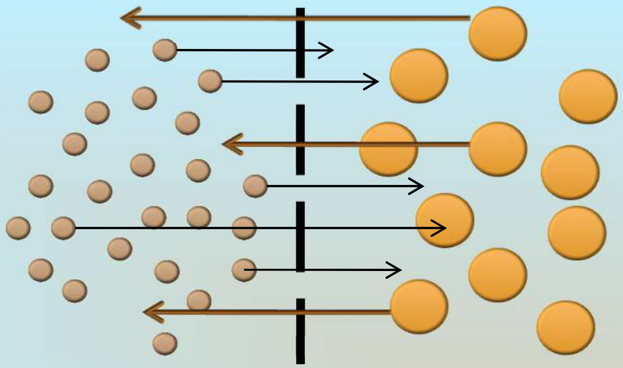
$$\left(\frac{N_b}{A}\right)_{net} = -D\,\frac{dP_b}{RT\,dx}$$

Heat, Mass, and Momentum Transport

MASS TRANSPORT: (ECD)

REGION A

-Mass
(species A)



REGION B

-Mass
(species B)

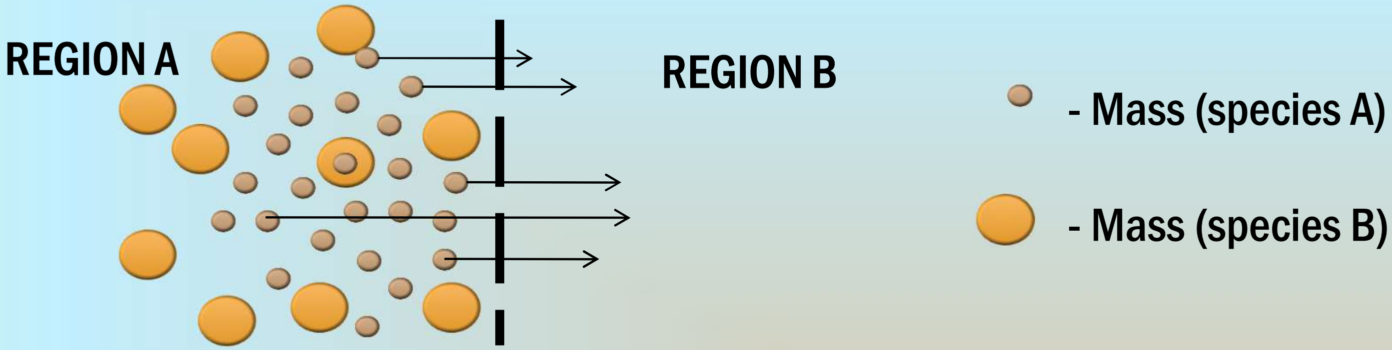
Generalizations:

In ECD, component A diffuses at a rate through component B, which is also diffusing at the same molar rate as A, but in opposite direction.

$$\overline{N_a} = -\overline{N_b}$$

Heat, Mass, and Momentum Transport

MASS TRANSPORT: Diffusion Through Stationary Medium (DTSM)



Generalizations:

The boundary of the system is permeable to only one component.

Equation is based on the total mass transfer of both components in the system.

Derivation of Mass Transfer Equation Through Stationary Gas

Definition of terms:

$(N_A)_t$ = total mass transfer rate of A

$(N_B)_t$ = total mass transfer rate of B

$(N_A)_b$ = bulk flow rate of A

$(N_B)_b$ = bulk flow rate of B

$(N_A)_m$ = molecular transport rate of A

$(N_B)_m$ = molecular transport rate of B

B – stationary gas

gas impermeable to the interphase

At any point the total mass transfer rate of A is:

$$(N_A)_t = (N_A)_b + (N_A)_m$$

Dividing by A = transfer area

$$\left(\frac{N_A}{A}\right)_t = \left(\frac{N_A}{A}\right)_b + \left(\frac{N_A}{A}\right)_m$$

For component B

$$(N_B)_t = (N_B)_b + (N_B)_m$$

$$\left(\frac{N_B}{A}\right)_t = \left(\frac{N_B}{A}\right)_b + \left(\frac{N_B}{A}\right)_m$$

Since B is a stationary gas, then $\left(\frac{N_B}{A}\right)_t = 0$

Then $\left(\frac{N_B}{A}\right)_b = -\left(\frac{N_B}{A}\right)_m$

At constant T and P:

$$\left(\frac{N_A}{N_B}\right)_b = \frac{C_A}{C_B}$$

$$(N_A)_b = \frac{C_A}{C_B}(N_B)_b$$

Divide both sides by A:

$$\left(\frac{N_A}{A}\right)_b = \frac{C_A}{C_B}\left(\frac{N_B}{A}\right)_b$$

Also: $\left(\frac{N_A}{A}\right)_b = \frac{C_A}{C_B}\left(-\frac{N_B}{A}\right)_m$

Since ECD applies on the bulk gas, then

$$\left(\frac{N_A}{A}\right)_m = -\left(\frac{N_B}{A}\right)_m$$

Substitute this equation into the above equation

$$\left(\frac{N_A}{A}\right)_b = -\frac{C_A}{C_B}\left(-\frac{N_A}{A}\right)_m$$

$$\left(\frac{N_A}{A}\right)_b = \frac{C_A}{C_B}\left(\frac{N_A}{A}\right)_m$$

Substitute this equation into the total mass transfer rate of B divided by area will give:

$$\left(\frac{N_A}{A}\right)_t = -\frac{C_A}{C_B}\left(\frac{N_A}{A}\right)_m + \left(\frac{N_A}{A}\right)_m$$

Simplifying:

$$\left(\frac{N_A}{A}\right)_t = -\left(\frac{C_A}{C_B} + 1\right)\left(\frac{N_A}{A}\right)_m$$

$$\left(\frac{N_A}{A}\right)_t = -\left(\frac{C_A + C_B}{C_B}\right)\left(\frac{N_A}{A}\right)_m$$

Since $C_t = C_A + C_B$

Substituting:

$$\left(\frac{N_A}{A}\right)_t = \left(\frac{C_t}{C_B}\right)\left(\frac{N_A}{A}\right)_m$$

Since $\left(\frac{N_a}{A}\right)_m = -D\,\frac{dC_A}{dx}$

By substituting

$$\left(\frac{N_A}{A}\right)_t = -D\,\frac{C_t}{C_B}\frac{dC_A}{dx}$$

Where $C_t = \frac{P_t}{RT}$ $\quad C_A = \frac{P_A}{RT}$ $\quad C_B = \frac{P_B}{RT}$

$$\left(\frac{N_A}{A}\right)_t = -D\,\frac{\frac{P_t}{RT}}{\frac{P_B}{RT}}\frac{d\,\frac{P_A}{RT}}{dx}$$

$$\left(\frac{N_A}{A}\right)_t = -D\,\frac{P_t}{P_B}\frac{dP_A}{dx}$$

Two Types of Mass Transport Mechanism

1. Equimolar Counter Diffusion (ECD)

- Component A diffuses through B which is diffusing at the same molar rate as A but in opposite direction
- The boundaries of the system are permeable to both components
- At constant T and P, both A and B will diffuse because of their concentration gradient

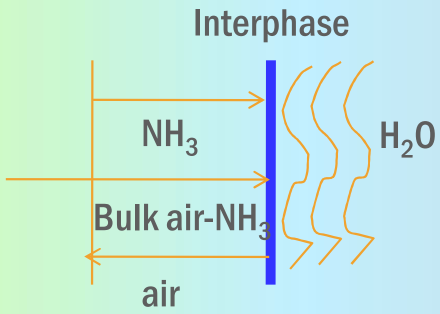
$$\left(\frac{N_a}{A}\right)_{net} = -D\,\frac{dC_a}{dx} \qquad \frac{N_a}{A} = -D\,\frac{dP_a}{RTdx}$$

$$\left(\frac{N_b}{A}\right)_{net} = -D\,\frac{dC_b}{dx} \qquad \frac{N_b}{A} = -D\,\frac{dP_b}{RTdx}$$

Two Types of Mass Transport Mechanism

2. Diffusion through a Stationary Medium (DSTM)

- Occurs when one boundary of the system is permeable to only one component
- Example: Absorption of NH_3 from NH_3-air mixture by H_2O



$$\left(\frac{N_a}{A}\right)_t = -D\,\frac{C_t}{C_b}\,\frac{dC_a}{dx}$$

$$\left(\frac{N_a}{A}\right)_t = -\frac{D}{RT}\,\frac{P_t}{P_b}\,\frac{dP_a}{dx}$$

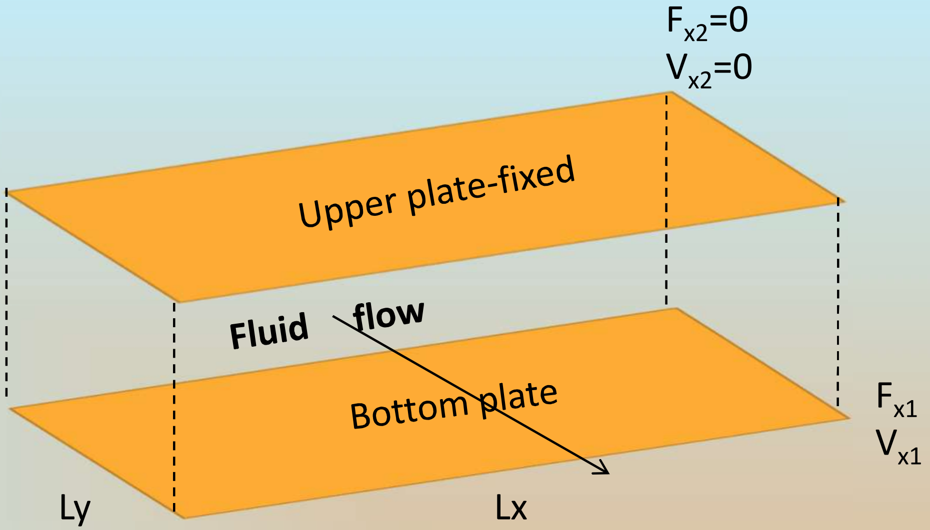
The bulk flow of air is equal to molecular flow

$(N_{air})_{bulk} = (N_{air})_{molecular}$

Momentum Transport

- Transport of momentum if there are differences in velocity

$$\tau_{yx} = \frac{F_y}{A} g_c = -\mu \frac{dv_y}{dx}$$



where : τ_{yx} momentum flux (kg/m.s^2)

y direction of flow or velocity

x direction of momentum flux

μ absolute viscosity (kg/m.s)

$\frac{dv_y}{dx}$ velocity gradient along x (m/s/m)

Momentum Transport

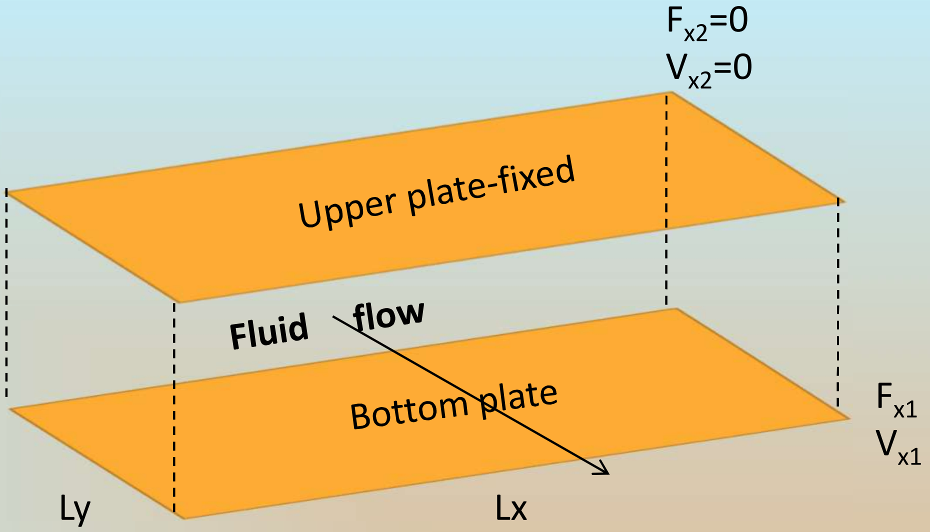
$\frac{F_y}{A}$ shear stress (N/m^2)

g_c gravitational acceleration (kg.m/N.s^2)

