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BOILING & CONDENSATION

1. INTRODUCTION

Boiling and condensation are vital links in the heat transfer of heat from a hot to a colder region in countless applications, e.g., thermal and nuclear power generation in steam plants, refrigeration, refining, heat transmission, etc.

When a liquid at saturation temperature is in contact with the surface of a solid (usually metal) at a higher temperature, heat is transferred to the liquid and a phase change (evaporation) of some of the liquid occurs. The nature and rate of this heat transfer changes considerably as the temperature difference between the metal surface and the liquid is increased.

Although *boiling* is a process familiar to everyone, the production of vapour bubbles is a very interesting and complex process. Due to surface tension, the vapour inside a bubble must be at a higher pressure then the surrounding liquid. The pressure difference increases as the diameter of the bubble decreases, and is insignificant when the bubble is large. However, when the bubble is minute, antimony appreciable pressure difference exists. (An analogy may be drawn with the inflation of a cylinder of a child's balloon - it is difficult to inflate when the balloon is small, but it becomes much easier as the diameter increases).

The pressure inside a bubble is the vapour pressure corresponding with the temperature of the surrounding liquid. Thus, when no bubbles exist (or are very small) it is possible for the liquid temperature in the region of the heat transfer surface to be well above the temperature of the bulk of the liquid. (This will be close to the saturation temperature corresponding with the pressure at the free liquid-vapour interface). The formation of bubbles normally associated with boiling is influenced by the foregoing.

Pool boiling is convenient to observe and understand the principal regimes of boiling. Pool boiling refers to the type of boiling experienced when the heating surface is surrounded by a relatively large body of fluid which is not flowing at any appreciable velocity and is agitated only by the motion of the bubbles and by natural-convection currents. Two types of pool boiling are possible: *subcooled pool boiling* and *saturated pool boiling*.

The general shape of the curve relating the heat transfer coefficient to ΔT_b, the temperature driving force (difference between the wall temperature and the bulk fluid temperature) is one of the few parametric relations that are reasonably well understood. The familiar boiling curve was originally demonstrated experimentally by *Nukiyama* [1]. This curve points out one of the great dilemmas for boiling equipment designers.

The regimes in pool boiling are natural convection, nucleate boiling, transition boiling and film boiling. In the transition to film boiling region, heat transfer rate decreases with driving force. The regimes of greatest commercial interest are the nucleate boiling and stable film boiling regimes [2].

2. THEORY

The boiling liquid may be contained in a vessel equipped with a heating surface fabricated from horizontal or vertical plates or tubes, which supplies the heat necessary to boil the liquid. Or the liquid may flow through heated tubes, under either natural or forced convection, and the heat is transferred to the fluid through the walls of the tubes.

When boiling is accomplished by a hot immersed surface, the temperature of the mass of the liquid is the same as the boiling point of the liquid under the pressure existing in the equipment. Bubbles of vapour are generated at the heating surface, rise through the mass of liquid, and disengage from the surface of the liquid. Vapour accumulates in a vapour space over the liquid; a vapour outlet from the vapour space removes the vapour as fast as it is formed. This type of boiling can be described as *pool boiling of saturated liquid* since the vapour leaves the liquid in equilibrium with the liquid at its boiling temperature.

When a liquid is boiled under natural circulation inside a vertical tube, relatively cool liquid enters the bottom of the tube and is heated as it flows upward at a low velocity. The liquid temperature rises to the boiling point under the pressure prevailing at that particular level in the tube. Vaporisation begins, and the upward velocity of the two phase liquid-vapour mixture increases enormously. The resulting pressure drop causes the boiling point to fall as the mixture proceeds up the tube and vaporisation continues. Liquid and vapour emerge from the top of the tubes at very high velocity.

With forced circulation through horizontal or vertical tubes the liquid may also enter at a fairly low temperature and be heated to its boiling point, changing into vapour near the discharge end of the tube. Sometimes a flow-control valve is placed in the discharge line beyond the tube so that the liquid in the tube may be heated to a temperature considerably above the boiling point corresponding to the downstream pressure. Under these conditions there is no boiling in the tube: the liquid is merely heated, as a liquid, to a high temperature, and flashes into vapour as it passes through the valve. Natural- and forced-circulation boilers are called *calandrias*.

