Chapter 6

Heat Exchanger Pipes and Tubes

INTRODUCTION

This chapter is primarily concerned with providing information on pipes and tubes. Both serve as the "arteries" and "veins" that supply the fluids enabling energy transfer to occur in heat exchangers.

Many types of heat exchangers and heat exchanger applications involve the transfer of heat between and/or across a metallic surface and a fluid that is either being heated or cooled. The metallic surface in question usually takes the form of a cylindrical pipe or tube. Although the terms pipe and tube have come to mean different things to different people, the two are routinely used interchangeably. However, there are differences. In a relative sense, pipes are generally "heavier," of shorter length, larger diameter, rougher internally, and can be threaded. The one common denominator is that both are almost always metallic. Some key properties of metals, many of which are employed in the making of pipes and tubes, are presented in Table 6.1.(1) Note that in addition to providing information on density (ρ), heat capacity (c_p), and thermal diffusivity (α) at 20°C, the table contains thermal conductivity (k) data over a wide temperature range.

Chapter contents include a separate treatment of pipes and tubing as well as sections on valves and fittings, non-circular conduits, and flow considerations.

PIPES

As noted in the Introduction, fluids are usually transported in pipes or tubes. Pipes are specified in terms of their diameter and wall thickness. The nominal diameters range from $\frac{1}{8}$ to 30 inches for steel pipe. Standard dimensions of steel pipe are provided in Table 6.2(2) and are known as IPS (iron pipe size) or NPS (nominal pipe size). The wall thickness of the pipe is indicated by the schedule number (SN), which can be approximated from

$$\mathrm{SN} = 1000(P/S) \tag{6.1}$$

Heat Transfer Applications for the Practicing Engineer. Louis Theodore

Table 6.1 Property Values for Metals

	Properties at 20°C				Thermal conductivity k, W/m · K (or W/m · °C)									
Metal	ρ, kg/m^3	c_p, kJ/kg · K	k, W/m · K	α, m^2/s ($\times 10^5$)	−100°C −148°F	0°C 32°F	100°C 212°F	200°C 392°F	300°C 572°F	400°C 752°F	600°C 1112°F	800°C 1472°F	1000°C 1832°F	1200°C 2192°F
Aluminum:														
Pure	2707	0.896	204	8.418	215	202	206	215	228	249				
Al-Cu (Duralumin), 94−96% Al 3−5% Cu trace Mg	2787	0.883	164	6.676	126	159	182	194						
Al-Si (Silumin, copper-bearing), 86.5% Al 1% Cu	2659	0.867	137	5933	119	137	144	152	161					
Al-Si (Alusil), 78−80% Al 20−22% Si	2627	0.854	161	7.172	144	157	168	175	178					
Al-Mg-Si, 97% Al 1% Mg 1% Si 1% Mn	2707	0.892	177	7.311		175	189	204						
Lead	11,373	0.130	35	2.343	36.9	35.1	33.4	31.5	29.8					
Iron:														
Pure	7897	0.452	73	2.034	87	73	67	62	55	48	40	36	35	35
Wrought iron, 0.5% C	7849	0.46	59	1.626		59	57	52	48	45	36	33	33	33
Steel (C max ≈ 1.5%):														
Carbon steel,														
C ≈ 0.5%	7833	0.465	54	1.474		55	52	48	45	42	35	31	29	31
1.0%	7801	0.473	43	1.172		43	43	42	40	36	33	29	28	29
1.5%	7753	0.486	36	0.970		36	36	36	35	33	31	28	28	29

(Continued)

