CM3120: Module 4

Diffusion and Mass Transfer II

I. Classic diffusion and mass transfer: d) EMCD
II. Classic diffusion and mass transfer: e) Penetration model
III. Unsteady macroscopic species A mass balances (Intro)
IV. Interphase species A mass transfers—To an interface—k_x, k_c, k_p
V. Unsteady macroscopic species A mass balances (Redux)
VI. Interphase species A mass transfers—Across multiple resistances—K_L, K_G
VII. Dimensional analysis
VIII. Data correlations

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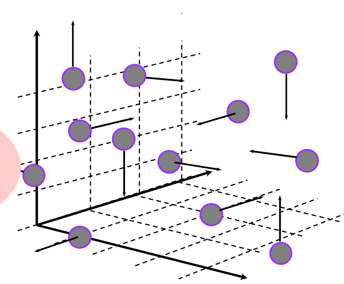
CM3120: Module 4

Module 4 Lecture VIII

Data Correlations

in Mass Transfer



Professor Faith A. Morrison
Department of Chemical Engineering
Michigan Technological University

www.chem.mtu.edu/~fmorriso/cm3120/cm3120.html

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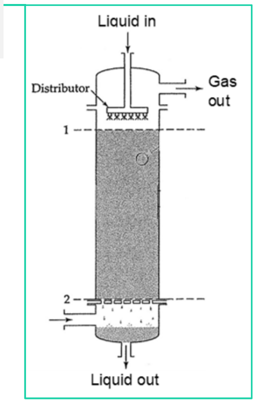
Dimensional Analysis in Mass Transfer

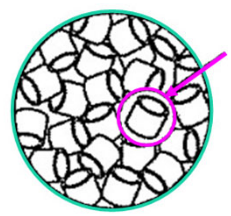
Steps to produce correlations

Returning to our question:

What do we do to understand complex <u>mass transfer</u>?

1. Find a simple problem that allows us to identify the physics
2. Non-dimensionalize:
   a. Choose characteristic values
   b. Produce a non-dimensional governing equation
   c. Produce a non-dimensional engineering quantity of interest
3. Explore that problem
4. Take data and correlate (confirm D.A. for chosen problem)
5. Solve real problems with the correlation





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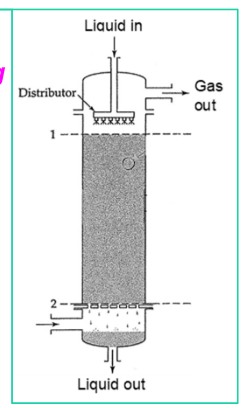
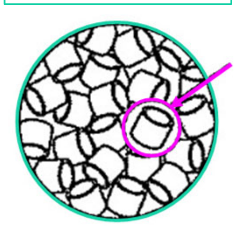
Dimensional Analysis in Mass Transfer

Returning to our question:

What do we do ~~to understand~~ *create predictions or designs involving* complex <u>mass transfer</u>?

1. ✓ Find a simple problem that allows us to identify the physics
2. ✓ Non-dimensionalize:
   a. Choose characteristic values
   b. Produce a non-dimensional governing equation
   c. Produce a non-dimensional engineering quantity of interest
3. ✓ Explore that problem
4. ✓ Take data and correlate (confirm D.A. for chosen problem) *Or look up someone else's data correlation*
5. Solve real problems with the correlation





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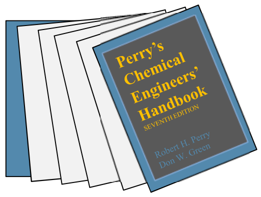
Dimensional Analysis in Mass Transfer



Perry's Chemical Engineers' Handbook

7th edition (1997)
Robert H. Perry
Don W. Green

See also: (Green and Southard, 9th edition, 2019)

Section 5: Heat and Mass Transfer

Authors of Mass Transfer:
Phillip C. Wankat
Kent S. Knaebel

Table 5-21: *Correlations* for Mass Transfer: *(pp 5-59 thru 5-77)*

- *From fluid to plate*
- *To a falling film*
- *In pipes and ducts*
- *Past submerged objects*
- *To/from bubbles, drops*
- *In agitated systems*
- *In fixed and fluidized beds*
- *In packed two-phase contactors (absorption, distillation, cooling towers)*