In some types of forced-circulation equipment the temperature of the mass of the liquid is below that of its boiling point, but the temperature of the heating surface is considerably above the boiling point of the liquid. Bubbles form on the heating surface but on release from the surface are absorbed by the mass of the liquid. This type of boiling is called *subcooled boiling* [3].

2.1. Pool Boiling of Saturated Liquid

Consider a horizontal wire immersed in a vessel containing a boiling liquid. Assume that q/A, the heat flux, and ΔT_e, the difference between the temperature of the wire surface, T_w, and that of the boiling liquid T_{sat}, are measured. Start with a very low temperature drop ΔT_e. Now raise T_w and increase the temperature drops by steps, measuring q/A and ΔT_e at each step, until very large values of ΔT_e are reached. A plot of q/A vs. ΔT_e on logarithmic coordinates will give a curve of the type shown in Figure 1.

This curve can be divided into four segments. In the first segment, at low temperature drops, the line AB is straight and has a slope of 1.25. This is consistent with the equation (1).

$$\frac{q}{A} = a \cdot \Delta T_e^{1.25} \tag{1}$$

where a is a constant. The second segment, line BC, is also approximately straight, but its slope is greater than that of line AB. The slope of the line BC depends upon the specific experiment; it usually lies between 3 and 4. The second segment terminates at a definite point of *maximum heat flux*, which is point C in Figure 1. The temperature drop corresponding to point C is called the *critical temperature drop*, and the flux in point C is the *peak flux*. In the third segment, line CD in Figure 1, the flux decreases as the temperature drop rises and reaches a minimum at point D. Point D is called the Leidenfrost point. In the last segment, line DE, the flux again increases with ΔT and, at large temperature drops, surpasses the previous maximum reached at point C.

Because, by definition, $h = (q/A)/\Delta T$, the plot of Figure 1 is readily convertible into a plot of h vs. ΔT. This curve is shown in Figure 2. They do not, however, occur at the same values of the temperature drops as the maximum and minimum fluxes indicated in Figure 1. The coefficient is normally a maximum at a temperature drop slightly lower than that at the *peak flux*; the minimum coefficient occurs at a much higher temperature drop than that at the Leidenfrost point.

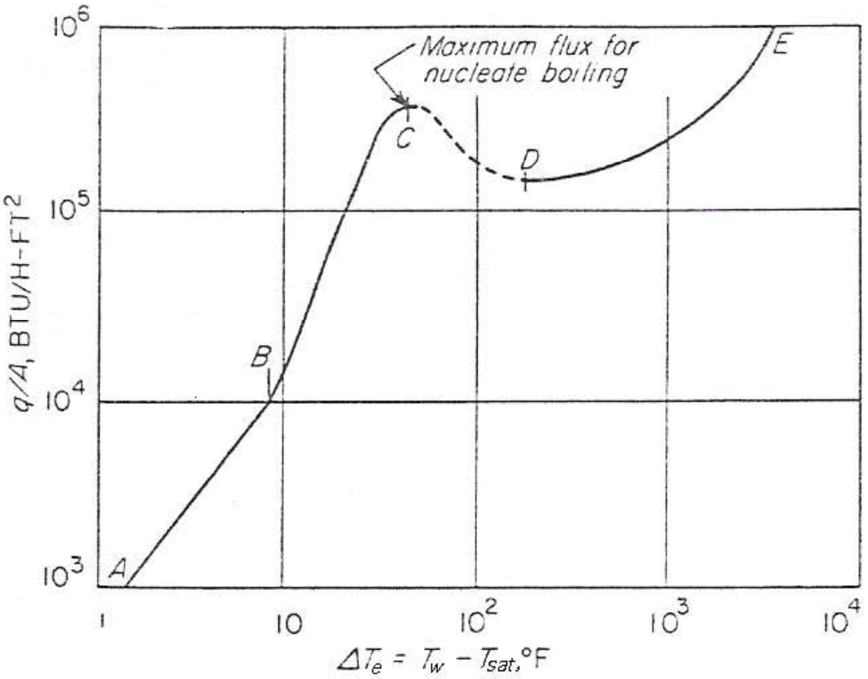

Figure 1. Heat flux vs. temperature drop, boiling water at 212°F on an electrically heated wire; AB, natural convection; BC, nucleate boiling; CD, transition boiling; DE, film boiling.

