Kirk-Othmer Encyclopedia of Chemical Technology.

HEAT-EXCHANGE TECHNOLOGY, NONAQUEOUS HEAT-TRANSFER MEDIA

Water, in any of its phases, is an excellent heat-transfer medium. High rates of heat transfer and high latent heat of vaporization make water attractive when condensing steam (qv) for heating or boiling water when cooling. Liquid water affords high rates of heat transfer and resultant economical pumping costs. Steam is also used to remove or to add sensible heat when the steam is superheated. Water is relatively inexpensive, thermally stable, nontoxic, and nonflammable, and is frequently the heat-transfer medium of choice. There are, however, definite limitations. For example, water freezes at 0°C and the critical temperature, T_c, is 374.1°C. Additionally, the vapor pressure is relatively high and the saturation pressure at T_c is 22.10 MPa (218.2 atm). At temperatures above 100°C, the saturation pressure of water may require the use of expensive equipment to contain the heat-transfer medium. The economics of using water as a heat-transfer medium must be evaluated for each installation. At temperatures below 0°C or above 200°C, heat-transfer media other than water often are the more optimum choice.

Cooling high temperature streams using typical cooling waters is not economically attractive. In addition to the obvious disadvantage of the loss of the high level heat, there is also the possible corrosion and fouling of hot surfaces by cooling waters unless expensive water-treatment methods are employed. Ambient air frequently is used as a coolant to avoid corrosion problems when high level energy cannot be recovered. Warm streams cannot be cooled below the summer design temperatures of cooling water systems.

Glycol/water, typically ethylene glycol or propylene glycol solutions, are widely used for liquid-phase secondary cooling and heating applications (see Glycols). Using appropriate inhibitors, the glycol-based fluids can be used over a temperature range of -50 to 175°C. When mixed with water, glycols are not flammable in concentrations up to 80 vol % glycol. Undiluted glycols have flash points not far removed from 100°C, and it is therefore possible to ignite the pure glycols if glycol concentration is increased above 80 vol %. Glycol/water solutions intended for heat-transfer systems are manufactured by Union Carbide Corp. and Dow Chemical (1, 2).

1. High Level Heat-Transfer Media

The ideal high level heat-transfer medium would have excellent heat-transfer capability over a wide temperature range, be low in cost, noncorrosive to common materials of construction, nonflammable, ecologically safe, and thermally stable. It also would remain liquid at winter ambient temperatures and afford high rates of heat transfer. In practice, the value of a heat-transfer medium depends on several factors: its physical properties in relation to system efficiency; its thermal stability at the service temperature; its adaptability to various systems; and certain of its physical properties.

Physical properties of heat-transfer media that are important, in addition to the thermophysical properties include vapor pressure, low temperature pump-ability, freezing or pour point, flash point, fire point, and autoignition temperature. The heat-transfer medium must exhibit sufficient thermal stability at the service temperature and high enough flash and fire points to permit safe operation. Most high level heat-transfer fluids are used at temperatures above the flash and fire points under proper protection from flames and arcs, but are not used above their autoignition temperatures. Other factors that must be considered include ease of reprocessing fluid that experiences thermal degradation and ease of monitoring the system to detect the presence of decomposition products or contaminants. Compatibility with process fluids and the ability to resist damage from nuclear radiation also may be important.

The highest economical service temperature of a fluid may depend on whether the fluid is being used for heating or cooling. Thermal stability at the service temperature must permit a long operating life so that system failures and costly equipment shutdowns are limited. A heating fluid normally reaches its highest temperature in a fired or electric heater or vaporizer. The important criterion is the maximum film (or wall) temperature to which the fluid can be economically subjected. A coolant fluid reaches its maximum temperature in a heat exchanger or reactor, both of which frequently result in more moderate heat fluxes than do fired heaters. High heat fluxes are, however, possible when cooling. When the coolant does not undergo a phase change, conditions associated with control at reduced rates of heat removal may establish the maximum film temperature to which the fluid is subjected. This may result in a bulk fluid temperature for the application that is lower than that which is practical when the fluid is used as a heating medium. Vapor-phase systems are sometimes preferred in order to avoid this condition.

Several generalizations can be made concerning thermal stability and degradation of organic heat-transfer media. (*1*) Aromatic materials exhibit thermal stabilities that generally are superior to aliphatic compounds. (*2*) The recommended maximum operating temperature for commercially available products is a rough measure of relative thermal stability. (*3*) Polymer formation is detrimental. Polymers increase fluid viscosity and promote carbonization which leads to fouling. However, none of the heat-transfer fluids noted herein exhibit exothermic polymerization unless contaminated with oxygen, organic material, or a polymerization catalyst. (*4*) Fluid degradation should produce a minimum of volatile materials. Volatile components increase operating losses and may present a safety hazard. The formation of volatile materials can be handled by proper design of the expansion-tank venting system. (*5*) Degradation should not produce reactive or corrosive materials. (*6*) Oxidation stability may be an important factor if air is present at high temperatures. Low insoluble sludge formation is an advantage.

2. Vapor-Phase and Liquid-Phase Operation

When establishing whether liquid-phase or vapor-phase systems are better, it is necessary to consider the overall process and economics, the thermal tolerance of the process, and the required equipment. In many cases, the costs for the two systems do not differ significantly. In vapor-phase systems, heat is transferred at the saturation temperature of the vapor, which affords uniform and precisely controlled temperatures. In liquid-phase systems, the temperature of the fluid necessarily changes as heat is transferred, therefore, temperatures are not uniform even if large circulation rates are employed for the heat-transfer fluid. In systems having multiple heat users, a combination of both vapor and liquid phase may be preferred. For small, compact systems, natural-convection vapor-phase systems generally are preferred. Electrically heated packaged units are commonly used for small liquid-phase systems. For large systems, heat losses from fluid piping may be greater for vapor-phase systems. Larger vapor-phase systems frequently require forced circulation condensate return when there are several users at different temperature levels.

Advantages of liquid-phase systems over vapor-phase systems are (*1*) no condensate return system is required, an important factor when there are multiple users operating at widely different temperatures; (*2*) simple and more easily operable systems when heating and cooling must be alternated; (*3*) there is no temperature gradient as a result of pressure drop in the supply piping; (*4*) liquid systems afford a positive flow through equipment and minimize problems associated with improper venting and natural-convection vaporizer tube burnout; (*5*) liquid phase eliminates the problems associated with condensate removal from complex geometries; and (*6*) liquid-phase systems generally have less mechanical leakage.

