CHEN3001-TP
Mass Transport - 4

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Outline

- Convective mass transfer
  - What is convective mass transfer?
  - Concentration boundary layer – External flow
    - Momentum, thermal and mass diffusivity
    - Equations for Sherwood number
    - Reynolds analogy and Chilton-Colburn analogy
    - Classroom examples
  - Similarity between h.t. and m.t. equations
  - Classroom examples

Convective mass transfer

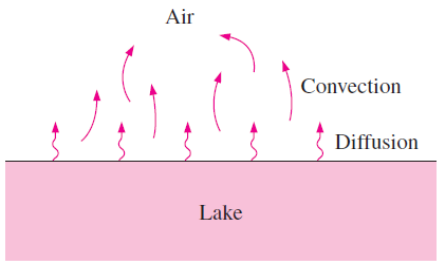
- What is convective mass transfer?
  - So far we have considered mass diffusion, which is the transfer of mass due to a concentration gradient. Now we consider mass convection (or convective mass transfer), which is the transfer of mass between a surface and a moving fluid due to both mass diffusion and bulk fluid motion.

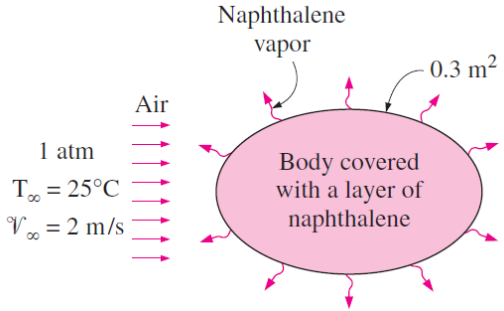
  - Fluid motion enhances mass transfer considerably by removing the highconcentration fluid near the surface and replacing it by the lower-concentration fluid farther away.

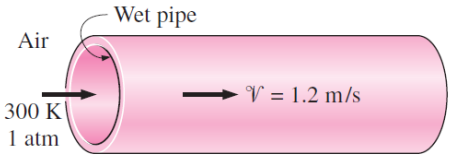
  - The analogy between heat and mass convection holds for both forced and natural convection, laminar and turbulent flow, and internal and external flow.

Convective mass transfer

- What is convective mass transfer?
  - Mass transfer between a fluid and a surface

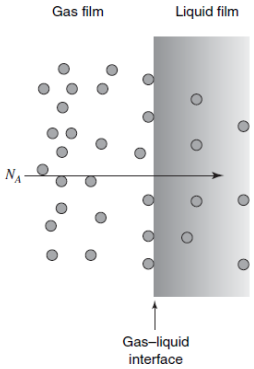




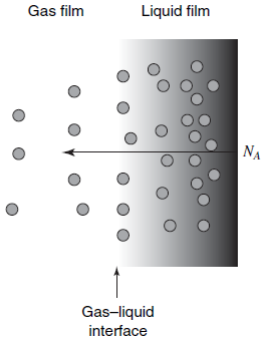


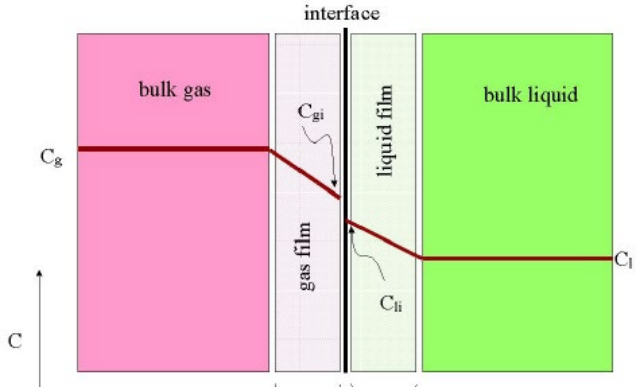
  - Mass transfer between immiscible fluids