Each of the four segments of the graph in Figure 2 corresponds to a definite mechanism of boiling. In the first section, at low temperature drops, the mechanism is that of heat transfer to a liquid in *natural convection*. When the heating surface temperature is slightly hotter than the saturation temperature of the liquid, the excess vapour pressure is unlikely to produce bubbles. The locally warmed liquid expands and convection currents carry it to the liquid-vapour interface where evaporation takes place and thermal equilibrium is restored. Thus, in this mode, evaporation takes place at small temperature differences and with no bubble formation.

The action occurring at temperature drops below the critical temperature drop is called *nucleate boiling*, in reference to the formation of tiny bubbles, or vaporisation nuclei, on the heating surface. As the surface becomes hotter, the excess of vapour pressure over local liquid pressure increases and eventually bubbles are formed. These occur at nucleating points on the hot surface where minute gas pockets existing in surface defects form the nucleus for the formation of a bubble. As soon as a bubble is formed, it expands rapidly as the warmed liquid evaporates in on it. The buoyancy detaches the bubble from the surface and another starts to form. Nucleate boiling is characterised by vigorous bubble formation and turbulence. Exceptionally high heat transfer rates and heat transfer coefficients with moderate temperature differences occur in nucleate boiling, and in practical applications, boiling is nearly always in this mode.

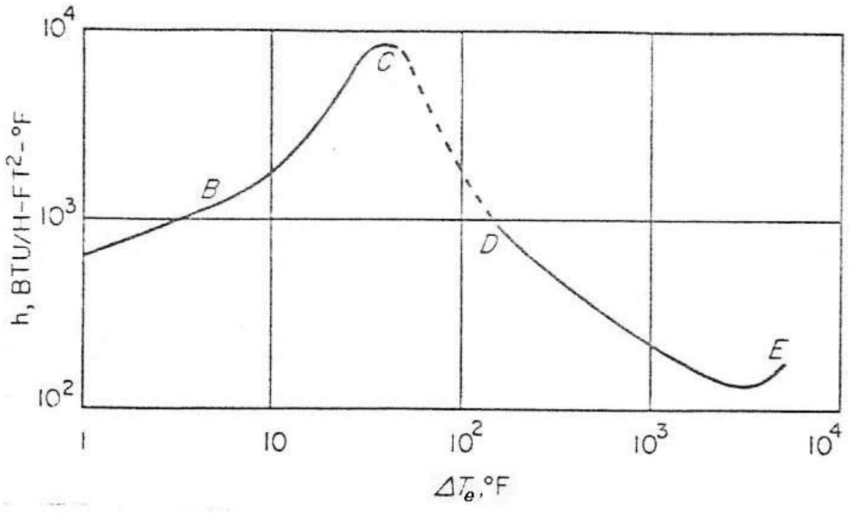

Figure 2. Heat transfer coefficient vs. ΔT, boiling of water at 1 atm.

Eventually, however, so many bubbles are present that they tend to coalesce on the heating surface to form a layer of insulating vapour. This layer has a highly unstable surface, from which miniature *explosions* send jets of vapour away from the heating element into the bulk of the liquid. This type of action is called *transition boiling*. In this region increasing the temperature drop increases the thickness of the vapour film and reduces the number of explosions that occur in a given time. The heat flux and heat transfer coefficient both fall as the temperature drop is raised.

