Design of Double pipe Heat exchanger

Flow pattern

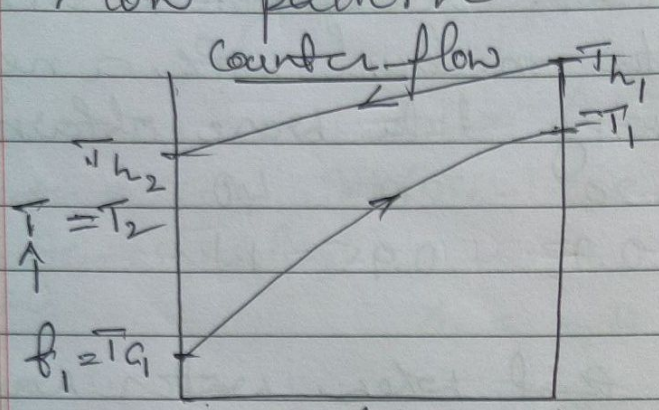


Fig (a)

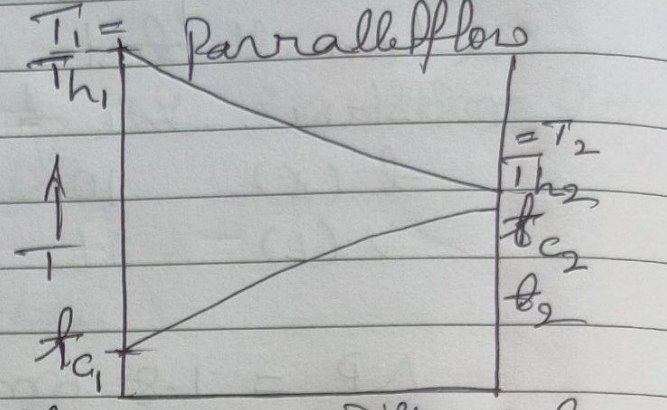


Fig (b)

Parallel (parallel) flow is not commonly used, especially in case of single-pass H.E. It is desired. Parallel flow is used in situations where

i. it is required to limit the maximum temperature of the coolant
ii. it is important to change the temperature of one of the fluids rapidly.

Counter flow is desired both in single pass exchanger and multipass exchanger

Observations from Fig (a) and Fig (b)

Parallel flow: T_{c_2} and T_{h_2} are approaches $T_{h_2}(T_2)$ is slightly higher than $t_{c_2}(t_2)$

Counter flow:

The exit temperature of cold fluid t_2 can be brought closer to entrance temp. of the other (T_1) fluid.

Parallel flow arrangement gives less Heat transfer than in Counter flow.

Q1 65,000 kg/h of nitrobenzene is to be cooled from 124°C to 95°C by using benzene which is heated from 25°C to 50°C.

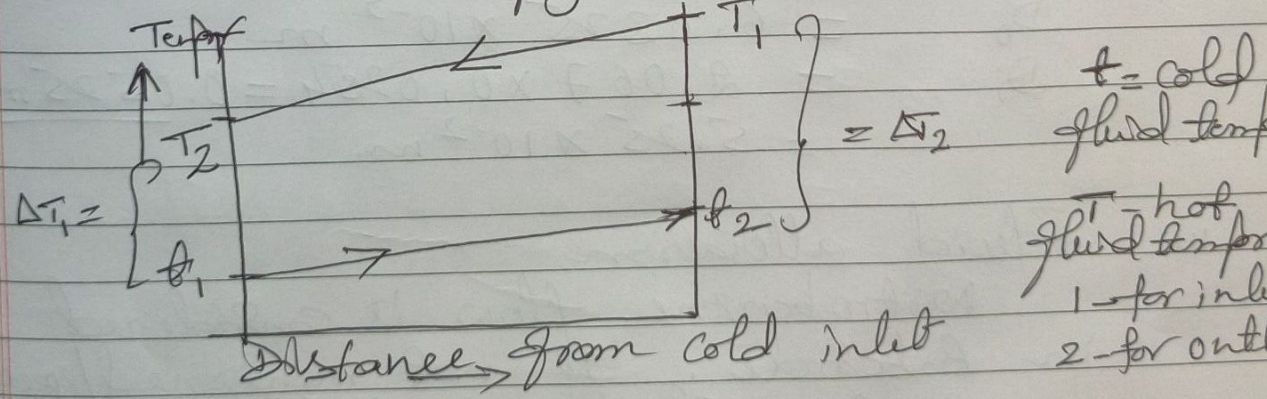
The pipe sections available are 2" and 1.25" IPS standard pipes. Length of the pipe is 5m. The dirt co-efficient is 1500 W/m²°C. Find the ~~no.~~ number of hairpins required and the pressure drop on either sides of the pipe and also the nozzle dimensions.

Solution:

i. Flow pattern and LMTD

Flow pattern is not mentioned in the statement of the numerical, and hence counter current flow is assumed.

The temperature profile is represented in the below figure.



$$LMTD = \frac{\Delta T_1 - \Delta T_2}{\ln \Delta T_1 / \Delta T_2}$$

Given $t_1 = 25°C$, $t_2 = 50°C$

$T_1 = 124°C$, $T_2 = 95°C$

TABLE 11. DIMENSIONS OF STEEL PIPE (IPS)

Nominal pipe size, IPS, in.	OD, in.	Schedule No.	ID, in.	Flow area per pipe, in.²	Surface per lin ft, ft.²/ft.		Weight per lin ft, lb steel
					Outside	Inside	
⅛	0.405	40*	0.269	0.058	0.106	0.070	0.25
		80†	0.215	0.036		0.056	0.32
¼	0.540	40*	0.364	0.104	0.141	0.095	0.43
		80†	0.302	0.072		0.079	0.54
⅜	0.675	40*	0.493	0.192	0.177	0.129	0.57
		80†	0.423	0.141		0.111	0.74
½	0.840	40*	0.622	0.304	0.220	0.163	0.85
		80†	0.546	0.235		0.143	1.09
¾	1.05	40*	0.824	0.534	0.275	0.216	1.13
		80†	0.742	0.432		0.194	1.48
1	1.32	40*	1.049	0.864	0.344	0.274	1.68
		80†	0.957	0.718		0.250	2.17
1¼	1.66	40*	1.380	1.50	0.435	0.362	2.28
		80†	1.278	1.28		0.335	3.00
1½	1.90	40*	1.610	2.04	0.498	0.422	2.72
		80†	1.500	1.76		0.393	3.64
2	2.38	40*	2.067	3.35	0.622	0.542	3.66
		80†	1.939	2.95		0.508	5.03
2½	2.88	40*	2.469	4.79	0.753	0.647	5.80
		80†	2.323	4.23		0.609	7.67
3	3.50	40*	3.068	7.38	0.917	0.804	7.58
		80†	2.900	6.61		0.760	10.3
4	4.50	40*	4.026	12.7	1.178	1.055	10.8
		80†	3.826	11.5		1.002	15.0
6	6.625	40*	6.065	28.9	1.734	1.590	19.0
		80†	5.761	26.1		1.510	28.6
8	8.625	40*	7.981	50.0	2.258	2.090	28.6
		80†	7.625	45.7		2.000	43.4
10	10.75	40*	10.02	78.8	2.814	2.62	40.5
		60	9.75	74.6		2.55	54.8
12	12.75	30	12.09	115	3.338	3.17	43.8
14	14.0	30	13.25	138	3.665	3.47	54.6
16	16.0	30	15.25	183	4.189	4.00	62.6
18	18.0	20‡	17.25	234	4.712	4.52	72.7
20	20.0	20	19.25	291	5.236	5.05	78.6
22	22.0	20‡	21.25	355	5.747	5.56	84.0
24	24.0	20	23.25	425	6.283	6.09	94.7

* Commonly known as standard.
† Commonly known as extra heavy.
‡ Approximately.

$\Delta T_1 = 95 - 28 = 70$

$\Delta T_2 = 124 - 50 = 74$

$\Delta T_{Ln} = LMTD = \frac{70 - 74}{Ln\ 70/74} = 71.98$

ii. Tubing characteristics

Given

Pipes are 2" and 1.25"

Reference Page No. :

Table No. :

2" pipe — O.D = D_o = 2.3766"

ID = D_i = 2.067"

1¼" Pip — O.D = d_o = 1.66"

ID = d_i = 1.38"

d_o = 4.216×10^{-2} m.

d_i = 3.5×10^{-2} m

D_o = 6.0325×10^{-2} m

D_i = $2.067 \times 0.0254 = 0.0525$ m

= 5.25×10^{-2} m

iii. Fluid allocation

Nitrobenzene flow is considered in tube side. If not mentioned/specified

Note: Fluid with high flow rate should be considered in tube side/annulus based on cross sectional area available

Fluid with less temperature drop may be considered in annulus.

Corrosive fluid should be considered in tube side.

