infinite. The flow within the boundary layer immediately downstream from the leading edge will be laminar, and is called *laminar forced convection*. As the flow proceeds along the plate, the laminar boundary layer increases in thickness until a critical value is reached. Then, turbulent eddies develop within the boundary layer, except for a thin *laminar sublayer* adjacent to the plate. The boundary layer beyond this point is referred to as a *turbulent boundary layer* and the flow is termed *turbulent forced convection*. The region between the breakdown of the laminar boundary layer and the establishment of the turbulent boundary layer is called the *transition region*. Since the turbulent eddies greatly enhance the transport of heat into the main stream, the heat transfer coefficient begins to increase rapidly through the transition region. For a flat plate with a smooth leading edge, the turbulent boundary layer starts at Reynolds numbers, based on distance from the leading edge, of about 300,000 to 500,000. For blunt-edged plates, it can start at much smaller Reynolds numbers.

For flow in long tubes or channels of small hydraulic diameter, the laminar boundary layers on each wall will grow until they meet, provided the velocity is sufficiently low. Beyond this point the velocity distribution will not change and no transition to turbulent flow will take place. This is referred to as *fully developed laminar flow*. On the other hand, for tubes of large diameter or at higher velocities, transition to turbulence will take place and *fully developed turbulent flow* will be established as shown in Fig. 3. Therefore, the length dimension which determines the critical Reynolds number is the hydraulic diameter of the channel. For smooth circular tubes, flow is laminar for Reynolds number below 2100 and turbulent above 3000.

The forced convection correlations are presented in Table 6. As indicated by the generalized, dimensionless formula

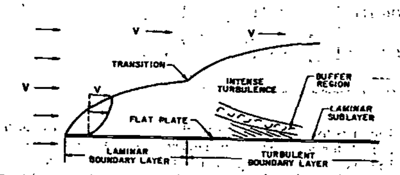

Fig. 2 . . . Boundary Layer Build-up on a Flat Plate (Vertical Scale Magnified)

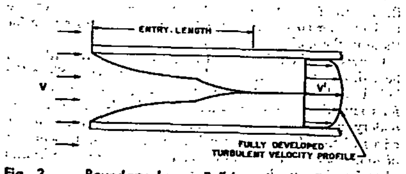

Fig. 3 . . . . Boundary Layer Build-up in the Entry Length of a Tube or Channel

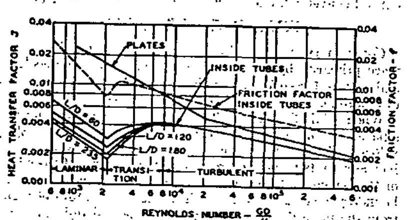

Fig. 4 . . . . Typical Dimensionless Representation of Forced Convection Heat Transfer

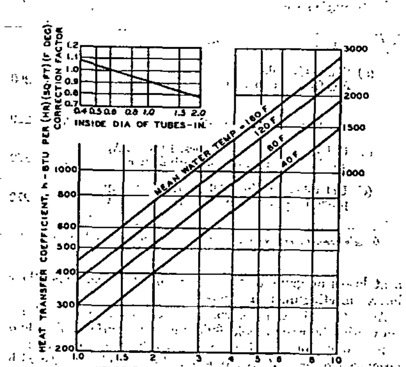

Fig. 5 . . . . Heat Transfer Coefficient for Turbulent Flow of Water in Tubes

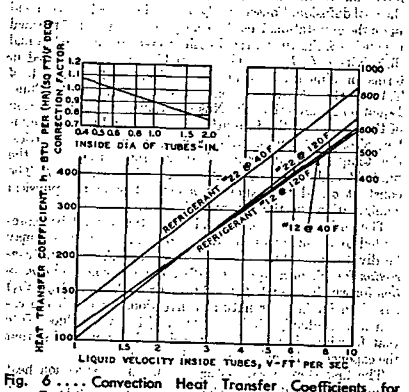

Fig. 6 . . . . Convection Heat Transfer Coefficients for Turbulent Flow of Liquid Refrigerants 12 and 22 in Tubes

given by Equation 1 of Table 6, the heat transfer is determined by the flow conditions, as indicated by the Reynolds number, and by the fluid properties, as indicated by the Prandtl number. Equation 1 of Table 6 may be modified to the form given by Equation 4 (Table 6) so as to present the *heat transfer factor*, j. The heat transfer factor is related to the *friction factor* f, due to the interrelationship between the transport of momentum and heat, and approximately equals $f/2$ for turbulent flow in straight ducts. These factors are plotted in Fig. 4.

The characteristic length d is the diameter of the tube, outside or inside, or the length of the plane plate. For other shapes, the hydraulic diameter D_e, is used, where $D_e = 4r_h = 4$ (cross-sectional area for flow)/(total wetted perimeter). This reduces to twice the distance between surfaces in the case of parallel plates or an annulus.