(T)-theoretical
(S)-semi-empirical
(E)-empirical

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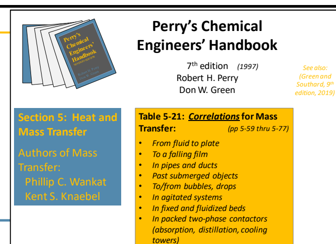
Dimensional Analysis in Mass Transfer



Advice from Wankat and Knaebel

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

1. Because of its importance, there are many studies of mass transfer in the literature
2. For simple geometries, theoretical results are obtainable (T)
3. For very complex systems, only empirical (E) forms can be found
4. Theoretical correlations can be "improved" by fitting to data, resulting in a semi-empirical correlation (S)
5. The major limits and constraints are listed in Perry's Table 5-21; many details are not included, however
6. Readers are *strongly encouraged* to check the references before using the correlations; look for comparisons to actual data
7. Even authoritative sources have typos

(Perry's, 7th ed, p 5-58)

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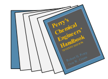
Dimensional Analysis in Mass Transfer

MORE Advice from Wankat and Knaebel



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

When there are several correlations that are applicable (which often happens), how do we choose?

1. Determine which correlations are closest to the situation under study (similarity of geometries, checking the range of dimensionless numbers and other parameters)
2. Check to see if correlations under consideration have been compared in the literature, both to each other, and to data
3. Check for "rules of thumb" shared by experts

(Perry's, 7th ed, p 5-58 through 5-60)

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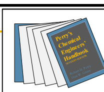
Dimensional Analysis in Mass Transfer

MORE Advice from Wankat and Knaebel



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

Rules of Thumb

1. If arithmetic concentration difference was used to determine k for the correlation, that should only be used in such an expression
2. Semi-empirical correlations are often preferred to empirical (do *not* extrapolate empirical) or purely theoretical (can be far off; assumptions)
3. Correlations with a broader data base are preferred
4. Heat/mass transfer analogy is pretty good within its bounds; good heat transfer data (without radiation) can often be used to predict mass-transfer coefficients
5. Recent data is preferred over older data
6. With complex geometries, $k_y a$ (or HTU) correlations are more accurate than k_y correlations
7. **If a mass-transfer correlation looks too good to be true, it probably is.**

(Perry's, 7th ed, p 5-60)

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Dimensional Analysis in Mass Transfer

Routes to Mass Transfer Correlations

Theoretical

- Based on a model of the situation; can be solved for flux, and thus for k_x
- All models have assumptions; how good the assumptions are determine how good the correlations are
- The heat-transfer analogy counts as a theoretical pathway

Semi-empirical

- Shortcomings in theoretical models may be "fixed" by adjusting a theoretically derived coefficient or exponent to achieve a better fit to the data
- The theoretical underpinnings give some hope that extrapolation outside the range of the data fit may be valid

Empirical

- A pure fit to the data is a convenient way to use data directly in downstream calculations
- With no theoretical underpinnings it is extremely unwise to use empirical correlations outside the range of the data fit

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Dimensional Analysis in Mass Transfer

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The Heat/Mass Transfer Analogy

Theoretical Pathway to Mass Transfer Coefficients:

The Heat/Mass Transfer Analogy

Routes to Mass Transfer Correlations

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- Based on a model of the situation; can be solved for flux, and thus for k_x
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mass

Example: A spherical medical pill dissolves slowly in a stagnant fluid (water). What is the mass transfer coefficient k_c? What is the Sherwood number for this situation?

heat

Example: A spherical pellet of reacting solid slowly emits heats steadily into a stagnant fluid such that the surface temperature is constant. What is the heat transfer coefficient h? What is the Nusselt number for this situation?