Table 6.1 *Continued*

	Properties at 20°C				Thermal conductivity k, W/m · K (or W/m · °C)									
Metal	ρ, kg/m^3	c_p, kJ/kg · K	k, W/m · K	α, m^2/s ($\times 10^5$)	−100°C −148°F	0°C 32°F	100°C 212°F	200°C 392°F	300°C 572°F	400°C 752°F	600°C 1112°F	800°C 1472°F	1000°C 1832°F	1200°C 2192°F
Nickel steel,														
Ni ≈ 0%	7897	0.452	73	2.206										
20%	7933	0.46	19	0.526										
40%	8169	0.46	10	0.279										
80%	8618	0.46	35	0.872										
Invar, 36% Ni	8137	0.46	10.7	0.286										
Chrome steel,														
Cr = 0%	7897	0.452	73	2.026	87	73	67	62	55	48	40	36	35	36
1%	7865	0.46	61	1.665		62	55	52	47	42	36	33	33	
5%	7833	0.46	40	1.110		40	38	36	36	33	29	29	29	
20%	7689	0.46	22	0.635		22	22	22	22	24	24	26	29	
Cr-Ni (chrome-nickel):														
15% Cr 10% Ni	7865	0.46	19	0.527										
18% Cr 8% Ni (V2A)	7817	0.46	16.3	0.444		16.3	17	17	19	19	22	27	31	
20% Cr 15% Ni	7833	0.46	15.1	0.415										
25% Cr 20% Ni	7865	0.46	12.8	0.361										
Tungsten steel,														
W = 0%	7897	0.452	73	2.206										
1%	7913	0.448	66	1.858										
5%	8073	0.435	54	1.525										
10%	8314	0.419	48	1.391										
Copper:														
Pure	8954	0.3831	386	11.234	407	386	379	374	369	363	353			
Aluminum bronze, 95% Cu 5% Al	8666	0.410	83	2.330										

(*Continued*)

Table 6.1 *Continued*

	Properties at 20°C				Thermal conductivity k, W/m · K (or W/m · °C)									
Metal	ρ, kg/m^3	c_p, kJ/kg · K	k, W/m · K	α, m^2/s ($\times 10^5$)	−100°C −148°F	0°C 32°F	100°C 212°F	200°C 392°F	300°C 572°F	400°C 752°F	600°C 1112°F	800°C 1472°F	1000°C 1832°F	1200°C 2192°F
Bronze, 75% Cu 25% Sn	8666	0.343	26	0.859										
Red brass, 85% Cu 9% Sn 6% Zn	8714	0.385	61	1.804		59	71							
Brass, 70% Cu 30% Zn	8522	0.385	111	3.412	88		128	144	147	147				
German silver, 62% Cu 15% Ni 22% Zn	8618	0.394	24.9	0.733	19.2		31	40	45	48				
Constantan, 60% Cu 40% Ni	8922	0.410	22.7	0.612	21		22.2	26						
Magnesium:														
Pure	1746	1.013	171	9.708	178	171	168	163	157					
Mg-Al (electrolytic), 6–8% Al 1–2% Zn	1810	1.00	66	3.605		52	62	74	83					
Molybdenum	10,220	0.251	123	4.790	138	125	118	114	111	109	109	102	99	92
Nickel:														
Pure (99.9%)	8906	0.4459	90	2.266	104	93	83	73	64	59				
Ni-Cr, 90% Ni, 10% Cr	8666	0.444	17	0.444		17.1	18.9	20.9	22.8	24.6				
80% Ni 20% Cr	8314	0.444	12.6	0.343		12.3	13.8	15.6	17.1	18.0	22.5			
Silver:														
Purest	10,524	0.2340	419	17.004	419	417	415	412						
Pure (99.9%)	10,525	0.2340	407	16.563	419	410	415	374	362	360				
Tin, pure	7304	0.2265	64	3.884	74	65.9	59	57						
Tungsten	19,350	0.1344	163	6.271		166	151	142	133	126	112	76		
Zinc, pure	7144	0.3843	112.2	4.106	114	112	109	106	100	93				

Table 6.2 Dimensions, Capacities, and Weights of Standard Steel Pipes

Nominal pipe size, in	Schedule number	Outside diameter, in	Wall thickness, in	Inside diameter (ID), in	Cross-sectional area of metal, in^2	Inside sectional area, ft^2	Pipe weight, lb/ft
$\frac{1}{8}$	40	0.405	0.068	0.269	0.072	0.00040	0.24
	80		0.095	0.215	0.093	0.00025	0.31
$\frac{1}{4}$	40	0.540	0.088	0.364	0.125	0.00072	0.42
	80		0.119	0.302	0.157	0.00050	0.54
$\frac{3}{8}$	40	0.675	0.091	0.493	0.167	0.00133	0.57
	80		0.126	0.423	0.217	0.00098	0.74
$\frac{1}{2}$	40	0.840	0.109	0.622	0.250	0.00211	0.85
	80		0.147	0.546	0.320	0.00163	1.09
$\frac{3}{4}$	40	1.050	0.113	0.824	0.333	0.00371	1.13
	80		0.154	0.742	0.433	0.00300	1.47
1	40	1.315	0.133	1.049	0.494	0.00600	1.68
	80		0.179	0.957	0.639	0.00499	2.17
$1\frac{1}{4}$	40	1.660	0.140	1.380	0.668	0.01040	2.27
	80		0.191	1.278	0.881	0.00891	3.00
$1\frac{1}{2}$	40	1.900	0.145	1.610	0.800	0.01414	2.72
	80		0.200	1.500	1.069	0.01225	3.63
2	40	2.375	0.154	2.067	1.075	0.02330	3.65
	80		0.218	1.939	1.477	0.02050	5.02