Advantages of vapor-phase systems over liquid-phase systems are (*1*) vapor-phase systems provide much more heat per unit mass of heat-transfer fluid; (*2*) condensing or boiling affords more uniform heat removal or addition and more precise temperature control; (*3*) vapor-phase heat transfer has an advantage when using equipment that does not permit easy control of liquid flow pattern and velocity; (*4*) natural circulation systems can be employed, thereby obviating pumps; (*5*) vapor systems require lower working inventories of the heat-transfer fluid; and (*6*) vapor systems frequently permit higher rates of heat transfer.

3. Heat-Transfer Fluids

3.1. Petroleum Oils

The most widely used heat-transfer medium at temperature levels above that obtained with moderate pressure steam is a high boiling petroleum fraction. Several oils are used. In general these are safe, essentially nontoxic, relatively low cost, noncorrosive fluids that have been refined to standard physical property specifications for heat-transfer service. These oils are flammable and a compromise must be established between flash point and viscosity. Usually, it is not practical to select an oil having a flash point above the maximum operating temperature of the system. To obtain a high flash point entails the use of a heavier stock having a resultant decrease in heat-transfer efficiency. The poorer thermophysical properties of the fluid reduce the rate at which heat can be transferred. If oils having high flash points leak from the system, insulation fires can occur.

Petroleum oils are subject to two kinds of deterioration: oxidation and thermal cracking. Petroleum oil at temperatures above 200°C and in contact with air or oxygen is oxidized at relatively high rates. Oxidation results in the buildup of organic acids and the formation of insoluble materials or sludge. Sludge causes the fluid viscosity to increase. Further, the sludge is deposited on the heat-transfer surfaces, thereby reducing the rate of heat transfer. Petroleum oils generally produce more oxidation sludge than do synthetic fluids. Many heat-transfer oils are compounded with an inhibitor to reduce oxidative deterioration (see Antioxidants). However, closed systems in which oxygen is excluded from contact with the hot oil are recommended. Thermal cracking occurs when petroleum oils are exposed to high temperatures. Thermal cracking results in the formation of new materials, some of which are light, relatively volatile products. The more volatile products lower the flash point of the oil; the heavier and more viscous products reduce the rate at which heat is transferred. The less volatile products also increase fouling of heat-transfer surfaces.

Heat-transfer oils that are offered by most suppliers resist thermal cracking and chemical oxidation. Generally, these are intended for use in closed systems, and, because vapor pressures are low, are limited mostly to liquid-phase systems having forced circulation. Most have viscosities that permit pumping readily at both starting and operating temperatures. When applied according to the recommended guidelines, these fluids provide long service life and afford good heat-transfer performance in a wide range of applications. Properly designed systems which are well maintained and operated permit maximum film (or wall) temperatures approximately 20°C higher than the recommended maximum operating temperature for the fluids.

Several companies offer oils for heat-transfer service. Physical characteristics are summarized in Table 1. The oils discussed herein are widely used. Product brochures on the fluids are available from the manufacturers (3–12).

3.1.1. Mobiltherm 603

Mobiltherm 603, manufactured by Mobil Oil Corp., is a high paraffinic oil suitable for systems in which combined heating and cooling cycles are used. It functions efficiently at both low and high temperatures and withstands repeated thermal cycling.

Table 1. Commercially Available Heat-Transfer Fluids

Fluid	Chemical composition	Temperature range, °C		Viscosity,[a] mPa·s(= cP)	Vapor pressure,[b] kPA[c]	Pour point, °C	Flash point, °C	Fire point, °C	AIT,[d] °C
		Min	Max						
				Petroleum oils					
Mobiltherm 603	paraffinic oil	40	290	20	21	−7	170		350
Caloria HT 43	paraffinic oil	40	315	5	80	−9	204		354
Thermia Oil C	paraffinic oil	40	290	230	5	−12	235		
Calflo FG	paraffinic oil	40	260	15	9	−21	194	204	285
Calflo AF	paraffinic oil	40	290	25	10	−18	204	225	343
Calflo HTF	paraffinic oil	40	325	35	15	−16	212	239	355
Multitherm PG-1	mineral oil	65	315	7	32	−40	171	196	366
Multitherm IG-2	paraffinic oil	65	315	10	7	−18	227	260	371
Multitherm 503	1-decene dimer	50	260	400	20	−60	160	174	324
Paratherm NF	mineral oil	65	315	7	32	−40	174	196	366
Paratherm HE	paraffinic oil	65	315	10	6	−15	227	260	371
Therminol HFP	paraffinic oil	4	300	300	5	−15	227	263	385
Therminol XP	mineral oil	−15	315	1200	32	−29	182	196	324
				Synthetic fluids					
Tetralin	hydronaphthalene	40	310	5	675	−32.5	77	90	384
UCON HTF-500	polyalkylene glycol	40	260	50	0	−37	244	316	415
Dowtherm A	diphenyl/diphenyl oxide	40	400	2.5	1050	12[e]	116	135	621
Dowtherm G	aryl ethers	0	370	75	365	4	141	146	584
Dowtherm LF	alkylated aromatic	−40	340	400	410	−40	115	125	467
Dowtherm J	alkylated aromatic	−70	315	10	1205	−73	56	68	420
Dowtherm Q	alkylated aromatic	0	330	10	330	−40	120	124	411
Dowtherm HT	hydrogenated terphenyls	10	340	250	110	0	179	191	350
Therminol 55	alkylated aromatic	−20	290	1150	26	−40	177	210	357
Therminol 59	alkylated aromatic	−45	315	1000	161	−61	146	154	404
Therminol 60	polyaromatic mixture	−50	315	2100	165	−68	154	160	446
Therminol 66	hydrogenated terphenyls	0	340	500	100	−26	177	193	374
Therminol 75	alkyl polyphenyls	160	400	2	130	70	199	227	538
Therminol LT	alkylated aromatic	−70	315	10	1510	−75	57	66	429
Therminol D-12	synthetic hydrocarbon	−45	260	10	395	−95	59	71	277
Therminol VP-1	diphenyl/diphenyl oxide	40	400	2.5	1065	12[e]	124	127	621
Marlotherm S	dibenzylbenzenes	−15	350	1000	315	−35	190	235	500
Marlotherm L	benzyl toluenes	−50	350	200	4200	−70	120	145	500
Thermalane L	synthetic paraffin	−45	260	100	90	−84	165	183	332
Thermalane 600	synthetic paraffin	−15	300	500	7	−65	240	271	377
Thermalane 800	synthetic paraffin	−15	325	250	30	−73	229	257	377
Syltherm 800	dimethylsiloxane polymer	−40	400	50	1360	−60[e]	177	193	385
Syltherm XLT	polydimethylsiloxane	−70	260	12	525	−105	47	54	350
Hitec Salt	nitrates and nitrites	150	540	20	535	145[e]			

[a] At minimum temperature.

