Engineering Flow and Heat Exchange

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PREFACE

This volume presents an overview of fluid flow and heat exchange.

In the broad sense, fluids are materials which are able to flow under the right conditions. These include all sorts of things: pipeline gases, coal slurries, toothpaste, gases in high-vacuum systems, metallic gold, soups and paints, and, of course, air and water. These materials are very different types of fluids, and so it is important to know the different classifications of fluids, how each is to be analyzed (and these methods are quite different), and where a particular fluid fits into this broad picture.

This book treats fluids in this broad sense including flows in packed beds and fluidized beds. Naturally, in so small a volume, we do not go deeply into the study of any particular type of flow, however we do show how to make a start with each. We avoid supersonic flow and the complex subject of multiphase flow where each of the phases must be treated separately.

The approach here differs from most introductory books on fluids which focus on the Newtonian fluid and treat it thoroughly, to the exclusion of all else. I feel that the student engineer or technologist preparing for the real world should be introduced to these other topics.

Introductory heat transfer books are devoted primarily to the study of the basic rate phenomena of conduction, convection, and radiation, showing how to evaluate "h," "U," and "k" for this and that geometry and situation. Again, this book's approach is different. We rapidly summarize the basic equations of heat transfer, including the numerous correlations for "h". Then we go straight to the problem of how to get heat from here to there and from one stream to another.

The recuperator (or through-the-wall exchanger), the direct contact exchanger, the heat storing accumulator (or regenerator), and the exchanger which uses a third go-between stream—these are distinctly different ways of transferring heat from one stream to another, and this is what we concentrate on. It is surprising how much creativity may be needed to develop a good design for the transfer of heat from a stream of hot solid particles to a stream of cold solid particles. The flavor of this presentation of heat exchange is that of Kern's unique book; certainly simpler, but at the same time broader in approach.

Wrestling with problems is the key to learning and each of the chapters has illustrative examples and a number of practice problems. Teaching and learning should be interesting so I have included a wide variety of problems, some whimsical, others directly from industrial applications. Usually the information given in these practice problems has been designed so as to fall on unique points on the design charts, making it easy for the student and also for the instructor who is checking the details of a student's solution.

I think that this book will interest the practicing engineer or technologist who wants a broad picture of the subject, or on having a particular problem to solve, wants to know what approach to take.

In the university it could well form the basis for an undergraduate course in engineering or applied fluids and heat transfer, after the principles have been introduced in a basic engineering course such as transport phenomena. At present, such a course is rarely taught; however, I feel it should be an integral part of the curriculum, at least for the chemical engineer and the food technologist. Who knows, some day it may be.

Finally, my thanks to supertypists Laurie Campbell, Vi Campbell, and Nancy Platz for their boundless patience with this mid-space writer, to Richard Turton, who coaxed our idiot computer into drawing charts for this book, and to Eric Swenson, who so kindly consented to put his skilled hand to the creation of drawing and sketch to enliven and complement the text.

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NOMENCLATURE

a	specific surface, surface of solid/volume of vessel $[\text{m}^{-1}]$
A	area normal to flow, exterior surface area of a particle, area of exchanger $[\text{m}^2]$
A_t	cross-sectional area of flow channel $[\text{m}^2]$
Ar	Archimedes number, for fluidized beds $[-]$; see equation (7.4) and Appendix T
Bi	Biot number, for heat transfer $[-]$; see equation (11.4) and Appendix T
c	speed of sound in the fluid [m/s]; see equation (3.2)
C_D	drag coefficients for falling particles $[-]$; see equation (8.2) and Appendix T
C_g, C_l, C_s	specific heat of gas, liquid, or solid at constant pressure [J/kg K]
C_p	specific heat at constant pressure [J/kg K]; see Appendices P and U
C_v	specific heat at constant volume [J/kg K]
C_{12}	conductance for flow between points 1 and 2 in a flow channel $[\text{m}^3/\text{s}]$; see equation (4.3)
d	diameter [m]
d_e	equivalent diameter of noncircular channel [m]; see equation (2.16) or (9.15)