Near the Leidenfrost point another distinct change in mechanism occurs. The boiling action in this region is known as *film boiling*. Above a critical surface-liquid temperature difference, it is found that the surface becomes *vapour-locked* and the liquid is unable to wet the surface. When this happens there is a considerable reduction in heat transfer rate if the heat input to the metal is not immediately reduced to match the lower ability of the surface to transfer the heat. The metal temperature will rise until radiation from the surface plus the limited film boiling heat transfer, is equal to the energy input. If the energy input is in the form of work (including electrical energy), there is no limit to the temperature which could be reached by the metal and its temperature can rise until a failure or a *burn out* occurs. If the source is radian energy from, for example, a combustion process, a similar failure can occur, and many tube failures in the radiant section of advanced boilers are attributed to this cause.

Film boiling is not usually desired in commercial equipment because the heat transfer rate is low for such a large temperature drop. Heat transfer apparatus should be so designed and operated that the temperature in the film of boiling liquid is smaller than the critical temperature drop.

The important factor in controlling the rate of bubble detachment is the interfacial tension between the liquid and the heating surface. If this interfacial tension is large, the bubble tends to spread along the surface and blanket the heat transfer area, as shown in Figure 3c, rather than leaving the surface to make room for other bubbles. If the interfacial tension between the liquid and the solid is low, the bubble will pinch off easily, in the manner shown in Figure 3a. An example of intermediate interfacial tension is shown in Figure 3b [3, 4].

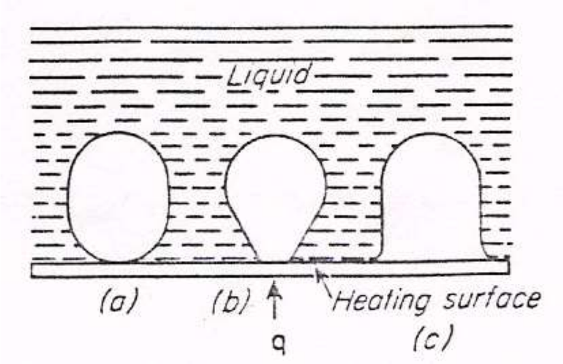

Figure 3. Effect on bubble formation of interfacial tension between liquid and heating surface.

2.2. Maximum Flux and Critical Temperature Drop

The maximum flux $(q/A)_{max}$ depends somewhat on the nature of the boiling liquid and on the type of heating surface but is chiefly sensitive to pressure. It is a maximum at an absolute pressure about one-third of the thermodynamic critical pressure P_c and decreases toward zero at very low pressures and at pressures approaching the *critical pressure*. If the maximum flux is divided by the critical pressure of the boiling substance, a curve is obtained, shown in Figure 4, which is about the same for many pure substances and mixtures. The corresponding *critical temperature drop* (not to be confused with *critical temperature*) also varies with pressure, from large values at low pressures to very small ones near the critical pressure. At pressures and temperatures above the critical values, of course, there is no difference between liquid and vapour phases, and *vaporisation* has no meaning. At atmospheric pressure the critical temperature drop for water is usually between 70 and 90°F (39 and 50°C); for common organic liquids it is often between 40 and 50°F (22 and 28°C).