BSL2 p321, problem 10B.1, p678

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The Heat/Mass Transfer Analogy

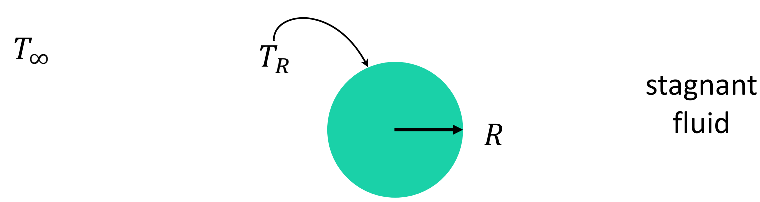
heat

Example 16: A spherical pellet of reacting solid slowly emits heats steadily into a stagnant fluid such that the surface temperature is constant. What is the heat transfer coefficient h? What is the Nusselt number for this situation?

Routes to Mass Transfer Correlations

Theoretical

- Based on a model of the situation; can be solved for flux, and thus for k_x
- All models have assumptions; how good the assumptions are determine how good the correlations are
- The heat-transfer analogy counts as a theoretical pathway



Solve.

BSL2 p321, problem 10B.1

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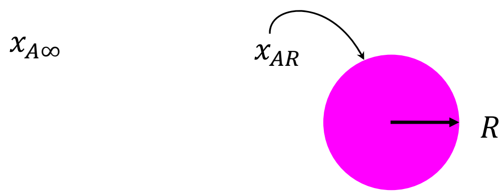
The Heat/Mass Transfer Analogy

Routes to Mass Transfer Correlations

Theoretical
- Based on a model of the situation; can be solved for flux, and thus for k_x
- All models have assumptions; how good the assumptions are determine how good the correlations are
- The heat-transfer analogy counts as a theoretical pathway

mass

Example 17: A spherical medical pill dissolves slowly in a stagnant fluid (water). What is the mass transfer coefficient k_c? What is the Sherwood number for this situation?



stagnant fluid

Solve.

BSL2 p321, problem 10B.1

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The Heat/Mass Transfer Analogy

Theoretical Pathway to Mass Transfer Coefficients:

The Heat/Mass Transfer Analogy

Routes to Mass Transfer Correlations

Theoretical
- Based on a model of the situation; can be solved for flux, and thus for k_x
- All models have assumptions; how good the assumptions are determine how good the correlations are
- The heat-transfer analogy counts as a theoretical pathway

Results for transfer from sphere to stagnant fluid:

- $\mathrm{Sh} = \mathrm{Nu} = 2$
- **Limited to low mass transfer rates $(\underline{v}^* \approx 0)$**
- At low mass transfer rates and stagnant fluid, $\underline{J}_A^* = \underline{N}_A$ and $\underline{j}_A = \underline{n}_A$; this makes it easy to convert units moles to mass

Assumptions of the analogy between heat and mass

1. Constant physical properties
2. **Small net mass transfer rates**
3. No chemical reactions
4. No viscous dissipation heating
5. No absorption or emission of radiant energy
6. No pressure diffusion, thermal diffusion, or forced diffusion

BSL2 p681

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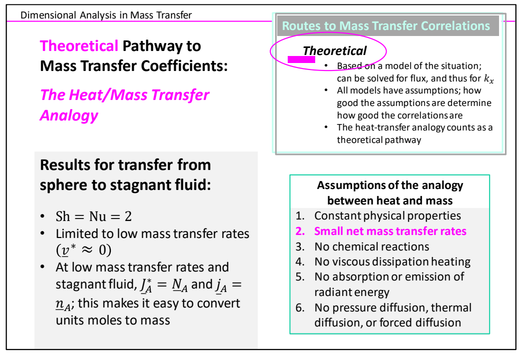
The Heat/Mass Transfer Analogy



Comment from the experts:

> "It would be very misleading to leave the impression that all mass transfer coefficients can be obtained from the analogous heat transfer coefficient correlations. For mass transfer we encounter a much wider variety of boundary conditions and other ranges of relevant variables."