[b] At maximum operating temperature.

[c] o convert kPa to psi, multiply by 0.145.

[d] AIT = autoignition temperature.

[e] Melting point.

3.1.2. Caloria HT 43

Caloria HT 43, manufactured by Exxon Co., is a paraffinic-based oil that is compounded with an oxidation inhibitor.

3.1.3. Thermia Oil C

Thermia Oil C, Shell Oil Co., is a selected mineral-oil fraction containing appropriate antioxidants.

3.1.4. Petro-Canada Oils

Petro-Canada manufactures three oils specially refined for use as heat-transfer fluids. Calflo FG is a semisynthetic, paraffinic heat-transfer fluid specifically developed for use in systems where incidental contact with food may result. Calflo AF is a saturated paraffinic oil containing inhibitors to minimize oxidation. Calflo HTF is a saturated paraffinic oil inhibited to minimize oxidation.

3.1.5. Monsanto Chemical Company Oils

Monsanto Chemical Co. manufactures two oils for heat-transfer applications. Therminol HFP is a solvent refined paraffinic oil; Therminol XP is a clear white mineral oil essentially identical to Multitherm PG-1 and Paratherm NF.

3.1.6. Multitherm Corporation

Multitherm Corp. manufacturers two oils for heat-transfer applications: Multitherm PG-1, a clear white mineral oil essentially identical to Therminol XP and Paratherm NF, and Multitherm IG-2, a solvent refined paraffinic oil essentially identical to Paratherm HE.

3.1.7. Paratherm Corporation

Paratherm Corp. manufactures two oils for heat-transfer applications: Paratherm NF, a clear white mineral oil essentially identical to Therminol XP and Multitherm PG-1, and Paratherm HE, a solvent refined paraffinic oil essentially identical to Multitherm IG-2.

3.2. Synthetic Fluids

Petroleum oils are products of nature and this is reflected in their cost. There are some serious limitations imposed by the chemical characteristics of natural products. These have led to the development of synthetic heat-transfer fluids that supplement natural products and permit more efficient operation at both lower and higher operating temperatures than can generally be obtained using natural products. These synthetic fluids also are subject to thermal cracking and chemical oxidation, and systems should be designed so that oxygen and other contaminants do not contact the fluids. Maximum fluid film and bulk temperatures should not exceed those recommended by the manufacturer in order to achieve long operating life. Properly designed systems which are well maintained and operated permit film (or wall) temperatures approximately 20°C greater than the recommended maximum operating temperature for the fluids.

Synthetic fluids are safe, noncorrosive, essentially nontoxic, and thermally stable when operated under conditions recommended by the manufacturers. Generally, these fluids are more expensive than petroleum oils, but the synthetics can usually be reprocessed to remove degradation products. There are several classes of chemicals offered permitting a wide temperature range of application. Any heat-transfer fluid in use should be examined periodically to monitor degradation or contamination.

The manufacturers of synthetic fluids offer technical service and consultation, and fluid reprocessing service can be arranged between the supplier and the user. Complete physical properties and detailed information concerning synthetic fluids are reported in the manufacturers' product literature (13–36). The physical characteristics of the synthetic fluids can be found in Table 1.

3.2.1. Tetralin

Tetralin is a trade name of Du Pont for 1,2,3,4-tetrahydronapththalene [119-64-2], $C_{10}H_{12}$. Tetralin, a derivative of naphthalene, is made by hydrogenating one ring completely and leaving the other unchanged. Tetralin is produced by several manufacturers and is one of the oldest heat-transfer fluids. Tetralin can be used both in liquid- and vapor-phase systems. The normal boiling point is 207°C.

3.2.2. Dowtherm Heat-Transfer Fluids

Dow Chemical Co. manufactures a family of heat-transfer fluids to meet differing applications. Dow Chemical also markets the Syltherm fluids produced by Dow-Corning Corp. Design and operating guidelines are offered in many of the company publications describing the Dowtherm fluids.

Dowtherm A, an eutectic mixture of 73.5% diphenyl oxide [101-84-8], $C_{12}H_{10}O$, and 26.5% diphenyl [92-52-4], $C_{12}H_{10}$, is one of the oldest and most widely used synthetic heat-transfer fluids (see Biphenyl and terphenyls). It has a characteristic aromatic odor even at low concentrations. Dowtherm A is used in both liquid- and vapor-phase systems. Because of its high freezing point (12°C), it often requires protection against freezing. The normal boiling point is 257°C. The recommended maximum service temperature is 400°C at a pressure of 16 mPa (150 psia); however, higher operating temperatures can be used where the higher decomposition rate can be justified economically. Dowtherm A has been used in applications to 430°C in properly designed systems. Dowtherm A and Therminol VP-1 are essentially identical fluids.

Dowtherm G is a mixture of di- and triaryl compounds and has good flow characteristics at low temperatures. Dowtherm G is highly stable, and the products of decomposition consist of high molecular weight materials which remain in solution in the liquid. Dowtherm G is intended for use in liquid-phase systems. The fluid has a striking odor even at extremely low concentrations.

Dowtherm LF is a mixture of diphenyl oxide and methylated biphenyl for use in liquid-phase systems. The low crystal point and low viscosity obviate protection from freezing at temperatures down to $-30°C$.

Dowtherm J is a mixture of isomers of an alkylated aromatic that contains only carbon and hydrogen. Dowtherm J can be used in liquid-phase systems at temperatures as low as $-73°C$ and in vapor-phase systems at temperatures from 185 to 315°C. Dowtherm Q is a mixture of diphenylethane and alkylated aromatics intended for liquid-phase systems. It can be used at temperatures as low as $-34°C$. Dowtherm HT is a mixture of hydrogenated terphenyls intended for liquid-phase systems. Dowtherm HT and Therminol 66 are essentially identical.

3.2.3. Therminol Heat-Transfer Fluids

Monsanto Chemical Co. manufactures a series of synthetic heat-transfer fluids that offer a wide operating temperature range. All of these fluids, except for Therminol VP-1 and Therminol LT, are intended for liquid-phase operation only. Monsanto also offers the two natural petroleum oil-based heat-transfer fluids discussed.