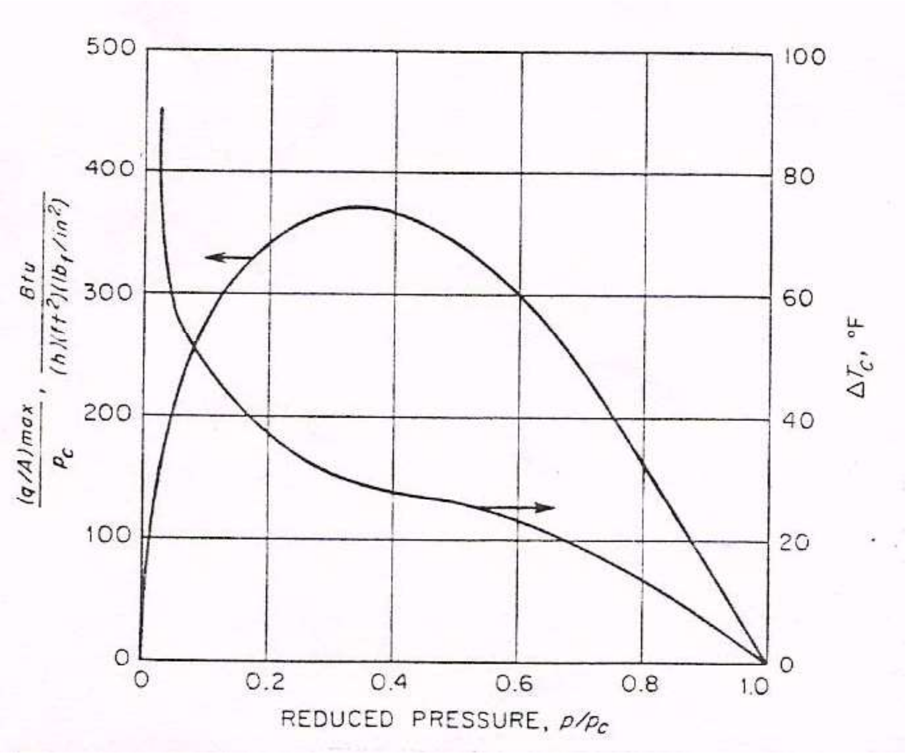

Figure 4. Maximum boiling heat flux and critical ΔT as functions of reduced pressure

The critical temperature drop can be exceeded in actual equipment unless precautions are taken. If the source of heat is another fluid, such as condensing steam or hot liquid, the only penalty for exceeding the critical temperature drop is a decrease in flux to a level between that at the peak and that at the Leidenfrost point. If the heat is supplied by an electric heater, exceeding the critical temperature drop may burn out the heater as the boiling liquid cannot absorb heat fast enough at a large temperature drop and the heater immediately becomes very hot.

The peak flux at the critical temperature drop is large. For water, it is in the range 115000 to 400000 Btu/ft^2-h (363 to 1260 kW/m^2) depending on the purity of water, the pressure, and the type and condition of the heating surface. For organic liquids, the peak flux is in the range 40000 to 130000 Btu/ft^2-h (126 to 410 kW/m^2). These limits apply to boiling under atmospheric pressure.

Many correlations have been proposed for estimating the *peak flux* from the properties of the fluid, based on various models of the physical phenomena. In one approach it is assumed that near the critical temperature drop the streams of bubbles characteristic of nucleate boiling are progressively replaced by jets of vapour leaving the heat-transfer surface. These must, of course, be accompanied by streams of liquid flowing toward the surface. At the peak value of the heat flux, the countercurrent flows of vapour and liquid reach a limiting condition, the process becomes unstable, and the jets of vapour collapse to form a continuous vapour sheath. The phenomenon is analogous to the flooding in a pocked tower. Using this model, *Zuber* [5] has derived the following dimensionally consistent equation for maximum heat flux, $(q/A)_{max}$:

$$\left(\frac{q}{A}\right)_{max} = \frac{\pi\lambda}{24}\left[\sigma g_c g(\rho_L - \rho_V)\right]^{1/4} \rho_V^{1/2}\left(1+\frac{\rho_V}{\rho_L}\right)^{1/2} \quad (2)$$

where σ is the interfacial tension between liquid and vapour, ρ_L and ρ_V are the densities of liquid and vapour, respectively, and the other symbols have their usual meanings. Increasing the pressure on the system increases ρ_V without greatly affecting the other terms in Eq.(2) and consequently increases the maximum heat flux. If the pressure is increased sufficiently, the latent heat of vaporisation tends toward zero, so that ultimately a reduction in the peak flux occurs, as shown in Figure 4 [2, 3].