From Newton' s 2nd Law

$$F_y = m.a \quad \text{and} \quad a = \frac{d\bar{v}}{dt}$$

$$F_y = m\frac{d\bar{v}}{dt} \rightarrow \frac{F_y}{A} = \frac{\frac{d(m\bar{v})}{dt}}{A}$$



SUMMARY

From the three laws, an analogy was developed with respect to the ultrasimplified kinetic theory of gases.

$$\Psi = \frac{-lc}{6}\left(\frac{d\Gamma}{dx}\right) = -\delta\frac{d\Gamma}{dx}$$

where: δ – proportionality constant

$$Q = \frac{q}{A} = -k\frac{dT}{dx}$$

$$\frac{\overline{N_a}}{A} = -D\frac{dC_a}{dx}$$

$$\tau_{yx} = \frac{F_y}{A}g_c = -\mu\frac{dv_y}{dx}$$

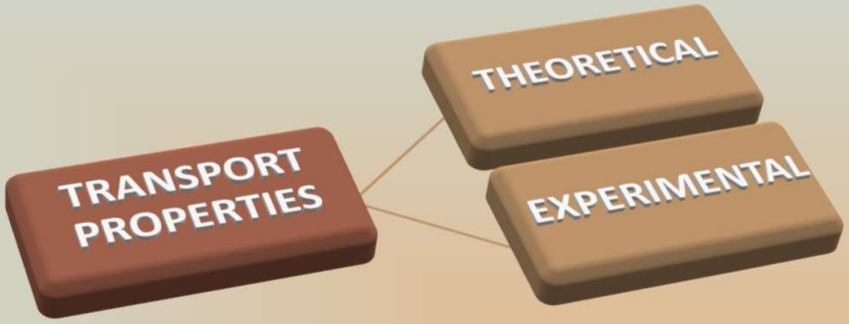
Analogous Form of Molecular Transport Equations

General	Mass	Heat	Momentum
ψ	Na	Q	τ_{yx}
δ	D	α	v
Γ	mass/vol or mol/vol	$\rho c_p T$	ρv_y
$\frac{d\Gamma}{dx}$	$\frac{dC_a}{dx}$	$\frac{d\rho c_p T}{dx}$	$\frac{d\rho v_y}{dx}$
Phenomenological Equation	Fick's law of molecular diffusion	Fourier's law of heat conduction	Newton's law of viscosity
Diffusivity	D = D	$\mathrm{k} = \rho c_p T$	$M = \rho v_y$
Ratio of Diffusivities			
	Momentum/mass	Momentum/thermal	Thermal/mass
	$\frac{v}{D} = \frac{\mu}{\rho D} = N_{sc}$	$\frac{v}{\alpha} = \frac{\mu c_p}{k} = N_{sc}$	$\frac{\alpha}{D} = \frac{k}{\rho c_p D} = \frac{N_{sc}}{N_{pr}} = N_{le}$
Dimensionless number	Schmidt number	Prandtl number	Lewis number

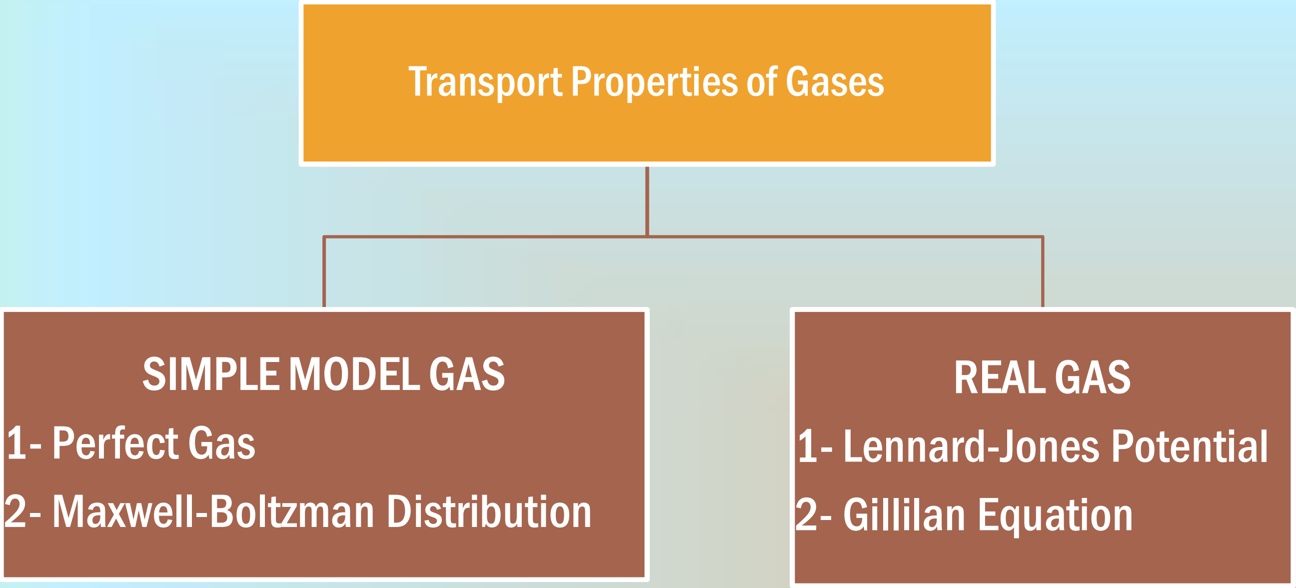
TRANSPORT PROPERTIES OF GASES, LIQUIDS, AND SOLIDS

TRANSPORT PROPERTIES

- The general term transport properties includes the **mass diffusivity, thermal conductivity, and absolute viscosity** of gases liquids, and solids.
- Obtained from the derivation of relationships for the mean path, *l* and mean speed, *c* **(theoretical)** and the consideration of forces acting between molecules **(experimental)**.
- The general term “transport properties” includes the mass diffusivity, thermal conductivity, and absolute viscosity of gases liquids, and solids.



Transport Properties of GASES



Transport Properties of Gases

SIMPLE MODEL GAS

1- Perfect Gas
2- Maxwell-Boltzman Distribution

REAL GAS

1- Lennard-Jones Potential
2- Gillilan Equation

TRANSPORT PROPERTIES OF GASES

SIMPLE MODEL GAS

- Basically, derived from the kinetic theory of gases which derives for expressions of **mean path**, ***l*** and **mean speed**, ***c*** under ideal assumptions
- Assumptions:

1. Molecule is a perfect sphere
2. No attraction and repulsion between particles
3. Volume of particle is very small compared to the volume of the space between molecules
4. Exact collision between molecules

SIMPLE MODEL GAS

Mean Speed

- By ideal gas law

$$\bar{c} = \left(\frac{3RT}{M}\right)^{1/2}$$

- By Maxwell-Boltzmann distribution

$$\bar{c} = \left(\frac{8RT}{\mu M}\right)^{1/2}$$

where:

- R = ideal gas constant
- T = absolute Temperature
- M = molecular weight

SIMPLE MODEL GAS

Mean Free Path

- By ideal gas law

$$l = \frac{RT}{\left(\frac{1}{2} + \frac{3}{2}\sqrt{2}\right)\bar{A}P\pi\sigma^2}$$

- By Maxwell-Boltzmann distribution

$$l = \frac{RT}{\left(\sqrt{2}\right)\bar{A}P\pi\sigma^2}$$

where:

- P = pressure
- T = absolute Temperature
- M = molecular weight
- $\bar{A}$ = Avogadro's
- σ = molecular diameter

Elastic-Sphere Equivalent Diameter

Gas	σ, 10^{-8} cm	Gas	σ, 10^{-8} cm
H_2	2.74	C_2H_6	5.3
Ne	3.75	O_2	3.61
CH_4	4.14	HCl	4.46
NH_3	4.43	A	3.64
H2O	4.6	CO_2	4.59
N_2	3.75	Kr	4.16
C_2H_4	4.95	Xe	4.85

SIMPLE MODEL GAS

Diffusivity Constant

- For gases with sufficiently low densities

$$P_r = \frac{P}{P_c} < 0.6, \quad T_r = \frac{T}{T_c} > 1.3$$

Mass Diffusivity

$$D = \frac{4.81 \times 10^{-24} T^{3/2}}{P\sigma^2 M^{1/2}}$$

Thermal Conductivity

- Note: $k = \alpha\rho c_p \quad \rho = \frac{PM}{RT} \quad C_p = \frac{5}{2}\left(\frac{R}{M}\right)$

$k = \frac{1.203\times10^{-2} \ (TM)^{1/2}}{\sigma^2}$ (mole basis) $k = \frac{1.203\times10^{-23} (T/M)^{1/2}}{\sigma^2}$ (mass basis)

SIMPLE MODEL GAS

For gases with sufficiently low densities

Absolute Viscosity

- Note: $\mu = \upsilon\rho \quad \rho = \frac{PM}{RT}$

$$\mu = \frac{5.79 \times 10^{-25}(MT)^{1/2}}{\sigma^2}$$

- The transport properties using the simple model gas, σ has no real physical meaning and it cannot be measured directly. Instead it must be determined from some measurable property, such as the viscosity
  - ✓ Relationship of k and μ $k = \frac{5\rho\mu}{2M}$
  - ✓ Relationship of D and μ $D = \frac{\mu}{\rho}$

REAL GASES

- Lennard-Jones Potential – valid for non-polar molecules only
- Evaluated from the concept of collision diameter

$$\sigma_{ab} = \frac{1}{2}(\sigma_a + \sigma_b)$$

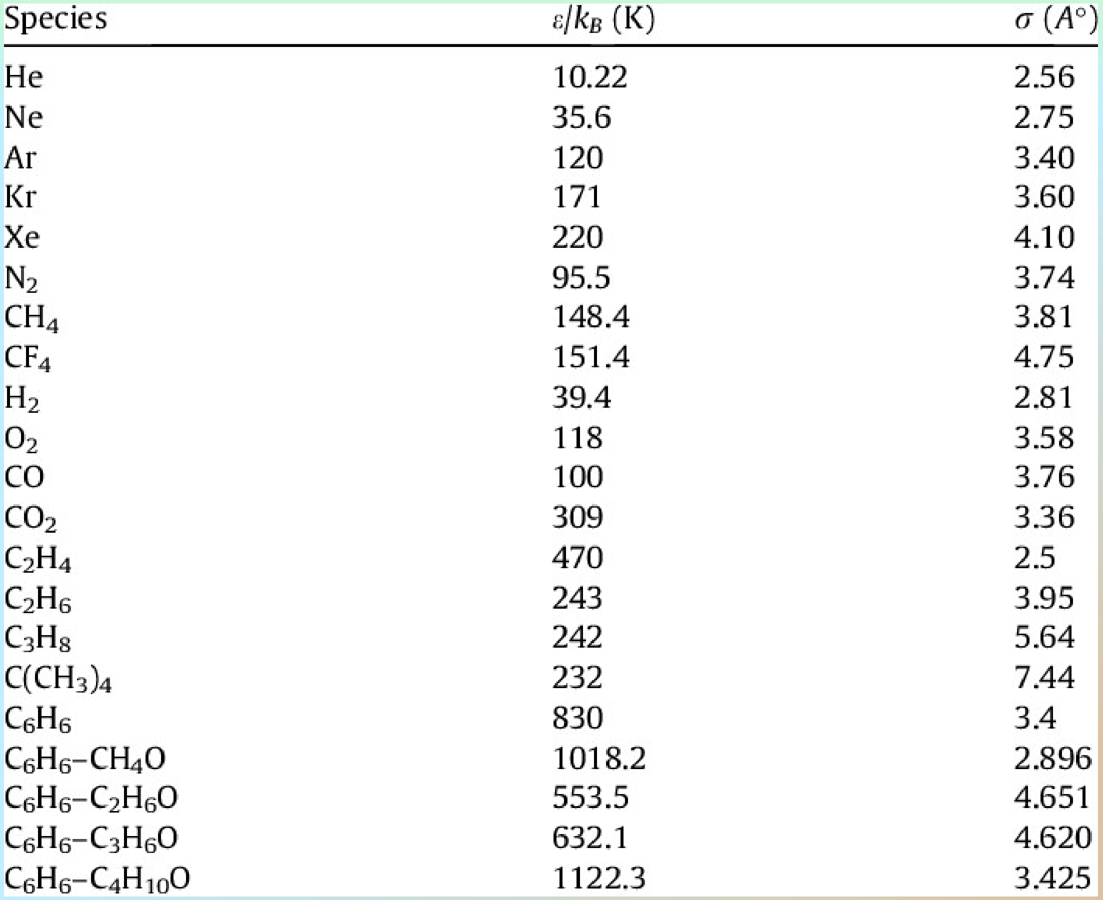
- Potential parameters are also considered