TABLE 2-318 Viscosities of Liquids: Coordinates for Use with Fig. 2-32

Liquid	X	Y	Liquid	X	Y
Acetaldehyde	15.2	4.8	Freon-113	12.5	11.4
Acetic acid, 100%	12.1	14.2	Glycerol, 100%	2.0	30.0
Acetic acid, 70%	9.5	17.0	Glycerol, 50%	6.9	19.6
Acetic anhydride	12.7	12.8	Heptane	14.1	8.4
Acetone, 100%	14.5	7.2	Hexane	14.7	7.0
Acetone, 35%	7.9	15.0	Hydrochloric acid, 31.5%	13.0	16.6
Acetonitrile	14.4	7.4	Iodobenzene	12.8	15.9
Acrylic acid	12.3	13.9	Isobutyl alcohol	7.1	18.0
Allyl alcohol	10.2	14.3	Isobutyric acid	12.2	14.4
Allyl bromide	14.4	9.6	Isopropyl alcohol	8.2	16.0
Allyl iodide	14.0	11.7	Isopropyl bromide	14.1	9.2
Ammonia, 100%	12.6	2.0	Isopropyl chloride	13.9	7.1
Ammonia, 26%	10.1	13.9	Isopropyl iodide	13.7	11.2
Amyl acetate	11.8	12.5	Kerosene	10.2	16.9
Amyl alcohol	7.5	18.4	Linseed oil, raw	7.5	27.2
Aniline	8.1	18.7	Mercury	18.4	16.4
Anisole	12.3	13.5	Methanol, 100%	12.4	10.5
Antimony trichloride	13.9	14.5	Methanol, 90%	12.3	11.8
Benzene	12.5	10.9	Methanol, 40%	7.8	15.5
Brine, $CaCl_2$, 25%	6.6	15.9	Methyl acetate	14.2	8.2
Brine, NaCl, 25%	10.2	16.6	Methyl acrylate	13.0	9.5
Bromine	14.3	13.2	Methyl i-butyrate	12.3	9.7
Bromotoluene	20.0	15.9	Methyl n-butyrate	13.2	10.3
Butyl acetate	12.3	11.0	Methyl chloride	15.0	3.8
Butyl acrylate	11.3	12.6	Methyl ethyl ketone	13.9	8.6
Butyl alcohol	8.6	17.2	Methyl formate	14.2	7.5
Butyric acid	12.1	15.3	Methyl iodide	14.3	9.3
Carbon dioxide	11.6	0.3	Methyl propionate	13.5	9.0
Carbon disulfide	16.1	7.5	Methyl propyl ketone	14.3	9.5
Carbon tetrachloride	12.7	13.1	Methyl sulfide	15.3	6.4
Chlorobenzene	12.3	12.4	Napthalene	7.9	18.1
Chloroform	14.4	10.2	Nitric acid, 95%	12.8	13.8
Chlorosulfonic acid	11.2	18.1	Nitric acid, 60%	10.8	17.0
Chlorotoluene, ortho	13.0	13.3	Nitrobenzene	10.6	16.2
Chlorotoluene, meta	13.3	12.5	Nitrogen dioxide	12.9	8.6
Chlorotoluene, para	13.3	12.5	Nitrotoluene	11.0	17.0
Cresol, meta	2.5	20.8	Octane	13.7	10.0
Cyclohexanol	2.9	24.3	Octyl alcohol	6.6	21.1
Cyclohexane	9.8	12.9	Pentachloroethane	10.9	17.3
Dibromomethane	12.7	15.8	Pentane	14.9	5.2
Dichloroethane	13.2	12.2	Phenol	6.9	20.8
Dichloromethane	14.6	8.9	Phosphorus tribromide	13.8	16.7
Diethyl ketone	13.5	9.2	Phosphorus trichloride	16.2	10.9
Diethyl oxalate	11.0	16.4	Propionic acid	12.8	13.8
Ethylene glycol	5.0	24.7	Propyl acetate	13.1	10.3
Diphenyl	12.0	18.3	Propyl alcohol	9.1	16.5
Dipropyl ether	13.2	8.6	Propyl bromide	14.5	9.6
Dipropyl oxalate	10.3	17.7	Propyl chloride	14.4	7.5
Ethyl acetate	13.7	9.1	Propyl formate	13.1	9.7
Ethyl acrylate	12.7	10.4	Propyl iodide	14.1	11.6
Ethyl alcohol, 100%	10.5	13.8	Sodium	16.4	13.9
Ethyl alcohol, 95%	9.8	14.3	Sodium hydroxide, 50%	3.2	25.8
Ethyl alcohol, 40%	6.5	16.6	Stannic chloride	13.5	12.8
Ethyl benzene	13.2	11.5	Succinonitrile	10.1	20.8
Ethyl bromide	14.5	8.1	Sulfur dioxide	15.2	7.1
Ethyl butyl acrylate	11.2	14.0	Sulfuric acid, 110%	7.2	27.4
Ethyl chloride	14.8	6.0	Sulfuric acid, 100%	8.0	25.1
Ethyl ether	14.5	5.3	Sulfuric acid, 98%	7.0	24.8
Ethyl formate	14.2	8.4	Sulfuric acid, 60%	10.2	21.3
Ethyl hexyl acrylate	9.0	15.0	Sulfuryl chloride	15.2	12.4
Ethyl iodide	14.7	10.3	Tetrachloroethane	11.9	15.7
Ethyl propionate	13.2	9.9	Thiophene	13.2	11.0
Ethyl propyl ether	14.0	7.0	Titanium tetrachloride	14.4	12.3
Ethyl sulfide	13.8	8.9	Toluene	13.7	10.4
Ethylene bromide	11.9	15.7	Trichloroethylene	14.5	10.5
Ethylene chloride	12.7	12.2	Triethylene glycol	4.7	24.8
Ethylene glycol	6.0	23.6	Turpentine	11.5	14.9
Ethylene chloride	14.1	8.7	Vinyl acetate	14.0	8.8
Fluorobenzene	13.7	10.4	Vinyl toluene	13.4	12.0
Formic acid	10.7	15.8	Water	10.2	13.0
Freon-11	14.4	9.0	Xylene, ortho	13.5	12.1
Freon-12	16.8	5.6	Xylene, meta	13.9	10.6
Freon-21	15.7	7.5	Xylene, para	13.9	10.9
Freon-22	17.2	4.7			

8th Edn

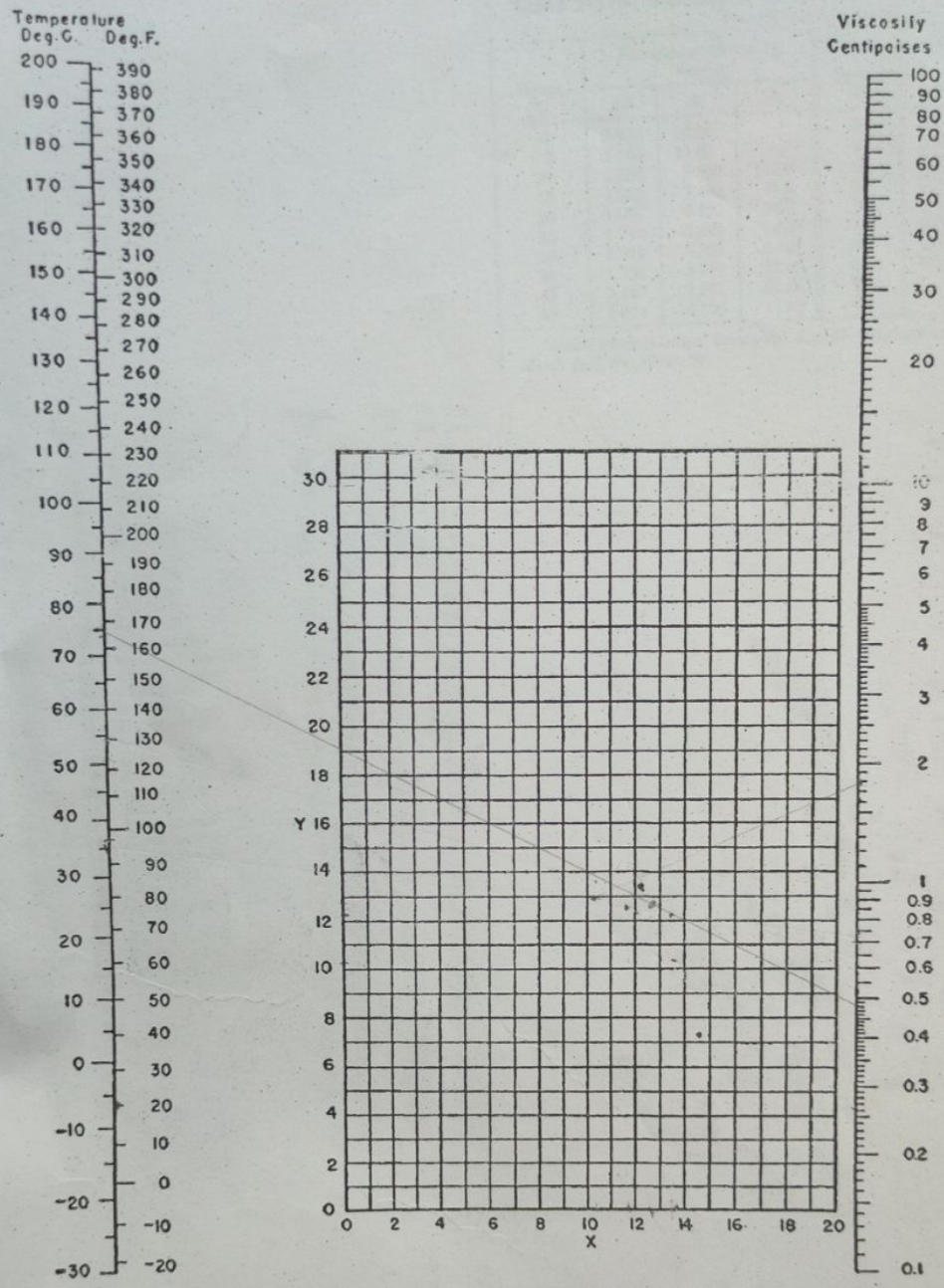


FIG. 2-32 Nomograph for viscosities of liquids at 1 atm. For coordinates see Table 2-318. To convert centipoises to pascal-seconds, multiply by 0.001.