Gas absorption



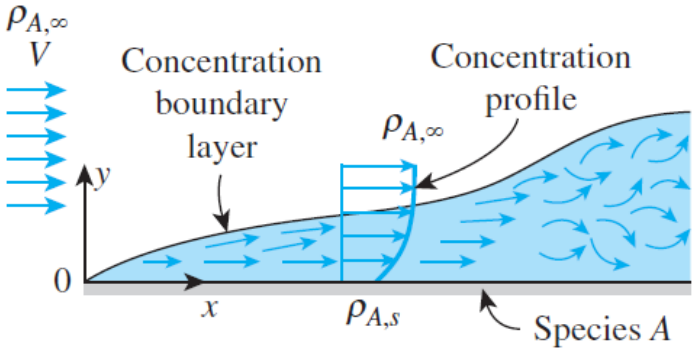
Stripping





Concentration B.L. – External flow

- Consider the flow of air over the free surface of a water body such as a lake under isothermal conditions. If the air is not saturated, the concentration of water vapour will vary from a maximum at the water surface where the air is always saturated to the free steam value far from the surface.



the region of the fluid in which concentration gradients exist as the **concentration boundary layer**

- In external flow, the thickness of the concentration boundary layer dc for a species A at a specified location on the surface is defined as the normal distance y from the surface at which

$$\frac{\rho_{A,s} - \rho_A}{\rho_{A,s} - \rho_{A,\infty}} = 0.99$$

where $\rho_{A,s}$and $\rho_{A,\infty}$ are the densities of species A at the surface (on the fluid side) and the free stream, respectively.

Concentration B.L. – External flow

Momenutm diffusivity

$$\upsilon = \frac{\mu}{\rho}$$

Thermal diffusivity

$$\alpha = \frac{k}{\rho C_p}$$

Mass diffusivity

$$D_{AB}$$

Prandtl number

$$Pr = \frac{\upsilon}{\alpha}$$

Governs the relative growth of the velocity and thermal boundary layers in laminar flow.

Pr ≈ 1 → Diffusion transfers of momentum and heat are comparable Velocity and thermal boundary layers almost coincide with each other.

Schmidt number

$$Sc = \frac{\upsilon}{D_{AB}}$$

Governs the relative growth of the velocity and concentration boundary layers in laminar flow.

Sc ≈ 1 → Diffusion transfers of momentum and mass are comparable Velocity and concentration boundary layers almost coincide with each other

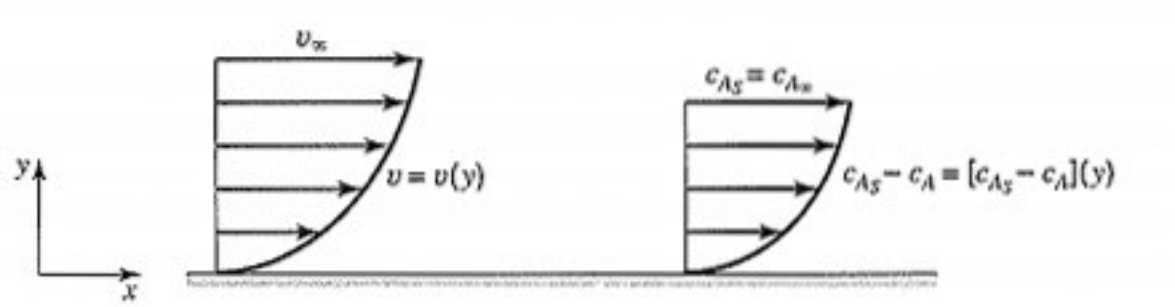
Lewis number

$$Le = \frac{\alpha}{D_{AB}}$$

$$\frac{\delta_{velocity}}{\delta_{thermal}} = Pr^n, \qquad \frac{\delta_{velocity}}{\delta_{concentration}} = Sc^n, \qquad \text{and} \qquad \frac{\delta_{thermal}}{\delta_{concentration}} = Le^n$$

- n = 1/3 for most applications in all three relations (laminar conditions)
- In general, n ≠ 1/3 for turbulent boundary layers
  - Diffusion process dominated by turbulent mixing

Concentration B.L. – External flow



A stream with uniform concentration of species A flowing over a solid surface

$$N_A = k_{xA}\left(x_{As} - x_{A\infty}\right) = k_c\left(c_{As} - c_{A\infty}\right)$$