d_p	characteristic diameter of particles to use in flow problems [m]; see equation (6.3)
d_{scr}	screen diameter of particles [m]; see discussion in text between equations (6.3) and (6.4)
d_{sph}	equivalent spherical diameter of particles [m]; see equation (6.2)
f_D	Darcy friction factor, for flow in pipes [−]; see text after equation (2.5)
f_f	friction factor, for flow in packed beds [−]; see equation (6.10) and Appendix T
f_F	Fanning friction factor, for flow in pipes [−]; see equation 2.1, Figs. 2.4 and 2.5, and Appendix T
F	force [N]
Fo	Fourier number, for unsteady state heat conduction [−], see equation (11.2) and Appendix T
$F_{12}, F'_{12}, \bar{F}_{12}, \mathcal{F}_{12}$	various view factors for radiation between two surfaces, fraction of radiation leaving surface 1 which is intercepted by surface 2 [−]; see equations (9.74), (9.79), (9.81), and (9.83)
$\mathcal{F}$	efficiency factor for shell-and-tube heat exchangers [−]; see equation (13.17a)
F_d	drag force on a falling particle [N]; see equation (8.1)
ΣF	lost mechanical work of a flowing fluid due to friction [J/kg]; see equation (1.5)
g	acceleration of gravity, about 9.8 $\mathrm{m/s^2}$ at sea level [$\mathrm{m/s^2}$]
$g_c = 1\ \mathrm{kg\,m/s^2\,N}$	conversion factor needed to get a consistent system of units; see Appendix E for additional values
$G = u\rho = G_0/\varepsilon$	mass velocity of flowing fluid, that based on the mean cross-sectional area available for the flowing fluid in the packed bed [$\mathrm{kg/m^2}$ open · s]
$G_0 = u_0\rho = G\varepsilon$	mass velocity of flowing fluid, that based on the total cross-sectional area of packed bed [$\mathrm{kg/m^2}$ bed · s]
Gr	Grashof number, for natural convection [−]; see text above equation (11.31) and Appendix T
h	heat transfer coefficient, for convection [$\mathrm{W/m^2\,K}$]; see text above equation (9.11)
h_L	head loss of fluid resulting from frictional effects [m]; see equation (1.6) and the figure below equation (2.2)
H	enthalpy [J/kg]
He	Hedstrom number, for flow of Bingham plastics [−]; see equation (5.8) and Appendix T
i.d.	inside diameter [m]
k	thermal conductivity [W/m K]; see equation (9.1) and Appendices O and V
$k = C_p/C_v$	ratio of specific heats of fluid [−]; $k \cong 1.67$ for monotonic gases; $k \cong 1.40$ for diatomic gases; $k \cong 1.32$ for triatomic gases; $k \cong 1$ for liquids