(*Continued*)

Table 6.2 *Continued*

Nominal pipe size, in	Schedule number	Outside diameter, in	Wall thickness, in	Inside diameter (ID), in	Cross-sectional area of metal, in^2	Inside sectional area, ft^2	Pipe weight, lb/ft
$2\frac{1}{2}$	40	2.875	0.203	2.469	1.704	0.03322	5.79
	80		0.276	2.323	2.254	0.02942	7.66
3	40	3.500	0.216	3.068	2.228	0.05130	7.58
	80		0.300	2.900	3.016	0.04587	10.25
$3\frac{1}{2}$	40	4.000	0.226	3.548	2.680	0.06870	9.11
	80		0.318	3.364	3.678	0.06170	12.51
4	40	4.500	0.237	4.026	3.17	0.08840	10.79
	80		0.337	3.826	4.41	0.07986	14.98
5	40	5.563	0.258	5.047	4.30	0.1390	14.62
	80		0.375	4.813	6.11	0.1263	20.78
6	40	6.625	0.280	6.065	5.58	0.2006	18.97
	80		0.432	5.761	8.40	0.1810	28.57
8	40	8.625	0.322	7.981	8.396	0.3474	28.55
	80		0.500	7.625	12.76	0.3171	43.39
10	40	10.75	0.365	10.020	11.91	0.5475	40.48
	80		0.594	9.562	18.95	0.4987	64.40
12	40	12.75	0.406	11.938	15.74	0.7773	53.36
	80		0.688	11.374	26.07	0.7056	88.57

where P is the maximum internal service pressure (psi) and S is the allowable bursting stress in the pipe material (psi). (The S value varies by material, grade of material, and temperature; allowable S values may be found in standard piping handbooks.) As noted above, the internal walls of a pipe are generally "rough," as opposed to tubes whose walls are generally "smooth."

ILLUSTRATIVE EXAMPLE 6.1

Obtain the inside diameter in inches of 2 inch schedule 40 nominal steel pipe.

***SOLUTION*:** Refer to Table 6.2. The answer is 2.067 in. ■

ILLUSTRATIVE EXAMPLE 6.2

Determine the inside diameter (ID), outside diameter (OD), wall thickness, and pipe weight (in lb/ft) of 3 inch schedule 40 steel pipe.

***SOLUTION*:** Obtain the pipe inside diameter, outside diameter, wall thickness, and weight using Table 6.2.

ID = 3.068 in
OD = 3.5 in
Wall thickness = 0.216 in
Pipe weight = 7.58 lb/ft ■

ILLUSTRATIVE EXAMPLE 6.3

The following information is provided for a steel pipe:

ID = 0.957 in
OD = 1.315 in
Wall thickness = 0.179 in
Pipe weight = 2.17 lb/ft

Determine the nominal size and schedule number of the pipe.

***SOLUTION*:** A quick check of Table 6.2 indicates that the steel pipe is 1 inch schedule 80. ■

TUBES

Generally speaking, tubes are thin-walled and often come in coils. Tube sizes are indicated by the outside diameter. The wall thickness is usually given a BWG (Birmingham Wire Gauge) number. The smaller the BWG, the heavier the tube.