Since mass transfer at the surface is by molecular diffusion, we can also write:

$$N_A = -D_{AB}\left.\frac{dc_A}{dy}\right|_{y=0}$$

$$k_c\left(c_{As} - c_{A\infty}\right) = -D_{AB}\left.\frac{d}{dy}\left(c_A - c_{As}\right)\right|_{y=0}$$

Concentration B.L. – External flow

$$k_c\left(c_{As}-c_{A\infty}\right)=-D_{AB}\frac{d}{dy}\left(c_A-c_{As}\right)\Big|_{y=0} \Leftrightarrow \frac{k_c}{D_{AB}}=-\frac{d\left(c_A-c_{As}\right)/dy}{\left(c_{As}-c_{A\infty}\right)}\Big|_{y=0}$$

With characteristic length (L):

$$\frac{k_c L}{D_{AB}}=-\frac{d\left(c_A-c_{As}\right)/dy}{\left(c_{As}-c_{A\infty}\right)/L}\Big|_{y=0}$$

Sherwood number (Sh)

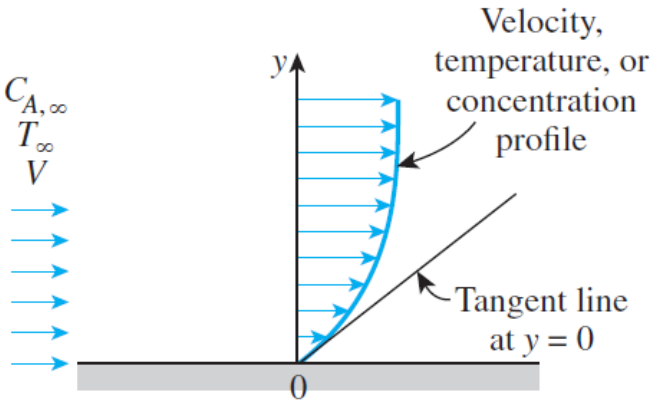
~ Nusselt number in heat transfer!

Ratio of conc. gradient at the surface to an overall (ref.) concentration gradient

[Ratio of convective transport resistance to molecular transport resistance (diffusion)]

Concentration B.L. – External flow

Consider laminar flow over a flat plate, under steady state:



Momentum	Heat	Mass
$V_x \frac{\partial V_x}{\partial x} + V_y \frac{\partial V_x}{\partial y} = \nu \frac{\partial^2 V_x}{\partial y^2}$	$V_x \frac{\partial T}{\partial x} + V_y \frac{\partial T}{\partial y} = \alpha \frac{\partial^2 T}{\partial y^2}$	$V_x \frac{\partial c_A}{\partial x} + V_y \frac{\partial c_A}{\partial y} = D_{AB} \frac{\partial^2 c_A}{\partial y^2}$

Solution of this equation → Blasius equation

	If $Pr = 1$	If $Sc = 1$
$\left.\frac{dV_x}{dy}\right\|_{y=0} = 0.332 v_\infty \sqrt{\frac{\rho V_\infty}{\mu x}}$	$\left.\frac{dT}{dy}\right\|_{y=0} = 0.322 \frac{(T_\infty - T_s)}{x} Re_x^{1/2}$	$\left.\frac{\partial c_A}{\partial y}\right\|_{y=0} = \left(c_{A,\infty} - c_{A,s}\right) \frac{0.332}{x} \mathrm{Re}_x^{1/2}$
	$Nu_x = 0.332\,\mathrm{Re}_x^{1/2}$	$Sh_x = \frac{k_c x}{D_{AB}} = 0.332\,\mathrm{Re}_x^{1/2}$

Concentration B.L. – External flow

If $Sc = 1$

$$\left.\frac{\partial c_A}{\partial y}\right|_{y=0} = \left(c_{A,\infty} - c_{A,s}\right)\frac{0.332}{x}\mathrm{Re}_x^{1/2}$$

