themselves with the large dimensions parallel as the filled carton is subjected to handling in warehousing and shipping, and this so-called "stacking" action brings about a real problem of excessive outage when the package of flakes reaches the consumer.

Bulk flakes and chips are packaged directly from the chip drier, or after mixing in of builders with the dry-mixer. A large amount of such bulk production is represented by an unbuilt chip used as a catalyst in the polymerization step in synthetic-rubber making.

ONE OF THE MORE ACTIVE commercial areas at the moment is that of liquid synthetic detergents both for light- and heavy-duty washing. The original light-duty products appeared in glass but, since some consumers seem to prefer a can, are now also being packaged in that fashion. Though as mild as soaps, their long exposure-time caused a corrosion problem with the cans, which has been overcome by the use of treated can plate and polyethylene nozzles among other innovations. The heavy-duty liquids now appearing on the market are also in cans, and many packaging problems of the same type have had to be solved. In general, these products are mixtures of alkyl benzene sulfonates or other actives, phosphates, and various additives such as brighteners and suds builders, all solubilized into a single phase mixture. The elimination of the dissolving period is an advantage of this type of retail product heavily stressed in the advertising.

Liquid soaps usually are potash coconut soaps sold in bulk for washroom dispensers and similar uses. If not chilled and filtered during making, they frequently develop an unsightly precipitate.

In the miscellaneous field there are many specialty products, such as cleaners, cleansers, dishwashing compounds, cold-water washing products for woolens, shaving cream, and many more. While they all have some soap or synthetic detergent present to provide cleansing action, they are not usually considered soaps. Likewise the shampoos form a field of their own.

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# Heat Transfer

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HEAT TRANSFER continues to be one of the most important operations in a majority of industrial companies. It is not surprising then that research in this field is and has been conducted by a large number of investigators. As a result, new developments and equipment designs are common.

In the last few years much heat transfer research has been done in nuclear and aeronautical fields (10, 11, 12). Numerous studies have been reported of heat transfer through molten metals and through gases flowing at high Mach numbers. Development and research work has continued, in addition, in chemical and oil processing industries. The results of these studies have thrown considerable light on the basic fundamentals of heat transfer.

The general basic theory of heat transfer and some of the common correlations will be outlined here. In addition, recent developments, especially those that might apply in the oil processing industry, will be reviewed.

### Modes of Heat Transfer

Heat transfer can occur by three modes (4, 22, 30, 34). Briefly these are as follows: conduction, or transfer of kinetic energy from one molecule to an adjacent one; convection, or transfer of heat caused by the mixing of molecules or portions of a fluid with other molecules (Convection may be either natural or forced. Mechanical agitation is provided for forced convection.); and radiation, or transfer of energy through space by means of electromagnetic waves. (These waves can be transmitted, reflected, or absorbed by matter. Only that portion which is absorbed will appear as heat.)

In most industrial operations, heat transfer occurs by more than one of the above modes. Frequently the operation can be divided into steps though, in which only one or possibly two modes are significant.

The basic equation for steady-state unidirectional heat flow by conduction is Fourier's equation (4, 22, 30, 34):

$$(1)\quad Q = -kA\frac{dT}{dX}$$

In the case of constant k and A (as frequently occurs),

$$(2)\quad Q = -\frac{kA}{\triangle X}\triangle T$$

where $\triangle X$ is the thickness of the material across which heat is being transferred, $\triangle T$ is the temperature difference, or the driving force. The resistance to heat transfer is $(\triangle X/kA)$. If heat were being transferred by conduction through a series of substances, the sum of the resistances would have to be obtained. The $\triangle T$ to be used then would be the total. In industrial processes heat transfer through solids is generally by conduction although in some cases radiation may be significant too.