Table 6.3 Dimensions of Heat Exchanger Tubes

Tube OD, in	BWG gauge	Thickness, in	Tube inside diameter (ID), in	Flow area, in^2	Surface area, per foot of length, ft	
					External	Internal
$\frac{1}{4}$	22	0.028	0.194	0.0295	0.0655	0.0508
$\frac{1}{4}$	24	0.022	0.206	0.0333	0.0655	0.0539
$\frac{1}{2}$	18	0.049	0.402	0.1269	0.1309	0.1052
$\frac{1}{2}$	20	0.035	0.430	0.1452	0.1309	0.1126
$\frac{1}{2}$	22	0.028	0.444	0.1548	0.1309	0.1162
$\frac{3}{4}$	10	0.134	0.482	0.1825	0.1963	0.1262
$\frac{3}{4}$	14	0.083	0.584	0.2679	0.1963	0.1529
$\frac{3}{4}$	16	0.065	0.620	0.3019	0.1963	0.1623
$\frac{3}{4}$	18	0.049	0.652	0.3339	0.1963	0.1707
1	8	0.165	0.670	0.3526	0.2618	0.1754
1	14	0.083	0.834	0.5463	0.2618	0.2183
1	16	0.065	0.870	0.5945	0.2618	0.2278
1	18	0.049	0.902	0.6390	0.2618	0.2361
$1\frac{1}{4}$	8	0.165	0.920	0.6648	0.3272	0.2409
$1\frac{1}{4}$	14	0.083	1.084	0.9229	0.3272	0.2838
$1\frac{1}{4}$	16	0.065	1.120	0.9852	0.3272	0.2932
$1\frac{1}{4}$	18	0.049	1.152	1.042	0.3272	0.3016
2	11	0.120	1.760	2.433	0.5236	0.4608
2	12	0.109	1.782	2.494	0.5236	0.4665
2	13	0.095	1.810	2.573	0.5236	0.4739
2	14	0.083	1.834	2.642	0.5236	0.4801

(1 in = 25.4 mm; 1 in^2 = 645.16 mm^2; 1 ft = 0.3048 m; 1 ft^2 = 0.0929 m^2).

Table 6.3$^{(2)}$ lists the sizes and wall thicknesses of condenser and heat exchanger tubes. Standard exchanger tubing is $\frac{1}{4}$, $\frac{3}{8}$, $\frac{1}{2}$, $\frac{5}{8}$, $\frac{3}{4}$, 1, $1\frac{1}{4}$, and 2 inch outside diameter. The most commonly used tubes in the chemical process industry and petroleum refineries are $\frac{3}{4}$ and 1 inch outside diameter. Standard tube lengths are 8, 10, 12, 16, and 20 ft with 16 ft as the most common. Longer lengths are usually coiled. It is common practice to specify a heat exchanger's surface in terms of the total external square feet of tubing. Tubing can be easily drawn and is usually set to minimum wall specifications.

When corrosive atmospheres or concern with temperature excursions limit the use of a single metal for the tubes, bimetallic (or duplex) tubes may be employed. These tubes can be made from almost any possible combination of metals. For thin gauges, the wall thickness is generally divided equally between the two components. As one might expect with heavier gauges, the more expensive component usually comprises from a fifth to a third of the total thickness.

ILLUSTRATIVE EXAMPLE 6.4

Determine the inside diameter, wall thickness, outside diameter, and external area per foot (EA) of a $\frac{3}{4}$ inch 16 BWG tube.

***SOLUTION*:** From Table 6.3,

$$\text{ID} = 0.620\ \text{in}$$
$$\text{Wall thickness} = 0.065\ \text{in}$$
$$\text{OD} = 0.620 + (2)(0.065) = 0.75\ \text{in}$$
$$\text{EA} = 0.1963\ \text{ft}$$

■

ILLUSTRATIVE EXAMPLE 6.5

The tube weight of 2.0 inch 16 BWG tubing is 1.699 lb/ft. Comment on the weight of comparably-sized pipes and tubes.

***SOLUTION*:** With reference of Table 6.1, the pipe weight of 2.0 inch schedule 80 pipe is 5.02 lb/ft. The pipe is three (2.95 = 5.02/1.699) times heavier than the tubing! ■

VALVES AND FITTINGS

As indicated earlier, pipes and tubes, as well as other conduits, are used for the transportation of gases, liquids, and slurries. These ducts are often connected and may also contain a variety of valves and fittings, including expansion and contraction joints. The two major types of connecting conduits include:

1. Threaded
2. Welded

Extensive information on these two classes of connections is available in the literature.(1)

Details on valves and fittings are provided in the following two subsections. Changes in cross-sectional area receive treatment in Illustrative Examples 6.6 and 6.7.