Fick's law:

$$N_A = -D_{AB}\left.\frac{\partial c_A}{\partial y}\right|_{y=0} = k_c\left(c_{A,\infty} - c_{As}\right)$$

$$k_c = \frac{0.332 D_{AB}}{x}\mathrm{Re}_x^{1/2}$$

$$Sh_x = \frac{k_c x}{D_{AB}} = 0.332\,\mathrm{Re}_x^{1/2}$$

If $Sc \neq 1 \rightarrow \upsilon = D_{AB}$

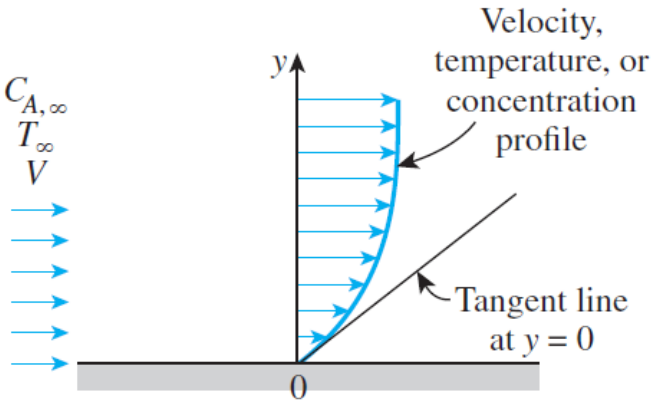
$$\frac{\delta}{\delta_c} = Sc^{1/3}$$

$$\left.\frac{\partial c_A}{\partial y}\right|_{y=0} = \left(c_{A,\infty} - c_{As}\right)\frac{0.332}{x}\mathrm{Re}_x^{1/2}\,Sc^{1/3}$$

$$Sh_x = 0.332\,\mathrm{Re}_x^{1/2}\,Sc^{1/3}$$

Concentration B.L. – External flow

Consider laminar flow over a flat plate, under steady state:



If Pr and Sc = 1 ⇒ $Nu_x = 0.332\,\mathrm{Re}_x^{1/2}$

$$Sh_x = \frac{k_c x}{D_{AB}} = 0.332\,\mathrm{Re}_x^{1/2}$$

If Pr and Sc ≠ 1 ⇒ $Nu_x = 0.332\,\mathrm{Re}_x^{1/2}\,\mathrm{Pr}^{1/3}$ $\quad Sh_x = 0.332\,\mathrm{Re}_x^{1/2}\,Sc^{1/3}$

Average over length of plate: ⇒ $Nu_L = 0.664\,\mathrm{Re}_L^{1/2}\,\mathrm{Pr}^{1/3}$ $\quad Sh_L = 0.332\,\mathrm{Re}_L^{1/2}\,Sc^{1/3}$

Concentration B.L. – External flow

- For Pr = 1 ($C_p\mu = k$), the diffusion of momentum and heat are equal

$$\left.\frac{d}{dx}\frac{u_x}{u_\infty}\right|_{y=0} = \left.\frac{d}{dx}\frac{(T-T_s)}{(T_\infty - T_s)}\right|_{y=0} \Rightarrow C_p\mu \left.\frac{d}{dx}\frac{u_x}{u_\infty}\right|_{y=0} = k\left.\frac{d}{dx}\frac{(T-T_s)}{(T_\infty - T_s)}\right|_{y=0}$$

$$\left.\frac{C_p\mu}{u_\infty}\frac{du_x}{dx}\right|_{y=0} = \left.\frac{-k}{(T_s - T_\infty)}\frac{d(T-T_s)}{dx}\right|_{y=0}$$

Momentum flux $\left.\mu\frac{du_x}{dx}\right|_{y=0} = C_f\frac{\rho u_\infty{}^2}{2}$

Coefficient of skin friction

$\left.-k\frac{d(T-T_s)}{dx}\right|_{y=0} = h(T_s - T_\infty)$

Heat transfer Coefficient

$$\left.\frac{C_p\mu}{u_\infty}\frac{du_x}{dx}\right|_{y=0} = h \Rightarrow \frac{C_p\rho C_f u_\infty}{2} = h \Rightarrow \frac{C_f}{2} = \frac{h}{\rho u_\infty C_p}$$

Concentration B.L. – External flow

Reynolds analogy

$$\frac{C_f}{2} = \frac{h}{\rho u_\infty C_p}$$

Stanton number, St

Conditions of validity:

- Pr = 1
- No form drag (i.e. drag caused by pressure gradients)