TABLE 2-320

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

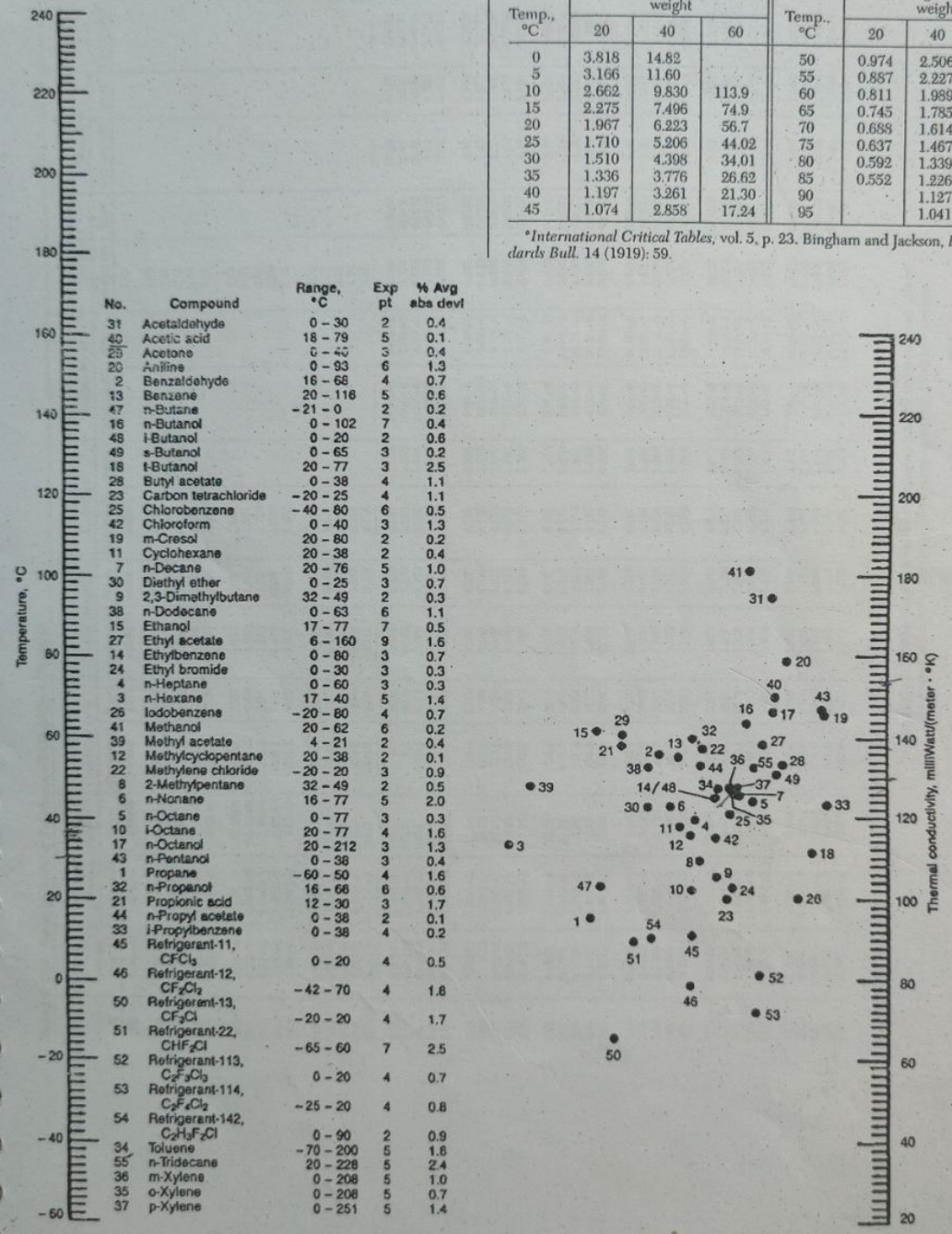


FIG. 2-33 and TABLE 2-320 Nomograph (*right*) for thermal conductivity of organic liquids. (*From Mallu and Rao, Hydroc. Proc. 78, 1988.*)

TABLE 2-319 Viscosity of Sucrose Solutions*

Viscosity in centipoises

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

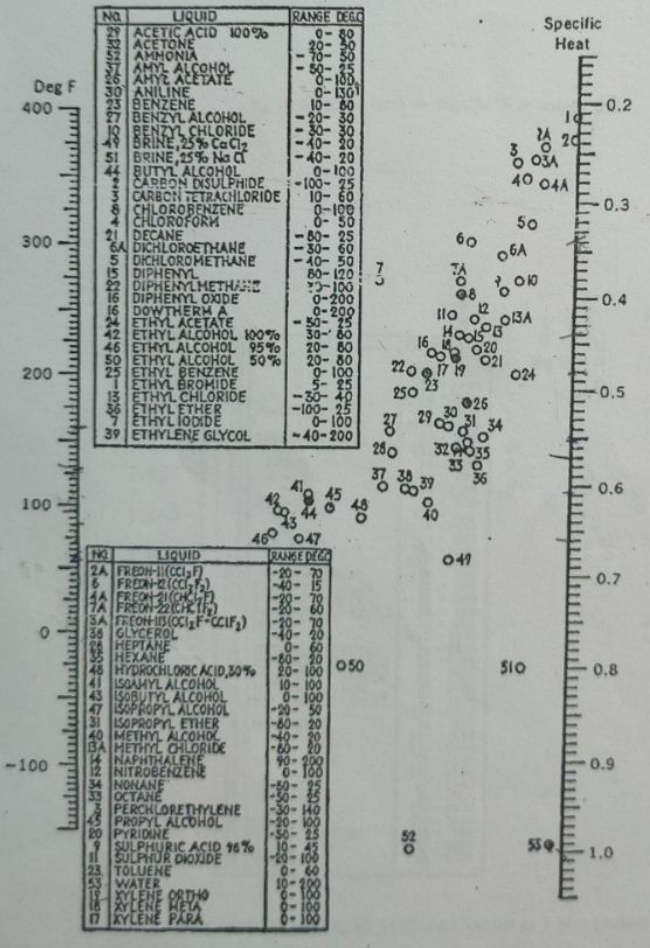
International Critical Tables, vol. 5, p. 23. Bingham and Jackson, *Bur. Standards Bull.* 14 (1919): 59.

APPENDIX 16 SPECIFIC HEATS OF LIQUIDS†

Specific heat = Btu/lb-°F = cal/g-°C

No.	LIQUID	RANGE DEG
29	ACETIC ACID 100%	0- 50
32	ACETONE	20- 50
52	AMMONIA	-70- 50
37	AMYL ALCOHOL	-50- 25
26	AMYL ACETATE	0-100
30	ANILINE	0-130
23	BENZENE	10- 80
27	BENZYL ALCOHOL	-20- 30
10	BENZYL CHLORIDE	-30- 30
49	BRINE, 25% $CaCl_2$	-40- 20
51	BRINE, 25% Na Cl	-40- 20
44	BUTYL ALCOHOL	0-100
2	CARBON DISULPHIDE	-100- 25
3	CARBON TETRACHLORIDE	10- 60
8	CHLOROBENZENE	0-100
4	CHLOROFORM	0- 50
21	DECANE	-80- 25
6A	DICHLOROETHANE	-30- 60
5	DICHLOROMETHANE	-40- 50
15	DIPHENYL	80-120
22	DIPHENYLMETHANE	20-100
16	DIPHENYL OXIDE	0-200
16	DOWTHERM A	0-200
24	ETHYL ACETATE	-50- 25
42	ETHYL ALCOHOL 100%	30- 80
46	ETHYL ALCOHOL 95%	20- 80
50	ETHYL ALCOHOL 50%	20- 80
25	ETHYL BENZENE	0-100
1	ETHYL BROMIDE	5- 25
13	ETHYL CHLORIDE	-30- 40
36	ETHYL ETHER	-100- 25
7	ETHYL IODIDE	0-100
39	ETHYLENE GLYCOL	-40-200

No.	LIQUID	RANGE DEG
2A	FREON-11 (CCl_3F)	-20- 70
6	FREON-12 (CCl_2F_2)	-40- 15
4A	FREON-21 ($CHCl_2F$)	-20- 70
7A	FREON-22 ($CHClF_2$)	-20- 60
3A	FREON-113 (CCl_2F-$CClF_2$)	-20- 70
38	GLYCEROL	-40- 20
28	HEPTANE	0- 60
35	HEXANE	-80- 20
48	HYDROCHLORIC ACID, 30%	20- 100
41	ISOAMYL ALCOHOL	10- 100
43	ISOBUTYL ALCOHOL	0- 100
47	ISOPROPYL ALCOHOL	-20- 50
31	ISOPROPYL ETHER	-80- 20
40	METHYL ALCOHOL	-40- 20
13A	METHYL CHLORIDE	-80- 20
14	NAPHTHALENE	90-200
12	NITROBENZENE	0-100
34	NONANE	-50- 25
33	OCTANE	-50- 25
9	PERCHLORETHYLENE	-30-140
45	PROPYL ALCOHOL	-20-100
20	PYRIDINE	-50- 25
9	SULPHURIC ACID 98%	10- 45
11	SULPHUR DIOXIDE	-20-100
23	TOLUENE	0- 60
53	WATER	10-200
19	XYLENE ORTHO	0-100
18	XYLENE META	0-100
17	XYLENE PARA	0-100