The basic equation for the radiation of a "black" body is as follows (4, 22, 30, 34):

$$(3)\quad Q = \sigma AT^4$$

Since radiation is proportional to the absolute temperature raised to the fourth power, it is obvious that radiation is much more significant at high temperatures. Radiation is industrially of importance in furnaces, flames, etc. Correction terms must generally be applied to the above equation to account for the "non-blackness" of the surface and the geometry.

When heat is being transferred from a solid surface to a fluid, both conduction and convection are generally of importance. The basic equation used is as follows (4, 22, 30, 34):

$$(4)\ Q = h\,A\,\triangle T$$

The magnitude of h depends on the fluid and its flow characteristics near the solid surface. When a fluid is moving across the surface of a solid, the fluid next to the surface flows laminarly (or in streamline flow). Conduction is the main means of heat transfer in this region. If the fluid velocity is high enough, turbulent flow will occur at all distances except those next to the solid. Convection is the principal means of heat transfer in turbulent flow. A theoretical study on heat transfer through a homogenous isotropic turbulent field has just been reported by Hanratty (16). The effect of the time dependency on the operation was studied.

### Heat Exchangers

The most common type of heat exchanger is probably the shell-and-tube exchanger. Procedures and semi-theoretical equations for designing it for most common uses are found in numerous books (4, 22, 30, 34) dealing with heat transfer. Equations are available for calculating the film coefficients for heat transfer of fluids flowing inside the tubes. Probably the most common equation used for this purpose is the Dittus-Boelter equation. It should be emphasized though that this equation is limited to turbulent flow (*i.e.*, Reynolds numbers greater than about 6,000) and for liquids with fairly low thermal conductivities (i.e., Prandl numbers of 1 to 5). Most fluids used in oil processing industries will have Prandl numbers in this range. Molten metals have lower Prandl numbers, and the equation is not applicable for them. The Sieder-Tate equation is more difficult to use than the Dittus-Boelter equation, but the former equation is more accurate for fluids whose viscosity changes are relatively large with temperature. Fluids in this category include glycerine and some oils and fats.

Equations are also available (4, 22, 30, 34) for predicting h values when a vapor condenses as a film on the outside of a tube. When dropwise condensation occurs, the h values are much higher, indicating lower resistances to heat flow. Unfortunately no reliable equations are available for predicting film coefficients of dropwise condensation. Suitable promoters are often added (30) to the vapors to promote this type of condensation. Promoters which have been suggested include mercaptans for copper and its alloys, and oleic acid for copper, brass, nickel, and chromium. These substances apparently adsorb on the surface of the metal so the vapors condense on the adsorbed promoters and not on the metal itself.

Several months ago Donahue (9) published a series of papers on the design, construction, and maintenance of tube-and-shell heat exchangers. He included not only semi-theoretical equations used for design purposes but also practical suggestions. The advantages and disadvantages of fixed-tubes, floating heads, multipasses on both the tube and shell side of the exchanger, etc., were discussed. In addition, the tube layout (or arrangement) is of importance not only in regard to heat transfer but also for maintenance purposes. Some arrangements allow much better mechanical cleaning of the outside of the tubes. Chemical cleaning is frequently used if the fouling material is soluble in a fairly cheap solvent. If the insides of the tubes have to be mechanically cleaned frequently or if tubes will probably need frequent replacement, the exchanger should be designed so that the heads are easily removable or so that the entire tube bundle can be removed from the equipment. Such arrangements are generally initially more expensive but result in lower maintenance costs. C. F. Braun and Company of Alhambra, Calif., released in 1954 an excellent film strip on heat exchangers. A total of 89 colored pictures describe the use and construction of several varieties of tube-and-shell heat exchangers. This film should be of considerable value to all engineers interested in heat transfer equipment.