BSL2 p682

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Dimensional Analysis in Mass Transfer

Routes to Mass Transfer Correlations

Theoretical

- Based on a model of the situation; can be solved for flux, and thus for k_x
- All models have assumptions; how good the assumptions are determine how good the correlations are
- The heat-transfer analogy counts as a theoretical pathway

Semi-empirical

- Shortcomings in theoretical models may be "fixed" by adjusting a theoretically derived coefficient or exponent to achieve a better fit to the data
- The theoretical underpinnings give some hope that extrapolation outside the range of the data fit may be valid

Empirical

- A pure fit to the data is a convenient way to use data directly in downstream calculations
- With no theoretical underpinnings it is extremely unwise to use empirical correlations outside the range of the data fit

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Dimensional Analysis in Mass Transfer

Semi-Empirical Pathway to Mass Transfer Coefficients

Routes to Mass Transfer Correlations

Semi-Empirical

- Shortcomings in theoretical models may be "fixed" by adjusting a theoretically derived coefficient or exponent to achieve a better fit to the data
- The theoretical underpinnings give some hope that extrapolation outside the range of the data fit may be valid

Inspired by theoretical results and a model (a picture of how the mass transfer may be explained), correlations may be created that are then fine-tuned to match the data

For example, **Colburn's extension of the Reynolds analogy**

BSL2 p681

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Dimensional Analysis in Mass Transfer

Reynolds Analogy, Colburn's, Prandtl's extensions

Routes to Mass Transfer Correlations

Semi-Empirical

- Shortcomings in theoretical models may be "fixed" by adjusting a theoretically derived coefficient or exponent to achieve a better fit to the data
- The theoretical underpinnings give some hope that extrapolation outside the range of the data fit may be valid

- Reynolds noted the similarities in mechanism between energy and momentum transfer
- He derived, for restrictive conditions ($\mathrm{Pr} = 1$, no form drag), the following equation:

$$\frac{h}{\rho V_\infty \hat{C}_p} = \mathrm{St}_h = \frac{f}{2}$$

(Stanton number for heat transfer)

- Coleburn modified the Reynolds result to work at more values of Pr and proposed the following:

$$\mathrm{St}_h \mathrm{Pr}^{2/3} = \frac{f}{2}$$

- This improved relationship does a better job of predicting heat transfer coefficients and
- Separating the turbulent core from the laminar sublayer in boundary layer flow allows it to be extended to mass transfer (Prandtl), resulting in a refined empirical correlation (WRF eqn 28-54)

BSL2 p681; WRF p580

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Routes to Mass Transfer Correlations

Theoretical

- Based on a model of the situation; can be solved for flux, and thus for k_x
- All models have assumptions; how good the assumptions are determine how good the correlations are
- The heat-transfer analogy counts as a theoretical pathway

Semi-empirical

- Shortcomings in theoretical models may be “fixed” by adjusting a theoretically derived coefficient or exponent to achieve a better fit to the data
- The theoretical underpinnings give some hope that extrapolation outside the range of the data fit may be valid

Empirical

- A pure fit to the data is a convenient way to use data directly in downstream calculations
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Empirical Pathway to Mass Transfer Coefficients

Routes to Mass Transfer Correlations

Empirical

- A pure fit to the data is a convenient way to use data directly in downstream calculations
- With no theoretical underpinnings it is extremely unwise to use empirical correlations outside the range of the data fit

Inspired by looking at data from a variety of systems, correlations may be created that are fine-tuned to match the data.

These may be based purely on dimensional analysis or there may be a model that the researchers have in mind.

Empirical models are judged by how accurately they represent the data.

BSL2 p681

Dimensional Analysis in Mass Transfer

Chilton-Colburn Analogy

Inspired by semi-empirical analogies such as the Reynolds Analogy, define the "j factors":

$$j_H \equiv \frac{\text{Nu}}{\text{RePr}^{\frac{1}{3}}} = \frac{h}{\rho \hat{C}_p V_\infty}\left(\frac{\hat{C}_p \mu}{k}\right)^{2/3}$$

$$j_M \equiv \frac{\text{Sh}}{\text{ReSc}^{1/3}} = \frac{k_x}{c V_\infty}\left(\frac{\mu}{\rho D_{AB}}\right)^{2/3}$$

Compare to data.