† *Courtesy of T. H. Chilton.*

TABLE 2-370 Thermophysical Properties of Miscellaneous Saturated Liquids

Substance	Property	Temperature, °C														
		−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90	100
Acetaldehyde	ρ (kg/m³)	863	852	840	828	816	804	794	783								
	c_p (kJ/kg·K)	2.05	2.08	2.11	2.14	2.17	2.20	2.24	2.28								
	μ (10⁻⁴ Pa·s)	460	404	358	321	290	263	241	222								
	k (W/m·K)	0.211	0.206	0.200	0.195	0.189	0.184	0.182	0.180								
	Pr	4.47	4.08	3.78	3.52	3.33	3.14	2.97	2.81								
Acetic acid	ρ (kg/m³)								1049	1039	1028	1018	1006	995	984	972	960
	c_p (kJ/kg·K)								2.031								
	μ (10⁻⁴ Pa·s)								1210	1102	1010	795	600				
	k (W/m·K)								0.173	0.170	0.168	0.167	0.165	0.163	0.161		
	Pr								14.2								
Aniline	ρ (kg/m³)	—	—	—	—	—	1039	1030	1022	1013	1005	996	987	978	969	960	951
	c_p (kJ/kg·K)	—	—	—	—	—	2.024	2.047	2.071	2.093	2.113	2.132	2.17	2.20	2.23	2.27	2.32
	μ (10⁻⁴ Pa·s)	—	—	—	—	—	10200	6500	4400	3160	2370	1850	1510	1270	1090	935	825
	k (W/m·K)	—	—	—	—	—	0.186	0.184	0.182	0.180	0.177	0.174	0.171	0.169	0.168	0.167	0.167
	Pr	—	—	—	—	—	111	72	50	36.7	28.3	22.7	19.2	16.5	14.5	12.7	11.5
Butanol	ρ (kg/m³)	845	841	837	833	829	825	817	810	803	797	791	784	776	768	760	753
	c_p (kJ/kg·K)	1.947	1.996	2.046	2.100	2.153	2.202	2.262	2.345	2.437	2.524	2.621					
	μ (10⁻⁴ Pa·s)	34700	22400	14700	10300	7400	5190	3870	2950	2300	1780	1410	1140	930	760	630	535
	k (W/m·K)	0.175	0.174	0.173	0.172	0.171	0.170	0.168	0.167	0.166	0.165	0.164	0.163	0.162	0.161	0.160	0.159
	Pr	3860	2570	1740	1260	930	670	120	41	33.8	27.2	22.5					
Carbon disulfide	ρ (kg/m³)	1362	1348	1334	1320	1306	1292	1278	1263								
	c_p (kJ/kg·K)	0.988	0.989	0.990	0.991	0.993	0.996	1.004	1.017								
	μ (10⁻⁴ Pa·s)	630	580	535	496	463	435	405	375	350	330						
	k (W/m·K)	0.194	0.190	0.186	0.182	0.178	0.174	0.170	0.166	0.161	0.158	0.156	0.154	0.152	0.150		
	Pr	3.21	3.02	2.85	2.70	2.58	2.49	2.39	2.30								
Cyclohexane	ρ (kg/m³)	—	—	—	—	—	—	789	779	769	759	750	740	731	721		
	c_p (kJ/kg·K)	—	—	—	—	—	—	2.068	2.081	2.094	2.106	2.119					
	μ (10⁻⁴ Pa·s)	—	—	—	—	—	—	1175	980	820	710	605	540				
	k (W/m·K)	—	—	—	—	—	—	0.122	0.120	0.119	0.118	0.117	0.116	0.114	0.112		
	Pr	—	—	—	—	—	—	19.9	17.0	14.4	12.7	11.0					
Ethanol	ρ (kg/m³)						806	798	789	781	776	763	754	745	735	725	716
	c_p (kJ/kg·K)	2.01	2.04	2.08	2.13	2.19	2.27	2.35	2.43	2.52	2.62	2.73	2.83	2.93	3.03	3.19	3.30
	μ (10⁻⁴ Pa·s)	6400	4790	3650	2825	2220	1770	1470	1200	1000	835	700	590	500	435	370	314
	k (W/m·K)	0.188	0.186	0.184	0.181	0.179	0.177	0.175	0.173	0.171	0.168	0.165	0.162	0.159	0.156	0.153	0.151
	Pr	68.4	52.5	41.3	33.2	27.2	22.7	19.7	16.9	14.7	13.0	11.6	10.3	9.2	8.4	7.7	6.9
Ethyl acetate	ρ (kg/m³)					947	935	924	912	901	888	876	863	851	838	825	811	797
	c_p (kJ/kg·K)									2.01								
	μ (10⁻⁴ Pa·s)	1090						580	510	455	400	370	345	310	280	250	230	220
	k (W/m·K)									0.145	0.142	0.139	0.136	0.133	0.130	0.127	0.123	0.119
	Pr									6.3								
Ethylamine	ρ (kg/m³)	761	750	739	729	718	707	695	683	671	658	646	633	620	607			
	c_p (kJ/kg·K)	2.95	2.97	2.98	3.00	3.01	3.03											
	μ (10⁻⁴ Pa·s)	580	500	435	390	350	320											
	k (W/m·K)	0.204	0.201	0.199	0.196	0.194	0.191											
	Pr	8.39	7.39	6.51	5.97	5.43	5.08											
Ethyl ether	ρ (kg/m³)	790	780	769	758	747	736	725	714	702	689	676	666	653	640	625	611
	c_p (kJ/kg·K)	2.135	2.156	2.179	2.205	2.233	2.265	2.299	2.332	2.36	2.39	2.43	2.47	2.51			
	μ (10⁻⁴ Pa·s)	550	470	410	365	330	290	265	233	214	197	181	166	153	140	129	118
	k (W/m·K)	0.159	0.155	0.151	0.147	0.144	0.140	0.139	0.134	0.129	0.125	0.120	0.116	0.112			
	Pr	7.39	6.54	5.92	5.48	5.12	4.69	4.38	4.05	3.92	3.77	3.67	3.54	3.43			
Ethyl iodide	ρ (kg/m³)																
	c_p (kJ/kg·K)				0.656	0.663	0.670	0.677	0.684	0.691	0.698	0.705	0.712	0.718	0.724		
	μ (10⁻⁴ Pa·s)							730	655	590	539	495	455	420	390		
	k (W/m·K)							0.092	0.090	0.088	0.086	0.085	0.083	0.081	0.080		
	Pr							5.37	4.98	4.63	4.30	4.11	3.90	3.72	3.53		
Ethylene glycol	ρ (kg/m³)																
	c_p (kJ/kg·K)							1127	1120	1113	1106	1099	1092	1085	1077	1070	1063	1056
	μ (10⁻⁴ Pa·s)							2.272	2.327	2.381	2.431	2.484	2.536	2.586	2.636	2.685	2.734	2.779
	k (W/m·K)							57000	33300	20200	13400	9100	7070	4000	3450	3000	2440	2000
	Pr							0.254	0.255	0.256	0.258	0.259	0.260					
								510	305	190	126	87.3	69.0					
Formic acid	ρ (kg/m³)																
	c_p (kJ/kg·K)							1241	1231	1220	1209	1196	1184	1170	1156	1140	1124	1108
	μ (10⁻⁴ Pa·s)								2260	1800	1470	1220	1030	890	780	680	615	550
	k (W/m·K)							0.265	0.261	0.257	0.257	0.253	0.250	0.246	0.243	0.240	0.236	0.232
	Pr																	

TABLE 2-370 Thermophysical Properties of Miscellaneous Saturated Liquids

Substance	Property	Temperature, °C														
		−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90	100
Acetaldehyde	ρ (kg/m³)	863	852	840	828	816	804	794	783								
	c_p(kJ/kg·K)	2.05	2.08	2.11	2.14	2.17	2.20	2.24	2.28								
	μ (10⁻⁶Pa·s)	460	404	358	321	290	263	241	222								
	k (W/m·K)	0.211	0.206	0.200	0.195	0.189	0.184	0.182	0.180								
	Pr	4.47	4.08	3.78	3.52	3.33	3.14	2.97	2.81								
Acetic acid	ρ (kg/m³)								1049	1039	1028	1018	1006	995	984	972	960
	c_p (kJ/kg·K)								2.031								
	μ (10⁻⁶Pa·s)								1210	1102	1010	795	600				
	k (W/m·K)								0.173	0.170	0.168	0.167	0.165	0.163	0.161		
	Pr								14.2								
Aniline	ρ (kg/m³)	—	—	—	—	—	1039	1030	1022	1013	1005	996	987	978	969	960	951
	c_p(kJ/kg·K)	—	—	—	—	—	2.024	2.047	2.071	2.093	2.113	2.132	2.17	2.20	2.23	2.27	2.32
	μ (10⁻⁶Pa·s)	—	—	—	—	—	10200	6500	4400	3160	2370	1850	1510	1270	1090	935	825
	k (W/m·K)	—	—	—	—	—	0.186	0.184	0.182	0.180	0.177	0.174	0.171	0.169	0.168	0.167	0.167
	Pr	—	—	—	—	—	111	72	50	36.7	28.3	22.7	19.2	16.5	14.5	12.7	11.5
Butanol	ρ (kg/m³)	845	841	837	833	829	825	817	810	803	797	791	784	776	768	760	753
	c_p(kJ/kg·K)	1.947	1.996	2.046	2.100	2.153	2.202	2.262	2.345	2.437	2.524	2.621					
	μ (10⁻⁶Pa·s)	34700	22400	14700	10300	7400	5190	3870	2950	2300	1780	1410	1140	930	760	630	535
	k (W/m·K)	0.175	0.174	0.173	0.172	0.171	0.170	0.168	0.167	0.166	0.165	0.164	0.163	0.162	0.161	0.160	0.159
	Pr	3860	2570	1740	1260	930	670	120	41	33.8	27.2	22.5					
Carbon disulfide	ρ (kg/m³)	1362	1348	1334	1320	1306	1292	1278	1263								
	c_p(kJ/kg·K)	0.988	0.989	0.990	0.991	0.993	0.996	1.004	1.017								
	μ (10⁻⁶Pa·s)	630	590	535	496	463	435	405	375	350	330						
	k (W/m·K)	0.194	0.190	0.186	0.182	0.178	0.174	0.170	0.166	0.161	0.158	0.156	0.154	0.152	0.150		
	Pr	3.21	3.02	2.85	2.70	2.58	2.49	2.39	2.30								
Cyclohexane	ρ (kg/m³)	—	—	—	—	—	—	789	779	769	759	750	740	731	721		
	c_p(kJ/kg·K)	—	—	—	—	—	—	2.068	2.081	2.094	2.106	2.119					
	μ (10⁻⁶Pa·s)	—	—	—	—	—	—	1175	980	820	710	605	540				
	k (W/m·K)	—	—	—	—	—	—	0.122	0.120	0.119	0.118	0.117	0.116	0.114	0.112		
	Pr	—	—	—	—	—	—	19.9	17.0	14.4	12.7	11.0					
Ethanol	ρ (kg/m³)						806	798	789	781	776	763	754	745	735	725	716
	c_p(kJ/kg·K)	2.01	2.04	2.08	2.13	2.19	2.27	2.35	2.43	2.52	2.62	2.73	2.83	2.93	3.03	3.19	3.30
	μ (10⁻⁶Pa·s)	6400	4790	3650	2825	2220	1770	1470	1200	1000	835	700	590	500	435	370	314
	k (W/m·K)	0.188	0.186	0.184	0.181	0.179	0.177	0.175	0.173	0.171	0.168	0.165	0.162	0.159	0.156	0.153	0.151
	Pr	68.4	52.5	41.3	33.2	27.2	22.7	19.7	16.9	14.7	13.0	11.6	10.3	9.2	8.4	7.7	6.9
Ethyl acetate	ρ (kg/m³)				947	935	924	912	901	888	876	863	851	838	825	811	797
	c_p(kJ/kg·K)								2.01								
	μ (10⁻⁶Pa·s)	1090					580	510	455	400	370	345	310	280	250	230	220
	k (W/m·K)								0.145	0.142	0.139	0.136	0.133	0.130	0.127	0.123	0.119
	Pr								6.3								
Ethylamine	ρ (kg/m³)	761	750	739	729	718	707	695	683	671	658	646	633	620	607		
	c_p(kJ/kg·K)	2.95	2.97	2.98	3.00	3.01	3.03										
	μ (10⁻⁶Pa·s)	580	500	435	390	350	320										
	k (W/m·K)	0.204	0.201	0.199	0.196	0.194	0.191										
	Pr	8.39	7.39	6.51	5.97	5.43	5.08										
Ethyl ether	ρ (kg/m³)	790	780	769	758	747	736	725	714	702	689	676	666	653	640	625	611
	c_p(kJ/kg·K)	2.135	2.156	2.179	2.205	2.233	2.265	2.299	2.332	2.36	2.39	2.43	2.47	2.51			
	μ (10⁻⁶Pa·s)	550	470	410	365	330	290	265	233	214	197	181	166	153	140	129	118
	k (W/m·K)	0.159	0.155	0.151	0.147	0.144	0.140	0.139	0.134	0.129	0.125	0.120	0.116	0.112			
	Pr	7.39	6.54	5.92	5.48	5.12	4.69	4.38	4.05	3.92	3.77	3.67	3.54	3.43			
Ethyl iodide	ρ (kg/m³)				0.656	0.663	0.670	0.677	0.684	0.691	0.698	0.705	0.712	0.718	0.724		
	c_p(kJ/kg·K)							730	655	590	539	495	455	420	390		
	μ (10⁻⁶Pa·s)							0.092	0.090	0.088	0.086	0.085	0.083	0.081	0.080		
	k (W/m·K)							5.37	4.98	4.63	4.30	4.11	3.90	3.72	3.53		
	Pr																
Ethylene glycol	ρ (kg/m³)							1127	1120	1113	1106	1099	1092	1085	1077	1070	1063	1056
	c_p(kJ/kg·K)							2.272	2.327	2.381	2.431	2.484	2.536	2.586	2.636	2.685	2.734	2.779
	μ (10⁻⁶Pa·s)							57000	33300	20200	13400	9100	7070	4000	3450	3000	2440	2000
	k (W/m·K)							0.254	0.255	0.256	0.258	0.259	0.260					
	Pr							510	305	190	126	87.3	69.0					
Formic acid	ρ (kg/m³)							1241	1231	1220	1209	1196	1184	1170	1156	1140	1124	1108
	c_p(kJ/kg·K)								2260	1800	1470	1220	1030	890	780	680	615	550
	μ (10⁻⁶Pa·s)							0.265	0.261	0.257	0.257	0.253	0.250	0.246	0.243	0.240	0.236	0.232
	k (W/m·K)																	
	Pr																	