$$\frac{\varepsilon_{ab}}{k} = \sqrt{\frac{\varepsilon_a}{k}\frac{\varepsilon_b}{k}}$$; ε is the energy constant

with corresponding collision integral, Ω

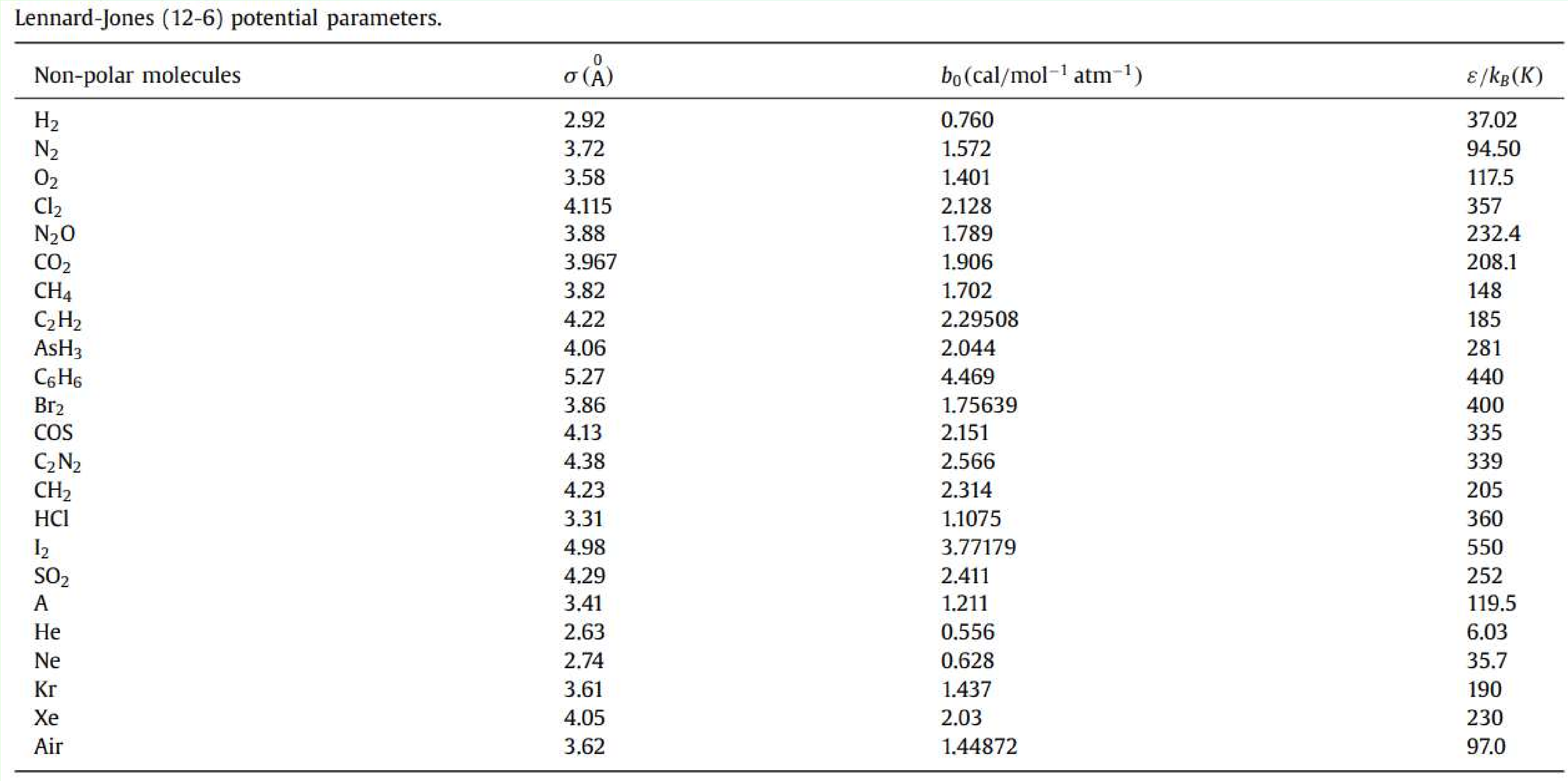
$$T^*_{ab} = \frac{kT}{\varepsilon_{ab}}$$

Constants for Lennard-Jones Potential



Species	ε/k_B (K)	σ (A°)
He	10.22	2.56
Ne	35.6	2.75
Ar	120	3.40
Kr	171	3.60
Xe	220	4.10
N_2	95.5	3.74
CH_4	148.4	3.81
CF_4	151.4	4.75
H_2	39.4	2.81
O_2	118	3.58
CO	100	3.76
CO_2	309	3.36
C_2H_4	470	2.5
C_2H_6	243	3.95
C_3H_8	242	5.64
$C(CH_3)_4$	232	7.44
C_6H_6	830	3.4
C_6H_6–CH_4O	1018.2	2.896
C_6H_6–C_2H_6O	553.5	4.651
C_6H_6–C_3H_6O	632.1	4.620
C_6H_6–$C_4H_{10}O$	1122.3	3.425

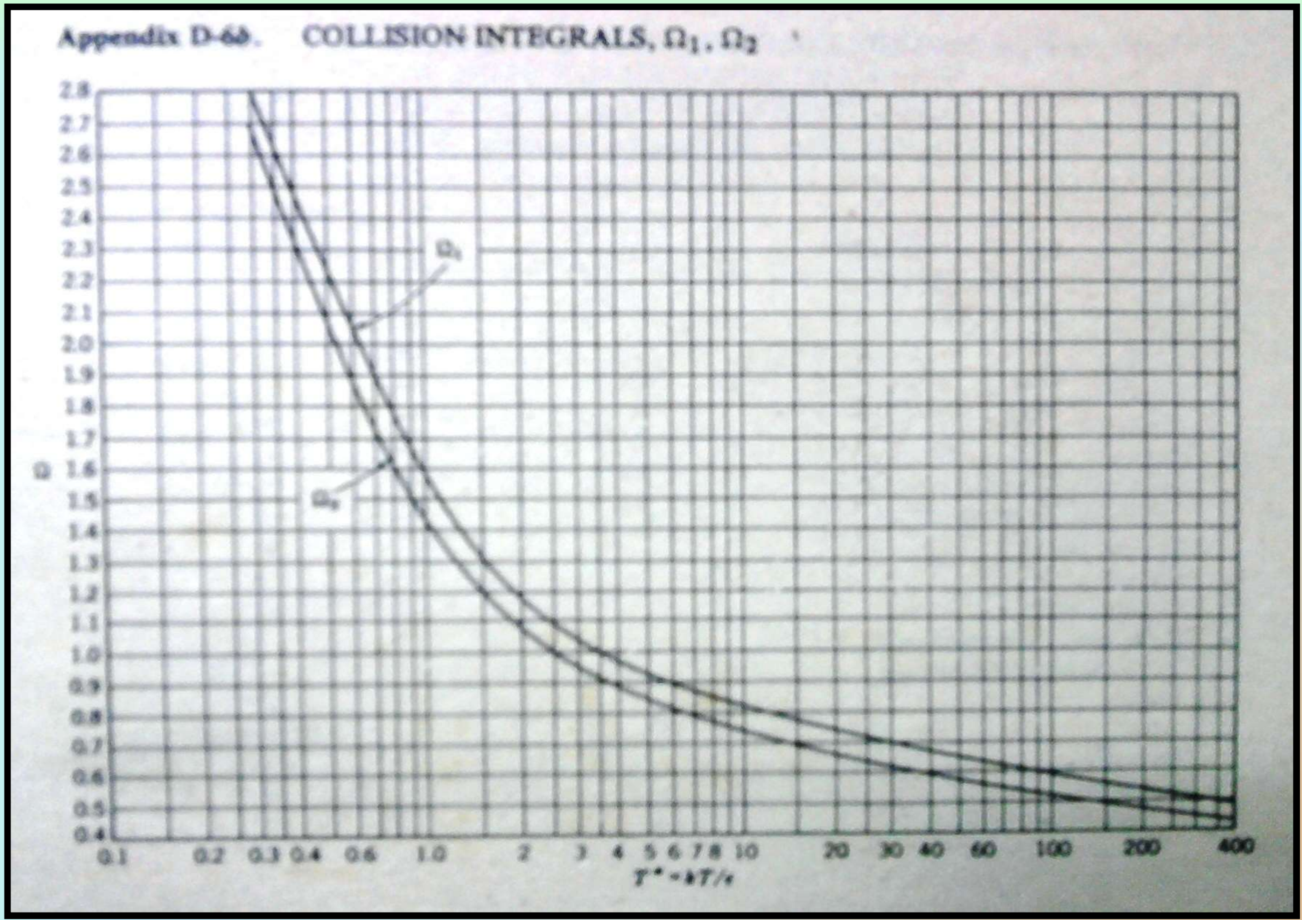
Constants for Lennard-Jones Potential



Lennard-Jones (12-6) potential parameters.

Non-polar molecules	$\sigma\,(\overset{0}{\mathrm{A}})$	$b_0(\mathrm{cal/mol^{-1}\ atm^{-1}})$	$\varepsilon/k_B(K)$
H_2	2.92	0.760	37.02
N_2	3.72	1.572	94.50
O_2	3.58	1.401	117.5
Cl_2	4.115	2.128	357
N_2O	3.88	1.789	232.4
CO_2	3.967	1.906	208.1
CH_4	3.82	1.702	148
C_2H_2	4.22	2.29508	185
AsH_3	4.06	2.044	281
C_6H_6	5.27	4.469	440
Br_2	3.86	1.75639	400
COS	4.13	2.151	335
C_2N_2	4.38	2.566	339
CH_2	4.23	2.314	205
HCl	3.31	1.1075	360
I_2	4.98	3.77179	550
SO_2	4.29	2.411	252
A	3.41	1.211	119.5
He	2.63	0.556	6.03
Ne	2.74	0.628	35.7
Kr	3.61	1.437	190
Xe	4.05	2.03	230
Air	3.62	1.44872	97.0

Collision Integrals



Appendix D-6b. COLLISION INTEGRALS, Ω_1, Ω_2

REAL GASES

Lennard-Jones Potential

- **Absolute Viscosity**

$$\mu = \frac{8.42 \times 10^{-25} (MT)^{1/2}}{\sigma^2 \Omega_1}$$

For multicomponent gas mixtures at low density

$$\mu_{mix} = \sum_{i=1}^{n} \frac{x_i \mu_i}{\sum_{j=1}^{n} x_j \Phi_{ij}}$$

$$\Phi_{ij} = \frac{1}{\sqrt{8}} \left(1 + \frac{M_i}{M_j}\right)^{-1/2} \left[1 + \left(\frac{\mu_i}{\mu_j}\right)^{1/2} \left(\frac{M_i}{M_j}\right)^{1/4}\right]^2$$

