



WOLVERINE TUBE HEAT TRANSFER DATA BOOK

5.1. Trufin in Boiling Heat Transfer

Boiling is the formation of vapor bubbles at the heating surface. These bubbles form at nucleation sites whose number and location depend upon the surface roughness or cavities, fluid properties, and operating conditions. The boiling heat transfer coefficient is very sensitive to the temperature difference between the surface and the liquid. In addition, the heat transfer coefficient is affected by the local vapor-liquid mixture ratios and velocities, which are a function of the vaporizer design and operating conditions. The complex interaction of all these variables makes the accurate prediction of a boiling coefficient virtually impossible, but in large commercial vaporizers the two-phase flow heat transfer becomes controlling and reduces the number of variables.

In this section these variables will be discussed and some references given with the aim of providing the engineer an understanding of these factors that affect design of vaporizers. Also some design principles to allow him to produce a vaporizer design will be given. In general, the philosophy of design is that of a designer of process vaporizers.

5.1.1. Pool Boiling Curve

If a heating surface is immersed in a pool of liquid that is at the boiling point and the surface temperature is slowly increased, then a plot of the heat flux and the derived heat transfer coefficient versus the temperature difference between the heating surface and the liquid boiling point results in a curve as shown in Fig. 5.1.

For the present we are considering a single component liquid; mixtures will be discussed later. Up to the point A or A', heat transfer occurs by natural convection and no bubbles are seen. The liquid pool is superheated and evaporation occurs at the liquid-vapor interface. At point A or A', the local superheat is sufficient to activate nucleation sites on the heating surface and vapor bubbles are formed.

The very rapid, almost explosive, formation of the bubbles causes a very strong local velocity within the liquid film and increases heat transfer. In the region from A to B (A' to B') more bubble nucleation sites are activated and this is the region of nucleate boiling. At point B on the heat flux curve (defined as the critical temperature difference also called the departure from nucleate boiling, DNB, or the bum-out point) the heat flux decreases with a further increase of the surface temperature. Note that point B does not correspond to point B' on the coefficient curve but is at the ΔT where the slope of

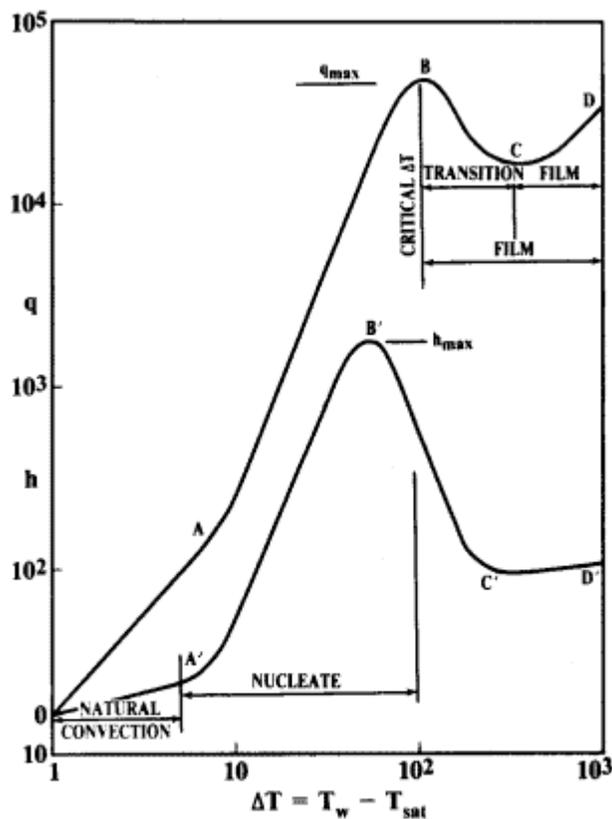


Fig. 5.1 Typical Pool Boiling Curve for Single Component Liquids



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the h vs. ΔT curve is -1. Several phenomena are occurring as one approaches point B and passes it into the B to C region. The numerous nuclei and the rapid evolution of vapor prevent the liquid from approaching the surface and thus starve the surface of liquid, which was defined by Zuber (1) as a hydrodynamic crisis phenomenon. However, just beyond B after a short transition zone, film boiling occurs. Happel and Stephan (2) have also observed and reported the formation of continuous vapor films well before the minimum heat flux, point C.