TABLE 2-370 Thermophysical Properties of Miscellaneous Saturated Liquids (*Concluded*)

Substance	Property	Temperature, °C															
		−50	−40	−30	−20	−10	0	10	20	30	40	50	60	70	80	90	100
Gasoline	ρ (kg/m³)				784	775	767	759	751	743	735	721	717	708	699	690	681
	c_p (kJ/kg·K)				1.88	1.92	1.97	2.02	2.06	2.11	2.15	2.20	2.25	2.30	2.35	2.41	2.46
	μ (10^{-6} Pa·s)	1710	1400	1170	990	850	735	645	530	464	410	367	330	298	270	246	225
	k (W/m·K)	0.131	0.128	0.125	0.123	0.121	0.120	0.118	0.116	0.114	0.112	0.110	0.108	0.106	0.104	0.102	0.100
	Pr				15.1	13.5	12.1	11.0	9.41	8.59	7.87	7.34	6.88	6.47	6.10	5.81	5.54
Glycerol	ρ (kg/m³)	—	—	—	—	—	1276	1270	1260	1254	1248	1242					
	c_p (kJ/kg·K)								2.393	2.406	2.457	2.504	2.548	2.588	2.625	2.657	2.686
	μ (10^{-6} Pa·s)						1.2+7	4.0+6	1.5+6								
	k (W/m·K)								0.284	0.285	0.287	0.288	0.289	0.291	0.293	0.294	0.295
	Pr								12650								
Kerosine	ρ (kg/m³)						781	774	767	760	754	748	742				
	c_p (kJ/kg·K)						1.91	1.96	2.02	2.07	2.13	2.18	2.23	2.28	2.32	2.35	2.38
	μ (10^{-6} Pa·s)	1150	725	500	360	275	215	173	149	126	108	95	83	73	66	60	55
	k (W/m·K)						0.140	0.139	0.139	0.138	0.138	0.137	0.137				
	Pr						2.93	2.44	2.17	1.89	1.67	1.51	1.35				
Methanol	ρ (kg/m³)									783	774	766	756	746	736	725	711
	c_p (kJ/kg·K)	2.30	2.32	2.35	2.37	2.40	2.42	2.45	2.47	2.49	2.52	2.55	2.65	2.78	2.94	3.13	3.30
	μ (10^{-6} Pa·s)	2305	1800	1410	1170	975	820	692	590	510	[illegible]	400	355	315	271	240	218
	k (W/m·K)	0.225	0.222	0.219	0.216	0.212	0.209	0.206	0.203	0.199	[illegible]	0.192	0.189	0.187	0.184	0.182	0.180
	Pr	23.6	18.8	15.1	12.9	11.0	9.53	8.23	7.18	6.38	5.88	5.31	4.98	4.68	4.34	4.13	3.99
Methyl formate	ρ (kg/m³)	1069	1056	1043	1030	1017	1003	989	975	960	944	929	913	897	880	863	845
	c_p (kJ/kg·K)	1.84	1.86	1.88	1.90	1.92	1.95	1.99	2.03	2.08							
	μ (10^{-6} Pa·s)	830	711	618	544	481	430	380	345	315							
	k (W/m·K)	0.217	0.213	0.209	0.205	0.200	0.195	0.191	0.186	0.180							
	Pr	7.04	6.21	5.56	5.04	4.62	4.30	3.96	3.77	3.64							
Oil, castor	ρ (kg/m³)																
	c_p (kJ/kg·K)																
	μ (10^{-6} Pa·s)							2,420,000	986,000	451,000	231,000	125,000	74,000	43,000			
	k (W/m·K)							0.182	0.181	0.180	0.179	0.178	0.177	0.176	0.175	0.174	0.17
	Pr																
Oil, olive	ρ (kg/m³)								914								
	c_p (kJ/kg·K)								1.633								
	μ (10^{-6} Pa·s)							138,000	84,000	52,000	36,300	24,500	17,000	12,400			
	k (W/m·K)							0.170	0.169	0.168	0.167	0.166	0.166	0.165	0.165	0.164	0.164
	Pr								810								
Pentane	ρ (kg/m³)	693	684	674	665	656	646	636	626	616	606	596	585	574	562	550	538
	c_p (kJ/kg·K)	2.060	2.084	2.110	2.137	2.167	2.206	2.239	2.273								
	μ (10^{-6} Pa·s)	489	428	379	339	307	279	254	234	209	190	175	161	148	137	124	113
	k (W/m·K)	0.142	0.139	0.136	0.132	0.128	0.125	0.122	0.119	0.115	0.112	0.108	0.105	0.101	0.098	0.095	0.091
	Pr	7.14	6.42	5.88	5.49	5.20	4.92	4.66	4.47								
Propanol	ρ (kg/m³)	849					819	811	814	796	788	779	770	761	752	747	743
	c_p (kJ/kg·K)	1.955					2.219										
	μ (10^{-6} Pa·s)	20,200	13,500	9500	6900	5110	3900	2900	2245	1720	1400	1130	921	760	630	508	447
	k (W/m·K)	0.167	0.166	0.165						0.171	0.169	0.168	0.167	0.165	0.164	0.163	0.162
	Pr	236															
Sulfuric acid	ρ (kg/m³)								1834								
	c_p (kJ/kg·K)								1.382								
	μ (10^{-6} Pa·s)						48,400	35,200	25,400	15,700	11,500	8820	7220	6090	5190		
	k (W/m·K)						0.314										
	Pr																
Toluene	ρ (kg/m³)	932	923	913	904	895	886	876	867	858	848	839	829	820	810	800	790
	c_p (kJ/kg·K)	1.514	1.535	1.556	1.579	1.602	1.633	1.652	1.675	1.701	1.73	1.76	1.80	1.83	1.87	1.92	1.97
	μ (10^{-6} Pa·s)	2120	1670	1345	1100	915	770	670	590	520	470	420	380	355	325	295	270
	k (W/m·K)	0.152	0.149	0.147	0.144	0.142	0.139	0.137	0.134	0.132	0.129	0.126	0.124	0.122	0.119	0.117	0.114
	Pr	21.1	17.8	14.2	12.1	10.3	9.0	8.1	7.4	6.7	6.3	5.9	5.5	5.3	5.1	4.8	4.7
Turpentine	ρ (kg/m³)											1.93					
	c_p (kJ/kg·K)						1.72	1.76	1.80			925	820	730	675		
	μ (10^{-6} Pa·s)						2250	1780	1490	1270	1070	0.125					
	k (W/m·K)						0.130	0.129	0.128	0.127	0.126	14.3					
	Pr						29.8	24.3	20.9	18.4	16.1						

TABLE 2-32 Densities of Inorganic and Organic Liquids (mol/dm³)