Therminol 55 is an alkylated aromatic available for use at moderate temperatures. Therminol 59 is an alkyl-substituted aromatic available for both heating and cooling applications. Therminol 60 is a mixture of polyaromatic compounds available for both heating and cooling applications. Therminol 66 is a modified terphenyl intended for liquid-phase systems. Therminol 66 and Dowtherm HT are essentially identical. Therminol 75 is a mixture of terphenyls and quaterphenyls. Therminol 75 was developed for systems operating at temperatures from 370–400°C. At ambient conditions, Therminol 75 is a soft solid material having a melting range of about 40–70°C. Therminol LT is an alkyl substituted aromatic intended for both liquid- and vapor-phase operation. Its normal boiling point is 181°C. Therminol D-12 is a synthetic hydrocarbon intended for liquid-phase systems operating over a wide temperature range developed for systems in which incidental contact with food products may result. Lastly, Therminol VP-1 is essentially identical to Dowtherm A.

3.2.4. Marlotherm Heat-Transfer Fluids

Two heat-transfer fluids are manufactured by Hüls America: Marlotherm S is a mixture of isomeric dibenzylbenzenes intended for liquid-phase systems, and Marlotherm L is a mixture of benzyl toluenes that are suitable for both liquid- and vapor-phase applications. Marlotherm L can be pumped readily at temperatures as low as -50°C and can be used in vapor-phase systems at temperatures from 290–350°C. The low temperature characteristics of Marlotherm enable it to be used in processes involving both heating and cooling.

3.2.5. Thermalane Heat-Transfer Fluids

Coastal Chemical Co. manufactures three heat-transfer fluids intended for liquid-phase systems. Thermalane L is a synthetic paraffin intended for low temperature applications. Thermalane 600 and Thermalane 800 are synthetic paraffins.

3.2.6. Multitherm 503

Multitherm 503 is manufactured by Multitherm Corp. and is a synthetic hydrocarbon intended for liquid-phase systems in which both heating and cooling are required. It was developed for systems in which incidental contact with food products may result.

3.2.7. Ucon HTF-500

Union Carbide Corp. manufactures Ucon HTF-500, a polyalkylene glycol suitable for liquid-phase heat transfer. The fluid exhibits good thermal stability in the recommended temperature range and is inhibited against oxidation. The products of decomposition are soluble and viscosity increases as decomposition proceeds. The vapor pressure of the fluid is negligible and it is not feasible to recover the used fluid by distillation. Also, because the degradation products are soluble in the fluid, it is not possible to remove them by filtration; any spent fluid usually must be burned as fuel or discarded. The fluid is soluble in water.

3.2.8. Syltherm Heat-Transfer Fluids

Dow Corning Corp. manufactures two heat-transfer fluids which are silicone polymers rather than organic fluids and are less susceptible to fouling as a result of fluid degradation (see Silicon compounds, silicones). These fluids are marketed by Dow Chemical Co. All lines containing Syltherm 800 volatiles must be maintained at temperatures above 65°C because one of the breakdown components of the volatiles freezes at 61°C. This requirement generally requires heat tracing of lines to safety relief devices, instrumentation, and vent systems.

Syltherm XLT is a polydimethylsiloxane intended for liquid-phase systems which operate at low temperatures. Syltherm 800 is a modified dimethylsiloxane polymer intended for liquid-phase systems. The recommended maximum fluid temperature is greater than the autoignition temperature.

3.2.9. Hitec Heat-Transfer Salt

Hitec heat-transfer salt, manufactured by Coastal Chemical Co., is an eutectic mixture of water-soluble inorganic salts: potassium nitrate (53%), sodium nitrite (40%), and sodium nitrate (7%). It is suitable for liquid-phase heat transfer at temperatures of 150–540°C. The melting point of fresh Hitec is 142°C. Hitec heat-transfer salt is very stable but does undergo a slow endothermic breakdown of the nitrite to nitrate, alkali metal oxide, and nitrogen. The nitrogen must be vented from the system. The nitrite also slowly oxidizes to nitrate in the presence of oxygen. Any carbon dioxide present is absorbed to form carbonates which may precipitate. Water vapor also is absorbed to form alkali metal hydroxides. All of these reactions occur accompanied by a rise in the freezing point of the salt. When all of the nitrite changes to nitrate, the freezing point rises to 220°C. Further, the formation of only 0.5 mol % sodium carbonate causes the freezing point to rise to 250°C.

Although Hitec is nonflammable, it is a strong oxidizer and supports the combustion of other materials. Consequently, combustible materials must be excluded from contact with the molten salt. Hitec is compatible with carbon steel at temperatures up to 450°C. At higher temperatures, low alloy or austenitic stainless steel is recommended. Adding water to Hitec does not appreciably alter its corrosion behavior.

Because Hitec is an excellent heat-transfer fluid which does not foul heat-transfer surfaces, American Hydrotherm Corp. developed a proprietary salt dilution technique to counter the disadvantage of high freezing point and to extend the range of application of the molten salt. Controlled dilution of the salt with water permits reduction of its freezing point to any desired level down to ambient temperatures. This extends the range of applicability and enables the fluid to be used in operations where temperature requirements vary widely. The water that is added for dilution gradually is evaporated and removed as the system is heated. As the system is cooled, water is gradually added to prevent freezing of the salt. It is essential that all of the water be removed before heating the mixture to high temperatures in order to avoid steam explosions which result from rapid liberation of steam. If water dilution is not employed, Hitec systems are generally limited to bath types owing to the large volumetric contraction upon freezing.

3.2.10. Other Synthetic Fluids

Other synthetic fluids are used as heat-transfer fluids although most of them are not sold specifically for this purpose. Fluids that sometimes are used include diethylene glycol, triethylene glycol, propylene glycol, butyl carbitol, *para*-cymene, several silanes, several silicone fluids, some silicate fluids, other polyalkylene glycols, other organic ethers, and other molten salts. Fluidized solids also are used as heat-transfer media.

3.3. Gases

The common permanent gases can be used as heat-transfer media and are the only substances capable of spanning the entire range of temperatures required in industrial applications. These gases exhibit excellent thermal stability and are relatively easy to handle. Unfortunately, they also exhibit relatively poor heat-transfer characteristics because of thermophysical properties. Gas systems for heat transfer are characterized by low rates of heat transfer, large volumetric flow rates, and high pumping costs. However, most of these disadvantages can be offset by operating at moderate pressures, eg, 2 MPa (20 atm), and by using extended (finned) surfaces for heat transfer. The choice of a particular gaseous medium is frequently a compromise between the use of inexpensive gases, eg, air and flue gases, or the use of commercially prepared gases, eg, nitrogen (qv) and carbon dioxide (qv). Commonly used gases include air, flue gases, nitrogen, carbon dioxide, hydrogen, helium, and argon. Superheated steam is also frequently used as a heat-transfer fluid.

3.4. Liquid Metals

Liquid metals (37, 38) are used as heat-transfer media at temperature levels as high as can be contained by suitable materials of construction. High rates of heat transfer are achieved with liquid metals, thus they are suitable for operation requiring high heat flux or low temperature differences. Liquid metals offer a broad operating temperature range, ie, the difference between their melting and boiling points ranges from 500–1000°C. Liquid metals also have low vapor pressures and exhibit high thermal stability.