REAL GASES

Lennard-Jones Potential

Thermal Conductivity

$$k = \frac{2.63 \times 10^{-23} \left({}^{T}\!/_{M} \right)^{1/2}}{\sigma^2 \Omega_1}$$

Relationship of k and μ

For monoatomic (noble gases He, Ar, Xe) gases: $k = \frac{15R\mu}{4M}$

For polyatomic (N_2, O_2) gases: $k = \frac{15R\mu}{4M}\left(\frac{4C_v}{15} + \frac{3}{5}\right)$

REAL GASES

Lennard-Jones Potential

- <u>**Mass Diffusivity**</u>

$$D_{ab} = \frac{8.42 \times 10^{-247} \sqrt{T^3 \left(\frac{1}{2}\right)\left(\frac{1}{M_a} + \frac{1}{M_b}\right)}}{P\sigma_{ab}^2 \Omega_2}$$

For gas mixture of several components:

$$D_{1-mixtur} = \frac{1}{\frac{y_2}{D_{1-2}} + \frac{y_3}{D_{1-3}} + \cdots \ldots \ldots . + \frac{y_n}{D_{1-n}}}$$

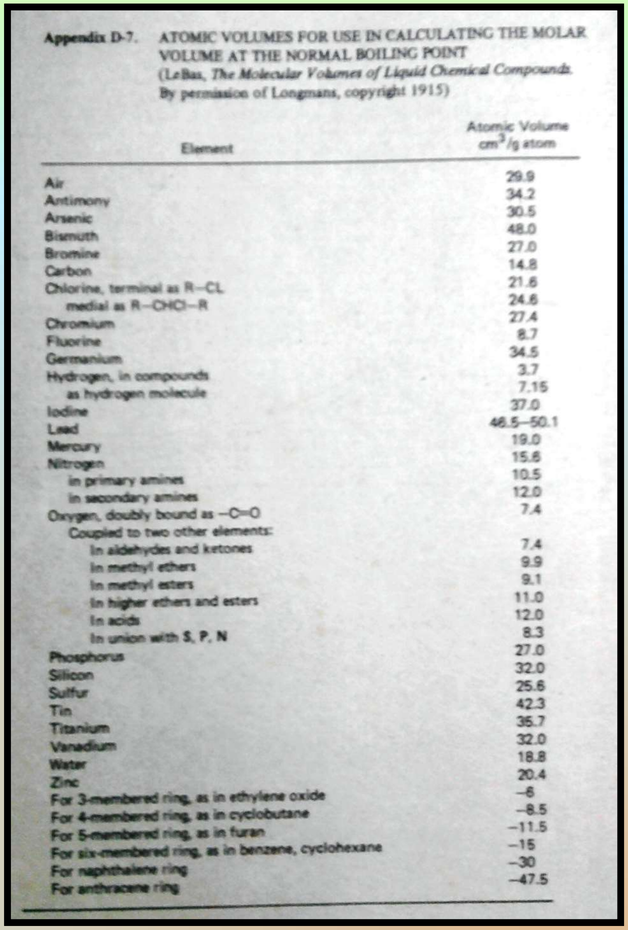
- **Gilliland Equation – valid for many gases**

$$D_{ab} = \frac{1.38 \times 10^{-7} \sqrt{T^3 \left(\frac{1}{M_a} + \frac{1}{M_b}\right)}}{P\left(V_a^{1/3} + V_b^{1/3}\right)^2}$$

where V is the molar volume.

✓ **The term $V^{1/3}$ is a measure of the molecular diameter of each constituent and is analogous to σ.**

Atomic Volumes for Use In Calculating the Molar Volume at the Normal Boiling Point



Appendix D-7. ATOMIC VOLUMES FOR USE IN CALCULATING THE MOLAR VOLUME AT THE NORMAL BOILING POINT
(LeBas, *The Molecular Volumes of Liquid Chemical Compounds.* By permission of Longmans, copyright 1915)

Element	Atomic Volume cm^3/g atom
Air	29.9
Antimony	34.2
Arsenic	30.5
Bismuth	48.0
Bromine	27.0
Carbon	14.8
Chlorine, terminal as R–CL	21.6
medial as R–CHCl–R	24.6
Chromium	27.4
Fluorine	8.7
Germanium	34.5
Hydrogen, in compounds	3.7
as hydrogen molecule	7.15
Iodine	37.0
Lead	46.5–50.1
Mercury	19.0
Nitrogen	15.6
in primary amines	10.5
in secondary amines	12.0
Oxygen, doubly bound as –C=O	7.4
Coupled to two other elements:	
In aldehydes and ketones	7.4
In methyl ethers	9.9
In methyl esters	9.1
In higher ethers and esters	11.0
In acids	12.0
In union with S, P, N	8.3
Phosphorus	27.0
Silicon	32.0
Sulfur	25.6
Tin	42.3
Titanium	35.7
Vanadium	32.0
Water	18.8
Zinc	20.4
For 3-membered ring, as in ethylene oxide	–6
For 4-membered ring, as in cyclobutane	–8.5
For 5-membered ring, as in furan	–11.5
For six-membered ring, as in benzene, cyclohexane	–15
For naphthalene ring	–30
For anthracene ring	–47.5

TRANSPORT PROPERTIES OF LIQUIDS

- The kinetic theory of liquids is not well organized and no single theory has been generally accepted.
- Liquids have complex structure and since the molecules are close together, therefor the intermolecular forces are strong.

EYRING SIMPLE "HOLE" MODEL

- Molecular Migration

  A molecule may migrate into a neighboring hole, provided that enough force is available to overcome IMFA

- Molecular Vibration/Collision

  The molecule vibrates within a limited space confined by the forces of neighboring molecules.

EYRING SIMPLE “HOLE” MODEL

- Applicable for short temperature ranges.

Absolute Viscosity

$$\mu = Ce^{\left(\frac{B}{RT}\right)}$$

- When no viscosity data is available:

$$\mu = \frac{4 \times 10^{-10} e^{\frac{3.8T_b}{T}}}{V}$$

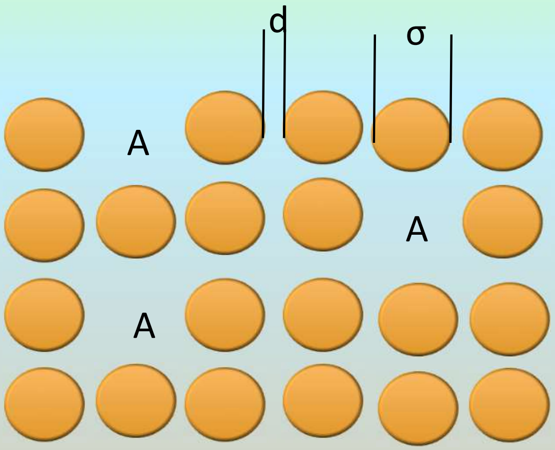
where:

T = temperature, K

B and C are constants

V = molar volume, m^3/mol

T_b = normal boiling point



To cause “flow” in a liquid, a relatively large force must be applied to overcome the strong IMFA tending to hold molecules in place

EYRING SIMPLE “HOLE” MODEL

Applicable for short temperature ranges.

Thermal Conductivity

$$k = 3.59 \times 10^{-9} C_p \rho \left(\frac{\rho}{M}\right)^{1/3}$$

where:

K = thermal conductivity, J/s-m-ºC

C_p = heat capacity, J/kg-ºC

M = molecular weight, kg/mol

ρ = density, kg/m^3

Mass Diffusivity

$$\frac{T}{D\mu} = \frac{1}{AC} = F$$

where:

D = mass diffusivity m^2/s

F = function of molar volume

TRANSPORT PROPERTIES OF SOLIDS

Structures

1. Crystalline – atoms are arranged in a regular pattern called a crystal lattice as in metals and salts
2. Amorphous – do not have a crystal lattice although they do have some order to their arrangement of atoms, e.g. glass, plastics, paint, rubber

Diffusivities in solids at 1 atm.

SYSTEM	TEMPERATURE, °C	D, m^2/s
H_2 in Ni	400	0.95×10^{-10}
H_2 in Pd	400	0.316×10^{-6}
O_2 in Ag	400	0.32×10^{-12}
CO in mild steel	400	0.67×10^{-8}
He in SiO_2	400	0.81×10^{-16}
Au in Ag	870	0.43×10^{-13}
Ni in Cu	400	0.23×10^{-12}

SUMMARY of TRANSPORT PROPERTIES

Determination of Gas Phase Diffusivity

1. Equations and Correlations for Gas Diffusivity: Tables 5-13, 5-14, 5-15, 5-16 (PCEH 7th ed.)
2. Diffusivities of pairs of gases and vapors: Table 2-371 (PCEH 7th ed.)

Determination of Liquid Phase Diffusivity

1. Correlations and diffusivities of dilute, binary mixture of non-electrolyte liquids: Table 5-18 (PCEH 7th ed.)
2. Diffusivities of Liquids at 25 ° C: Table 2-372 (PCEH 7th ed.)

Determination of Viscosities of Gases and Liquids

- Table 2-364 and Table 2-365 (PCEH 7th ed.)

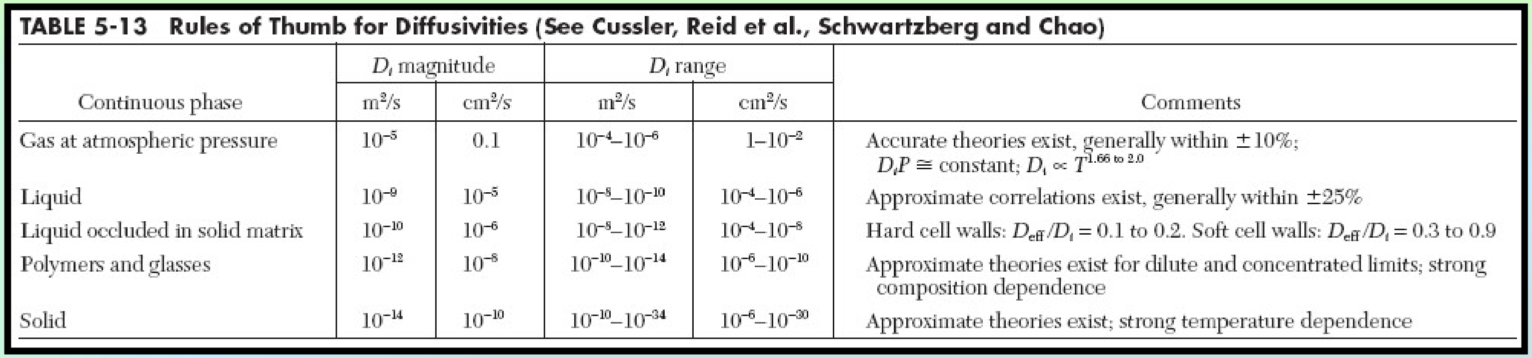


TABLE 5-13 Rules of Thumb for Diffusivities (See Cussler, Reid et al., Schwartzberg and Chao)

Continuous phase	D_i magnitude		D_i range		Comments
	m²/s	cm²/s	m²/s	cm²/s	
Gas at atmospheric pressure	10^{-5}	0.1	10^{-4}–10^{-6}	1–10^{-2}	Accurate theories exist, generally within ±10%; $D_iP \cong$ constant; $D_i \propto T^{1.66 \text{ to } 2.0}$
Liquid	10^{-9}	10^{-5}	10^{-8}–10^{-10}	10^{-4}–10^{-6}	Approximate correlations exist, generally within ±25%
Liquid occluded in solid matrix	10^{-10}	10^{-6}	10^{-8}–10^{-12}	10^{-4}–10^{-8}	Hard cell walls: $D_{eff}/D_i = 0.1$ to 0.2. Soft cell walls: $D_{eff}/D_i = 0.3$ to 0.9
Polymers and glasses	10^{-12}	10^{-8}	10^{-10}–10^{-14}	10^{-6}–10^{-10}	Approximate theories exist for dilute and concentrated limits; strong composition dependence
Solid	10^{-14}	10^{-10}	10^{-10}–10^{-34}	10^{-6}–10^{-30}	Approximate theories exist; strong temperature dependence