Cmpd. no.	Name	Formula	CAS no.	Mol. wt.	C1	C2	C3	C4	T_{min}, K	Density at T_{min}	T_{max}, K	Density at T_{max}
1	Acetaldehyde	C_2H_4O	75-07-0	44.053	1.6994	0.26167	466	0.2913	150.15	21.499	466.00	6.4944
2	Acetamide	C_2H_5NO	60-35-5	59.067	1.016	0.21845	761	0.26116	353.33	16.936	761.00	4.5509
3	Acetic acid	$C_2H_4O_2$	64-19-7	60.052	1.4486	0.25892	591.95	0.2529	289.81	17.492	591.95	5.5948
4	Acetic anhydride	$C_4H_6O_3$	108-24-7	102.089	0.86852	0.25187	606	0.31172	200.15	11.643	606.00	3.4483
5	Acetone	C_3H_6O	67-64-1	58.079	1.2332	0.25886	508.2	0.2913	178.45	15.683	508.20	4.7640
6	Acetonitrile	C_2H_3N	75-05-8	41.052	1.3064	0.22597	545.5	0.28678	229.32	20.628	545.50	5.7813
7	Acetylene	C_2H_2	74-86-2	26.037	2.4507	0.27448	308.3	0.28752	192.40	23.692	308.30	8.9285
8	Acrolein	C_3H_4O	107-02-8	56.063	1.3261	0.26124	506	0.2489	185.45	16.822	506.00	5.0762
9	Acrylic acid	$C_3H_4O_2$	79-10-7	72.063	1.2414	0.25822	615	0.30701	286.15	14.693	615.00	4.8075
10	Acrylonitrile	C_3H_3N	107-13-1	53.063	1.0816	0.2293	535	0.28939	189.63	17.265	535.00	4.7170
11	Air	Mixture	132259-10-0	28.960	2.8963	0.26733	132.45	0.27341	59.15	33.279	132.45	10.8340
12	Ammonia	H_3N	7664-41-7	17.031	3.5383	0.25443	405.65	0.2888	195.41	43.141	405.65	13.9070
13	Anisole	C_7H_8O	100-66-3	108.138	0.77488	0.26114	645.6	0.28234	235.65	9.668	645.60	2.9673
14	Argon	Ar	7440-37-1	39.948	3.8469	0.2881	150.86	0.29783	83.78	35.491	150.86	13.3530
15	Benzamide	C_7H_7NO	55-21-0	121.137	0.7371	0.25487	824	0.28571	403.00	8.938	824.00	2.8921
16	Benzene	C_6H_6	71-43-2	78.112	1.0259	0.26666	562.05	0.28394	278.68	11.422	562.05	3.8472
17	Benzenethiol	C_6H_6S	108-98-5	110.177	0.83573	0.26326	689	0.30798	258.27	10.074	689.00	3.1745
18	Benzoic acid	$C_7H_6O_2$	65-85-0	122.121	0.71587	0.24812	751	0.2857	395.45	8.894	751.00	2.8852
19	Benzonitrile	C_7H_5N	100-47-0	103.121	0.8552	0.26785	699.35	0.30523	260.40	10.011	699.35	3.1928
20	Benzophenone	$C_{13}H_{10}O$	119-61-9	182.218	0.43743	0.24833	830	0.27555	321.35	5.950	830.00	1.7615
21	Benzyl alcohol	C_7H_8O	100-51-6	108.138	0.59867	0.22849	720.15	0.23567	257.85	9.905	720.15	2.6201
22	Benzyl ethyl ether	$C_9H_{12}O$	539-30-0	136.191	0.60917	0.26925	662	0.2632	275.65	7.065	662.00	2.2625
23	Benzyl mercaptan	C_7H_8S	100-53-8	124.203	0.70797	0.25982	718	0.32144	243.95	8.862	718.00	2.7248
24	Biphenyl	$C_{12}H_{10}$	92-52-4	154.208	0.52257	0.25833	773	0.27026	342.20	6.425	773.00	2.0229
25	Bromine	Br_2	7726-95-6	159.808	2.1872	0.29527	584.15	0.3295	265.85	20.109	584.15	7.4075
26	Bromobenzene	C_6H_5Br	108-86-1	157.008	0.8226	0.26632	670.15	0.2821	242.43	9.909	670.15	3.0888
27	Bromoethane	C_2H_5Br	74-96-4	108.965	1.1908	0.25595	503.8	0.29152	154.55	15.833	503.80	4.6525
28	Bromomethane	CH_3Br	74-83-9	94.939	1.6762	0.26141	467	0.28402	179.47	20.640	467.00	6.4121
29	1,2-Butadiene	C_4H_6	590-19-2	54.090	1.187	0.26114	452	0.3065	136.95	15.123	452.00	4.5455
30	1,3-Butadiene	C_4H_6	106-99-0	54.090	1.2346	0.27216	425	0.28707	164.25	14.058	425.00	4.5363
31	Butane	C_4H_{10}	106-97-8	58.122	1.0677	0.27188	425.12	0.28688	134.86	12.620	425.12	3.9271
32	1,2-Butanediol	$C_4H_{10}O_2$	584-03-2	90.121	0.81696	0.24755	680	0.24535	220.00	11.734	680.00	3.3002
33	1,3-Butanediol	$C_4H_{10}O_2$	107-88-0	90.121	0.81856	0.24967	676	0.22023	196.15	11.872	676.00	3.2786
34	1-Butanol	$C_4H_{10}O$	71-36-3	74.122	0.98279	0.26830	563.1	0.25488	183.85	12.035	563.10	3.6630
35	2-Butanol	$C_4H_{10}O$	78-92-2	74.122	0.9682	0.26244	535.9	0.26749	158.45	12.471	535.90	3.6892
36	1-Butene	C_4H_8	106-98-9	56.106	1.0877	0.26454	419.5	0.2843	87.80	14.264	419.50	4.1117
37	*cis*-2-Butene	C_4H_8	590-18-1	56.106	1.1591	0.27085	435.5	0.28116	134.26	13.894	435.50	4.2795
38	*trans*-2-Butene	C_4H_8	624-64-6	56.106	1.1448	0.27154	428.6	0.28419	167.62	13.080	428.60	4.2160
39	Butyl acetate	$C_6H_{12}O_2$	123-86-4	116.158	0.67794	0.2637	575.4	0.29318	199.65	8.337	575.40	2.5709
40	Butylbenzene	$C_{10}H_{14}$	104-51-8	134.218	0.50812	0.25238	660.5	0.29373	185.30	7.026	660.50	2.0133
41	Butyl mercaptan	$C_4H_{10}S$	109-79-5	90.187	0.89458	0.27463	570.1	0.28512	157.46	10.585	570.10	3.2574
42	*sec*-Butyl mercaptan	$C_4H_{10}S$	513-53-1	90.187	0.89137	0.27365	554	0.2953	133.02	10.761	554.00	3.2573
43	1-Butyne	C_4H_6	107-00-6	54.090	1.3409	0.27892	440	0.29661	147.43	14.901	440.00	4.8075
44	Butyraldehyde	C_4H_8O	123-72-8	72.106	1.0361	0.26731	537.2	0.28397	176.75	12.589	537.20	3.8760
45	Butyric acid	$C_4H_8O_2$	107-92-6	88.105	0.88443	0.25828	615.7	0.248	267.95	11.087	615.70	3.4243
46	Butyronitrile	C_4H_7N	109-74-0	69.105	0.87533	0.24331	582.25	0.28586	161.25	13.047	582.25	3.5976
47	Carbon dioxide	CO_2	124-38-9	44.010	2.768	0.26212	304.21	0.2908	216.58	26.828	304.21	10.5600
48	Carbon disulfide	CS_2	75-15-0	76.141	1.7968	0.28749	552	0.3226	161.11	19.064	552.00	6.2500
49	Carbon monoxide	CO	630-08-0	28.010	2.897	0.27532	132.92	0.2813	68.15	30.180	132.92	10.5220
50	Carbon tetrachloride	CCl_4	56-23-5	153.823	0.99835	0.274	556.35	0.287	250.33	10.843	556.35	3.6436
51	Carbon tetrafluoride	CF_4	75-73-0	88.004	1.955	0.27884	227.51	0.28571	89.56	21.211	227.51	7.0112
52	Chlorine	Cl_2	7782-50-5	70.906	2.23	0.27645	417.15	0.2926	172.12	24.242	417.15	8.0666
53	Chlorobenzene	C_6H_5Cl	108-90-7	112.557	0.8711	0.26805	632.35	0.2799	227.95	10.385	632.35	3.2498
54	Chloroethane	C_2H_5Cl	75-00-3	64.514	1.3	0.26019	460.35	0.27155	134.80	17.016	460.35	4.9963
55	Chloroform	$CHCl_3$	67-66-3	119.378	1.0841	0.2581	536.4	0.2741	209.63	13.702	536.40	4.2003
56	Chloromethane	CH_3Cl	74-87-3	50.488	1.817	0.25877	416.25	0.2833	175.43	22.347	416.25	7.0217
57	1-Chloropropane	C_3H_7Cl	540-54-5	78.541	1.087	0.26832	503.15	0.28055	150.35	13.328	503.15	4.0511
58	2-Chloropropane	C_3H_7Cl	75-29-6	78.541	1.1202	0.27669	489	0.27646	155.97	12.855	489.00	4.0486
59	*m*-Cresol	C_7H_8O	108-39-4	108.138	0.9061	0.28268	705.85	0.2707	285.39	9.612	705.85	3.2054