Routes to Mass Transfer Correlations

Empirical

- A pure fit to the data is a convenient way to use data directly in downstream calculations
- With no theoretical underpinnings it is extremely unwise to use empirical correlations outside the range of the data fit

Chilton-Colburn Analogy

$$j_H = j_M = \frac{f}{2}$$

(f is the Fanning friction factor)

WRF p581

Dimensional Analysis in Mass Transfer

Chilton-Colburn Analogy

$$j_H = j_M = \frac{f}{2}$$

(f is the Fanning friction factor)

Chilton-Colburn Analogy

$$j_H \equiv \frac{\text{Nu}}{\text{RePr}^{\frac{1}{3}}} = \frac{h}{\rho \hat{C}_p V_\infty}\left(\frac{\hat{C}_p \mu}{k}\right)^{2/3}$$

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Routes to Mass Transfer Correlations

Empirical

- A pure fit to the data is a convenient way to use data directly in downstream calculations
- With no theoretical underpinnings it is extremely unwise to use empirical correlations outside the range of the data fit

Conditions:

- Exact for flat plates
- Satisfactory in other geometries as long as form drag is not present
- Relates convective heat and mass transfer
- Permits evaluation of one transfer coefficient through information obtained on another
- Experimentally validated for gases and liquids within the ranges $0.60 \leq \text{Sc} \leq 2500, 0.6 \leq \text{Pr} \leq 100$
- Constant physical properties data

WRF pp581-2

Dimensional Analysis in Mass Transfer

Final thoughts on Literature Mass-Transfer Coefficient Correlations

- Choose correlation carefully
- Check the original reference (how k_y defined, what are the assumptions, how well does it represent the data
- With complex geometries, $k_y a$ (or HTU) correlations are more accurate than k_y correlations

Routes to Mass Transfer Correlations

Theoretical

- Based on a model of the situation; can be solved for flux, and thus for k_x
- All models have assumptions; how good the assumptions are determine how good the correlations are
- The heat-transfer analogy counts as a theoretical pathway

Semi-empirical

- Shortcomings in theoretical models may be "fixed" by adjusting a theoretically derived coefficient or exponent to achieve a better fit to the data
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Dimensional Analysis in Mass Transfer

More final thoughts on Literature Mass-Transfer Coefficient Correlations

E. L. Cussler, Diffusion: Mass Transfer in Fluid Systems, 3rd Edition, Cambridge, 2009

Table 8.3-1 *Significance of common dimensionless groups*

Group[a]	Physical meaning	Used in
Sherwood number $\frac{kl}{D}$	$\frac{\text{mass transfer velocity}}{\text{diffusion velocity}}$	Usual dependent variable
Stanton number $\frac{k}{v^0}$	$\frac{\text{mass transfer velocity}}{\text{flow velocity}}$	Occasional dependent variable
Schmidt number $\frac{\nu}{D}$	$\frac{\text{diffusivity of momentum}}{\text{diffusivity of mass}}$	Correlations of gas or liquid data
Lewis number $\frac{\alpha}{D}$	$\frac{\text{diffusivity of energy}}{\text{diffusivity of mass}}$	Simultaneous heat and mass transfer
Prandtl number $\frac{\nu}{\alpha}$	$\frac{\text{diffusivity of momentum}}{\text{diffusivity of mass}}$	Heat transfer; included here for completeness
Reynolds number $\frac{lv}{\nu}$	$\frac{\text{inertial forces}}{\text{viscous forces}}$ or $\frac{\text{flow velocity}}{\text{"momentum velocity"}}$	Forced convection
Grashof number $\frac{l^3 g \Delta\rho/\rho}{\nu^2}$	$\frac{\text{buoyancy forces}}{\text{viscous forces}}$	Free convection
Péclet number $\frac{v^0 l}{D}$	$\frac{\text{flow velocity}}{\text{diffusion velocity}}$	Correlations of gas or liquid data
Second Damköhler number or (Thiele modulus)^2 $\frac{\kappa l^2}{D}$	$\frac{\text{reaction velocity}}{\text{diffusion velocity}}$	Correlations involving reactions (see Chapters 16–17)

Note: [a] The symbols and their dimensions are as follows: D diffusion coefficient (L^2/t); g acceleration due to gravity (L/t^2); k mass transfer coefficient (L/t); l characteristic length (L); v^0 fluid velocity (L/t); α thermal diffusivity (L^2/t); κ first-order reaction rate constant (t^{-1}); ν kinematic viscosity (L^2/t); $\Delta\rho/\rho$ fractional density change.