In film boiling a continuous layer of vapor covers the heating surface and keeps the liquid from contacting the surface. The insulating effect of the vapor reduces the rate of heat transfer and the coefficient. As the temperature difference increases, the vapor film becomes thicker and eventually reaches a maximum thickness somewhere near point C' and then the coefficient slowly increases due to the effect of radiation and perhaps further convection effects within the vapor film. The transition from nucleate to film boiling involves a zone where the rapid vapor evolution blankets the tube with a rough vapor-liquid interface that pulsates and occasionally collapses thus wetting the tube.

However, as the ΔT is further increased this film becomes smooth and stable but the heat flux is less. The extent of this transition seems to depend upon its definition. Many references define the transition to be between the maximum, B, and the minimum heat flux, C, points as shown by the upper arrows in Figure 5.1. However, some experiments (2,3) have seen stable films well before the minimum flux, C, is reached.

Film boiling appears to be closely related to the Leidenfrost effect. This phenomenon was first described by Leidenfrost in 1756 and bears his name. He noted that when liquids were spilled or placed on very hot surfaces, drops were formed which did not contact the surface but floated above the surface and slowly evaporated. However, when the surface temperature was reduced below a certain temperature the drops contacted the surface and rapidly evaporated. The Leidenfrost phenomenon has undergone several periods of intense experimentation and neglect but references to the early literature are found in [references 3 and 4 and more recent work in references 5, 6 and 7]. As noted by Drew and Mueller (3) the temperature differences for the Leidenfrost effect and the boiling critical temperature difference seemed to be closely related. Hence, the actual maximum flux, point B, may be governed by both the hydrodynamic and the film boiling effects. However, film boiling can occur without ever entering the nucleate boiling region as for example in the quenching of metals.

From a practical standpoint only the A-B portion of the curve is of interest as operation in the B-C region results in excessive surface temperatures. However, there are occasions when film boiling is unavoidable as in the vaporization of low boiling liquids or in cryogenic vaporizers. The deliberate use of film boiling in attempting to reduce fouling or corrosion has been suggested but is impractical due to variation of operating conditions during start up or shut down and the fluctuations of the film in the transition region.

The start up procedure of a vaporizer can affect its subsequent operation whenever the temperature of the heating medium would correspond to a temperature difference greater than the critical ΔT or point B. If the heating source is applied before any liquid is in the vaporizer, then the tube surface temperature, T_w , will reach the medium (steam) temperature, T_s , since no heat transfer is occurring. Then when the liquid is fed to the vaporizer, boiling would begin in the film or B-C region; i.e., $(T_s - T_{sat}) > \Delta T_c$. However, if the vaporizer is full of liquid when the steam is turned on, then the wall temperature starts at the liquid temperature and rises on the A-B portion of the curve until at equilibrium the wall temperature, T_w , corresponds to a temperature less than point B and the temperature difference, $T_s - T_w$, results from the heating medium resistance, fouling resistance, and tube wall resistance. Hence, whenever $T_s > (T_{sat} + \Delta T_c)$ then the liquid should be in the vaporizer for a cold start up. In normal operation the wall temperature, T_w , would be less than $T_{sat} + \Delta T_c$ due to other resistances.