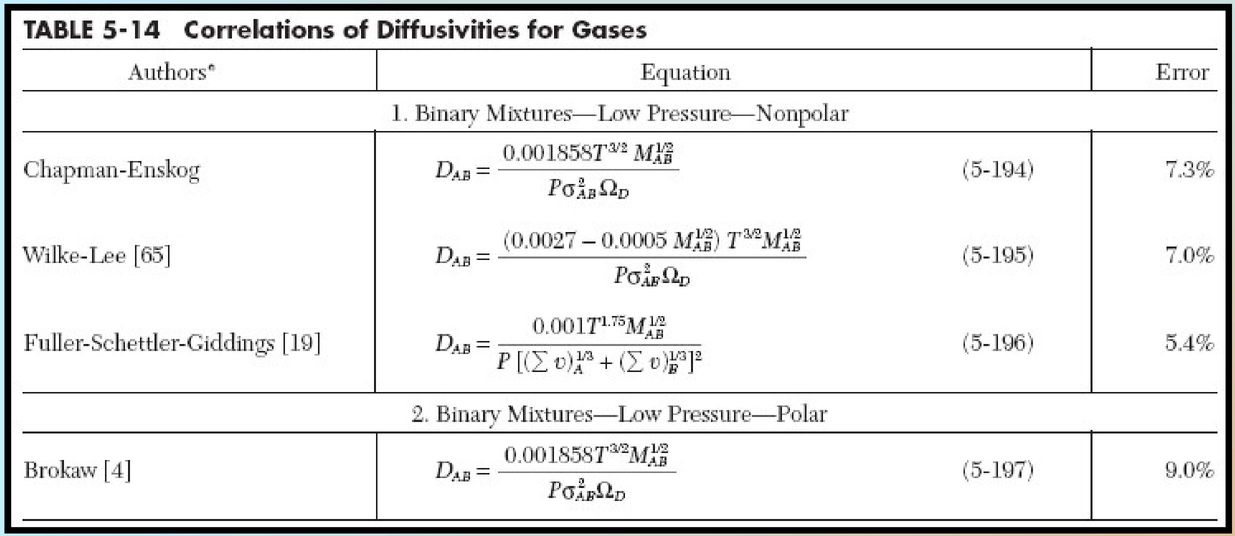


TABLE 5-14 Correlations of Diffusivities for Gases

Authors*	Equation		Error
1. Binary Mixtures—Low Pressure—Nonpolar			
Chapman-Enskog	$D_{AB} = \dfrac{0.001858 T^{3/2} M_{AB}^{1/2}}{P \sigma_{AB}^2 \Omega_D}$	(5-194)	7.3%
Wilke-Lee [65]	$D_{AB} = \dfrac{(0.0027 - 0.0005\, M_{AB}^{1/2})\, T^{3/2} M_{AB}^{1/2}}{P \sigma_{AB}^2 \Omega_D}$	(5-195)	7.0%
Fuller-Schettler-Giddings [19]	$D_{AB} = \dfrac{0.001 T^{1.75} M_{AB}^{1/2}}{P\,[(\sum v)_A^{1/3} + (\sum v)_B^{1/3}]^2}$	(5-196)	5.4%
2. Binary Mixtures—Low Pressure—Polar			
Brokaw [4]	$D_{AB} = \dfrac{0.001858 T^{3/2} M_{AB}^{1/2}}{P \sigma_{AB}^2 \Omega_D}$	(5-197)	9.0%

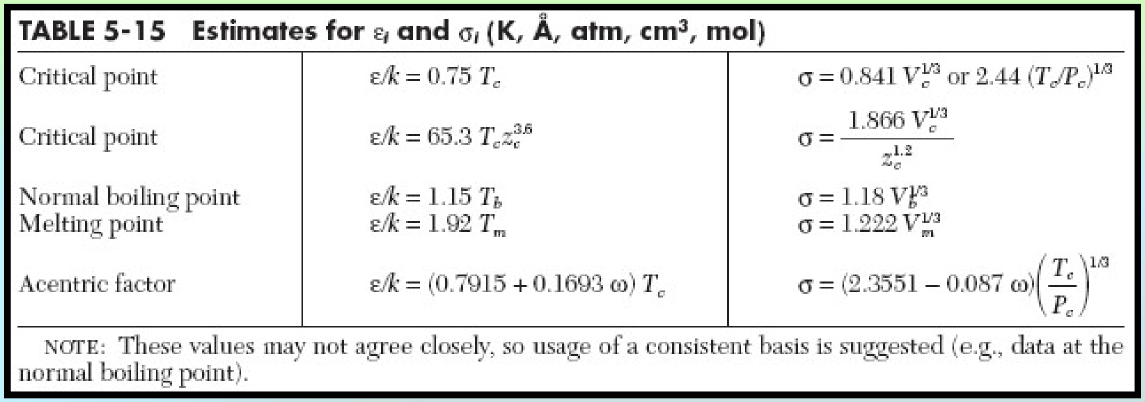


TABLE 5-15 Estimates for ε_i and σ_i (K, Å, atm, cm³, mol)

Critical point	$\varepsilon/k = 0.75\ T_c$	$\sigma = 0.841\ V_c^{1/3}$ or $2.44\ (T_c/P_c)^{1/3}$
Critical point	$\varepsilon/k = 65.3\ T_c z_c^{3.6}$	$\sigma = \dfrac{1.866\ V_c^{1/3}}{z_c^{1.2}}$
Normal boiling point	$\varepsilon/k = 1.15\ T_b$	$\sigma = 1.18\ V_b^{1/3}$
Melting point	$\varepsilon/k = 1.92\ T_m$	$\sigma = 1.222\ V_m^{1/3}$
Acentric factor	$\varepsilon/k = (0.7915 + 0.1693\ \omega)\ T_c$	$\sigma = (2.3551 - 0.087\ \omega)\left(\dfrac{T_c}{P_c}\right)^{1/3}$

NOTE: These values may not agree closely, so usage of a consistent basis is suggested (e.g., data at the normal boiling point).

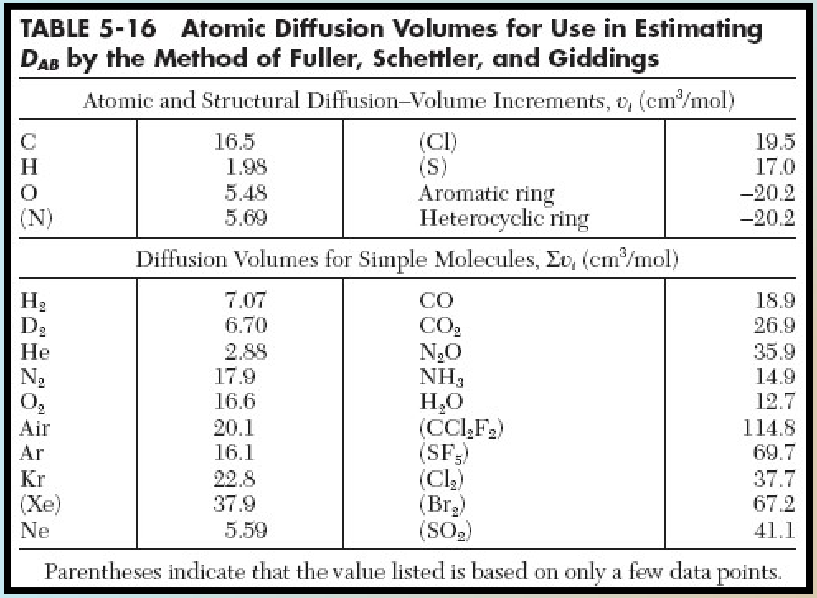


TABLE 5-16 Atomic Diffusion Volumes for Use in Estimating D_{AB} by the Method of Fuller, Schettler, and Giddings

Atomic and Structural Diffusion–Volume Increments, v_i (cm³/mol)			
C	16.5	(Cl)	19.5
H	1.98	(S)	17.0
O	5.48	Aromatic ring	−20.2
(N)	5.69	Heterocyclic ring	−20.2
Diffusion Volumes for Simple Molecules, Σv_i (cm³/mol)			
H_2	7.07	CO	18.9
D_2	6.70	CO_2	26.9
He	2.88	N_2O	35.9
N_2	17.9	NH_3	14.9
O_2	16.6	H_2O	12.7
Air	20.1	(CCl_2F_2)	114.8
Ar	16.1	(SF_6)	69.7
Kr	22.8	(Cl_2)	37.7
(Xe)	37.9	(Br_2)	67.2
Ne	5.59	(SO_2)	41.1

Parentheses indicate that the value listed is based on only a few data points.

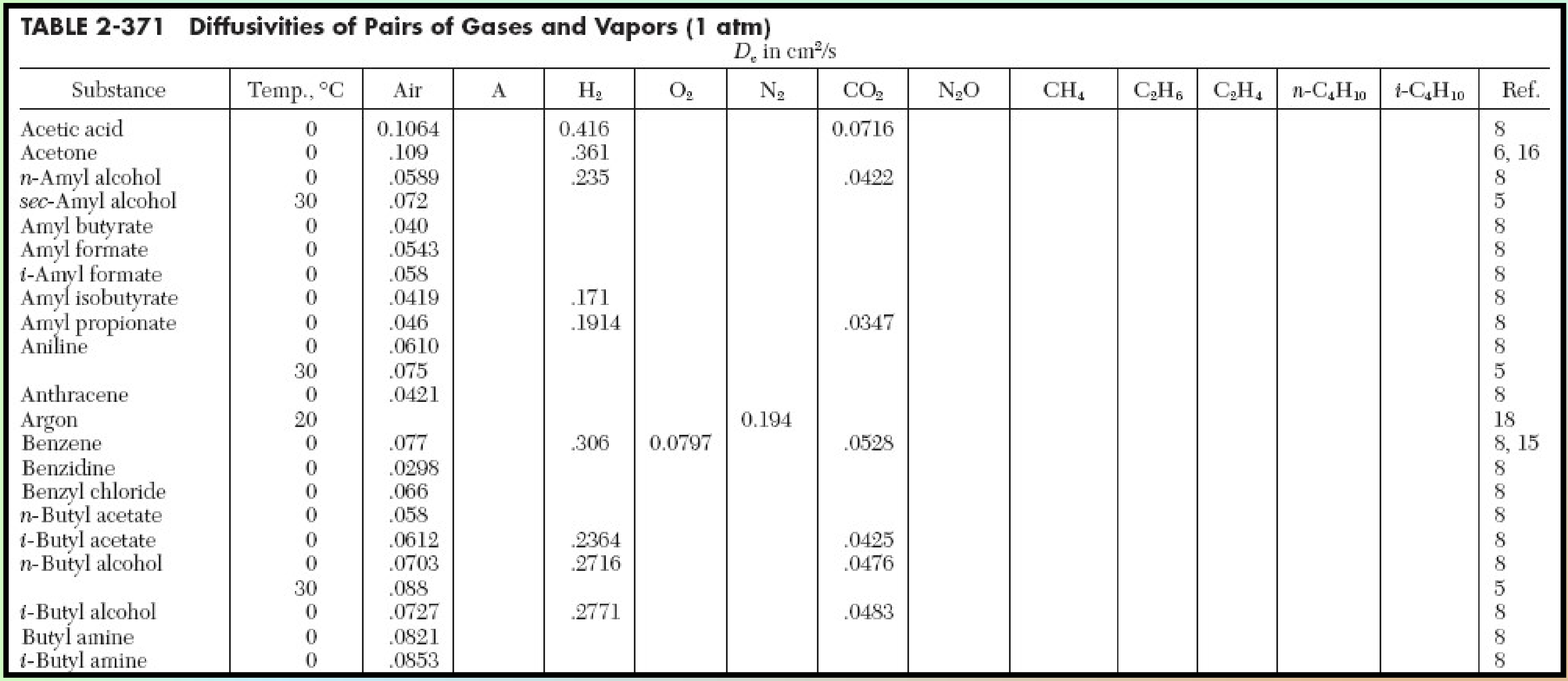


TABLE 2-371 Diffusivities of Pairs of Gases and Vapors (1 atm)