K	fluid consistency index of power law fluids and general plastics, a measure of viscosity $[\mathrm{kg/m\,s^{2-n}}]$; see equations (5.3) and (5.4)
$\mathrm{KE} = u^2/2g_c$	shorthand notation for the kinetic energy of the flowing fluid [J/kg]
Kn	Knudsen number, for molecular flow [−]; see beginning of Chapter 4 and see Appendix T
l	length or distance [m]
L	length of flow channel or vessel [m]
L, L_p	characteristic length of particle [m]; see equation (11.3) and text after equation (15.10)
m	mass of particle [kg]
$\dot{m}$	mass flow rate [kg/s]
M	number of standard deviations; see equation (15.10)
$\mathrm{Ma} = u/c$	Mach number, for compressible flow of gas [−]; see equations (3.1) and (3.2)
(mfp)	mean free path of molecules [m]; see Chapter 4
(mw)	molecular weight [kg/mol]; see Appendix J; $(mw) = 0.0289$ kg/mol, for air
n	flow behavior index for power law fluids and general plastics [−]; see equations (5.3) and (5.4)
$\dot{n}$	molar flow rate [mol/s]
N	number of stages in a multistage heat exchanger [−]; see Chapter 14
$N = 4f_F L/d$	pipe resistance term [−]; see equation (3.7)
N	rotational rate of a bob of a rotary viscometer $[\mathrm{s^{-1}}]$; see equation (5.15)
NNs	shorthand notation for non-Newtonian fluids
$\mathrm{NTU} = UA/\dot{M}C$	number of transfer units [−]; see Fig. 11.4
Nu	Nusselt number, for convective heat transfer [−]; see equation (9.11) and Appendix T
P	pressure $[\mathrm{Pa} = \mathrm{N/m^2}]$; see Appendix G
$P = \Delta T_i/\Delta T_{max}$	temperature change of phase i compared to the maximum possible [−]; see Fig. 13.4
$\mathrm{PE} = zg/g_c$	shorthand notation for the potential energy of the flowing fluid [J/kg]
Pr	Prandtl number for fluids [−]; see Appendix T
q	heat added to a flowing fluid [J/kg]
$\dot{q}$	heat transfer rate [W]
$\dot{q}_{12}$	flow rate of energy from surface 1 to surface 2 [W]; see equation (9.65)
Q	heat lost or gained by a fluid up to a given point in the exchanger [J/kg of a particular flowing phase]; see Fig. 13.4
$R = 8.314$ J/mol K	gas constant for ideal gases; see Appendix K
R	ratio of temperature changes of the two fluids in an exchanger [−]; see Fig. 13.4

Re	Reynolds number for flowing fluids [–]; see text after equation (2.4) and Appendix T
$\mathrm{Re} = du\rho/\mu$	for flow of Newtonians in pipes; see equation (2.4)
$\mathrm{Re} = du\rho/\eta$	for flow of Bingham plastics in pipes; see equation (5.8)
$\mathrm{Re}_{\mathrm{gen}} = \left(\dfrac{d^n u^{2-n}\rho}{8^{n-1}K}\right)\left(\dfrac{4n}{1+3n}\right)^n$	for flow of power law fluids in circular pipes; see equation (5.10)
$\mathrm{Re}_p = d_p u_0 \rho/\mu$	for flow in packed and fluidized beds; see equation (6.9)
$\mathrm{Re}_t = d_p u_t \rho/\mu$	at the terminal velocity of a falling particle; see equation (8.6)
S	entropy of an element of flowing fluid [J/kg K]
s	pumping speed, volumetric flow rate of gas at a given location in a pipe [m^3/s]; see equation (4.4)
t	time [s]
T	temperature [K]
$\overline{\Delta T}$	proper mean temperature difference between the two fluids in an exchanger [K]
u	velocity or mean velocity [m/s]
u_{mf}	minimum fluidizing velocity [m/s]
u_0	superficial velocity for a packed or fluidized bed, thus the velocity of fluid if the bed contained no solids [m/s]; see equation (6.9)
U	internal energy [J/kg]; see equation (1.1)
U	overall heat transfer coefficient [W/m^2 K]; see text after equation (10.4)
u_t	terminal velocity of a particle in a fluid [m/s]
$\dot{v}$	volumetric flow rate of fluid [m^3/s]
V	volume [m^3.]
W	mass of a batch of material [kg]
W_{flow}	work done by fluid in pushing back the atmosphere; this work is not recoverable as useful work [J/kg]
W_s	shaft work; this is the mechanical work produced by the fluid which is transmitted to the surroundings [J/kg]
$\dot{W}_s$	pumping power; that produced by fluid and transmitted to the surroundings [W]
y	distance from the wall of a flow channel [m]; first sketch in Chapter 2
z	height above some arbitrarily selected level [m]
Z	compressibility factor, correction factor to the ideal gas law [–]; see text after equation (3.15)