Applicable to laminar and turbulent flow conditions

If $Pr = Sc = Le = 1$

No form drag (i.e. drag caused by pressure gradients)

$$\frac{C_f}{2} = \frac{h}{\rho V_\infty C_p} = \frac{k_c}{V_\infty}$$

$$\frac{C_f}{2} = \frac{Nu}{\mathrm{Re}\,\mathrm{Pr}} = \frac{Sh}{\mathrm{Re}\,Sc}$$

$$\frac{C_f}{2} = St = St_{mass}$$

Concentration B.L. – External flow

Pr ≠ Sc ≠ 1

$$\frac{C_f}{2} = St\,\mathrm{Pr}^{2/3} = St_{mass}Sc^{2/3} \quad \Leftrightarrow \quad \frac{C_f}{2} = j_H = j_D$$

for $0.6 < \mathrm{Pr} < 60$ and $0.6 < \mathrm{Sc} < 3000$

j factors for heat and mass transfer

Applies for some geometries: flow over flat plates and flow in pipes
→ Flows where no Form Drag is present.

If there is form drag, e.g. in flow over cylinders:

$$\frac{St}{St_{mass}} = \left(\frac{Sc}{\mathrm{Pr}}\right)^{2/3} \quad OR \quad \frac{h}{k_c} = \rho C_p \left(\frac{Sc}{\mathrm{Pr}}\right)^{2/3} = \rho C_p \left(\frac{\alpha}{D_{AB}}\right)^{2/3} = \rho C_p Le^{2/3}$$

Concentration B.L. – External flow

Consider:

Air-water vapour mixtures @ 298K

$D_{AB} = 2.5 \times 10^{-5}\ m^2/s$

$a = 2.18 \times 10^{-5}\ m^2/s$

A value for dry air instead of moist air, as the fraction of vapour in the air at atmospheric conditions is low

$$(\alpha/D_{AB})^{2/3} = (0.872)^{2/3} = 0.913 \approx 1.0$$

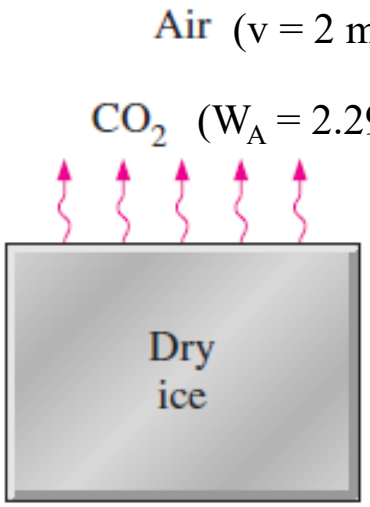
The value of *Le* is relatively constant with temperature

Therefore, $h \approx \rho C_p k_c$ (For air-water vapour mixtures) **Lewis relation**

Concentration B.L. – External flow

Classroom example-1:

Air flows over a solid slab of frozen carbon dioxide with an exposed cross-sectional surface area of 1 x 10^{-3} m^2. The carbon dioxide sublimes into the 2 m/s flowing stream at a total release rate of 2.29 x 10^{-4} mol/s. The air is at 293 K and 1.013 x 10^5 Pa. At that temperature, the diffusivity of carbon dioxide in air is 1.5 x 10^{-5} m^2/s and the kinematic viscosity of the air is 1.55 x 10^{-5} m^2/s.



A = 1x10^{-3} m^2

D_{AB} = 1.5x10^{-5} m^2/s
ν = 1.55x10^{-5} m^2/s
P_A = 4.74 x 10^3 Pa (vapour pressure of CO_2)

Determine:

- The mass transfer coefficient of CO_2 subliming into the flowing air at the conditions of the experiment
- The heat transfer coefficient for the air stream

Concentration B.L. – External flow

Classroom example-2:

A stream of air at 100 kPa pressure and 290 K is flowing on the top surface of a thin flat sheet of solid naphthalene of length 1 m with a velocity of 20 m/s and surface temperature of 310K. Calculate:

- The average mass transfer coefficient over the flat plate
- The rate of loss of naphthalene from the surface per unit width

Data @ $T_f = 300K$:

$D_{AB} = 6 \times 10^{-6}$ m^2/s (naphthalene vapour in air)

$\nu = 1.5 \times 10^{-5}$ m^2/s (kinematic viscosity of air)

$C_{As} = 1 \times 10^{-5}$ kmol/m^3 (conc. of naphthalene at the air-solid interface)

Concentration B.L. – External flow

Classroom example-3:

Dry air at 1.013 x 10^5 Pa blows across a thermometer whose bulb has been covered with a dampened wick. The classical "wet bulb" thermometer indicates a steady-state temperature is reached by a small amount of liquid water evaporating into a large reservoir of unsaturated vapour-gas mixture. The thermometer reads 290 K. At this temperature, the following properties were evaluated:

Vapour pressure of water	1.94 x 10^3 Pa
Density of air	1.219 kg/m^3
Latent heat of vaporisation of water	2461 kJ/kg
Prandtl number	0.71
Schmidt number	0.61
Specific heat of air	1.006 kJ/kg.K

What is the temperature of the dry air?

Concentration B.L. – External flow

Classroom example-4: (Heat and mass analogy)

Water evaporates from a wetted surface of rectangular shape, with an air stream (1 atm, 35 ^{o}C) blown over the surface at a velocity of 15 m/s. Heat transfer measurements indicate that for air at 1 atm and 35 ^{o}C, the average heat transfer coefficient is given by the following empirical relation:

$$\langle h \rangle = 21\, V_{\infty}^{0.6}$$

where is the average heat transfer coefficient in W/m^2.K and is the air velocity in m/s. Estimate the mass transfer coefficient and the rate of evaporation of water from the surface if the area is 1.5 m^2.

Concentration B.L. – External flow

Classroom example-5: (Heat and mass analogy)

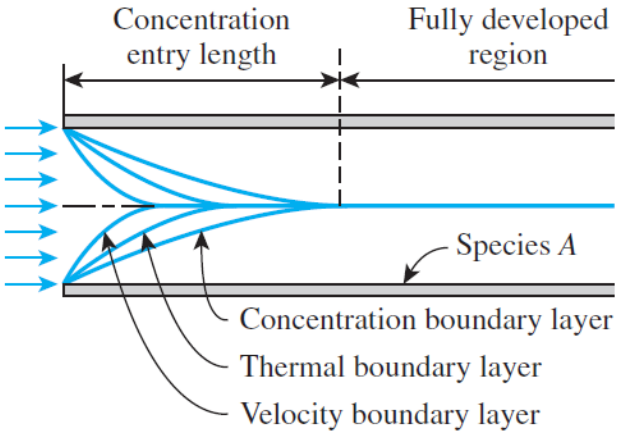
The following correlation has been proposed to characterise the heat transfer of fluids flowing in the annular section between concentric tubes:

$$Nu_{d_1} = \frac{hd_1}{k} = C\,\mathrm{Re}_{d_1}^{0.8}\,\mathrm{Pr}^{1/3}\left(\frac{\mu}{\mu_s}\right)^{0.14}\left(\frac{d_2}{d_1}\right)^{0.15}$$

Show how this equation can be used to predict the mass-transfer coefficient from a napthalene rod that is used to form the inner tube of an annular duct. d_1 and d_2 are the diameters of the inner and outer tubes, respectively, whereas μ and μ_s are the viscosity of the fluid at the bulk and surface temperatures.

Concentration B.L. – Internal flow

- In internal flow, a concentration entrance region where the concentration profile develops, in addition to the hydrodynamic and thermal entry regions.



Concentration boundary layer continues to develop in the flow direction until its thickness reaches the tube center and the boundary layers merge.

- The distance from the tube inlet to the location where this merging occurs is called the concentration entry length L_c, and the region beyond that point is called the **fully developed region**.

Heat transfer and mass transfer analogy

Limitation of convection analogy:

Nu → usually evaluated for smooth surfaces, but many mass transfer problems involve wavy or roughened surfaces.

Difficulties in defining surface area!

Nu relations → usually obtained for constant surface temperature situations, but the concentration may not be constant over the entire surface...

The heat-mass convection analogy is valid for low mass flux cases!