304	Propylbenzene	C_9H_{12}	103-65-1	120.192	0.57233	0.25171	638.35	0.29616	173.55	7.982	638.35	2.2738
305	Propylene	C_3H_6	115-07-1	42.080	1.4403	0.26852	364.85	0.28775	87.89	18.070	364.85	5.3638
306	Propyl formate	$C_4H_8O_2$	110-74-7	88.105	0.915	0.26134	538	0.28	180.25	11.590	538.00	3.5012
307	2-Propyl mercaptan	C_3H_8S	75-33-2	76.161	1.093	0.27762	517	0.29781	142.61	12.610	517.00	3.9370
308	Propyl mercaptan	C_3H_8S	107-03-9	76.161	1.0714	0.27214	536.6	0.29481	159.95	12.716	536.60	3.9369
309	1,2-Propylene glycol	$C_3H_8O_2$	57-55-6	76.094	1.0923	0.26106	626	0.20459	213.15	14.363	626.00	4.1841
310	Quinone	$C_6H_4O_2$	106-51-4	108.095	0.83228	0.25385	683	0.23658	388.85	10.082	683.00	3.2786
311	Silicon tetrafluoride	F_4Si	7783-61-1	104.079	1.1945	0.24128	259	0.16693	186.35	15.635	259.00	4.9507
312	Styrene	C_8H_8	100-42-5	104.149	0.7397	0.2603	636	0.3009	242.54	9.109	636.00	2.8417
313	Succinic acid	$C_4H_6O_4$	110-15-6	118.088	0.70284	0.22268	806	0.28571	460.65	10.261	806.00	3.1563
314	Sulfur dioxide	O_2S	7446-09-5	64.064	2.106	0.25842	430.75	0.2895	197.67	25.298	430.75	8.1495
315	Sulfur hexafluoride	F_6S	2551-62-4	146.055	1.3587	0.2701	318.69	0.2921	223.15	12.631	318.69	5.0304
316	Sulfur trioxide	O_3S	7446-11-9	80.063	1.4969	0.19013	490.85	0.4359	289.95	24.241	490.85	7.8730
317	Terephthalic acid	$C_8H_6O_4$	100-21-0	166.131	0.42685	0.181	1113	0.28571	700.15	8.546	1113.00	2.3583
318	*o*-Terphenyl	$C_{18}H_{14}$	84-15-1	230.304	0.3448	0.25116	857	0.29268	329.35	4.553	857.00	1.3728
319	*o*-Terphenyl [use Eq. (2)]	$C_{18}H_{14}$	84-15-1	230.304	5.7136	−0.003474			288.15	4.713	313.19	4.6256
320	Tetradecane	$C_{14}H_{30}$	629-59-4	198.388	0.27248	0.24007	693	0.28571	279.01	3.889	693.00	1.1350
321	Tetrahydrofuran	C_4H_8O	109-99-9	72.106	1.2543	0.28084	540.15	0.2912	164.65	13.998	540.15	4.4662
322	1,2,3,4-Tetrahydronaphthalene	$C_{10}H_{12}$	119-64-2	132.202	0.67717	0.27772	720	0.2878	237.38	7.638	720.00	2.4383
323	Tetrahydrothiophene	C_4H_8S	110-01-0	88.171	1.1628	0.28954	631.95	0.28674	176.99	12.408	631.95	4.0160
324	2,2,3,3-Tetramethylbutane	C_8H_{18}	594-82-1	114.229	0.58988	0.27201	568	0.27341	373.96	5.724	568.00	2.1686
325	Thiophene	C_4H_4S	110-02-1	84.140	1.2874	0.28194	579.35	0.30781	234.94	13.430	579.35	4.5662
326	Toluene	C_7H_8	108-88-3	92.138	0.8792	0.27136	591.75	0.29241	178.18	10.487	591.75	3.2400
327	1,1,2-Trichloroethane	$C_2H_3Cl_3$	79-00-5	133.404	0.9062	0.25475	602	0.31	236.50	11.478	602.00	3.5572
328	Tridecane	$C_{13}H_{28}$	629-50-5	184.361	0.29934	0.2433	675	0.28571	267.76	4.182	675.00	1.2300
329	Triethyl amine	$C_6H_{15}N$	121-44-8	101.190	0.7035	0.27386	535.15	0.2872	158.45	8.284	535.15	2.5688
330	Trimethyl amine	C_3H_9N	75-50-3	59.110	1.0116	0.25683	433.25	0.2696	156.08	13.144	433.25	3.9388
331	1,2,3-Trimethylbenzene	C_9H_{12}	526-73-8	120.192	0.6531	0.27002	664.5	0.26268	243.15	7.728	664.50	2.4187
332	1,2,4-Trimethylbenzene	C_9H_{12}	95-63-6	120.192	0.60394	0.25956	649.1	0.27713	229.33	7.689	649.10	2.3268
333	2,2,4-Trimethylpentane	C_8H_{18}	540-84-1	114.229	0.59059	0.27424	543.8	0.2847	165.78	6.915	543.80	2.1536
334	2,3,3-Trimethylpentane	C_8H_{18}	560-21-4	114.229	0.6028	0.27446	573.5	0.2741	172.22	7.093	573.50	2.1963
335	1,3,5-Trinitrobenzene	$C_6H_3N_3O_6$	99-35-4	213.105	0.48195	0.23093	846	0.28571	398.40	7.083	846.00	2.0870
336	2,4,6-Trinitrotoluene	$C_7H_5N_3O_6$	118-96-7	227.131	0.37378	0.21379	828	0.29905	354.00	6.452	828.00	1.7484
337	Undecane	$C_{11}H_{24}$	1120-21-4	156.308	0.36703	0.24876	639	0.28571	247.57	4.945	639.00	1.4750
338	1-Undecanol	$C_{11}H_{24}O$	112-42-5	172.308	0.33113	0.23676	703.9	0.2762	288.45	4.859	703.90	1.3986
339	Vinyl acetate	$C_4H_6O_2$	108-05-4	86.089	0.9591	0.2593	519.13	0.27448	180.35	12.287	519.13	3.6988
340	Vinyl acetylene	C_4H_4	689-97-4	52.075	1.2703	0.26041	454	0.297	173.15	15.664	454.00	4.8781
341	Vinyl chloride	C_2H_3Cl	75-01-4	62.498	1.5115	0.2707	432	0.2716	119.36	18.481	432.00	5.5837
342	Vinyl trichlorosilane	$C_2H_3Cl_3Si$	75-94-5	161.490	0.59595	0.24314	543.15	0.24856	178.35	8.824	543.15	2.4511
344	Water [use Eq. (2)]	H_2O	7732-18-5	18.015	−13.851	0.64038	−0.00191	1.8211E-06	273.16	55.497	353.15	54.0012
345	*m*-Xylene	C_8H_{10}	108-38-3	106.165	0.68902	0.26086	617	0.27479	225.30	8.648	617.00	2.6413
346	*o*-Xylene	C_8H_{10}	95-47-6	106.165	0.69962	0.26143	630.3	0.27365	247.98	8.623	630.30	2.6761
347	*p*-Xylene	C_8H_{10}	106-42-3	106.165	0.67752	0.25887	616.2	0.27596	286.41	8.161	616.20	2.6172

Except for *o*-terphenyl and water, liquid density ρ is calculated by

$$\rho = C1/C2^{[1+(1-T/C3)^{C4}]}$$

where ρ is in mol/dm³ and T is in K. The pressure is equal to the vapor pressure for pressures greater than 1 atm and equal to 1 atm when the vapor pressure is less than 1 atm.

Equation (2), used for the limited temperature ranges as noted for *o*-terphenyl and water, is

$$\rho = C1 + C2T + C3T^2 + C4T^3$$

For water over the entire temperature range of 273.16 to 647.096 K, use

$$\rho = 17.863 + 58.606\tau^{0.35} - 95.396\tau^{2/3} + 213.89\tau - 141.26\tau^{4/3}$$

where $\tau = 1 - T/647.096$.

All substances are listed by chemical family in Table 2-6 and by formula in Table 2-7.

Values in this table were taken from the Design Institute for Physical Properties (DIPPR) of the American Institute of Chemical Engineers (AIChE), copyright 2007 AIChE and reproduced with permission of AIChE and of the DIPPR Evaluated Process Design Data Project Steering Committee. Their source should be cited as R. L. Rowley, W. V. Wilding, J. L. Oscarson, Y. Yang, N. A. Zundel, T. E. Daubert, R. P. Danner, DIPPR® Data Compilation of Pure Chemical Properties, Design Institute for Physical Properties, AIChE, New York (2007).

The number of digits provided for values at T_{min} and T_{max} was chosen for uniformity of appearance and formatting; these do not represent the uncertainties of the physical quantities, but are the result of calculations from the standard thermophysical property formulations within a fixed format.

Mass flow rate = $\dot{m}_h$ = 65,000 kg/h

= $\frac{65,000}{3600}$ = 18.06 kg/s

velocity of NaB = $\frac{\dot{m}}{\rho \times A_{cs}}$

$A_{cs} = \frac{\pi d_i^2}{4}$

$9.624 \times 10^{-4} = \pi (3.5 \times 10^{-2})^2 / 4 = 9.621 \times 10^{-4}$ m²

$v_{NaB} = \frac{18.06}{1.205 \times 10^3 \times 9.621 \times 10^{-4}}$

= 15.57 m/s

Note: Liquid flowrate range of 2-10 m/s is practiced. 2-4 m/s is suggested/chosen. velocity in the 15.57 m/s is high & may result in higher pressure drop.

$N_{Re} = \frac{d_i v \rho}{\mu}$

$= 0.035 \times 15.57 \times 1205 / 0.5 \times 10^{-3}$

$N_{Re} = 13,11742.4$

$N_{Pr} = \frac{C_p \mu}{K}$

$= 1574.94 \times 0.5 \times 10^{-3} / 152.3 \times 10^{-3}$

$N_{Pr} = 5.17$

Laminar flow ($2100 \geq N_{Re}$) $N_{Re} \leq 2100$

$N_{Nu} = 2.0 (N_{Nu})$

Colburn equation for transition condition;

$$N_{Nu} = \frac{h_i d_i}{k_i} = 0.023 (N_{Re})^{0.81} (N_{Pr})^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

$$h_i = \frac{0.023 \times 0.1523}{0.03505} (1311742)^{0.81} (5.17)^{0.33}$$

Assuming Sieder–Tate equation

$\mu = \mu_w$; $T_w = \frac{T_{cave} + T_{have}}{2}$

$T_{cave} = (25+93)/2 = 37.5$

$T_w = \frac{37.5 + 109.5}{2} = 73.5$

μ at 109.5°C and 73.5°C are almost same.

verify the above statement

μ at 73.5°C =

$h_i = 13475$ W/m²K

$h_{io} = h_i \frac{d_i}{d_o}$ = h_i based on d_o

(U_o requires h_{io})

$h_{io} = h_i d_i / d_o = 13475 \times \frac{0.03505}{0.04216} = 11,202 \frac{W}{m^2 K}$

V. Shell side/Annulus side HT co-efficient

$N_{Re} = D_e v \rho / \mu$

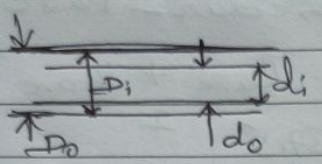
$N_{Nu} = \frac{h_o D_e}{k} = 0.023 (N_{Re})^{0.81} (N_{Pr})^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.14}$

$V = \dot{m} / A_{annulus} \times \rho$;

Consider $\frac{A_{annulus}}{wp}$ = $\frac{\text{c/s area of annulus}}{\text{wetted perimeter for HT}}$

$$A_{cs\ annulus} = \frac{\pi}{4}(D_i^2 - d_o^2)$$

$$= \_\_\_\_ m^2$$



Wetted perimeter $= \pi d_o$

Note: HT takes place across the inner surface of inner pipe

$$A_{annulus} = \frac{\pi(0.0525^2 - 0.04216^2)}{4}$$

$$= 7.687 \times 10^{-4}\ m^2$$

$$WP = \pi d_o = \pi \times 0.04216$$
$$= 0.132$$

$$D_e = 4 r_H$$

r_H = Hydraulic radius
= C/S area / WP

$$D_e = \frac{4\left(\frac{\pi}{4}(D_i^2 - d_o^2)\right)}{\pi d_o} = \frac{D_i^2 - d_o^2}{d_o}$$

$$D_e = 0.0232\ m$$

$\dot{m}_{benzene} = ?$ Under steady state condition

$$Q_{hot} = Q_{cold}$$

$$(\dot{m} C_p \Delta T)_{hot\ NR} = (\dot{m} C_p \Delta T)_{cold\ Benzene}$$

$Q_{hot} = \dot{m}_h C_{p_h} \Delta T_h$

$= 18.06 \times 1574.94 (124 - 95)$ W

$Q_{hot} = 8,24755 = 824.76$ KW

$Q_c = Q_h = (\dot{m} C_p \Delta T)_c$

$\dot{m}_c = 824.76 \times 10^3 / (C_p \Delta T)_{cold}$ kg/s

Properties of benzene at $T_{cave} = 37.5^\circ C$

Specific heat Capacity

Ref Page No. 3 - 139 P

Nomograph

$C_{p_c} = 0.42$ Cal/g °C

$= 0.42 \times 4.187 \times 10^3$ J/kg K

$= 1758.54$ J/kg K

$\dot{m}_c = 824.76 \times 10^3 / 1758.54 \times (50 - 25)$

$= 18.04$ kg/s $= 67544 \frac{kg}{h}$

Density of benzene at 37.5°C

879 kg/m³ — Ref : P/T

$V_a = \frac{\dot{m}_c}{A_{annulus} \times \rho} = \frac{18.04}{7.689 \times 10^{-4} \times 879}$