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5.1.2. Nucleation

Nucleation can be either homogenous (occurring within the liquid) or heterogeneous (occurring at a liquid-solid interface). The nucleation phenomenon has been extensively studied both theoretically and experimentally and even a brief review of all the factors involved is beyond the scope of this manual. Cole (8) has an excellent review of nucleation and considerable information is also available in (9, 10, 11). Very briefly, due to the surface tension forces we have across the interface of a spherical bubble

$$P_{sat} - P_\ell = 2\sigma / r_c \quad (5.1)$$

where P_{sat} is the saturation pressure of the vapor and P_ℓ the liquid pressure, σ the surface tension and r_c the radius of curvature of the bubble. Through the vapor pressure curve for a fluid, these pressures can be related to a superheat in the liquid in order to maintain a bubble of radius, r_c , at equilibrium. The superheat for homogenous nucleation is very large and is difficult to obtain in the presence of surfaces. In thermodynamic equilibrium theory the isotherms on a P-V diagram go through a minimum, $(\partial P / \partial V)_T = 0$, at a liquid superheat which is taken as a homogenous nucleation temperature. In kinetic theory there is a probability that a sufficient number of molecules with greater than average energy can join to form a cluster with an equilibrium radius. The resulting kinetic theory equation for superheat is

$$T - T_{sat} = \left(\frac{T_{sat} v_{lv}}{\lambda} \right) \left(\frac{\rho_\ell}{\rho_\ell - \rho_v} \right) \left(\frac{16\pi \sigma^3}{3kT \ln(nkT / hJ)} \right) \quad (5.2)$$

In this equation k is the Boltzmann constant and h the Planck constant. The heterogeneous nucleation requires less superheat and is in addition a function of the angle of contact between the vapor and solid. Cole (8) has shown the above equation can be modified to

$$T - T_{sat} = \left(\frac{T_{sat} v_{lv}}{\lambda} \right) \left(\frac{\rho_\ell}{\rho_\ell - \rho_v} \right) \left(\frac{16\pi \sigma^3 f(\theta)}{3kT \ln(nkT / hJ)} \right)^{1/2} \quad (5.3)$$

where the function of $f(\theta)$ is a factor involving the bubble contact angle θ . This contact angle is affected by the wettability of the surface, shape of the surfaces (pores etc.) local temperature gradients, etc. Although an excellent understanding of the factors involved in nucleation has been developed it is of little use in the design of vaporizers. This is due to the inability to manufacture and know in advance all the surface characteristics, to control the changes in surface during operation due to corrosion and fouling, and the effect of dissolved gases, mixtures, and solids upon the physical properties of the liquid especially with the local temperature and concentration gradients that will exist around a developing bubble. Further, the effectiveness of nucleation in improving heat transfer decreases as two-phase flow becomes the dominant factor. Figure 5.2 shows how sensitive the boiling flux is to surface conditions and how this surface can change during operation.



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Improving the nucleation characteristics of a surface has the effect of moving the curves of Figure 5.1 to the left but has little effect on the maximum heat flux at point B. The net result is a higher heat transfer at a given temperature difference or for a given heat flux, a lower temperature difference. These results become important when the available temperature differences are small or become very important as in cryogenic services where power consumption is closely related to ΔT .

Special proprietary surfaces have been developed and are commercially available (12), as well as mechanically formed surfaces including Trufin. These surfaces can substantially reduce the superheat required for nucleation and increase the heat transfer coefficients by factors of 3 to 10. The relative effectiveness of these surfaces can change for different fluids depending upon how well the specific surface characteristics (pore size and distribution, surface wettability, etc.) can be matched to the fluid characteristics. However, these surfaces must be used with care so that their effectiveness is not destroyed by fouling, corrosion, or accumulation of high boiling residues.

5.1.3. Nucleate Boiling Curve

The nucleate boiling curve is considered to start at point A of Figure 5.1 and ends at point B. This portion of the boiling curve has a very steep slope ranging from 2 to 4 and for the heat transfer coefficient, $h = a \Delta T^m$. Observations of boiling shows that as the temperature difference, ΔT , is increased more nuclei are activated; however, eventually when the nuclei spacing is less than the bubble diameter the effectiveness of additional nuclei should diminish. So far a theoretical proof of why the exponent, m , should be so high has not been made. Studies of bubble diameters and frequencies, heat transfer under the developing bubble and the pumping action of the bubbles in carrying away the superheated liquid from the film layers (9,10) have only partially explained the heat transfer in nucleate boiling.