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More final thoughts on Literature Mass-Transfer Coefficient Correlations

E. L. Cussler, Diffusion: Mass Transfer in Fluid Systems, 3[rd] Edition, Cambridge, 2009

Table 8.3-2 *Selected mass transfer correlations for fluid–fluid interfaces*[a]

Physical situation	Basic equation[b]	Key variables	Remarks
Liquid in a packed tower	$k\left(\frac{1}{\nu g}\right)^{1/3} = 0.0051\left(\frac{v^0}{a\nu}\right)^{0.67}\left(\frac{D}{\nu}\right)^{0.50}(ad)^{0.4}$	a = packing area per bed volume d = nominal packing size	Probably the best available correlation for liquids; tends to give lower value than other correlations
	$\frac{kd}{D} = 25\left(\frac{dv^0}{\nu}\right)^{0.45}\left(\frac{\nu}{D}\right)^{0.5}$	d = nominal packing size	The classical result, widely quoted; probably less successful than above
	$\frac{k}{v^0} = a\left(\frac{dv^0}{\nu}\right)^{-0.3}\left(\frac{D}{\nu}\right)^{0.5}$	d = nominal packing size	Based on older measurements of height of transfer units (HTUs); a is of order one
Gas in a packed tower	$\frac{k}{aD} = 3.6\left(\frac{v^0}{a\nu}\right)^{0.70}\left(\frac{\nu}{D}\right)^{1/3}(ad)^{-2.0}$	a = packing area per bed volume d = nominal packing size	Probably the best available correlation for gases
	$\frac{kd}{D} = 1.2(1-\varepsilon)^{0.36}\left(\frac{dv^0}{\nu}\right)^{0.64}\left(\frac{\nu}{D}\right)^{1/3}$	d = nominal packing size ε = bed void fraction	Again, the most widely quoted classical result
Pure gas bubbles in a stirred tank	$\frac{kd}{D} = 0.13\left(\frac{(P/V)d^4}{\rho\nu^3}\right)^{1/4}\left(\frac{\nu}{D}\right)^{1/3}$	d = bubble diameter P/V = stirrer power per volume	Note that k does not depend on bubble size
Pure gas bubbles in an unstirred tank	$\frac{kd}{D} = 0.31\left(\frac{d^3 g\Delta\rho/\rho}{\nu^2}\right)^{1/3}\left(\frac{\nu}{D}\right)^{1/3}$	d = bubble diameter $\Delta\rho$ = density difference between bubble and surrounding fluid	Drops 0.3-cm diameter or larger
Small liquid drops rising in unstirred solution	$\frac{kd}{D} = 1.13\left(\frac{dv^0}{D}\right)^{0.8}$	d = drop diameter v^0 = drop velocity	These small drops behave like rigid spheres
Falling films	$\frac{kz}{D} = 0.69\left(\frac{zv^0}{D}\right)^{0.5}$	z = position along film v^0 = average film velocity	Frequently embroidered and embellished

Notes: [a] The symbols used include the following: D is the diffusion coefficient; g is the acceleration due to gravity; k is the local mass transfer coefficient; v^0 is the superficial fluid velocity; and ν is the kinematic viscosity.

[b] Dimensionless groups are as follows: $\frac{dv^0}{\nu}$ and $v^0/a\nu$ are Reynolds numbers; ν/D is the Schmidt number; $d^3g(\Delta\rho/\rho)/\nu^2$ is the Grashof number, kd/D is the Sherwood number, and $k/(\nu g)^{1/3}$ is an unusual form of the Stanton number.