Liquid metals, however, present several disadvantages. Their weights must be considered with regard to equipment design. Additionally, liquid metals are difficult to contain and special pumps must be used for system safety. Alkali metals react violently with water and burn in air. Liquid metals also may become radioactive when used for cooling nuclear reactors (qv).

The most commonly used liquid metal is sodium–potassium eutectic. Sodium, potassium, bismuth, lithium, and other sodium–potassium alloys also are used. Mercury, lead, and lead–bismuth eutectic have also been used; however, these are all highly toxic and application has thus been restricted.

3.5. Comparison of Heat-Transfer Fluids

A large number of heat-transfer fluids are available for use at moderately high (100–300°C) temperatures. Several are utilized at temperatures up to, and sometimes exceeding, 400°C. A dozen fluids may fulfill the operating requirements of a specific application. Final fluid selection should be based on safety of the fluid during service, heat-transfer rate, operating pressure drop, and system cost. Table 2 offers a comparison of liquid-phase heat-transfer fluids on the basis of pumping rate, heat-transfer coefficient, frictional pressure drop, and minimum velocity required for turbulent flow. Table 2 shows the relative performance of each fluid as physical properties change with temperature.

Table 2. Performance Comparison of Heat-Transfer Fluids

					Heat-transfer factor	
Fluid	Temperature, °C	Minimum velocity, m/s	Pumping rate factor	Pressure drop factor	Outside tubes	Inside tubes
Mobiltherm 603	100	2.18	1.31	2.59	1.29	1.42
	50	1.04	1.26	2.15	1.55	1.98
	200	0.67	1.20	1.90	1.73	2.42
	250	0.46	1.18	1.68	1.88	2.82
	300	0.34	1.16	1.50	2.00	3.22
Caloria HT 43	100	3.56	1.34	2.82	1.00	1.00
	150	1.37	1.28	2.22	1.25	1.52
	200	0.76	1.24	1.89	1.42	1.93
	250	0.52	1.22	1.65	1.51	2.22
	300	0.39	1.21	1.48	1.54	2.40
Thermia Oil C	100	3.55	1.28	2.91	1.11	1.11
	150	1.42	1.23	2.31	1.41	1.66
	200	0.81	1.17	1.98	1.64	2.18
	250	0.50	1.16	1.73	1.82	2.70
	300	0.37	1.16	1.58	1.95	3.07
Calflo FG	100	1.84	1.32	2.48	1.35	1.55
	150	0.98	1.26	2.11	1.60	2.07
	200	0.63	1.21	1.87	1.79	2.54
	250	0.44	1.18	1.69	1.97	3.00
Calflo AF	100	2.84	1.35	2.70	1.20	1.25
	150	1.32	1.26	2.25	1.51	1.80
	200	0.77	1.22	1.96	1.71	2.32
	250	0.51	1.16	1.74	1.91	2.82
	300	0.36	1.11	1.57	2.08	3.29
Calflo HTF	100	3.13	1.28	2.78	1.19	1.22
	150	1.45	1.23	2.31	1.46	1.75
	200	0.84	1.19	2.00	1.69	2.25
	250	0.55	1.15	1.78	1.89	2.73
	300	0.39	1.10	1.62	2.07	3.22
Multitherm PG-1	100	2.14	1.27	2.64	1.16	1.28
	150	0.95	1.18	2.16	1.43	1.86
	200	0.55	1.14	1.85	1.61	2.34
	250	0.39	1.11	1.63	1.72	2.68
	300	0.28	1.11	1.43	1.79	2.98
Multitherm IG-2	100	3.45	1.20	2.83	1.12	1.13
	150	1.44	1.16	2.28	1.39	1.67

Table 2. ***Continued***

Fluid	Temperature, °C	Minimum velocity, m/s	Pumping rate factor	Pressure drop factor	Heat-transfer factor	
					Outside tubes	Inside tubes
	200	0.82	1.12	1.95	1.57	2.11
	250	0.55	1.11	1.72	1.68	2.45
	300	0.45	1.11	1.57	1.69	2.55
Multitherm 503	100	0.88	1.24	1.97	1.71	2.25
	150	0.51	1.21	1.69	1.94	2.86
	200	0.34	1.20	1.48	2.11	3.38
	250	0.25	1.18	1.32	2.16	3.69
Paratherm NF	100	2.14	1.27	2.64	1.16	1.28
	150	0.95	1.18	2.16	1.43	1.86
	200	0.55	1.14	1.85	1.61	2.34
	250	0.39	1.11	1.63	1.72	2.68
	300	0.28	1.11	1.43	1.79	2.98
Paratherm HE	100	3.45	1.20	2.83	1.12	1.13
	150	1.44	1.16	2.28	1.39	1.67
	200	0.82	1.12	1.95	1.57	2.11
	250	0.55	1.11	1.72	1.68	2.45
	300	0.45	1.11	1.57	1.69	2.55
Tetralin	100	0.41	1.21	2.12	2.02	3.12
	150	0.29	1.21	1.87	2.12	3.51
	200	0.19	1.21	1.61	2.29	4.13
	250	0.14	1.20	1.42	2.41	4.60
	300	0.11	1.17	1.26	2.46	4.95
UCON HTF-500	100	5.74	1.09	3.76	1.29	1.17
	150	2.39	1.05	3.03	1.57	1.69
	200	1.44	1.04	2.59	1.69	2.02
	250	0.89	1.00	2.29	1.77	2.34
Dowtherm A	100	3.75	1.28	2.37	1.88	2.78
	150	1.23	1.24	2.07	2.08	3.38
	200	0.65	1.21	1.84	2.21	3.94
	250	0.42	1.26	1.59	2.20	3.98
	300	0.30	1.20	1.50	2.25	4.28
	350	0.24	1.21	1.36	2.16	4.26
	400	0.20	1.25	1.22	2.05	4.30
Dowtherm G	100	1.12	1.24	2.90	1.56	1.96
	150	0.62	1.21	2.47	1.80	2.55
	200	0.39	1.18	2.16	1.97	3.08
	250	0.27	1.23	1.92	2.07	3.47
	300	0.19	1.16	1.72	2.20	3.93
	350	0.15	1.16	1.55	2.24	4.23
Dowtherm LF	100	0.57	1.23	2.32	1.86	2.69
	150	0.36	1.21	2.03	2.04	3.23
	200	0.23	1.16	1.81	2.13	3.63
	250	0.20	1.11	1.75	2.18	3.88
	300	0.17	1.09	1.51	2.15	3.97
Dowtherm J	100	0.25	1.35	1.66	2.21	3.73
	150	0.20	1.31	1.49	2.33	4.10
	200	0.17	1.29	1.36	2.37	4.34
	250	0.16	1.29	1.23	2.38	4.52
	300	0.15	1.31	1.10	2.35	4.45
Dowtherm Q	100	0.56	1.19	2.21	1.79	2.59
	150	0.33	1.31	1.90	1.96	3.25
	200	0.22	1.23	1.67	2.06	3.57