Valves(2,3)

Because of the diversity of the types of systems, fluids, and environments in which valves(2) must operate, a vast array of valve types employed in exchangers have been developed. Examples of the common types are the globe valve, gate valve, ball valve, plug valve, pinch valve, butterfly valve, and check valve. Each type of valve has been designed to meet specific needs and are almost always located external to the exchanger. Some valves are capable of throttling the flow of a fluid to be heated or cooled, other valve types can only stop flow, others work well in corrosive systems, and others handle high pressure fluids. Each valve type has advantages and disadvantages. Understanding these differences and how they affect the valve's application or operation is necessary for the successful operation of a heat exchanger.

Valves have two main functions in an exchanger: to control the amount of flow or to stop the flow completely. Of the many different types of valves, the most commonly used are the gate valve and the globe valve. The gate valve contains a disk that slides at right angles to the flow direction. This type of valve is used primarily for on–off control of a liquid flow. Because small lateral adjustments of the disk can cause extreme changes in the flow cross-sectional area, this type of valve is not suitable for accurately adjusting flow rates. As the fluid passes through the gate valve, only a small amount of turbulence is generated; the direction of flow is not altered and the flow cross-sectional area inside the valve is often only slightly smaller than that of the pipe. As a result, the valve causes only a minor pressure drop. Problems with abrasion and erosion of the disk can arise when the valve is used in positions other than fully open or fully closed.

Unlike the gate valve, the globe valve—so called because of the spherical shape of the valve body—is designed for more sensitive flow control. In this type of valve, the fluid to be heated or cooled passes through the valve in a somewhat circuitous route. In one form, the seal is a horizontal ring into which a plug with a slightly beveled edge is inserted when the stem is closed. Good control of flow is achieved with this type of valve, but at the expense of a higher pressure loss than a gate valve.

Stop valves are used to shut off or, in some cases, partially shut off the flow of fluid to the exchanger. Stop valves are controlled by the movement of the valve stem. Stop valves can be divided into four general categories: globe, gate, butterfly, and ball valves. Plug valves and needle valves may also be considered stop valves.

Ball valves, as the name implies, are stop valves that use a ball to stop or start the flow of fluid. The ball performs the same function as the disk in the globe valve. When the valve handle is operated to open the valve, the ball rotates to a point where the hole through the ball is in line with the valve body inlet and outlet. When the valve is shut, which requires only a 90-degree rotation of the handwheel for most valves, the ball is rotated so that the hole is perpendicular to the flow openings of the valve body, and flow is stopped.

A plug valve is a rotational motion valve, similar to a ball valve, used to stop or start fluid flow. The name is derived from the shape of the disk, which resembles a plug. The simplest form of a plug valve is the petcock. The body of a plug valve is machined to receive the tapered or cylindrical plug. The disk is a solid plug with a bored passage at a right angle to the longitudinal axis of the plug. In the open position, the passage in the plug lines up with the inlet and outlet ports of the valve. When the plug is turned 90° from the open position, the solid part of the plug blocks the ports and stops fluid flow.

Finally, check valves are designed to prevent the reversal of flow in a heat exchanger. These valves are activated by the flowing material in the exchanger. The pressure of the fluid passing through the piping/tubing system opens the valve, while any reversal of flow will close the valve. Closure is accomplished by the weight of the check mechanism, by back pressure, by a spring, or by a combination of these means. The general types (classification) of check valves are swing, tilting-disk, piston, butterfly, and stop.

Valves are also sometimes classified according to the resistance they offer to flow. The low resistance class of valves includes the straight-through flow units (e.g., gate, ball, and plug valves). Valves having a change in direction are high resistance valves; an example is the globe valve.

Fittings(2,3)

A fitting is a piece of equipment that has for its function one or more of the following:

1. The joining of two pieces of straight pipe or tube (e.g., couplings and unions).
2. The changing of flow direction (e.g., elbows and Ts).
3. The changing of pipe or tube diameter (e.g., reducers and bushings).
4. The terminating of a pipe or tube (e.g., plugs and caps).
5. The joining of two streams (e.g., Ts and Ys).

Since fittings find application primarily with pipes—as opposed to tubes—the next paragraph will key on pipe fittings.