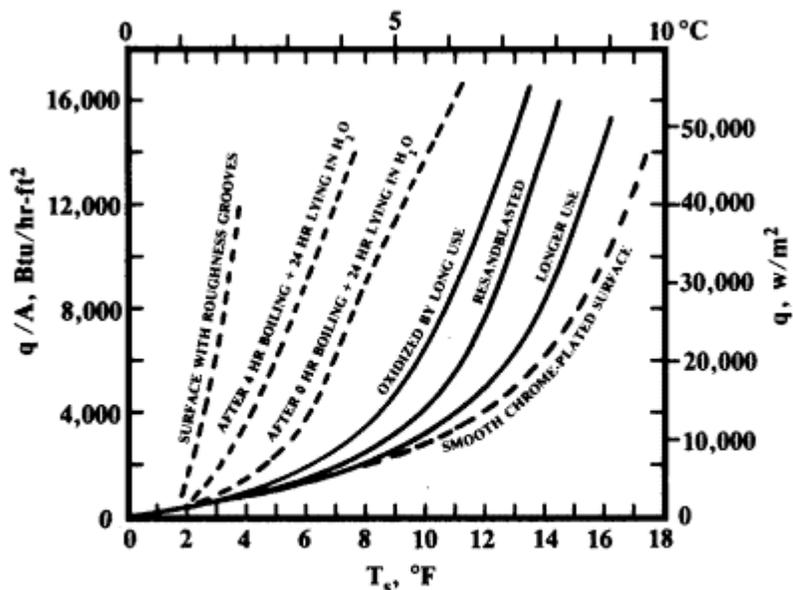


Fig. 5.2 Effect of surface conditions and exposure on nucleate boiling [11].

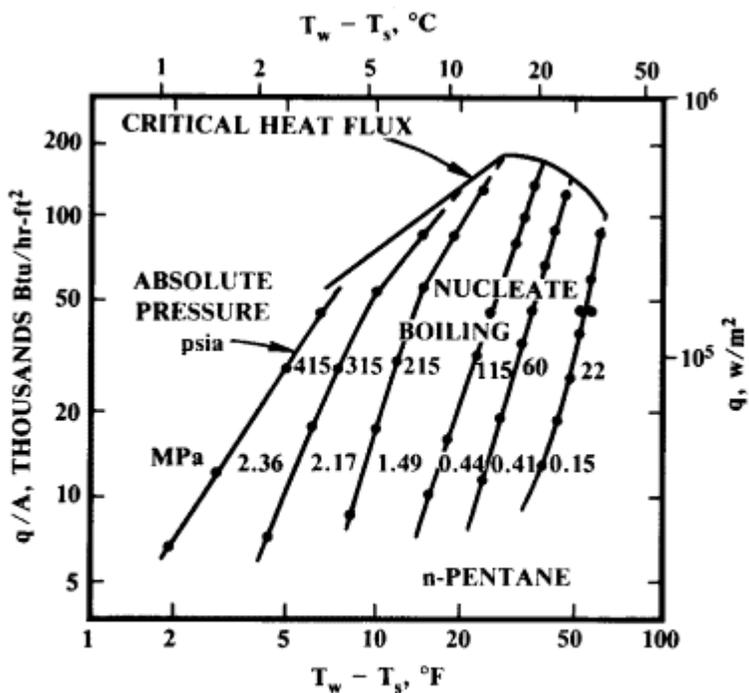


Fig. 5.3 Effect of pressure on boiling curve of n-pentane [13].



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The position of the A-B section of the boiling curve can be shifted to the left or right by changes in the surface characteristics, surface tension, pressure, dissolved gases or solids, or high boiling components in a mixture. As shown in Figure 5.2 any changes in surfaces affecting the nucleation properties of surfaces, changes the A-B curve, and the effect of pressure on the nucleate curves is shown in Figure 5.3.