The design of a heat exchanger head for low fluid holdup is explained by Cichelli and Boucher (5). They indicated that it is desirable to have equal flow through all tubes; otherwise decreased heat transfer coefficients result. It is recommended that this possible difficulty be considered in the design of all tube-and-shell heat exchangers, especially those with several passes on the tube side. In multi-pass exchangers the fluid velocities are high, and the direction of flow must change rapidly over short distances. West and Taylor (42) have presented data which show the effect of pulsating flow of water on heat transfer coefficients. The pulsations were caused by a reciprocating pump. When the pulsations were partially dampened, the film coefficients for the water were increased by 60–70%. Lemlich (26) however found that vibrations in the range of 39 to 122 cycles per minute caused marked improvement (up to a four-fold increase) of the film coefficients. Higher coefficients were obtained with an increase in amplitude or an increase in frequency. A generalized correlation of his results is presented. Induced vibrations may prove feasible in some commercial equipment to obtain high heat fluxes and hence larger capacity for a given piece of equipment. The effect of curved surfaces on heat transfer was reported by Kreith (23). Heat transfer coefficients were found to be appreciably higher for walls of concave curvature as compared to convex walls of similar curvature. Since these higher heat transfer rates can often be achieved without increases in the pumping requirements, special geometries might be considered in equipment where a high heat flux in a small space is required.

Finned tubes have found wide-spread use as a means of increasing the heat transfer area on the outside of the tube. If the largest resistance to heat transfer is caused by the film on the outside, finned tubes will generally increase the heat flux appreciably. New data of the finside coefficients in a heat exchanger were reported by Clarke and Winster (6). Various types of finned tubes are available, and their study includes cut and twisted finned tubes. Hobson and Weber (18) measured heat transfer characteristics of spined tubes. These tubes have extended surface areas for heat transfer on their outside, but their construction is quite different from that of finned tubes. The spines are shaved from the surface metal of the tube and in appearance almost resemble the back of a porcupine. They have correlated their data for three types of spined tubes.

External heaters for unsteady-state systems were studied by Lynch (28). A liquid was recirculated through a heat exchanger until the desired temperature of the liquid was obtained. His data and correlations will be of value for batch heat transfer problems.

Recently Miller, Byrnes, and Benforado (33) have collected heat transfer data for water in an annulus. Tests were performed at Reynolds numbers ranging from 5,000 to 22,000 (based on equivalent diameters), water temperatures of 70° and 125°F., and relatively high heat fluxes of 52,000 to 208,000 B.T.U./hr., sq. ft. The heat transfer coefficients can be correlated with an equation similar to the Dittus-Boelter equation.

Fuel-fired heaters of various types are often used for high temperature reaction heaters, steam boilers, etc., Most of these heaters include a combustion zone in which the fuel is burned and in which a substantial portion of the heat release in the chamber is transferred to the absorbing surface by direct radiation. McCarthy (31) presents a correlation for evaluating the performance in a combustion section of fuel-fired heaters and reboilers. Such a method should prove useful for designing and comparing furnaces.

A liquid-Dowtherm heating or cooling unit is described by Stack and Frieden (39). Temperatures can be maintained between 125 and 600°F. with only relatively low pressures on the Dowtherm stream. The Dowtherm is heated or cooled by a gas-fired heater or a water-cooling exchanger. Centrifugal pumps are provided to circulate the Dowtherm liquid. Molten metals such as potassium, sodium, mercury, etc., are sometimes used for heat transfer purposes. In general, they are used at relatively high temperatures. Molten sodium hydroxide is used at temperatures from 604 to about 1,200°F. Hoffman (19) has studied the heat transfer to molten sodium hydroxide in a circular tube. An empirical relationship has been derived to represent the heat transfer coefficients.