Table 2. ***Continued***

					Heat-transfer factor	
Fluid	Temperature, °C	Minimum velocity, m/s	Pumping rate factor	Pressure drop factor	Outside tubes	Inside tubes
	250	0.17	1.20	1.54	2.13	3.91
	300	0.14	1.20	1.39	2.12	4.03
Dowtherm HT	100	1.88	1.33	2.92	1.25	1.42
	150	0.84	1.25	2.39	1.54	2.06
	200	0.50	1.18	2.07	1.79	2.65
	250	0.34	1.13	1.84	1.98	3.12
	300	0.26	1.09	1.67	2.11	3.56
	350	0.22	1.07	1.57	2.18	3.80
Therminol 55	100	1.88	1.24	2.56	1.29	1.46
	150	0.86	1.20	2.11	1.55	2.06
	200	0.52	1.17	1.82	1.73	2.54
	250	0.35	1.17	1.60	1.84	2.91
	300	0.26	1.18	1.47	1.88	3.13
Therminol 59	100	0.73	1.18	2.35	1.59	2.18
	150	0.43	1.22	2.02	1.80	2.75
	200	0.29	1.19	1.79	1.95	3.22
	250	0.22	1.16	1.60	2.04	3.57
	300	0.17	1.15	1.44	2.08	3.83
Therminol 60	100	0.82	1.26	2.59	1.62	2.17
	150	0.48	1.21	2.13	1.85	2.76
	200	0.32	1.17	1.89	2.00	3.22
	250	0.25	1.14	1.71	2.07	3.54
	300	0.20	1.13	1.56	2.08	3.73
Therminol 66	100	1.73	1.28	2.90	1.22	1.46
	150	0.80	1.21	2.39	1.56	2.08
	200	0.48	1.16	2.08	1.74	2.59
	250	0.34	1.12	1.86	1.87	2.98
	300	0.27	1.09	1.69	1.93	3.23
	350	0.23	1.08	1.56	1.95	2.36
Therminol 75	100	3.75	1.23	3.73	1.14	1.13
	150	1.23	1.18	2.88	1.53	1.90
	200	0.65	1.14	2.44	1.80	2.54
	250	0.42	1.12	2.15	1.99	3.05
	300	0.30	1.10	1.93	2.11	3.45
	350	0.24	1.09	1.76	2.15	3.64
	400	0.20	1.09	1.61	2.14	3.81
Therminol LT	100	0.25	1.36	1.64	2.03	3.47
	150	0.18	1.32	1.45	2.07	3.78
	200	0.14	1.31	1.30	2.07	3.95
	250	0.12	1.32	1.15	2.00	3.98
	300	0.10	1.35	1.00	1.87	3.82
Therminol D-12	100	0.33	1.31	1.53	1.74	2.81
	150	0.22	1.29	1.34	1.80	3.14
	200	0.17	1.29	1.17	1.79	3.30
	250	0.14	1.32	1.03	1.67	3.19
Therminol HFP	100	3.45	1.20	2.83	1.18	1.13
	150	1.44	1.16	2.28	1.39	1.67
	200	0.82	1.12	1.95	1.57	2.11
	250	0.54	1.11	1.72	1.68	2.45
	300	0.45	1.11	1.57	1.69	2.55
Therminol XP	100	2.14	1.27	2.64	1.16	1.28
	150	0.95	1.18	2.16	1.43	1.86

Table 2. ***Continued***

Fluid	Temperature, °C	Minimum velocity, m/s	Pumping rate factor	Pressure drop factor	Heat-transfer factor	
					Outside tubes	Inside tubes
	200	0.55	1.14	1.85	1.61	2.34
	250	0.39	1.11	1.63	1.72	2.68
	300	0.28	1.11	1.43	1.70	2.98
Therminol VP-1	100	3.75	1.28	2.37	1.88	2.78
	150	1.23	1.24	2.07	2.08	3.39
	200	0.65	1.21	1.84	2.21	3.94
	250	0.42	1.26	1.59	2.20	3.98
	300	0.30	1.20	1.50	2.25	4.28
	350	0.24	1.21	1.36	2.16	4.26
	400	0.20	1.24	1.22	2.05	4.30
Marlotherm S	100	1.51	1.27	2.88	1.37	1.63
	150	0.81	1.20	2.45	1.60	2.15
	200	0.49	1.13	2.13	1.82	2.71
	250	0.34	1.09	1.91	1.96	3.13
	300	0.26	1.06	1.73	2.06	3.60
	350	0.21	1.04	1.59	3.11	3.71
Marlotherm L	100	0.55	1.30	2.24	1.76	2.56
	150	0.36	1.24	1.97	1.94	3.16
	200	0.26	1.20	1.76	2.07	3.49
	250	0.21	1.17	1.62	2.10	3.68
	300	0.18	1.15	1.49	2.11	3.85
	350	0.16	1.13	1.39	2.09	3.88
Thermalane L	100	0.82	1.30	1.94	1.71	2.30
	150	0.48	1.29	1.66	1.96	2.91
	200	0.31	1.20	1.44	2.15	3.49
	250	0.24	1.18	1.29	2.26	3.85
Thermalane 600	100	0.75	1.19	2.45	1.72	2.35
	150	0.42	1.19	2.08	1.92	2.94
	200	0.25	1.20	1.79	2.09	3.54
	250	0.19	1.20	1.59	2.15	3.87
	300	0.16	1.21	1.45	2.11	3.93
Thermalane 800	100	1.94	1.20	2.37	1.44	1.63
	150	0.96	1.18	1.97	1.71	2.22
	200	0.60	1.17	1.70	1.89	2.70
	250	0.46	1.16	1.55	1.98	2.98
	300	0.35	1.16	1.39	2.06	3.28
Syltherm XLT	100	0.37	1.59	1.72	1.63	2.55
	150	0.26	1.60	1.49	1.74	2.94
	200	0.21	1.65	1.29	1.80	3.18
	250	0.18	1.75	1.12	1.80	3.27
Syltherm 800	100	1.76	1.50	2.64	1.22	1.41
	150	1.05	1.51	2.26	1.33	1.69
	200	0.69	1.53	1.96	1.39	1.94
	250	0.48	1.56	1.71	1.43	2.13
	300	0.36	1.62	1.49	1.43	2.26
	350	0.28	1.70	1.29	1.38	2.30
	400	0.24	1.82	1.13	1.30	2.23
Hitec Salt	150	4.39	0.69	7.21	3.66	3.51
	200	1.97	0.70	6.05	4.51	5.08
	250	1.25	0.71	5.44	5.06	6.24
	300	0.90	0.72	4.98	5.49	7.23
	350	0.64	0.76	4.55	6.42	8.34