The flow rate of species undergoing mass transfer is *low* relative to the total flow rate of the liquid or gas mixture, i.e. the mass transfer between the fluid and the surface does not affect the flow velocity.

Other conditions: No mass/energy produced within the system, i.e. no chemical reaction within the system, no emission/absorption of radiant energy, no viscous dissipation of energy

Similarity between h.t and m.t equations

The analogy can be further invoked by simply applying correlations for heat transfer for mass transfer problems (with considerations of afore-mentioned limitations).

$$Nu = hL_C/k \quad \rightarrow \quad Sh = k_c L_C/D_{AB}$$

$$\mathrm{Pr} = \nu/\alpha \quad \rightarrow \quad Sc = \nu/D_{AB}$$

Note which property matters! As we're generally concerned with dilute, binary mixtures, generally the property of the mixture can be approximated with good accuracy as the properties of species B (the *convecting* fluid)

Similarity between h.t and m.t equations

Forced convection

$$\mathrm{Nu} = \frac{h_{\mathrm{conv}} L}{k} \quad \textit{Nusselt number}$$

$$Sh = \frac{k_C L}{D_{AB}} \quad \textit{Sherwood number}$$

$$\mathrm{Nu} = f(\mathrm{Re}, \mathrm{Pr})$$

$$\mathrm{Sh} = f(\mathrm{Re}, \mathrm{Sc})$$

Natural/free convection

$$\mathrm{Gr}_L = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2}$$ ***Natural convective heat transfer***

$$\mathrm{Gr} = \frac{g(\rho_\infty - \rho_s)\, L_c^3}{\rho\nu^2} = \frac{g(\Delta\rho/\rho)\, L_c^3}{\nu^2}$$ ***Natural convective mass transfer***

$$Nu = f(Gr, \mathrm{Pr}) \quad Sh = f(Gr_{AB}, Sc)$$

Similarity between h.t and m.t equations

- Natural convection → Driven by density gradients, which may result from:
  - Variation in temperature → $\mathrm{Gr}_L = \frac{g\beta(T_s - T_\infty)L_c^3}{\nu^2}$
  - Variation in concentrations → $\mathrm{Gr} = \frac{g(\rho_\infty - \rho_s)\,L_c^3}{\rho\nu^2} = \frac{g(\Delta\rho/\rho)\,L_c^3}{\nu^2}$

- Free convection can therefore be driven by temperature and/or concentration gradient, i.e. species transfer!
- If species transfer is assumed to have negligible influence on the free convection flow, i.e. it is driven by the temperature gradient only → Use heat transfer correlation ($Gr = g\beta(T_S - T_\infty){L_C}^3/\nu^2$) to determine HTC, then use heat and mass transfer analogy to determine k_c.
- If species transfer is driven by density/concentration gradients, then use $Gr = g(\rho_S - \rho_\infty){L_C}^3/\rho\nu^2$ to determine k_c.

Similarity between h.t and m.t equations

Analogy between the quantities that appear in the formulation and solution of heat convection and mass convection

Heat Convection	Mass Convection
T	C, y, ρ, or w
h_{conv}	h_{mass}
$\delta_{thermal}$	$\delta_{concentration}$
$\mathrm{Re} = \frac{\mathcal{V} L_c}{\nu}$	$\mathrm{Re} = \frac{\mathcal{V} L_c}{\nu}$
$\mathrm{Gr} = \frac{g\beta(T_s - T_\infty) L_c^3}{\nu^2}$,	$\mathrm{Gr} = \frac{g(\rho_\infty - \rho_s) L_c^3}{\rho\nu^2}$
$\mathrm{Pr} = \frac{\nu}{\alpha}$	$\mathrm{Sc} = \frac{\nu}{D_{AB}}$
$\mathrm{St} = \frac{h_{conv}}{\rho \mathcal{V} C_p}$	$\mathrm{St}_{mass} = \frac{h_{mass}}{\mathcal{V}}$
$\mathrm{Nu} = \frac{h_{conv} L_c}{k}$	$\mathrm{Sh} = \frac{h_{mass} L_c}{D_{AB}}$
$\mathrm{Nu} = f(\mathrm{Re}, \mathrm{Pr})$	$\mathrm{Sh} = f(\mathrm{Re}, \mathrm{Sc})$
$\mathrm{Nu} = f(\mathrm{Gr}, \mathrm{Pr})$	$\mathrm{Sh} = f(\mathrm{Gr}, \mathrm{Sc})$