A coupling is a short piece of pipe threaded on the inside and used to connect straight sections of pipe with no change in direction or size. When a coupling is opened, a considerable amount of piping must usually be dismantled. A union is also used to connect two straight sections but differs from a coupling in that it can be opened conveniently without disturbing the rest of the exchanger. An elbow is an angle fitting used to change flow direction, usually by 90°, although 45° elbows are also available. In addition, a T (shaped like the letter T) can be used to change flow direction; this fitting is more often used to combine two streams into one, i.e., when two branches of piping are to be connected at the same point. A reducer is a coupling for two pipe sections of different diameter. A bushing is also a connector for pipes of different diameter, but, unlike the reducer coupling, is threaded on both the inside and outside; the larger pipe screws onto the outside of the bushing and the smaller pipe screws into the inside of the bushing. Plugs, which are threaded on the outside, and caps, which are threaded on the inside, are used to terminate the flow of the heated or cooled fluid in a heat exchanger. Finally, a Y (shaped like the letter Y) is similar to the T and is used to combine two streams.

Fittings may be classified as reducing, expanding, branching, or deflecting. Reducing or expanding fittings are ones that change the area for flow; these include reducers, bushings, and sudden expansions and contractions. Branch fittings are Ts, crosses, or side outlet elbows. Deflecting fittings change the direction of flow, e.g., Ys, elbows and bends.

ILLUSTRATIVE EXAMPLE 6.6

Discuss when expansion and contraction effects can come into effect with heat exchangers.

***SOLUTION*:** Contraction effects can come into play when the fluid enters the exchanger. Expansion effects can appear as the fluid exits the exchanger. ■

ILLUSTRATIVE EXAMPLE 6.7

Provide equations that can be employed to calculate the pressure drop associated with:

1. a rapid (sudden) expansion
2. a rapid (sudden) contraction

***SOLUTION*:** If the cross-section of a conduit enlarges gradually so that the flowing fluid velocity in the heat exchanger does not undergo any disturbances, energy losses (pressure drop) are minor and may be neglected. However, if the change is sudden, as in a rapid expansion, it can result in friction losses. For such sudden enlargement/expansion situations, the pressure loss as the fluid exits the exchanger can be represented by

$$h_{f,e} = \frac{V_1^2 - V_2^2}{2g_c}; \quad e = \text{sudden expansion} \tag{6.2}$$

where $h_{f,e}$ is the loss in head, V_2 is the velocity at the larger cross-section and V_1 is the velocity at the smaller cross-section. When the cross-section of the conduit is reduced suddenly (a contraction), the loss may be expressed by:

$$h_{f,c} = \frac{KV_2^2}{2g_c}; \quad c = \text{sudden contraction} \tag{6.3}$$

where V_2 is the velocity in the small cross-section and K is a dimensionless loss coefficient that is a function of the ratio of the two cross-sectional areas. Both of the above calculations receive extensive treatment in the literature.$^{(2-4)}$ ■

NONCIRCULAR CONDUITS

Some heat transfer applications involve the flow of a fluid in a conduit or channel that does not have a circular cross-section. When the flow is turbulent, it is recommended that the flow is treated as if the flow occurs in a pipe. For this situation, a hydraulic radius, r_h, is defined as:

$$r_h = \frac{\text{cross-sectional area perpendicular to flow}}{\text{wetted perimeter}} = \frac{A_f}{P_w} \tag{6.4}$$

For flow in a circular tube of diameter D

$$r_h = \frac{(\pi D^2/4)}{\pi D} = \frac{D}{4}$$

and

$$D = 4r_h \tag{6.5}$$

One may extend this concept to any cross-section such that

$$D_h = 4r_h = \frac{4A_f}{P_w} \tag{6.6}$$

It is then possible to use this hydraulic or equivalent diameter in any circular pipe expression for pressure drop. Interestingly, the hydraulic diameter approach is usually valid for laminar flow but always valid for turbulent flow.