In binary mixtures where both components can be vaporized, the boiling curves for mixtures usually lie between those of the pure components. With mixtures, the effect of mass diffusion, local concentration gradients caused by the greater evaporation rate of the more volatile component and the resultant effects on the physical properties of the mixture as well as changes in interface saturation temperatures during bubble growth all influence the boiling curves. If one of the components has a very high boiling point so that it is essentially non-volatile, then the effect of increasing its concentration is to shift the curve A-B to the right reducing the coefficient. Further, the accumulation of the high boiler in the nuclei cavities can cause these to become inactive; hence, when certain special surfaces are used their effectiveness can be greatly reduced depending upon the ability of the circulating liquid to wash out the concentrated high boilers from these cavities.

5.1.4. Maximum or Critical Heat Flux

In Figure 5.1 point B is the maximum heat flux for the nucleate boiling regime. Theoretically higher fluxes can be obtained by proceeding along the C-D portion, the film boiling regime, of the curve to very high temperature differences. The above statements apply to single tube pool boiling only as maximum fluxes for boiling inside tubes or bundles are also experienced but are due to hydrodynamic conditions.

Several explanations have been made for the maximum heat flux, such as close packed nuclei forcing the liquid away from the surface and the non-wetting of the surface (the Leidenfrost effect). It is possible that both explanations may be simultaneously involved. The maximum flux is a function of pressure and also goes through a maximum as was first shown by Cichelli and Bonilla (13) in Figure 5.4.

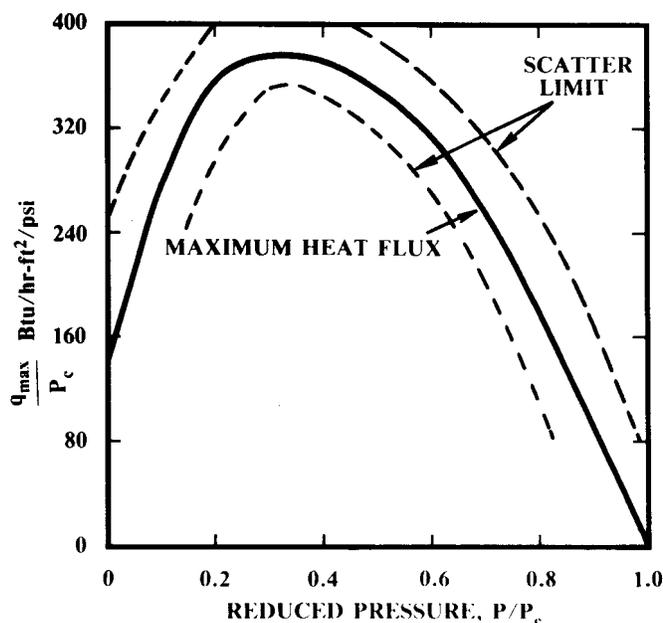


Fig. 5.4 Effect of pressure on maximum heat flux for pure liquids.

Based on models assuming force balances (14) the following equation for non-metallic liquids was derived with the constant determined empirically:

$$\frac{q_{\max}}{\rho_v \lambda} = 0.18 \left[\frac{\sigma(\rho_l - \rho_v) g g_c}{\rho_v^2} \right]^{1/4} \quad (5.4)$$

However since many physical properties can be related to the critical pressures, P_c , Mostinski (15) derived the following simple expression



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$$\frac{q_{\max}}{P_c} = 803(P_r)^{0.35}(1 - P_r)^{0.9} \quad (5.5)$$

The above equation implies the maximum flux goes to zero at the critical pressure; nevertheless, experiments (16) show there is still a similar effect at supercritical pressures due in part to local density differences as a result of local temperature variations.

The maximum flux is somewhat influenced by the heating surface orientation and shape; also some surface effects are seen but in general small changes in surface characteristics do not greatly affect the maximum. Mixtures and the presence of non-volatile liquids can also affect the maximum flux. However, these effects are unpredictable and are neglected in equipment design.