For convenience, a number of simplified equations applicable to common fluids under normal operating conditions have been presented in Equations 8 to 24 of Table 6. Graphical solutions for water and liquid refrigerants appear in Figs. 5 and 6. An excellent introduction to the theoretical foundations of forced convection heat transfer will be found in Reference 12.

BOILING

Heat transfer by boiling occurs in a wide variety of refrigeration equipment. Examples are flooded shell-and-tube evaporators, where refrigerants boil outside bundles of plain or finned horizontal tubes, flooded vertical or inclined tube evaporators, where boiling occurs inside tubes, and dry expansion evaporators, where the refrigerant flows inside tubes and is vaporized completely before being recirculated. A detailed description of various types of evaporators may be found in Chapters 34 and 43.

Forms of Boiling

Boiling from a submerged heated surface with movement of the liquid generated by free convection or the stirring action of bubbles is called *pool boiling*. Boiling on a surface past which liquid flows with a significant velocity is called *forced convection boiling*. If the bulk liquid is at or near the boiling point, vapor generated at the heated surface will move through the liquid and be released at the liquid interface. However, if the bulk liquid is below the boiling point, the

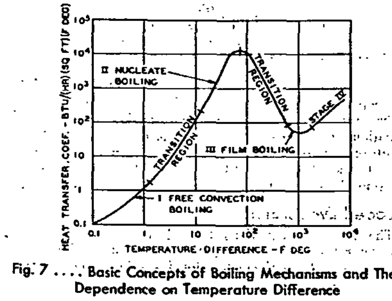

Fig. 7 . . . . Basic Concepts of Boiling Mechanisms and Their Dependence on Temperature Difference

vapor bubbles generated at the heated surface will recondense in the liquid. The former process is called *boiling with net evaporation*; the latter is termed *subcooled*, *surface*, or *local boiling*. The discussion which follows deals only with boiling with net evaporation.

As originally described by Nukiyama,[20] and later elucidated by Drew and Mueller,[21] boiling may take place in several radically different forms. The forms or regimes of boiling depend primarily on the difference, Δt, between the surface temperature and the boiling temperature of the fluid, as illustrated in Fig. 7 for pool boiling of water. When Δt is very small, the liquid in contact with the warmer surface becomes slightly superheated and rises to the liquid-vapor interface, where the evaporation takes place. This is called *natural convection boiling*. When Δt increases, the familiar form of bubble formation takes place. The bubble formation, and fluid agitation due to the movement of bubbles, result in high heat transfer coefficients. Since this is based primarily on the nuclei on which bubbles are formed, it is called *nucleate boiling*. The coefficient increases rapidly with Δt until a limit is reached, called the *critical temperature difference*. Beyond this, the coefficient is actually reduced by further increases of Δt. The third form of boiling, called *film boiling*, occurs when the temperature difference is so large that either the surface or the drops of fluid are covered by a vapor film, causing vapor binding. The coefficient continues to decrease in spite of increasing Δt, until a lower limit is reached. In the fourth stage, radiation heat transfer from the film becomes significant, and the coefficient again increases with Δt. The change from one form of boiling to another is generally separated by a transition region where both forms are mixed.

The heat flux corresponding to the critical Δt is sometimes called the *peak heat flux* or *burnout flux*. From Fig. 7, it can be seen that if the energy input to the heated surface is increased beyond this peak value, there will be a sudden transition from the nucleate boiling to film boiling regime, and a corresponding jump in surface temperature. The term *burnout* originates from the fact that, with water boiling at atmospheric pressure, this jump in surface temperature can carry most common metals past their melting point. The critical Δt for water is about 45 F, for *i*-propanol about 80 F, and for *n*-butanol about 70 F.[8] It is unknown for most refrigerants.

Natural Convection Boiling

When the temperature difference between the heated surface and the liquid is low, heat transfer takes place by natural convection since few, if any, bubbles are generated. As a consequence, correlations of experimental data in this regime are based on equations of the form of Equation 1, Table 5. Equations 1 and 2 of Table 7, for heat transfer from submerged vertical and horizontal surfaces, are based on the experiments of King and others conducted at atmospheric pressure. Simplified equations for Refrigerants 12 and 22 outside a submerged horizontal tube,[22] and water from a horizontal plate, are given in Equations 3, 4, and 5, Table 7.

Nucleate Boiling

For nucleate boiling, factors affecting bubble formation, growth, detachment from the surface, and rise through the liquid will influence heat transfer rates. Bubbles originate from cavities on the heated surface. The initial bubble diameter, which equals the diameter of the cavity from which it originates, can be estimated from Equation 6, Table 7. When the buoyant forces on the bubble exceed the adhesive force