D_v in cm^2/s

Substance	Temp., °C	Air	A	H_2	O_2	N_2	CO_2	N_2O	CH_4	C_2H_6	C_2H_4	$n\text{-}C_4H_{10}$	$i\text{-}C_4H_{10}$	Ref.
Acetic acid	0	0.1064		0.416			0.0716							8
Acetone	0	.109		.361										6, 16
n-Amyl alcohol	0	.0589		.235			.0422							8
sec-Amyl alcohol	30	.072												5
Amyl butyrate	0	.040												8
Amyl formate	0	.0543												8
i-Amyl formate	0	.058												8
Amyl isobutyrate	0	.0419		.171										8
Amyl propionate	0	.046		.1914			.0347							8
Aniline	0	.0610												8
	30	.075												5
Anthracene	0	.0421												8
Argon	20					0.194								18
Benzene	0	.077		.306	0.0797		.0528							8, 15
Benzidine	0	.0298												8
Benzyl chloride	0	.066												8
n-Butyl acetate	0	.058												8
i-Butyl acetate	0	.0612		.2364			.0425							8
n-Butyl alcohol	0	.0703		.2716			.0476							8
	30	.088												5
i-Butyl alcohol	0	.0727		.2771			.0483							8
Butyl amine	0	.0821												8
i-Butyl amine	0	.0853												8

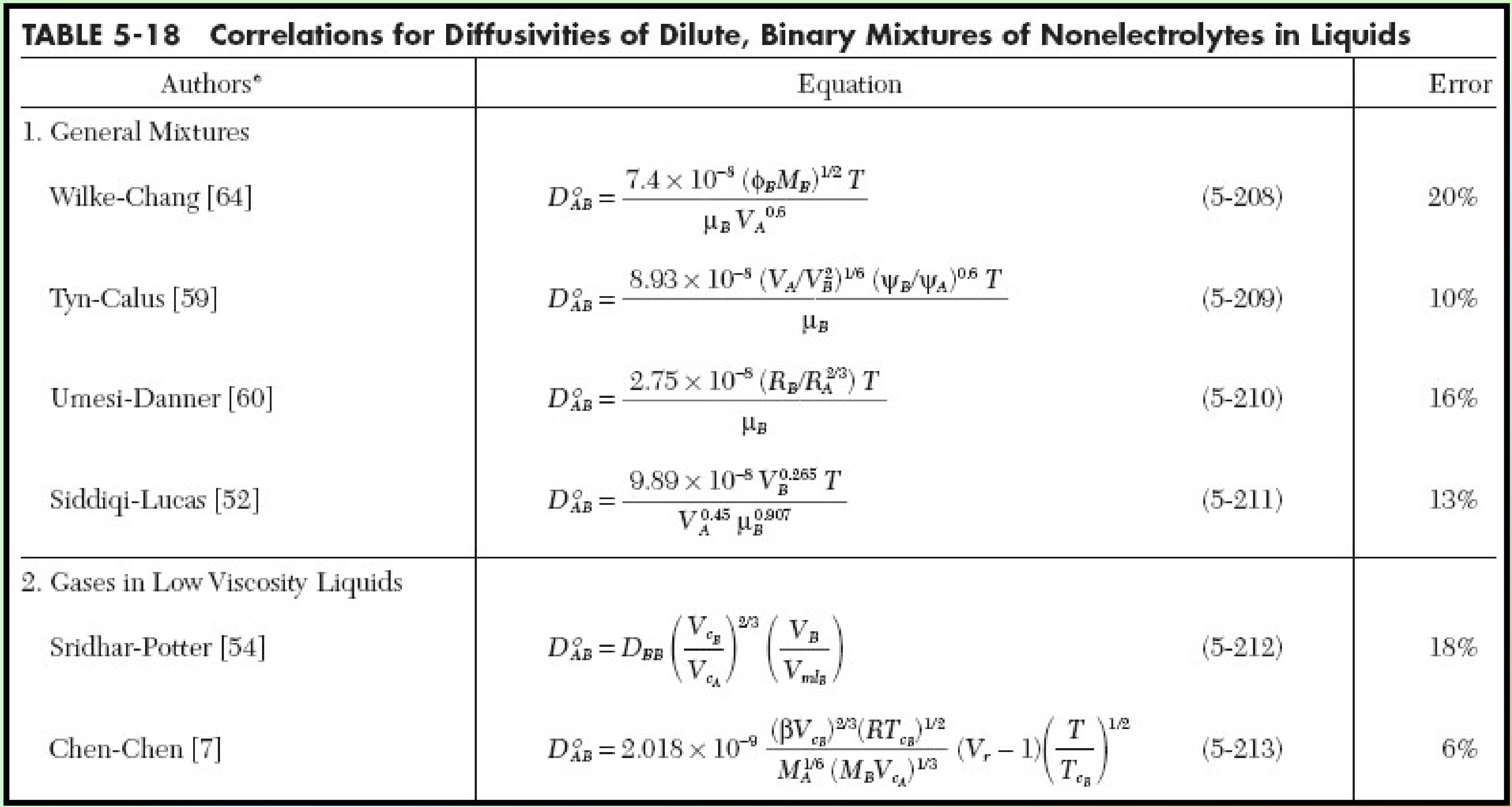


TABLE 5-18 Correlations for Diffusivities of Dilute, Binary Mixtures of Nonelectrolytes in Liquids

Authors*	Equation		Error
1. General Mixtures			
Wilke-Chang [64]	$D^{\circ}_{AB} = \dfrac{7.4 \times 10^{-8} (\phi_B M_B)^{1/2} T}{\mu_B V_A^{0.6}}$	(5-208)	20%
Tyn-Calus [59]	$D^{\circ}_{AB} = \dfrac{8.93 \times 10^{-8} (V_A/V_B^2)^{1/6} (\psi_B/\psi_A)^{0.6} T}{\mu_B}$	(5-209)	10%
Umesi-Danner [60]	$D^{\circ}_{AB} = \dfrac{2.75 \times 10^{-8} (R_B/R_A^{2/3}) T}{\mu_B}$	(5-210)	16%
Siddiqi-Lucas [52]	$D^{\circ}_{AB} = \dfrac{9.89 \times 10^{-8} V_B^{0.265} T}{V_A^{0.45} \mu_B^{0.907}}$	(5-211)	13%
2. Gases in Low Viscosity Liquids			
Sridhar-Potter [54]	$D^{\circ}_{AB} = D_{BB} \left(\dfrac{V_{c_B}}{V_{c_A}}\right)^{2/3} \left(\dfrac{V_B}{V_{ml_B}}\right)$	(5-212)	18%
Chen-Chen [7]	$D^{\circ}_{AB} = 2.018 \times 10^{-9} \dfrac{(\beta V_{c_B})^{2/3} (RT_{c_B})^{1/2}}{M_A^{1/6} (M_B V_{c_A})^{1/3}} (V_r - 1) \left(\dfrac{T}{T_{c_B}}\right)^{1/2}$	(5-213)	6%

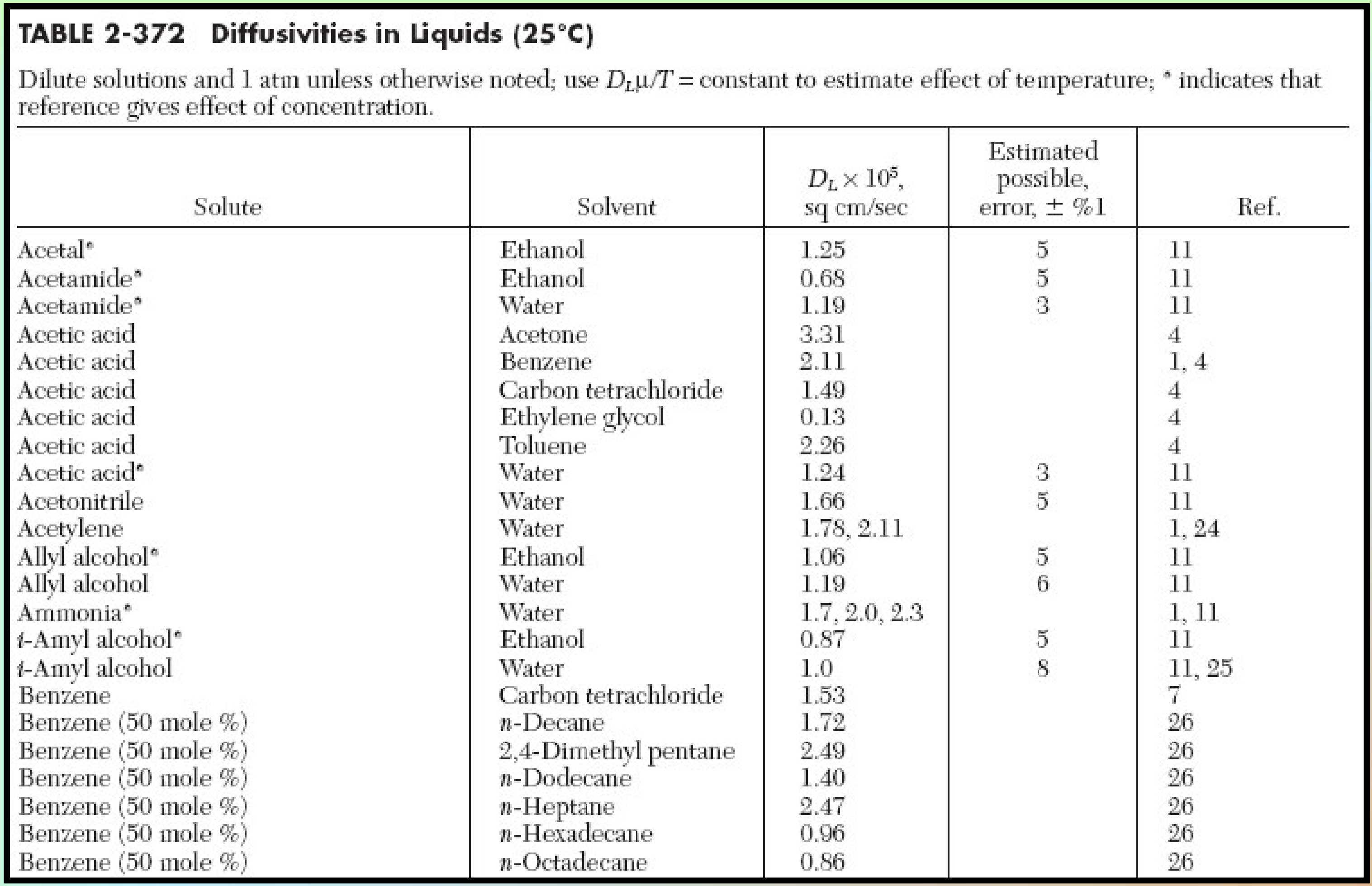


TABLE 2-372 Diffusivities in Liquids (25°C)

Dilute solutions and 1 atm unless otherwise noted; use $D_L\mu/T$ = constant to estimate effect of temperature; * indicates that reference gives effect of concentration.