5.1.5. Film Boiling

In fully developed film boiling the vapor blankets the heating surface in a smooth continuous film except where the generated vapor escapes from the film in very large bubbles. If the heating surface is vertical and extends through the liquid level, the vapor can escape from the ends of the annular spaces and bubbles may not be generated. There is a transitional region between nucleate and film boiling where the surface is essentially enveloped by the vapor but the interface is rough, tends to fluctuate, and the liquid may occasionally touch the surface for a brief period. This transition occurs in the B-C portion of the curve of Figure 5.1. Depending upon the investigator's definition of film boiling, it can be defined as starting in the B-C portion of the curve or starting at the minimum point C.

In fully developed film boiling no effect of surface finish is seen, Figure 5.5. The effect of mixtures, especially those containing non-volatile liquids, does not seem to have been published. In solutions containing dissolved solids, it is difficult to get to the fully developed film region due to rapid fouling of the surface.

While film boiling heat transfer is reasonably predictable (18) and it may appear to have some advantages (e.g., corrosion, or fouling by dissolved solids), it is largely avoided because of the high temperature differentials involved. With the high costs of energy, such wastage of temperature potential is uneconomical. Further, the implied advantages are likely to be illusionary. However, there are occasional instances, such as in cryogenic services or certain low boiling chemicals, where film boiling may be unavoidable due to plant constraints on heating sources.

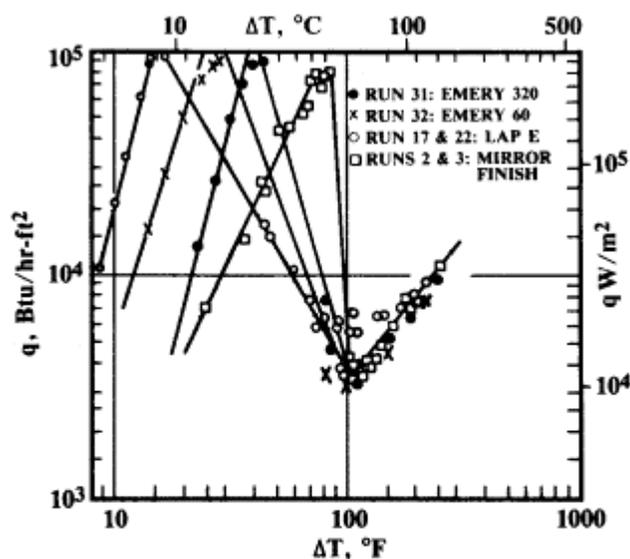


Fig. 5.5 Roughness effect on boiling pentane. [Data by Berenson (17) as given by Rohsenow in *Handbook of Heat Transfer*, W. M. Rohsenow and J. P. Hartnett eds., McGraw-Hill Book Co. New York 1973].



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5.1.6. Boiling Inside Tubes

Although boiling inside tubes may also be in nucleate or film boiling regimes, there are additional factors involved because the vapor and liquid must travel together through the tube. Both heat transfer and pressure drop are, therefore, affected by the pattern of the resulting two phase flow, which because of the evaporation of liquid, changes along the tube. Depending upon the fraction vaporized several different flow regimes are possible, Figure 5.6. For total evaporation in a circulating system the pressure drop through the tube causes an increase in the local boiling point with reference to the pressure existing at the tube outlet; hence, there will be a liquid heating zone at the inlet. When the local tube surface temperature is sufficiently superheated with reference to the local pressure then bubbles will form at the tube surface nuclei and the regimes governed by the nucleate boiling coefficients. As the two-phase mixture accelerates, the two-phase heat transfer can dominate. Depending on tube orientation, a two layer segregated regime (horizontal tubes) or a slug flow (vertical) regime can form which upon further evaporation will develop into an annular flow regime. When the vapor fraction is very large, greater than 60% by weight, a mist flow regime develops and the surface becomes dry and heat transfer is again a convective form but now forced convection to a vapor. The vapor tends to superheat and then evaporate the entrained droplets. If the tube wall temperatures are high enough, a film boiling regime may also occur. Note that in this case an inverted annular flow takes place with an annular vapor film surrounding a liquid core.