Table 2. ***Continued***

					Heat-transfer factor	
Fluid	Temperature, °C	Minimum velocity, m/s	Pumping rate factor	Pressure drop factor	Outside tubes	Inside tubes
	400	0.48	0.80	4.21	6.30	9.00
	450	0.41	0.82	3.98	6.30	9.67
	500	0.39	0.83	3.39	6.33	9.88
water	100	0.15	0.56	1.80	10.38	19.44
	150	0.10	0.57	1.58	11.53	23.82
	200	0.08	0.57	1.43	12.36	26.73
	250	0.07	0.59	1.28	11.66	26.14
	300	0.07	0.54	1.15	11.28	24.36

The minimum velocity required to maintain fully developed turbulent flow, assumed to occur at Reynolds number (*Re*) of 8000, is inside a 16-mm inner diameter tube. The physical property contribution to the heat-transfer coefficient inside and outside the tubes are based on the following correlations (39):

$$\textit{inside tubes} \qquad h/cG = 0.023\ Re^{-0.2}Pr^{-2/3}$$

$$\textit{outside tubes} \qquad h/cG = 0.33\ Re^{-0.4}Pr^{-2/3}$$

where h is the heat-transfer coefficient, c the specific heat, G the mass flow rate per unit area, and Pr the Prandtl number. These expressions are used for the physical property terms, yielding the following equations:

$$\textit{inside tubes} \qquad c^{1/3}k^{2/3}\rho^{0.8}\mu^{-0.467} = (h_i D_i^{0.2})/(0.023v_i^{0.8})$$

$$\textit{outside tubes} \qquad c^{1/3}k^{2/3}\rho^{0.6}\mu^{-0.267} = (h_o D_o^{0.4})/(0.33v_o^{0.6})$$

where k is the fluid thermal conductivity; ρ, fluid density; μ, fluid viscosity; D the tube diameter; and v linear velocity. Each value is normalized so that the lowest value of the physical property terms is unity.

Some physical properties, such as heat capacity and thermal conductivity, are difficult to measure accurately at higher temperatures and error as great as 20% are common. For critical applications, consult the heat-transfer fluid manufacturer concerning methods that were employed for these measurements.

The relative pressure drop, ΔP, expression is based on the Fanning pressure-drop equation:

$$\Delta P = (4fL/D)(\rho v^2/2)$$

If the friction factor f is assumed to be $\alpha Re^{-0.2}$ where α is a constant, and the Fanning equation is solved for physical property terms, the result is

$$\mu^{0.2}\rho^{0.8} = (\Delta P D^{1.2})/(2L\alpha v^{1.8})$$

For pressure drop inside tubes, α is 0.046 and L is the fluid-flow path length. Across tubes banks, α is 0.75 and L is the product of the number of tube rows and the number of fluid passes across the tube bank. The physical property term is again tabulated after being normalized so that the lowest value is approximately unity.

When the heat duty requirement, Q, is specified and the fluid temperature change, ΔT, is fixed, as a result of operating or equipment limitations, the required volumetric pumping rate from the heat balance is

$$V = (Q/\Delta T)(1/c\rho)$$

Table 2 tabulates the physical property contribution of the required volumetric pumping rate ($1/c\rho$) normalized to assign the value of unity to the lowest data point.

The relative energy requirement is the product of pressure drop and volumetric flow rate when comparing fluids at the same velocity. Fluid performance comparisons on the basis of constant pumping energy or constant power require the application of a multiplier. Consider two fluids, X and Y, having relative heat-transfer coefficients h_x and h_y and relative pressure drops ΔP_x and ΔP_y. If the fluids are operating under the same energy requirement, the coefficient ratio for fluids X and Y (h_x/h_y) should be multiplied by the factor $(\Delta P_y/\Delta P_x)^{\beta}$;. Using the correlations previously presented, β should be 0.8/2.8 for fluids inside tubes and 0.6/2.8 for fluids outside tubes.

The equations presented herein do not include any viscosity correction to reflect the difference between the viscosity at the wall temperature and the bulk fluid temperature. This effect is generally negligible, except at low temperatures for organic fluids having viscosities that are strongly temperature dependent. For such conditions, the values tabulated in Table 2 should be appropriately modified.

4. Low Level Heat-Transfer Media

Refrigeration is required to cool to temperatures lower than those attainable using cooling water or ambient air. Low temperature processing also requires a suitable low temperature fluid. Several fluids are used for both of these types of service. There are several types of refrigeration systems, each of which requires a suitable working fluid or refrigerant. Refrigerants absorb heat not wanted or needed and reject it elsewhere (see Refrigeration and refrigerants). Some refrigeration systems use only gases, eg, air. In others, heat is removed from the system by evaporation of a liquid refrigerant and is rejected by condensation of the refrigerant vapor. This evaporation–condensation process occurs in absorption refrigeration systems as well as in mechanical compression and steam-jet refrigeration systems.

4.1. Gas-Cycle Systems

In principle, any permanent gas can be used for the closed gas-cycle refrigeration system; however, the prevailing gas that is used is air. In the gas-cycle system operating on the Brayton cycle, all of the heat-transfer operations involve only sensible heat of the gas. Efficiencies are low because of the large volume of gas that must be handled for a relatively small refrigeration effect. The advantage of air is that it is safe and inexpensive.

4.2. Steam-Jet Systems

Low pressure water vapor can be compressed by high pressure steam in a steam jet. In this way, a vacuum can be created over water with resultant evaporation and cooling; water, therefore, serves as a refrigerant. This method frequently is used where moderate cooling (down to 2°C) is needed. The process is inefficient and usually is economically justified only when waste steam is available for the motive fluid in the steam jet.

4.3. Absorption Systems

Absorption refrigeration cycles employ a secondary fluid, the absorbent, to absorb the primary fluid, refrigerant vapor, which has been vaporized in the evaporator. The two materials that serve as the refrigerant–absorbent pair must meet a number of requirements; however, only two have found extensive commercial use: ammonia–water and water–lithium bromide.