Greek Symbols

α	kinetic energy correction factor [–]; see equation (2.12)
$\alpha = k/\rho C_p$	thermal diffusivity [m^2/s]; see equation (11.1) and Appendices Q and U

α	the absorptivity or the fraction of incident radiation absorbed by a surface [−]; see equation (9.59)
ϵ	pipe roughness [m]; see Table 2.1
ε	voidage in packed and fluidized beds [−]; see Figs. 6.3 and 6.4
ε	emissivity of a surface [−]; see equation (9.60)
η	pump efficiency [−]; see equation (1.14)
η	plastic viscosity of Bingham plastic non-Newtonian fluids [kg/m s]; see equation (5.2)
$\eta_i = \Delta T_i / \Delta T_{max}$	efficiency or effectiveness of heat utilization of stream *i*, or fractional temperature change of stream *i* [−]; see equation (17.3) or (18.2)
π	atmospheric pressure
μ	viscosity of a Newtonian fluid [kg/m s]; see equation (5.1) and Appendix M
ρ	density [kg/m^3]; see Appendices L and U
σ	standard deviation in the spread of the temperature front in a packed bed regenerator; see equation (15.9)
$\sigma = 5.73 \times 10^{-8}$ W/m^2 K^4	Stefan–Boltzmann radiation constant; see equation (12.5)
τ	shear stress (Pa = N/m^2); see text above equation (2.1) and beginning of Chapter 5
τ_w	shear stress at the wall [Pa]
τ_0	yield stress of Bingham plastics [Pa]; see equation (5.2)
ϕ	sphericity of particles [−]; see equation (6.1)
$\phi = \dot{m}_g C_g / \dot{m}_s C_s$	heat flow ratio of two contacting streams [−]; see equation (14.3)
ϕ'	heat flow ratio for each stage of a multistage contacting unit [−]; see equation (14.10)

Subscripts

f	property of the fluid at the film temperature, considered to be the average between the bulk and wall temperatures, or at $T_f = (T_{wall} + T_{bulk})/2$; see equation (9.24)
g	gas
l	liquid
lm	logarithmic mean
s	solid

CONTENTS

Part I: FLOW OF FLUIDS AND MIXTURES

Part II: HEAT EXCHANGE

Part I FLOW OF FLUIDS AND MIXTURES

Although the first part of this little volume deals primarily with the flow of fluids and mixtures through pipes, it also considers the flow of fluids through packed beds and through swarms of suspended solids called fluidized solids, as well as the flow of single particles through fluids. The term "fluids and mixtures" includes all sorts of materials under a wide range of conditions, such as Newtonians (e.g., air, water, whiskey), non-Newtonians (e.g., peanut butter, toothpaste), gases approaching the speed of sound, and gas flow under high vacuum where collisions between molecules are rare.

Chapter 1 presents the two basic equations which are the starting point for all analyses of fluid flow, the total energy balance and the mechanical energy balance. Chapters 2 through 8 then take up the different kinds of flow.

Chapter 1 BASIC EQUATIONS FOR FLOWING STREAMS

I. TOTAL ENERGY BALANCE

Consider the energy interactions as a stream of material passes in steady flow between points 1 and 2 of a piping system, as shown in Fig. 1.1. From the first law of thermodynamics we have for each unit mass of flowing fluid:

$$\overset{\text{Internal energy}}{\Delta U} + \Delta\underset{\text{Potential energy, PE}}{\left(\frac{gz}{g_c}\right)} + \Delta\overset{\text{Kinetic energy, KE}}{\left(\frac{u^2}{2g_c}\right)} + \Delta\underset{\text{Flow work}}{\left(\frac{p}{\rho}\right)} = \overset{\text{Heat added to fluid from surroundings}}{q} - \underset{\text{Work received by surroundings from fluid}}{W_s} \qquad \left[\frac{\text{J}}{\text{kg}}\right] \tag{1.1}$$

Consider the internal energy term in the above expression. From the second