$V_a = 27.76$ m/s

Comments: 'Va' is high / too high, pressure drop will be

$$N_{Re} = (D c V S / \mu)$$

$$N_{Re} = \frac{0.0232 \times 27.76 \times 879}{\mu_c}$$

viscosity of benzene at 37.5°C

$x = 12.5$, $y = 10.9$ } $\mu = 0.52$ cp $= 0.52 \times 10^{-3}$ kg/m s

$$N_{Re} = 0.0232 \times 27.76 \times 879 / 0.52 \times 10^{-3}$$

$$= 1088781.0$$

$$N_{Pr} = \frac{C_p \mu}{k}$$

$k = 0.1506$ W/m K — Ref Page

$$N_{Pr} = \frac{1758.54 \times 0.52 \times 10^{-3}}{0.1506}$$

$$N_{Pr} = 6.072$$

$$N_{Nu} = \frac{h_o D_c}{k_h} = 0.023 (N_{Re})^{0.81} (N_{Pr})^{0.33} \left(\frac{\mu}{\mu_w}\right)^{0.14}$$

μ_w at 73.5°C of benzene = kg/m s

μ at 37.5°C = kg/m s

$(\mu/\mu_w) \approx 1.0$

$$h_o = 0.023 \times \frac{0.1506}{0.0232} (1088781)^{0.81} (6.072)^{0.33}$$

$$= 18286 \text{ W/m}^2\text{K}$$

vi. Clean Heat transfer co-efficient based outside area of inner pipe

$$\frac{1}{U_c} = \frac{1}{h_{io}} + \frac{1}{h_o}$$, Assuming pipe is clean

$$\frac{1}{U_o(\pi d_o L)} = \frac{1}{h_i(\pi d_i L)} + \frac{1}{h_o(\pi d_o L)}$$

πL Cancels

Taking 'do' to RHS

$$\frac{1}{U_o} = \frac{1}{h_i}\frac{d_o}{d_i} + \frac{d_o}{h_o d_o} = \frac{1}{(h_i d_i/d_o)} + \frac{1}{h_o}$$

$$\frac{1}{U_o} = \frac{1}{U_c} = \frac{1}{h_{io}} + \frac{1}{h_o}\ ;\ \frac{h_i d_i}{d_o} = h_{io}$$

$\frac{1}{U_c} = 1.439\times10^{-4}\ \frac{m^2K}{W}$; $U_c = 6947\ W/m^2K$

vii. Overall HT Co-eff based on dirt factor and wall resistance

$$\frac{1}{U_d} = \frac{1}{h_{io}} + \frac{1}{h_o} + R_w + R_d$$

$R_w = \frac{d_o \ln d_o/d_i}{k_w}$; there is no information about k_w, R_w can be neglected

$R_d = \frac{1}{\text{Dirt Co-efficient}}$ Note: $k_w = 54\ W/m\,K$ for Steel

Given

$\frac{1}{R_d} = \frac{1}{1500} = 6.67\times10^{-4}\ \frac{m^2K}{W}$

$\frac{1}{U_d} = \frac{0.03505}{11203} +$

$\frac{1}{U_D} = \frac{0.042\,16}{11203\times0.03505} + \frac{1}{18286} + \frac{1}{1500}$

$$\frac{1}{U_d} = 8.112872 \times 10^{-4} \quad \frac{m^2 K}{W}$$

$$U_d = 1233.7 \ W/m^2K$$

$$U_d = 1233 \ W/m^2K$$

viii. Heat transfer area, A_{HT}

$$Q = U_d A_{HT} \Delta T_{Lm}$$

$$A_{HT} = \frac{Q}{U_d \Delta T_{Lm}}$$

$$A_{HT} = \frac{824.755 \times 10^3}{1233 \times 71.98}$$

$$= 9.3 \ m^2$$

$$A_{HT} = \pi d_o L N$$

N = Number of tubes

L = Length of each tube/pipe

$$N = A_{HT} / \pi d_o L$$

Given $L = 5 \ m$

$$N = \frac{9.3}{\pi \times 0.04216 \times 5}$$

$$= 14$$

No. of Hair pins

Two straight lengths joined using a 'U' bend represent an hairpin

Number of hairpins $= \frac{N}{2} = \frac{14}{2} = 7$

ix. Pressure drop calculations

Using Fanning's friction factor equation

Tube Side ΔP

$$\Delta P_t = \frac{4 f G^2 (nL)}{2 g \rho^2 d_i}$$

nL = Total length of flow of tube side fluid

$$\Delta P_{tube} = \Delta P_t \times \rho$$

$$f = 0.0035 + \frac{0.264}{(N_{Re})^{0.42}}$$

$$= 0.0035 + \frac{0.264}{(1311742.4)^{0.42}}$$

$$= 4.21 \times 10^{-3}$$

Let the equivalent length for 180° bend = 50 mm

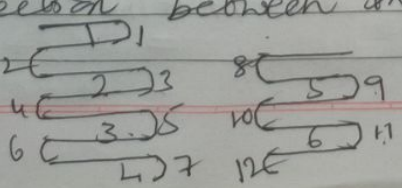
No. of bends = ?

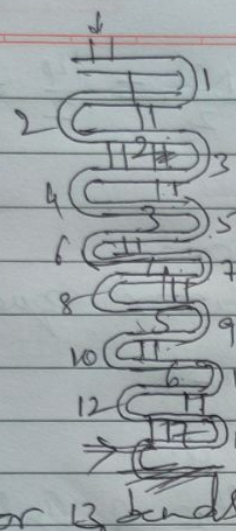
Straight length of bend = Length of fluid flow through each bend = 50mm

No. of hairpins = 7

Each hairpin requires '1' bend

Connection between the 2 hairpins = 1 bend





For 13 bends

7 hairpins
13 bends

$(L/D)_{eq} = 50$ mm

$\frac{L_{eq}}{d_i} = 50$

$L_{eq} = 50 \times d_i$

for one bend $L_{eq} = 50 \times 0.03505$ m

One bend $= 50 \times 13 \times 35.05 \times 10^{-3}$ m $= 650 \times 35.05$ mm

Total length due to bends $= 650 \times 10^{-3}$ m $\times 35.05$ mm $= 22.78$ m

'L' of straight tubes
$= 5\text{m} \times 14$ straight lengths
$= 70$ m

Entrance and exit losses total $= 4$ m

Total length to be considered for pressure drop calculations $= (70 + 650 \times 10^{-3})$ m
$= (70 + 22.78 + 4)$ m

$(L_n) = 96.78$ m

$$\Delta f_p = \frac{4 \times 4.21 \times 10^{-3} (15.5 \times 1205)^2 \times 96.78}{2 \times 9.81 (1205)^2 \times 0.03505}$$

$= 571.18$ m

$\Delta P_T = \Delta f_p \times \rho$

$= 688297$ kg/m^2

Choose 3" inner pipe
Since the pressure drop will be high & and pump capacity required will be high and standard pipe for outer pipe is 4".

Since the calculated value of pressure drop is high, the equipment should be redesigned the pressure drop can be overcome by increasing the dimensions (dia) of the tubes.

Pressure drop of annular side fluid

$$\Delta f_a = \frac{4 f G^2 L' / 2g \rho^2 D_e}$$

L' = Total length of annulus = fluid flow length

A short connector (short length of pipe) Taking 200 mm as the distance between the pipes — 8 such connections are required
$200 \times 8 = 1600$ mm

L = Total length of annulus where in HT transfer takesplace
$L = 14 \times 5 = 70$ m

$\Delta f_a \Rightarrow$ requires f and f requires N_{Re}

$$f = 0.0035 + \frac{0.264}{(N_{Re})^{0.42}} ; N_{Re} = \frac{D_e v_a \rho}{\mu}$$

$f = 4.58 \times 10^{-3}$

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

$$D_e = D_i - d_o$$
$$= 0.01034$$

$$N_{Re} = 0.0103 \times 27.76 \times 879 / 0.52 \times 10^{-3}$$

$$= 485205.3$$

$$L = 70 + 1.6 = 71.6 m$$

$$\Delta f_a = \frac{4 \times 4.58 \times 10^{-3} (27.76 \times 879)^2 \cancel{70}\ 71.6}{2 \times 9.81 \times 879^2 \times 0.01034}$$

$$\Delta f_a = 4871 m$$

In DPHE

The entrance loss for inner pipe may be neglected but for annulus losses are significant

$$\Delta f_L = 3 (V_a^2/2g) N_{tubes}$$
$$= 3 (27.76^2/(2 \times 9.81)) \times 14$$
$$= 1649$$

$$= 1649.64$$

$$\Delta P_{shell\ side} = (\Delta f_a + \Delta f_L) \rho$$
$$= 4871 + 1649.64$$

$\Delta P_s = 5731642 \text{ kg/m}^2$

The design pressure is high. Redesigning is required using 3" x 4" pipes.

Solution:

Tube characteristics

Inside: A_{cs} =
The tube

v =

N_{Re} =

h_i =

h_{i_0} =

Shell side

D_e =

$\Delta P_s = 5731642 \text{ kg/m}^2$

The design pressure is high. Redesigning is required using 3" x 4" pipes.

Solution:

Tube characteristics

Inside: A_{as} =

v =

N_{Re} =

h_i =

h_{i_0} =

Shell side

D_e =

$V_a =$

$N_{Re} =$

$h_o =$

$U_d =$

$A =$

$N =$

Pressure drop

ΔP_p

$\Delta P_{tube} =$

$f =$

$\Delta P_T =$

INDEX

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Notes by Dr. Y.K.S

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