Water–lithium bromide systems cannot be used for low temperature refrigeration because the refrigerant turns to ice at 0°C. Lithium bromide crystallizes at moderate concentrations and therefore usually is limited to applications in which the absorber is cooled with cooling water. Other disadvantages are associated with the low pressure required and with the high viscosities of the lithium bromide solution. The pair does offer the advantages of safety and stability and affords a high latent heat of vaporization. The system has wide application in air-conditioning (qv).

Ammonia–water systems are more complex than water–lithium bromide systems, but can be used at temperatures down to $-40^\circ\mathrm{C}$. Ammonia–water systems operate under moderate pressures and care must be taken to avoid leaks of the irritating and toxic ammonia (qv). Sometimes a third material with a widely different density, eg, hydrogen, is added to the cycle in order to eliminate the need for mechanical pumping.

4.4. Mechanical Compression Systems

The equipment in a refrigeration system serves only to provide the refrigerant in the liquid state at the place where cooling is desired. Because evaporation of the liquid is the only step in the refrigeration cycle that produces cooling, the properties of the refrigerant should permit high rates of heat transfer and minimize the volume of vapor to be compressed. High rates of heat transfer also should be afforded at the condenser, where heat must be rejected. Generally, the selection of a refrigerant is a compromise between conflicting requirements and often is influenced by properties not directly related to its ability to transfer heat. For example, flammability, toxicity, environmental effects, density, molecular weight, availability, cost, corrosion, electrical characteristics, freezing point, and the critical properties are often important factors in selection of a refrigerant.

Several types of fluids are used as refrigerants in mechanical compression systems: ammonia, halocarbon compounds, hydrocarbons, carbon dioxide, sulfur dioxide, and cryogenic fluids. A wide temperature range therefore is afforded. These fluids boil and condense isothermally. The optimum temperature or pressure at which each can be used can be determined from the economics of the system. The optimum refrigerant can be determined only for the specific refrigeration requirements needed. A discussion of refrigerants and a compilation of their physical properties has been reported (40).

4.5. Secondary Coolants

In many refrigeration applications, heat is transferred to a secondary coolant which is in turn cooled by the refrigerant. The secondary fluid may be any liquid that transfers heat without a change in its state. Secondary coolants, often known as *brines* (40), are frequently mixtures of water and an appropriate material that can form eutectic mixtures. Secondary coolants may be used where building codes restrict the use of certain refrigerants, in order to minimize the frequency and cost of leakage, where the users of refrigeration cannot be grouped close to the central refrigeration system, and where several users must be controlled at different temperature levels. The use of secondary coolants reduces the efficiency of the refrigeration system and often increases the investment and operating costs.

Secondary coolants frequently are called brines because such fluids originally were mixtures of salts and water. Common refrigeration brines are water solutions of calcium chloride or sodium chloride. These brines must be inhibited against corrosion.

Organic fluids also are mixed with water to serve as secondary coolants. The most commonly used fluid is ethylene glycol. Others include propylene glycol, methanol (qv), ethanol, glycerol (qv), and 2-propanol (see Propyl alcohols, isopropyl alcohol). These solutions must also be inhibited against corrosion. Some of these, particularly methanol, may form flammable vapor concentrations at high temperatures.

Water mixtures of salts or organic fluids offer a range of operating temperature levels down to $-60^{\circ}\mathrm{C}$. Heat-transfer characteristics vary with concentration and temperature. The viscosities of all of the brines are relatively high at the temperatures frequently encountered in refrigeration systems. Because of the relatively high viscosities of brines, many of the common refrigerants are sometimes employed as secondary coolants. Economic system design usually requires viscosities less than $10\mathrm{mPa{\cdot}s}(=\mathrm{cP})$ for the secondary coolants. Halocarbons are the most commonly used because of their nonflammability, but ozone depletion is an increasing concern with these fluids. Some of the synthetic heat-transfer fluids such as Dowtherm J, Therminol LF, and Syltherm XLT, are often used as the secondary fluid of choice because these offer excellent heat-transfer properties and viscosity remains low $(\mathrm{ca}10\mathrm{mPa{\cdot}s}(=\mathrm{cP}))$ at $-70^{\circ}\mathrm{C}$.

4.6. Heat Pumps

Heat pumps involve the application of external power to pump heat from a lower temperature to a higher temperature. Heat pumps are frequently used for space heating and are simply refrigeration cycles operated in reverse. The heat rejected in the condenser becomes the primary objective of operation. Consequently, refrigerants used for mechanical compression refrigeration have similar application in heat pumps.

Heat pumps also have application in processing plants. Frequently, a refrigerant is evaporated in the condenser of a distillation column and the refrigerant vapor is compressed to a level at which the vapor condenses in the reboiler of the same column, thereby providing the heat needed to operate the distillation process. Sometimes the vapor from the column serves as the refrigerant if the vapor properties are similar to those of the optimum refrigerant. Heat pumps applied to distillation (qv) processes have been economical for low temperature processing. They have been less frequently applied when processing at moderate temperatures. Changing energy economics require that this approach be examined periodically.

4.7. Thermal Engine Cycles

Thermal engine cycles operating with organic refrigerants are employed to recover energy from waste heat streams at temperatures below 150°C. Recovery of such heat is justified only when recovery cannot be effected through process-oriented heat utilization. Typical systems employ the Rankine cycle to produce electrical or shaft power. Thermal efficiencies of Rankine cycles are low, but thermal engines are applied when large quantities of waste heat are available. The most frequently used refrigerants are halocarbons and hydrocarbons. Mixed refrigerants that evaporate and condense over a selected temperature range are used when the available heat source undergoes a wide temperature change as heat is removed. Cascaded systems, ie, thermal engine cycles in series operating at different temperatures, sometimes are employed to increase thermal efficiencies. In such systems, each thermal engine cycle may employ a different refrigerant.

4.7.1. Nomenclature

	Parameter	Units
c	specific heat	J/(kg·K)
D	tube diameter	m
f	friction factor	
G	mass flow rate per unit area	$(\upsilon\rho)$, kg/(m^2·s)
h	heat-transfer coefficient	W/(m^2·K)
k	fluid thermal conductivity	W/(m·K)
L	length	m
Pr	Prandtl number	$c\mu/k$
Q	heat-transfer rate	W
Re	Reynolds number	DG/μ
V	volumetric flow rate	m^3/s
υ	linear velocity	m/s
X	arbitrary fluid	
Y	arbitrary fluid	
α	constant in friction factor equation	
β	exponent for correction factor multiplier	
ΔP	fluid pressure drop	
ΔT	fluid temperature change	°C
ρ	fluid density	kg/m^3
μ	fluid viscosity	Pa·s
Subscripts		
i	inside	
o	outside	
x	fluid X	
y	fluid Y	

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