2.3. Minimum Heat Flux and Film Boiling

When film boiling is established, undulations of a characteristic wavelength form in the interface between liquid and vapour. These undulations grow into bubbles, which leave the interface at regularly spaced intervals. The diameter of the bubbles is approximately one-half the wavelength of the undulations. Considerations of the dynamics of this process lead to the following equation for the minimum heat flux necessary for stable film boiling on a horizontal plate.

$$\left(\frac{q}{A}\right)_{min} = \frac{\pi\lambda\rho_V}{24}\left[\frac{\sigma g_c g(\rho_L - \rho_V)}{(\rho_L + \rho_V)^2}\right]^{1/4} \quad (3)$$

Film boiling is a more orderly process than either nucleate boiling or transition boiling and has been subjected to considerable theoretical analysis. Since the heat-transfer rate is governed solely by the vapour film, the nature of the heating surface has no effect in film boiling. For film boiling on a submerged horizontal tube, the following equation applies with considerable accuracy over a wide range of conditions.

$$h_o\left[\frac{\lambda_c \mu_V \Delta T}{k_V^3 \rho_V(\rho_L - \rho_V)\lambda' g}\right]^{1/4} = 0.59 + 0.069\frac{\lambda_c}{D_o} \quad (4)$$

In Eq.(4) λ' is the average difference in enthalpy between the liquid and the superheated vapour and is given by:

$$\lambda' = \lambda\left(1+\frac{0.34C_p\Delta T}{\lambda}\right)^2 \quad (5)$$

The term λ_C in Eq.(6) is the wavelength of the smallest wave which can grow in amplitude on a flat horizontal interface. It is related to the properties of the fluid by the equation:

$$\lambda_c = 2\pi \left[\frac{\sigma g_c}{g(\rho_L - \rho_V)} \right]^{1/2} \tag{6}$$

where σ is the interfacial tension between liquid and vapour. Eq.(6) does not include the effect of heat transfer by radiation.

Equations have also been developed for film boiling from submerged vertical tubes, but they have less general validity than Eq.(6). Vapour disengages from a vertical surface in a more complicated fashion than from a horizontal surface, and the theoretical analysis of the process is correspondingly more difficult [2, 3].

2.4. Condensation Heat Transfer

Condensation occurs when a saturated vapor comes in contact with a surface whose temperature is below the saturation temperature. Condensation of a vapour onto a cold surface may be *filmwise* or *dropwise*. When filmwise condensation occurs, the surface is completely wetted by the condensate and condensation is onto the outer layer of the liquid film, the heat passing through the film and into the surface largely by *conduction*.

By treating a surface with a suitable compound, it may be possible to promote dropwise condensation. When this occurs, the surface is not wetted by the liquid and the surface becomes covered with beads of liquid which coalesce to form drops which then fall away leaving the surface bare of a repetition of the action.

Film-type condensation is more common and more dependable. Dropwise condensation normally needs to be promoted by introducing an impurity into the vapor stream. Substantially, the heat transfer coefficients with dropwise condensation are higher than with filmwise owing to the absence of the liquid film, but design methods are not available. Therefore, the development of equations for condensation will be for the film type only. The physical properties of the liquid, rather than those of the vapor, are used for determining the film coefficient for condensation. *Nusselt* [6] derived theoretical relationships for predicting the film coefficient of heat transfer for condensation of a pure saturated vapor. A number of simplifying assumptions were used in the derivation.

For a complete investigation of filmwise and dropwise condensation at high heat fluxes, the Hilton Film and Dropwise Condensation Unit H910 should be used.

Boiling and condensation heat transfers are indispensable links in the production of power, all types of refining and chemical processes, refrigeration, heating systems, etc.

There is a constant pressure for more compact heat transfer units with high heat transfer rates and a clear understanding of the boiling and condensing process is essential for every mechanical and chemical engineer.

The Hilton Boiling Heat Transfer Unit has been designed to improve the understanding of boiling and condensing heat transfer and enables both a visual and analytical study of these processes [3, 4].

3. DESCRIPTION OF APPARATUS

An electric heating element in a copper sleeve submerged in SES 36 liquid is mounted horizontally in a vertical glass cylinder. The temperature of the copper sleeve is measured by a temperature sensor and displayed on the screen of the sofware.

The electrical input to the heater may be varied from 0 to approximately 300W, the actual heat transfer rate being obtained from the product of the voltmeter and ammeter readings.

A controller incorporated in the pressure indicator switches off the electrical input if the pressure of the heating surface exceeds a pre-set value (approximate switch-off vapour pressure is 2 bars).