## Heat Transfer to Boiling Liquids

Coefficients h for the film from a solid surface to a boiling liquid are available (4, 22, 30, 34), and they are useful for approximating coefficients for design purposes. The coefficients vary with the liquid, the solid surface, and the temperature of the boiling liquid. In addition, the temperature difference across the film is important. The maximum film coefficient for boiling water at 212°F. is at about 40°F. A recent paper by Larson (24) discusses the factors influencing heat transfer in boiling. The surfaces of the solids on which boiling occurs are almost always non-homogeneous in wetting properties. As a result the bubbles tend to appear at favored spots. Apparently the least wetted minute areas are those subjected to the greatest liquid superheat. Bubble formation occurs here first and most frequently. Absorbed gas and gas liberation due to chemical action are other sources of ebullition although gas in true solution does not promote nucleation (or bubble formation). Some heterogeneity of the solid heating surface appears desirable since it reduces local superheat and causes smoother, less explosive boiling action. Heat transfer in surface boiling appears to be a statistical process, unsteady in minute details. Larson reports that a well wetted smooth surface is desirable. The active boiling locations or nuclei should be small in a lateral direction and should be uniformly distributed. Rough surfaces promote bubble formation but tend to hinder bubble detachment. As a result the heat transfer coefficients of rough surfaces are frequently quite low. Pressures in the order of 35% of the critical generally give the highest coefficients.

Heat transfer for two-phase, one-dimensional type of flow has been studied by Harvey and Foust (17). Such flow occurs frequently as, for example, in an evaporator. The gas bubbles that are formed often decrease the film coefficients since gases offer more resistance to heat transfer than liquids. The effect of forced circulation on boiling-heat transfer and pressure drop was reported by Schweppe and Foust (38). The boiling in the tube causes a gas-vapor system. They explained the inversion of the pressure gradient by sonic choking in the tube. This choking tended to suppress vaporization in the tube. Rohsenow (36) has studied heat transfer associated with nucleate boiling. He made experimental measurements for both pool boiling and for forced circulation boiling. In pool boiling the effect of chemical composition of the solid surface was more pronounced at lower pressures. As the critical temperature is approached though, the attainable superheat approaches zero. He found the magnitude of liquid superheat before a bubble is formed to be as high as 100–200°F. Once bubbles are formed, the liquid is stirred by the motion of the bubbles, and the amount of superheat is reduced to a few degrees. Rohsenow reports that the process of boiling in a vertical tube is much more complicated than the pool boiling process. If a liquid entering at the bottom of a heated tube is well below the saturation temperature, boiling may take place at the surface. The bubbles tend to travel out into the main body of the liquid where they condense. This process is called local or surface boiling. This process is highly desirable for the rapid transfer of heat since the bubbles agitate the liquid and the bubbles do not tend to blanket the solid surface. Larsen (24) had reported fluxes in the order of millions of B.T.U./hr., sq. ft. for surface boiling.

Thermosiphon reboilers (natural circulation reboilers) were studied by Lee, Dorsey, Moore, and Mayfield (25). Over-all heat transfer coefficients as high as 2,500 B.T.U./hr., sq. ft., °F. were obtained with water. Heat fluxes were as high as 100,000 B.T.U./hr., sq. ft. Considerably lower values were obtained however for ethyl toluene. Vapor-lock points were noted, and the proper operating techniques to obtain maximum loadings were suggested. A table is included in that paper giving the reboiler standards of the Celanese Corporation of America.

## Heat Transfer to Granular Solids

Heat transfer to or from a granular solid is often of extreme importance, yet in many cases it is not even considered. Reactions involving solid granular catalysts are examples. When oils or fats, for instance, are hydrogenated in the presence of a nickel catalyst, the reactants (*i.e.*, the unsaturated fatty acid groups and the hydrogen) are transferred first from the main body of the liquid to the catalyst surface. The hydrogenation reaction occurs at or near the catalyst surface with the release of the heat of reaction. As a result, the catalyst surface will be hotter and have a higher concentration of saturated fats than the main body of the oil. There will then be a transfer of heat and hydrogenated product from the catalyst to the main portion of the oil. Agitation of the oil tends to decrease both the resistances of heat and mass transfer. With increased agitation there will then be changes of the temperature and fatty acid concentrations on the catalyst surface, and there will be differences in the rate, selectivity, and isomerization occurring during hydrogenation. Within the last few years information has been accumulated (4, 20, 34) which indicates that the factors affecting mass transfer also have similar effects on heat transfer. As a result, mass transfer data can frequently be used to predict heat transfer characteristics.