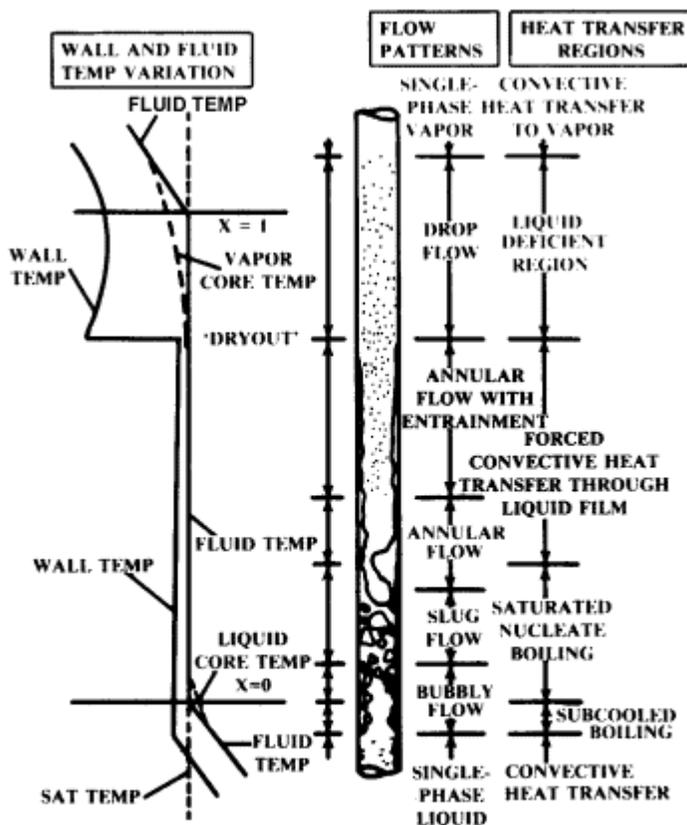


Fig. 5.6 Boiling inside vertical tubes: flow patterns, heat transfer regions, and wall and fluid temperatures, Collier [26].

The overall performance of a tube may also show a maximum heat flux effect similar to the A-B-C portion of the boiling curve in Figure 5.1. However, the maximum flux may be caused by: (a) film boiling, (b) high vapor fractions producing the dry wall regime, or (c) a hydrodynamic instability resulting in surging and unsteady flow through the tube. This latter, (c), effect is a result of the characteristics of the two-phase flow pressure drop curves as a function of the vapor fraction showing maximum and minimum points. Consequentially the instability limit, (c), is a function of the pressure drops in the entire flow circuit loop.

5.1.7. Subcooling and Agitation

All of the above discussion for both pool and in-tube boiling was based on the liquid feed being at the vapor saturation temperature.



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If the liquid pool is subcooled, the heat transfer to the liquid will be a natural convection coefficient if the tube wall temperature is too low to activate the nuclei. Once the nuclei are activated, heat transfer is high as in nucleate boiling but the bubbles rapidly collapse as they penetrate the liquid film on the surface or after the bubbles depart from the surface. This is defined as incipient boiling. Heat transfer coefficients, however, quickly approach those for saturation nucleate boiling.