At the upper end of the cylinder, there is a nickel-plated coil of copper tube through which cooling water flows. This coil condenses the vapour produced by the heat input and the liquid formed returns to the bottom of the cylinder for re-evaporation.

A cooling water flow meter used in conjunction with temperature sensors measuring the cooling water inlet and outlet temperatures, enables the rate of heat transfer at the condenser to be measured. The logarithmic mean temperature difference during condensation may also be determined.

Temperature sensors are also mounted inside the glass cylinder to indicate the temperature of the liquid and vapour (Figure 5).

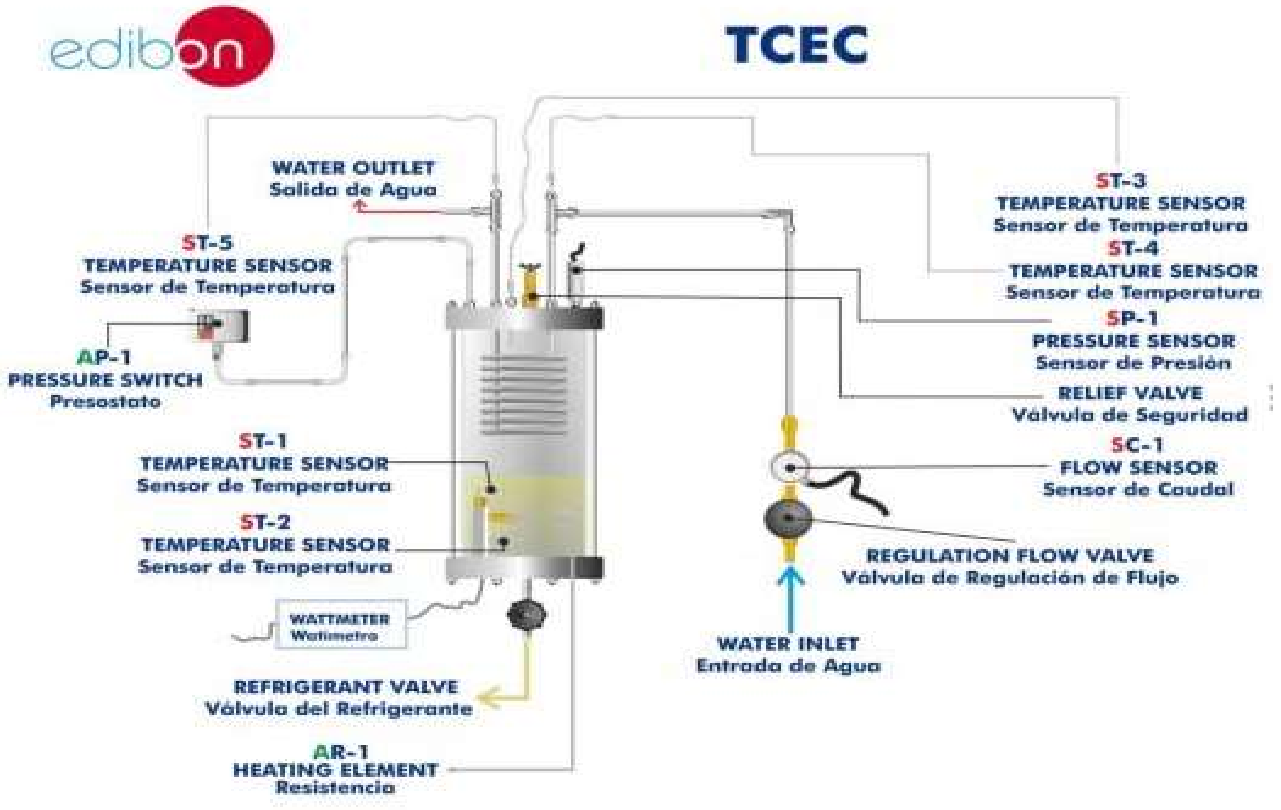

Figure 5. Boiling heat transfer apparatus

4. EXPERIMENTAL PROCEDURE

4.1. Determination of heat flux and surface heat transfer coefficient at constant pressure.

Adjust the electrical heater to about 50 watts and adjust the water flow rate until the desired pressure is reached. Note the voltage, current, vapour pressure, liquid temperature and metal temperature. Increase the power to say 75 watts, adjust the cooling water flow rate to give the desired pressure and then steady, wait 5 minutes then repeat the observation.