Dimensional Analysis in Mass Transfer

More final thoughts on Literature Mass-Transfer Coefficient Correlations

E. L. Cussler, Diffusion: Mass Transfer in Fluid Systems, 3[rd] Edition, Cambridge, 2009

Table 8.3-3 *Selected mass transfer correlations for fluid–solid interfaces*[a]

Physical situation	Basic equation[b]	Key variables	Remarks
Membrane	$\frac{kl}{D} = 1$	l = membrane thickness	Often applied even where membrane is hypothetical
Laminar flow along flat plate[c]	$\frac{kL}{D} = 0.646\left(\frac{Lv^0}{\nu}\right)^{1/3}\left(\frac{\nu}{D}\right)^{1/3}$	L = plate length v^0 = bulk velocity	Solid theoretical foundation, which is unusual
Turbulent flow through horizontal slit	$\frac{kd}{D} = 0.026\left(\frac{dv^0}{\nu}\right)^{0.8}\left(\frac{\nu}{D}\right)^{1/3}$	v^0 = average velocity in slit d = [2/π] (slit width)	Mass transfer here is identical with that in a pipe of equal wetted perimeter
Turbulent flow through circular pipe	$\frac{kd}{D} = 0.026\left(\frac{dv^0}{\nu}\right)^{0.8}\left(\frac{\nu}{D}\right)^{1/3}$	v^0 = average velocity in slit d = pipe diameter	Same as slit, because only wall regime is involved
Laminar flow through circular tube	$\frac{kd}{D} = 1.62\left(\frac{d^2v^0}{LD}\right)^{1/3}$	d = pipe diameter L = pipe length v^0 = average velocity in tube	Very strong theoretical and experimental basis
Flow outside and parallel to a capillary bed	$\frac{kd}{D} = 1.25\left(\frac{d^2v^0}{\nu l}\right)^{0.93}\left(\frac{\nu}{D}\right)^{1/3}$	d = 4 cross-sectional area/(wetted perimeter) v^0 = superficial velocity	Not reliable because of channeling in bed
Flow outside and perpendicular to a capillary bed	$\frac{kd}{D} = 0.80\left(\frac{dv^0}{\nu}\right)^{0.47}\left(\frac{\nu}{D}\right)^{1/3}$	d = capillary diameter v^0 = velocity approaching bed	Reliable if capillaries evenly spaced
Forced convection around a solid sphere	$\frac{kd}{D} = 2.0 + 0.6\left(\frac{dv^0}{\nu}\right)^{1/2}\left(\frac{\nu}{D}\right)^{1/3}$	d = sphere diameter v^0 = velocity of sphere	Very difficult to reach $(kd/D) = 2$ experimentally; no sudden laminar-turbulent transition
Free convection around a solid sphere	$\frac{kd}{D} = 2.0 + 0.6\left(\frac{d^3\Delta\rho g}{\rho\nu^2}\right)^{1/4}\left(\frac{\nu}{D}\right)^{1/3}$	d = sphere diameter g = gravitational acceleration	For a 1-cm sphere in water, free convection is important when $\Delta\rho = 10^{-9}$ g/cm^3
Packed beds	$\frac{k}{v^0} = 1.17\left(\frac{dv^0}{\nu}\right)^{-0.42}\left(\frac{D}{\nu}\right)^{2/3}$	d = particle diameter v^0 = superficial velocity	The superficial velocity is that which would exist without packing
Spinning disc	$\frac{kd}{D} = 0.62\left(\frac{d^2\omega}{\nu}\right)^{1/2}\left(\frac{\nu}{D}\right)^{1/3}$	d = disc diameter ω = disc rotation (radians/time)	Valid for Reynolds numbers between 100 and 20,000

Notes: [a] The symbols used include the following: D is the diffusion coefficient of the material being transferred; k is the local mass transfer coefficient; ρ is the fluid density; ν is the kinetmatic viscosity. Other symbols are defined for the specific situation.

[b] The dimensionless groups are defined as follows: (dv^0/ν) and $(d^2\omega/\nu)$ are the Reynolds number; ν/D is the Schmidt number; $(d^3\Delta\rho g/\rho\nu^2)$ is the Grashof number, kd/D is the Sherwood number; k/v^0 is the Stanton number.

[c] The mass transfer coefficient given here is the value averaged over the length L.

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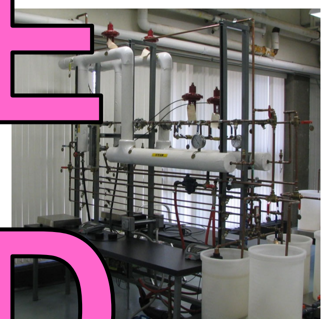
THE END



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