In packed catalytic beds, temperatures of the bed may vary significantly with the longitudinal or lateral position (20). Since the rates of the chemical reactions tend to increase with temperature, it is obvious that the reactant concentrations also vary with the lateral and longitudinal position in the bed. Recent studies (1, 8, 35, 37) have presented more data on the heat transfer and flow characteristics of packed beds. All investigators agree that heat transfer in these beds is far from simple since heat is transferred by conduction, convection, and, to some extent, radiation. General rules for predicting heat transfer characteristics are now available and can be used if sufficient data about the solid particles and the flowing fluid are known. In most correlations it is necessary to know the effective thermal conductivity of the bed. These conductivity values are functions of the Reynolds number (35).

When good temperature control is necessary for certain chemical reactions, a fluidized bed is sometimes used (4, 20, 30, 34). The fluidized solid particles increase the heat capacity of the reaction zone appreciably, and an essentially constant bulk temperature is maintained in the reaction vessel. Leva and Grummer (27) have presented a correlation of the solids turnover and its relationship to heat transfer between the fluidized solids and the gas. They think that a generalized correlation can be obtained of heat transfer data in terms of particle velocities. Insufficient equipment was investigated however to determine this correlation. Toomey and Johnstone (40) have studied heat transfer between the fluidized bed and the walls of the container. High-speed photography was used to determine the solid velocities and behavior. Michely and Fairbanks (32) were able to correlate their heat transfer coefficients to the square root of the thermal conductivity of the quiescent bed. Their results indicate that the controlling step for heat transfer may be the unsteady state of diffusion into the mobile elements of the quiescent bed material. They derived an equation for the heat transfer coefficient wherein the effect of the bed thermal properties were separated from the factors which accounted for bed motion and geometry. The mass transfer analogy was also derived and shown to correlate the available mass and heat transfer data reasonably well.

## Heat Transfer to Liquid Drops and Gas Bubbles

Evaporation from liquid drops and spray drying involve both heat and mass transfer. Marshall (29) has summarized the important information in this field up to 1954. The analogy between heat and mass transfer is now confirmed at low Reynolds numbers. The vaporization rates and heat transfer coefficients of several liquid hydrocarbon fuels were studied by Ingebo (21). His heat transfer coefficients were correlated by a new dimensionless number, the product of the Reynolds and Schmidt numbers.

Heat transfer in a liquid-liquid spray-tower operation was investigated by Garwin and Smith (14). Benzene-water was the system used, and coefficients were determined for the heat transfer from the benzene drops to the water.

Several months ago Coldiron, Albright, and Alexander (7) reported that the temperature of a highly exothermic reaction can be controlled excellently in a fused salt reactor. Propane and nitric acid, which react to form nitroparaffins, were bubbled up through the fused salt. Temperature control was much better than previously experienced in tubular reactors. Heat transfer to the fused salt was obviously excellent. Studies now in progress are being made to determine heat transfer coefficients from the fused salt to the gas bubbles.

## Plant Cooling

Cooling towers also involve simultaneous heat and mass transfer. Tips and suggestions on various aspects of cooling tower design are given by Brooke (3), Whitesell and Durando (43), Gutzwiller (15), and Gras (2). Cooling water filters are reported by Forbes (13) to save money in many cases. Dust, bugs, and other debris from the cooling tower or pond tend to foul up the equipment and may cause costly shut-downs if they are not removed.