Repeat in similar increments until the transition from nucleate to film boiling is reached. By careful adjustment of voltage near this condition, it is possible to make an accurate assessment of critical conditions. ~~When film boiling is established the voltage should be reduced and the readings continued until the heater temperature reaches 220°C~~.

4.2. Effect of pressure on critical heat flux.

The method is similar to that given in Part 4.1. but by carefully adjustment of the power and water flow rate, the heat flux at transition from nucleate to film boiling at a variety of pressure may be established.

4.3. Filmwise condensation

The filmwise condensation which occurs with SES 36 can be clearly seen, and the resistance offered by the liquid is readily appreciated. The overall heat transfer coefficient between the condensing vapour and the water may be found as follows:

Adjust the voltage and water flow rate until the desired pressure and condensing rate is established. When conditions are stable, note the water flow rate, water inlet and outlet temperatures and the saturation temperature of the SES 36.

4.4. Pressure-temperature relationship

The relationship between the saturation pressure and temperature of a pure substance is readily demonstrated up to a maximum pressure of 2 bars gauge. The electrical supply is switched on and adjusted to about 100W. Cooling water is circulated at the maximum rate and when conditions are stable the pressure and temperature are noted. The cooling water flow is reduced and the observations are repeated at a higher pressure, and so on.

5. CALCULATIONS

5.1. Determination of heat flux and surface heat transfer coefficient at constant pressure.

a. Calculate heat transfer rate, heat flux and surface heat transfer coefficient at different voltage values,

b. Calculate theoretical critical heat flux,

c. Plot q/A vs. ΔT_e and h vs. ΔT_e.

5.2. Effect of pressure on critical heat flux.

a. Calculate experimental critical heat fluxes,

b. Plot absolute pressure vs. critical heat flux.

5.3. Filmwise condensation

Calculate heat transfer rate at cooling coil, heat transfer rate from the heater, heat transfer to surroundings and overall heat transfer coefficient.

5.4. Pressure-temperature relationship

Plot saturation temperature vs. saturation pressure.

6. SYMBOLS

A	Area, m^2
a	Constant in Eq.(1)
C_p	Specific heat at constant pressure, J/g°C
D	Diameter, m; D_o outside diameter
ΔT	Temperature drop,°C; ΔT_b, difference between the wall temperature and the bulk fluid temperature, ΔT_e, the difference between the temperature of the wire surface and that of the boiling liquid, ΔT_c, critical temperature drop.
E	Potential differential, volts
g	Gravitational acceleration, m/s^2
g_c	Newton's law proportionality factor, $4.17*10^8$ ft.lbm/lbf.h^2
h	Surface heat transfer coefficient, W/m^2.K; h_o of outside tube
I	Current, amperes
k	Thermal conductivity, W/m°C; k_v, of vapour
λ	Heat of vaporisation, J/g; λ', average difference in enthalpy
λ_c	Wavelength of smallest wave that can grow on flat horizontal surface, m
$\dot{m}$	Mass flow rate, g/s; $\dot{m}_w$, of water
μ	Absolute viscosity, kg/m.s; μ_v, of vapour
P	Pressure, N/m^2, P_c: Critical pressure
q	Rate of heat transfer, J/s
(q/A)	Heat flux J/s.m^2
ρ	Density, kg/m^3; ρ_L,of liquid; ρ_V, of vapour
σ	Interfacial tension between liquid and vapour, N/m
T	Temperature,°C;T_{sat}, saturated temperature of vapour;T_w, surface temperature of wire, T_i, inlet temperature of cooling fluid, T_o, outlet temperature of cooling fluid.
U	Overall heat transfer coefficient, W/m^{2}K

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