Solute	Solvent	$D_L \times 10^5$, sq cm/sec	Estimated possible, error, ± %1	Ref.
Acetal*	Ethanol	1.25	5	11
Acetamide*	Ethanol	0.68	5	11
Acetamide*	Water	1.19	3	11
Acetic acid	Acetone	3.31		4
Acetic acid	Benzene	2.11		1, 4
Acetic acid	Carbon tetrachloride	1.49		4
Acetic acid	Ethylene glycol	0.13		4
Acetic acid	Toluene	2.26		4
Acetic acid*	Water	1.24	3	11
Acetonitrile	Water	1.66	5	11
Acetylene	Water	1.78, 2.11		1, 24
Allyl alcohol*	Ethanol	1.06	5	11
Allyl alcohol	Water	1.19	6	11
Ammonia*	Water	1.7, 2.0, 2.3		1, 11
t-Amyl alcohol*	Ethanol	0.87	5	11
t-Amyl alcohol	Water	1.0	8	11, 25
Benzene	Carbon tetrachloride	1.53		7
Benzene (50 mole %)	*n*-Decane	1.72		26
Benzene (50 mole %)	2,4-Dimethyl pentane	2.49		26
Benzene (50 mole %)	*n*-Dodecane	1.40		26
Benzene (50 mole %)	*n*-Heptane	2.47		26
Benzene (50 mole %)	*n*-Hexadecane	0.96		26
Benzene (50 mole %)	*n*-Octadecane	0.86		26

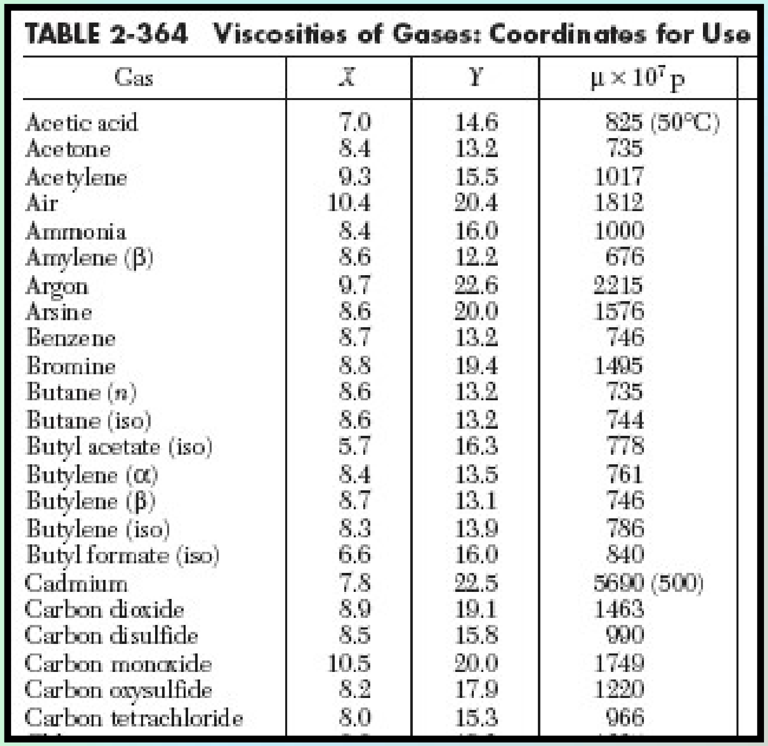


TABLE 2-364 Viscosities of Gases: Coordinates for Use

Gas	X	Y	μ × 10⁷ p
Acetic acid	7.0	14.6	825 (50°C)
Acetone	8.4	13.2	735
Acetylene	9.3	15.5	1017
Air	10.4	20.4	1812
Ammonia	8.4	16.0	1000
Amylene (β)	8.6	12.2	676
Argon	9.7	22.6	2215
Arsine	8.6	20.0	1576
Benzene	8.7	13.2	746
Bromine	8.8	19.4	1495
Butane (*n*)	8.6	13.2	735
Butane (iso)	8.6	13.2	744
Butyl acetate (iso)	5.7	16.3	778
Butylene (α)	8.4	13.5	761
Butylene (β)	8.7	13.1	746
Butylene (iso)	8.3	13.9	786
Butyl formate (iso)	6.6	16.0	840
Cadmium	7.8	22.5	5690 (500)
Carbon dioxide	8.9	19.1	1463
Carbon disulfide	8.5	15.8	990
Carbon monoxide	10.5	20.0	1749
Carbon oxysulfide	8.2	17.9	1220
Carbon tetrachloride	8.0	15.3	966

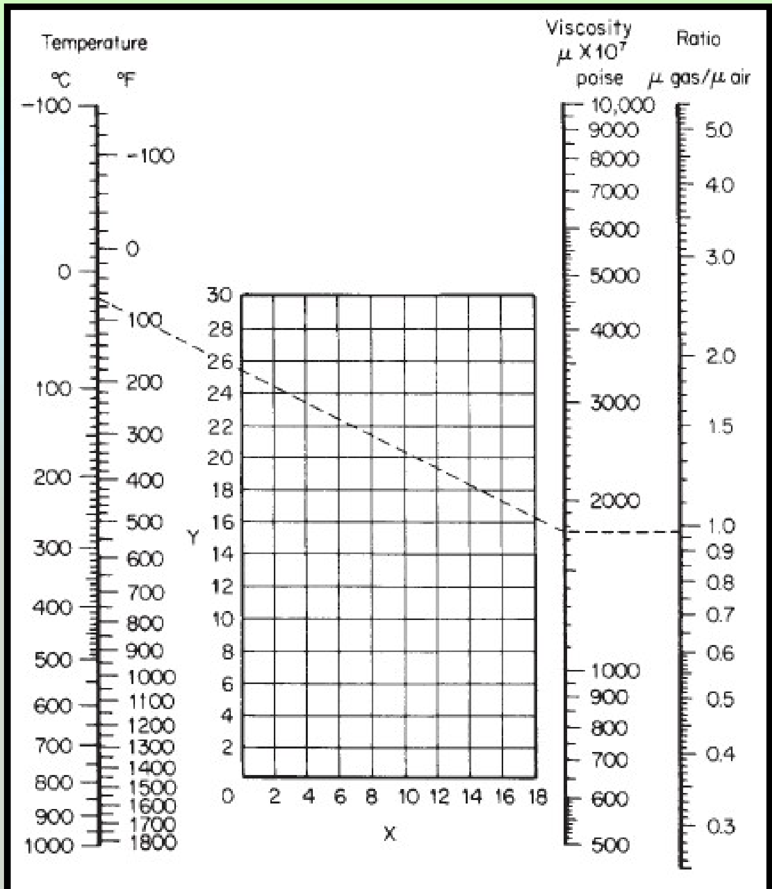


FIG. 2-32 Nomograph for determining (*a*) absolute viscosity of a gas as a function of temperature near ambient pressure and (*b*) relative viscosity of a gas compared with air. For coordinates see Table 2-364. To convert poises to pascal-seconds, multiply by 0.1. [*From Beerman,* Meas. Control, *154–157 (June 1982).*]

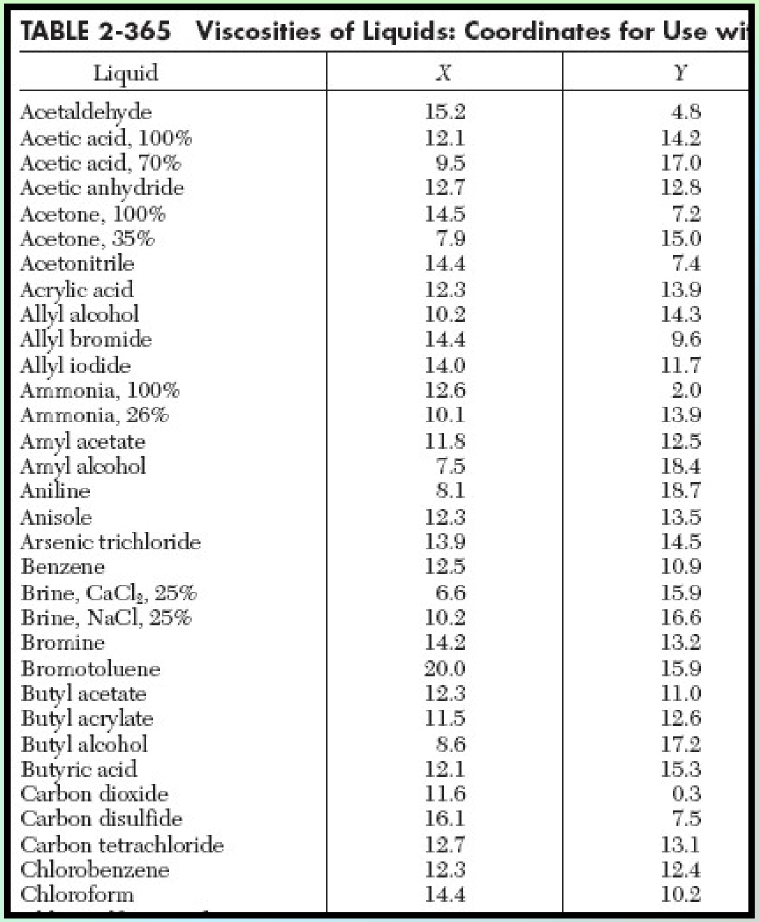


TABLE 2-365 Viscosities of Liquids: Coordinates for Use wi

Liquid	X	Y
Acetaldehyde	15.2	4.8
Acetic acid, 100%	12.1	14.2
Acetic acid, 70%	9.5	17.0
Acetic anhydride	12.7	12.8
Acetone, 100%	14.5	7.2
Acetone, 35%	7.9	15.0
Acetonitrile	14.4	7.4
Acrylic acid	12.3	13.9
Allyl alcohol	10.2	14.3
Allyl bromide	14.4	9.6
Allyl iodide	14.0	11.7
Ammonia, 100%	12.6	2.0
Ammonia, 26%	10.1	13.9
Amyl acetate	11.8	12.5
Amyl alcohol	7.5	18.4
Aniline	8.1	18.7
Anisole	12.3	13.5
Arsenic trichloride	13.9	14.5
Benzene	12.5	10.9
Brine, $CaCl_2$, 25%	6.6	15.9
Brine, NaCl, 25%	10.2	16.6
Bromine	14.2	13.2
Bromotoluene	20.0	15.9
Butyl acetate	12.3	11.0
Butyl acrylate	11.5	12.6
Butyl alcohol	8.6	17.2
Butyric acid	12.1	15.3
Carbon dioxide	11.6	0.3
Carbon disulfide	16.1	7.5
Carbon tetrachloride	12.7	13.1
Chlorobenzene	12.3	12.4
Chloroform	14.4	10.2

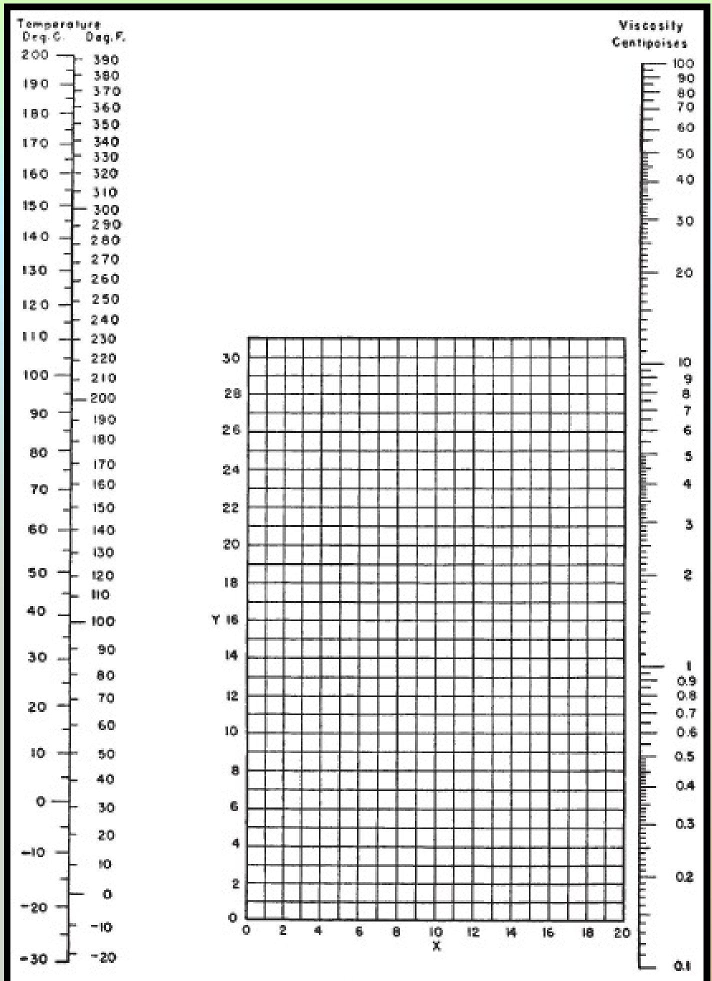


FIG. 2-33 Nomograph for viscosities of liquids at 1 atm. For coordinates see Table 2-365. To convert centipoises to pascal-seconds, multiply by 0.001.