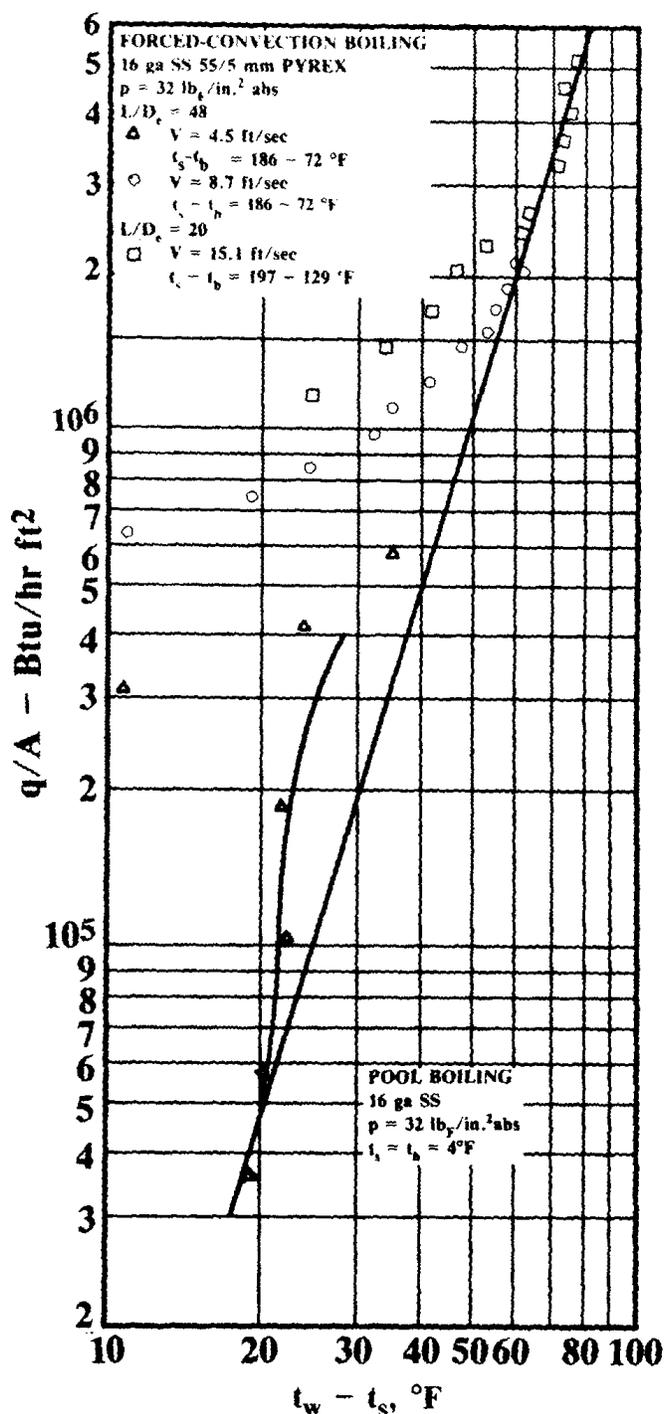


Fig. 5.7 Forced convection boiling and pool boiling [19].

Agitation in pool boiling (9) effects are shown in Figure 5.7. For in-tube forced convection, heat transfer follows the convective curve until nucleation begins and the nucleate boiling curve is followed, Figure 5.8. This figure also shows that surface finish has very little effect in the coefficients.

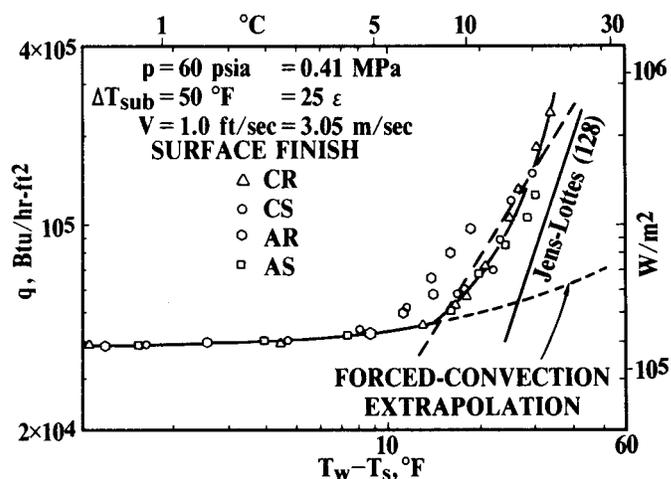


Fig. 5.8 Surface finish effect on force convection boiling. [Data by Brown (20) as given by Rohsenow in *Handbook of Heat Transfer*, W. M. Rohsenow and J. P. Hartnett, eds., McGraw-Hill Book Co. New York, 1973] boiling.