→ Denoted k_c in our notes

Similarity between h.t and m.t equations

Sherwood number relations in mass convection for specified concentration at the surface corresponding to the Nusselt number relations in heat convection for specified surface temperature

Convective Heat Transfer	Convective Mass Transfer
1. *Forced Convection over a Flat Plate*	
(*a*) Laminar flow ($Re < 5 \times 10^5$)	
$Nu = 0.664\, Re_L^{0.5}\, Pr^{1/3}$, $Pr > 0.6$	$Sh = 0.664\, Re_L^{0.5}\, Sc^{1/3}$, $Sc > 0.5$
(*b*) Turbulent flow ($5 \times 10^5 < Re < 10^7$)	
$Nu = 0.037\, Re_L^{0.8}\, Pr^{1/3}$, $Pr > 0.6$	$Sh = 0.037\, Re_L^{0.8}\, Sc^{1/3}$, $Sc > 0.5$
2. *Fully Developed Flow in Smooth Circular Pipes*	
(*a*) Laminar flow ($Re < 2300$)	
$Nu = 3.66$	$Sh = 3.66$
(*b*) Turbulent flow ($Re > 10{,}000$)	
$Nu = 0.023\, Re^{0.8}\, Pr^{0.4}$, $0.7 < Pr < 160$	$Sh = 0.023\, Re^{0.8}\, Sc^{0.4}$, $0.7 < Sc\ 160$
3. *Natural Convection over Surfaces*	
(*a*) Vertical plate	
$Nu = 0.59(Gr\, Pr)^{1/4}$, $10^5 < Gr\, Pr < 10^9$	$Sh = 0.59(Gr\, Sc)^{1/4}$, $10^5 < Gr\, Sc < 10^9$
$Nu = 0.1(Gr\, Pr)^{1/3}$, $10^9 < Gr\, Pr < 10^{13}$	$Sh = 0.1(Gr\, Sc)^{1/3}$, $10^9 < Gr\, Sc < 10^{13}$
(*b*) Upper surface of a horizontal plate	
Surface is hot ($T_s > T_\infty$)	Fluid near the surface is light ($\rho_s < \rho_\infty$)
$Nu = 0.54(Gr\, Pr)^{1/4}$, $10^4 < Gr\, Pr < 10^7$	$Sh = 0.54(Gr\, Sc)^{1/4}$, $10^4 < Gr\, Sc < 10^7$
$Nu = 0.15(Gr\, Pr)^{1/3}$, $10^7 < Gr\, Pr < 10^{11}$	$Sh = 0.15(Gr\, Sc)^{1/3}$, $10^7 < Gr\, Sc < 10^{11}$
(*c*) Lower surface of a horizontal plate	
Surface is hot ($T_s > T_\infty$)	Fluid near the surface is light ($\rho_s < \rho_\infty$)
$Nu = 0.27(Gr\, Pr)^{1/4}$, $10^5 < Gr\, Pr < 10^{11}$	$Sh = 0.27(Gr\, Sc)^{1/4}$, $10^5 < Gr\, Sc < 10^{11}$

Classroom example (Internal pipe flow)

Classroom example-6:

Dry air (310 K, 1.013×10^5 Pa, 1.5 m/s) is flowing through a pipe lined with a felt material that is continuously saturated with water at 290 K. The pipe is 0.15 m in diameter and 6 m long. The saturated felt material has a roughness index, e/D, of 0.00001. Assuming that the temperature of the air and pipe wall is constant, determine the rate at which water must be added to keep the felt continuously saturated.

Classroom example (natural convection)

Classroom example-7:

A 225 mm diameter pan of water is maintained at 37°C is exposed to a dry, still atmosphere at 17°C. Estimate the heat and mass transfer coefficients, as well as the evaporation rate from the pan,

a. Assuming the convection is driven by species transfer;
b. Assuming that the convection is driven by temperature gradients.