Air *versus* water cooling for a plant is discussed by Weatherby (41). If water is scarce or of poor quality, air cooling may be preferred. Air cooling gives the advantages of high salvageability or portability to a plant. An example is the Adena Plant in Colorado. Air is used to cool the process equipment directly or to cool oil streams which are used as heat transfer media. Since insufficient cooling water is available in many sections of this country, more air-cooled plants will probably be built.

## Conclusions

Numerous new heat transfer developments have been reported in the last few years. These developments are useful for a better understanding of the basic theory and for developing improved equipment. In many cases both heat and mass transfer occur simultaneously in commercial operations.

### NOMENCLATURE

| | |
|---|---|
| A | area of heat transfer |
| h | film coefficient often expressed as B.T.U./hr., sq. ft., °F. |
| k | thermal conductivity often expressed as B.T.U./hr., sq. ft., °F./ft. |
| Q | heat transfer often expressed as B.T.U./hr. |
| T | absolute temperature |
| v | velocity of fluid |
| x | distance |
| $\sigma$ | Stefan-Boltsmann constant for radiation |

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# Pumps and Compressors

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IN MOST OIL PROCESSING and chemical plants, progress would stop almost completely if it were not for pumps and compressors which maintain fluid flow through the equipment. The number and types of pumps used are almost endless, and recent developments in pumping are numerous. Within the last few years many studies have been made in the nuclear and aeronautical fields to develop pumping devices for liquids at high temperatures, such as molten metals and salts, and for air at fairly low pressures (63, 64, 65). In most cases those studies will not be of immediate value to the oil processing industry although they do give a better understanding of pump theory and operation.

A concentrated effort is now being made to standardize pumping equipment in the chemical industry. The subcommittee on pumps for the American Institute of Chemical Engineers (68) prepared and circulated a questionnaire to pump users. Most of the users were satisfied with the pump performances based on water, but a majority thought there was a need for more data for viscous fluids. Although most users indicated the present pumps were in general satisfactory, they voiced a need for specific improvements. It is estimated (5) that pump standardization will save the chemical industry $6,800,000 a year. Undoubtedly some of the dissatisfaction with the present pumps results from incorrect and inadequate pump selections. The correct choice of a pump for a particular problem is far from easy since many variables must be considered (27). A complete list of process specifications should be prepared and should include fluid characteristics, inlet and outlet pressures, flexibility of operations desired, etc. (36). The scaling up of pump sizes remains a problem. Mitchell (39) indicates that a type of pump satisfactory in the pilot plant is not always so in the full-size plant. In scaling up the pump size, the pump characteristics often change. Hutton (23) reports however that model tests are satisfactory for determining the efficiencies of some large-scale pumps and turbines. The pump manufacturers are attempting to improve their product and service (41). Standardization of pump designs will be expensive to the manufacturer, but the trend appears to be in that direction.

A brief survey was made of the various types of pumps and compressors that are of particular interest in the oil processing industry. New developments are also outlined.

## Pumps for Liquids

*Reciprocating Pumps.* Reciprocating pumps are one type of "positive displacement" pumps (7, 47). The basic design consists of a piston, plunger, or bucket that passes back and forth in a cylinder and displaces the fluid in the cylinder. Reciprocating pumps have been designed that are satisfactory for viscous liquids, but in general they are not. A power-driven reciprocating pump gives uniform fluid delivery over wide ranges of pressures. A steam-driven pump has high efficiencies over a wide range of operating conditions and has flexibility of capacity, head, and speed. Disadvantages of reciprocating pumps include high first cost, large floor requirement, noisy operation, and relatively high maintenance costs.

Within the last few years numerous pilot plants have been built and used for exploratory studies of reaction rates and mechanisms at high pressures. Pumping has proven to be one of the bottlenecks in these plants. Sheen and Fell (53) describe a reciprocating pump that will deliver 3–3,000 ml./hr. of fluid at 0–1,000 p.s.i. Jones (29) describes a pump to obtain fluid pressures of 10,000–30,000 p.s.i. The vol-