ILLUSTRATIVE EXAMPLE 6.8

A common non-circular geometry is the flow in a concentric tube annulus. For this application, the fluid passes through the annulus formed by the concentric tubes. Express the hydraulic diameter in terms of the inside diameter of the outer pipe, D_o, and the outside diameter of the inner pipe, $D_{i.}$

***SOLUTION*:** In this case the hydraulic diameter, D_h, is

$$D_{eq} = D_h = \frac{4A_f}{P_w} \tag{6.6}$$

Substituting,

$$D_h = \frac{4(\pi/4)(D_o^2 - D_i^2)}{\pi D_o + \pi D_i} = D_o - D_i$$

■

ILLUSTRATIVE EXAMPLE 6.9

Determine the area and perimeter of the following conduits:

1. Rectangle of length b and width a.
2. Parallelogram of height h and base b with angle between ab denoted by θ.
3. Trapezoid of height h and parallel sides a and b with base angles θ and ϕ.
4. Regular polygon of n sides each of length b.

***SOLUTION*:**

1. Area $= ab$

   Perimeter $= 2a + 2b$
2. Area $= bh = ab \sin\theta$

   Perimeter $= 2a + 2b$
3. Area $= \frac{1}{2}h(a + b)$

   $$\text{Perimeter} = a + b + h\left(\frac{1}{\sin\theta} + \frac{1}{\sin\phi}\right)$$

   $$= a + b + h(\csc\theta + \csc\phi)$$

4. Area $= \frac{1}{4} n b^2 \cot \frac{\pi}{n} = \frac{1}{4} n b^2 \frac{\cos(\pi/n)}{\sin(\pi/n)}$

Perimeter $= nb$ ■

ILLUSTRATIVE EXAMPLE 6.10

Refer to Illustrative Example 6.9. Outline how to determine the hydraulic diameter for cases (1–4).

***SOLUTION*:** Apply Equation (6.6) for each case, i.e.,

$$D_h = \frac{4A_f}{P_w}$$

For example, for (1)

$$\begin{aligned} D_h &= \frac{4(ab)}{2a + 2b} \\ &= \frac{2ab}{a + b} \end{aligned}$$

■

FLOW CONSIDERATIONS

Fluid flow through circular tubes (or pipes) is common in many heat exchanger applications. Such flow is always accompanied by frictional losses (e.g., between the fluid and the stationary wall and between portions of the fluid moving at different velocities), which cause a pressure drop in the direction of flow.

Flow in a pipe may be laminar or turbulent. Some characteristics of the two types of flow in terms of the dimensionless Reynolds number are given in Table 6.4. The Reynolds number is given by

$$\mathrm{Re} = DV\rho/\mu = \frac{DV}{\nu}; \quad \text{dimensionless} \tag{6.7}$$

where D = diameter
V = average fluid velocity
ρ = fluid density
μ = fluid viscosity
ν = kinematic viscosity

Table 6.4 Flow Characteristics

Flow type	Characteristics
Laminar (Re < 2300)	– Flow moves in axial direction – No motion normal to the tube axis
Turbulent (Re > 4000)	– No net flow normal to the tube axis – Strong, local, oscillating motion (or eddy) normal to the tube axis

The above Reynolds number is an important dimensionless number that plays a major role in determining a host of heat transfer coefficients to be introduced and discussed in the next Part.

The aforementioned pressure drop ΔP may be calculated from any of a host of equations,(1,2,4) including

$$\Delta P = \frac{4fLV^2}{2g_c D} \tag{6.8}$$

where L = pipe length
f = fraction factor

The friction factor is a function of Re and the internal roughness of the pipe. Details are available in the literature.(1,2,4)

Another important concept is that referred to as a "calming," "entrance," or "transition" length. This is the length of conduit required for a velocity profile to become fully developed following some form of disturbance in the conduit. This disturbance can arise because of a valve, a bend in the line, an expansion in the line, etc. This is an important concern when measurements are conducted in the cross-section of the pipe or conduit. An estimate of this "calming" length, L_c, for laminar flow is

$$\frac{L_c}{D} = 0.05\,\text{Re} \tag{6.9}$$

For turbulent flow, one may employ

$$L_c = 50D \tag{6.10}$$

ILLUSTRATIVE EXAMPLE 6.11

An air-conditioning duct has a rectangular cross-section of 1 m by 0.25 m. If the kinematic viscosity of the air is approximately $1 \times 10^{-5}\ \text{m}^2/\text{s}$, determine the maximum air velocity before the flow becomes turbulent. Assume the critical Reynolds number is 2300.