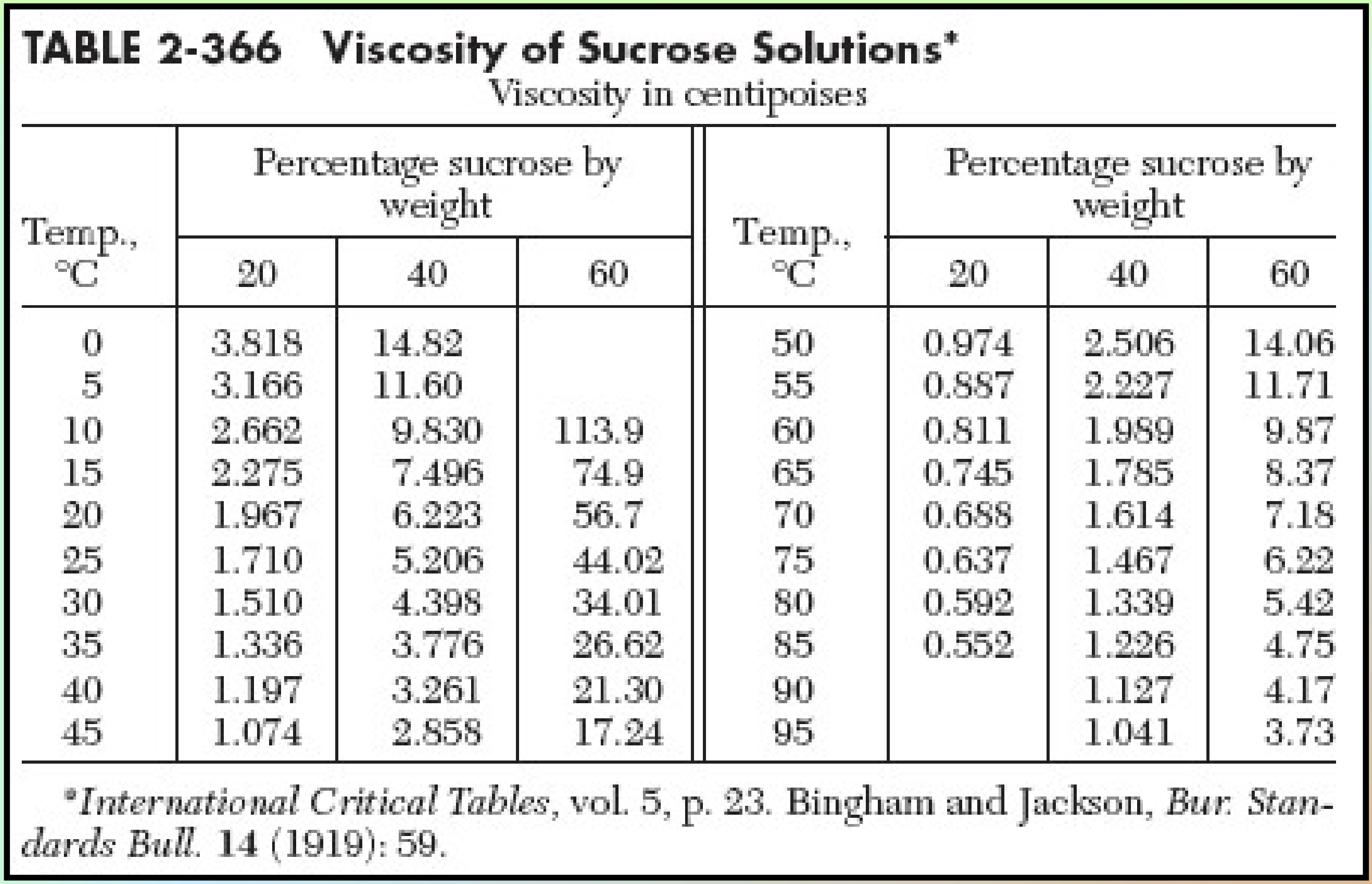
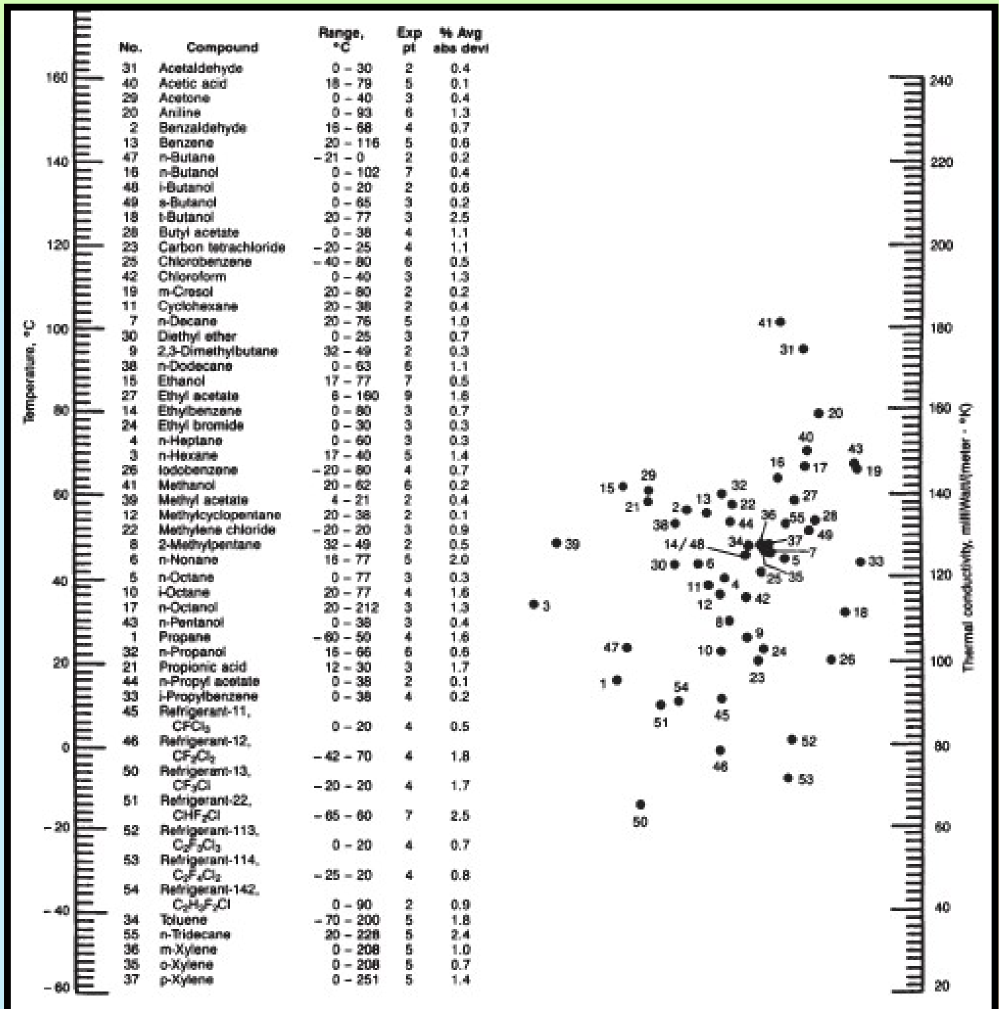


TABLE 2-366 Viscosity of Sucrose Solutions*

Viscosity in centipoises

Temp., °C	Percentage sucrose by weight			Temp., °C	Percentage sucrose by weight		
	20	40	60		20	40	60
0	3.818	14.82		50	0.974	2.506	14.06
5	3.166	11.60		55	0.887	2.227	11.71
10	2.662	9.830	113.9	60	0.811	1.989	9.87
15	2.275	7.496	74.9	65	0.745	1.785	8.37
20	1.967	6.223	56.7	70	0.688	1.614	7.18
25	1.710	5.206	44.02	75	0.637	1.467	6.22
30	1.510	4.398	34.01	80	0.592	1.339	5.42
35	1.336	3.776	26.62	85	0.552	1.226	4.75
40	1.197	3.261	21.30	90		1.127	4.17
45	1.074	2.858	17.24	95		1.041	3.73

**International Critical Tables*, vol. 5, p. 23. Bingham and Jackson, *Bur. Standards Bull.* 14 (1919): 59.



No.	Compound	Range, °C	Exp pt	% Avg abs devi
31	Acetaldehyde	0 – 30	2	0.4
40	Acetic acid	18 – 79	5	0.1
29	Acetone	0 – 40	3	0.4
20	Aniline	0 – 93	6	1.3
2	Benzaldehyde	16 – 68	4	0.7
13	Benzene	20 – 116	5	0.6
47	n-Butane	− 21 – 0	2	0.2
16	n-Butanol	0 – 102	7	0.4
48	i-Butanol	0 – 20	2	0.6
49	s-Butanol	0 – 65	3	0.2
18	t-Butanol	20 – 77	3	2.5
28	Butyl acetate	0 – 38	4	1.1
23	Carbon tetrachloride	− 20 – 25	4	1.1
25	Chlorobenzene	− 40 – 80	6	0.5
42	Chloroform	0 – 40	3	1.3
19	m-Cresol	20 – 80	2	0.2
11	Cyclohexane	20 – 38	2	0.4
7	n-Decane	20 – 76	5	1.0
30	Diethyl ether	0 – 25	3	0.7
9	2,3-Dimethylbutane	32 – 49	2	0.3
38	n-Dodecane	0 – 63	6	1.1
15	Ethanol	17 – 77	7	0.5
27	Ethyl acetate	6 – 160	9	1.6
14	Ethylbenzene	0 – 80	3	0.7
24	Ethyl bromide	0 – 30	3	0.3
4	n-Heptane	0 – 60	3	0.3
3	n-Hexane	17 – 40	5	1.4
26	Iodobenzene	− 20 – 80	4	0.7
41	Methanol	20 – 62	6	0.2
39	Methyl acetate	4 – 21	2	0.4
12	Methylcyclopentane	20 – 38	2	0.1
22	Methylene chloride	− 20 – 20	3	0.9
8	2-Methylpentane	32 – 49	2	0.5
6	n-Nonane	16 – 77	5	2.0
5	n-Octane	0 – 77	3	0.3
10	i-Octane	20 – 77	4	1.6
17	n-Octanol	20 – 212	3	1.3
43	n-Pentanol	0 – 38	3	0.4
1	Propane	− 60 – 50	4	1.6
32	n-Propanol	16 – 66	6	0.6
21	Propionic acid	12 – 30	3	1.7
44	n-Propyl acetate	0 – 38	2	0.1
33	i-Propylbenzene	0 – 38	4	0.2
45	Refrigerant-11, $CFCl_3$	0 – 20	4	0.5
46	Refrigerant-12, CF_2Cl_2	− 42 – 70	4	1.8
50	Refrigerant-13, CF_3Cl	− 20 – 20	4	1.7
51	Refrigerant-22, CHF_2Cl	− 65 – 60	7	2.5
52	Refrigerant-113, $C_2F_3Cl_3$	0 – 20	4	0.7
53	Refrigerant-114, $C_2F_4Cl_2$	− 25 – 20	4	0.8
54	Refrigerant-142, $C_2H_3F_2Cl$	0 – 90	2	0.9
34	Toluene	− 70 – 200	5	1.8
55	n-Tridecane	20 – 228	5	2.4
36	m-Xylene	0 – 208	5	1.0
35	o-Xylene	0 – 208	5	0.7
37	p-Xylene	0 – 251	5	1.4

FIG. 2-34 and TABLE 2-367 Nomograph (*right*) for thermal conductivity of organic liquids.