***SOLUTION*:** Compute the equivalent or hydraulic diameter (see Illustrative Example 6.10).

$$D_{eq} = D_h = \frac{2ab}{a+b} = \frac{2(1)(0.25)}{1+0.25}$$
$$= 0.4\,\text{m}$$

The equation for the "critical" Reynolds number is

$$\text{Re}_{\text{crit}} \approx 2300 = \frac{D_h V}{\nu} \tag{6.7}$$

Substitute and solve for V.

$$\begin{aligned} V &= 2300\frac{1\times 10^{-5}}{0.4} = 0.0575\,\text{m/s} \\ &= 5.8\,\text{cm/s} \end{aligned}$$

■

ILLUSTRATIVE EXAMPLE 6.12

A circular 2-inch diameter horizontal tube contains a cold liquid fluid of density and viscosity 70 lb/ft^3 and 0.1806 $\text{lb/ft}\cdot\text{s}$, respectively. If, the flow rate is 0.486 $\text{ft}^3\text{/s}$, determine if the flow is laminar.

***SOLUTION*:** Apply the continuity equation to obtain the flow velocity:

$$\begin{aligned} q &= VS = V(\pi D^2/4) \\ V &= \frac{4q}{\pi D^2} = \frac{4(0.486)}{\pi(0.1667)^2} \\ &= 22.3\ \text{ft/s} \end{aligned}$$

Check on the assumption of laminar flow:

$$\text{Re} = \frac{DV\rho}{\mu} = \frac{(0.1667)(22.3)(70)}{0.1806} = 1440 < 2100$$

The flow is laminar. ■

ILLUSTRATIVE EXAMPLE 6.13

Refer to Illustrative Example 6.12. How long must the pipe be to ensure a fully developed flow?

***SOLUTION*:** The pipe must be longer than the entrance length to have fully developed flow. Since the flow is laminar, apply Equation (6.9):

$$L_c = (0.05)(D)(\text{Re})$$

Substituting,

$$\begin{aligned} L_c &= (0.05)(2/12)(1440) \\ &= 12\ \text{ft} \end{aligned}$$

This is an abnormally long calming length for a pipe (or tube) in a heat exchanger. ■

ILLUSTRATIVE EXAMPLE 6.14

Calculate the average velocity of water flowing in a 2-inch schedule 40 standard pipe at 60°F for which the flow is viscous (laminar).

***SOLUTION*:** For laminar flow, assume Re < 2100, so the equation

$$\mathrm{Re} = \frac{DV\rho}{\mu} \leq 2100$$

can be solved for the velocity term.

$$V \leq \frac{2100\mu}{D\rho}$$

For water, $\mu = 6.72 \times 10^{-4}\,\mathrm{lb/ft \cdot s}$, $\rho = 62.4\,\mathrm{lb/ft^3}$. In addition, from Table 6.2, $D =$ 2.067 in. Therefore,

$$V \leq \frac{2100(6.72 \times 10^{-4})}{(2.067/12)(62.4)} = 0.13\ \mathrm{ft/s}$$

■

ILLUSTRATIVE EXAMPLE 6.15

Discuss some of the problems associated with pipes and tubing.

***SOLUTION*:** Some of the usual piping and tubing problems facing the practicing engineers are:

1. Choosing the correct material.
2. Selecting the most economical pipe size.
3. Selection of suitable means for joining piping and sealing joints.
4. Selection of anchors, hangars, and other supports.
5. Specifying an economic and appropriate insulation where required.
6. Determining proper pipe colors where required.
7. Be familiar with tubing and piping codes provided by:
    1. ASME (American Society of Mechanical Engineers)
    2. ASTM (American Society for Testing Materials)
    3. API (American Petroleum Institute)

■

REFERENCES

1. I. Farag and J. Reynolds, *Heat Transfer*, A Theodore Tutorial, Theodore Tutorials, East Williston, NY, 1996.
2. P. Abulencia and L. Theodore, *Fluid Flow for the Practicing Engineer*, John Wiley & Sons, Hoboken, NJ, 2009.
3. J. Santoleri, J. Reynolds, and L. Theodore, *Introduction to Hazardous Waste Incineration*, 2nd edition, John Wiley & Sons, Hoboken, NJ, 2000.
4. D. Green and R. Perry (editors), *Perry's Chemical Engineers' Handbook*, 8th edition, McGraw-Hill, New York City, NY, 2008.