

## EVAPORATION AND CONDENSATION

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### Summary

In manufacturing processes several heat transfer phenomena may occur, of which boiling or condensation play a very significant role. These processes are usually applied in heat removal from different surfaces and can be found in chemical engineering as well as other areas of contemporary technology and they have huge practical significance, just to mention perspective applications in removal of large heat fluxes in electronics or power technology. Conversion one phase into the other may proceed equally on the wall and inside the phase; however usually the first of these cases is found in technical applications. Evaporation is the process of turning a liquid, at its saturation temperature, into vapor by applying heat. Boiling on a solid surface takes place when the temperature of the heated surface is higher than the saturation temperature of the liquid. The process reverse to boiling is condensation, where vapor

turns into liquid due to the removal of heat. The necessary condition for the process to occur is that the temperature of surface should be lower than the corresponding saturation temperature of the liquid.

## **1. Introduction**

Evaporation and condensation are amongst the most important industrial processes which are used primarily in chemical technology as well as other areas of contemporary technology and they have huge practical significance, just to mention perspective applications in removal of large heat fluxes in electronics and power engineering. Conversion of one phase into another may proceed equally on the wall and inside the phase; however usually the first of these cases is found in technical applications. Evaporation is the process of turning a liquid, at its saturation temperature, into vapor by applying heat. A similar process occurs when the pressure, applied to a hot liquid is reduced. Such process is called flashing. Boiling is associated with rapid formation of vapor in the entire volume of a liquid; however it is mostly associated with superheated surfaces, where it is primarily promoted. Boiling on solid surface takes place when temperature of heated surface is higher than the saturation temperature of the liquid. The reverse process is the condensation process, where vapor turns into liquid due to removal of heat. The necessary condition for the process to occur is that the temperature of surface should be lower than the corresponding saturation temperature of the liquid. These phenomena are more complicated than issues of convection in the case of a single phase. Their mathematical description requires thus knowledge of the flow structure of both phases together with interfacial phenomena. Hence, the existing theories provide only simplified description of the issues related to these phenomena and require experimental validation.

## **2. Pool Boiling**

### **2.1. Bubble Formation, Growth and Departure**

The life of a single bubble may be summarized as occurring in the following sequence of processes: nucleation, growth and possible collapse. Waiting period occurs in a bubble site just after the departure of a bubble from a surface and before a new bubble is formed on the heated surface. Initial growth from the nucleation size is controlled by inertia and surface tension effects. In the next stage of growth heat transfer becomes important, while inertia effects begin to lose significance. If the bubble during its growth, contacts the subcooled liquid, it may collapse. The bubble growth in the case of a saturated or superheated liquid finally reaches the size allowing it to leave the surface.

Nucleation can only occur if a liquid is superheated. There are two types of nuclei which can promote such a process. One type is formed in a pure liquid resulting from fluctuations of liquid molecules. The other type can be a cavity on the heating wall or suspended foreign material (Figure 1). According to the kinetic theory of gases, in the case of pure gases and liquids the local fluctuations create clusters of molecules acting as nuclei for prospective vapor bubbles. Creation of nuclei is related to overcoming the energy barrier. If a liquid superheat is increased, more liquid molecules can be converted to vapor. The size of the nucleus, in order to be active, must exceed the

thermodynamic equilibrium. The condition for thermodynamic equilibrium at a vapor-liquid interface in pure substance can be written as:

$$p_G - p_L = \sigma \left( \frac{1}{R_1} + \frac{1}{R_2} \right) \quad (1)$$

In Eq. (1)  $R_1$  and  $R_2$  are the principal radii of interface curvature. For a spherical nucleus of radius  $R$ , Eq. (1) becomes the Laplace equation:

$$p_G - p_L = 2\sigma / R \quad (2)$$

Difference of pressure between gas and liquid corresponds to superheat of the liquid near the wall  $T_G - T_s$ . To determine the minimum radius of the bubble at equilibrium we make use of the Clausius-Clapeyron equation:

$$\frac{dp}{dT} = \frac{h_{LG}}{(v_G - v_L)T} \quad (3)$$

Expressing (3) with finite-differences instead of infinitesimal differences and assuming  $v_G \gg v_L$  one can obtain:

$$p_G - p_L = \frac{(T_G - T_{sat})h_{LG}\rho_G}{T_{sat}} \quad (4)$$

Combination of (2) and (4) yields the critical radius for the bubble at the equilibrium state:

$$R = \frac{2\sigma}{h_{LG}\rho_G} \frac{T_{sat}}{(T_G - T_{sat})} \quad (5)$$

Hence for increasing superheat, the nucleation site size can be smaller. A smaller nucleus will collapse and a larger nucleus will grow. Labuncow (1959) showed that most probable places for nucleation are cavities on the heating surface. Critical radius determined by (5) may be taken as equal to the radius of cavity. Possible examples of nucleation sites are shown in Fig. 1. The liquid temperature can be taken as in the liquid immediately adjacent to the heating surface. That means the temperature of the liquid can be represented by the temperature profile in the thermal boundary layer. Bubble will grow when its temperature of bubble is lower than the temperature of the liquid and the pressure inside the bubble is higher than the pressure of the surrounding liquid. The schematic of the favorable conditions for the bubble growth model is presented in Fig. 2.

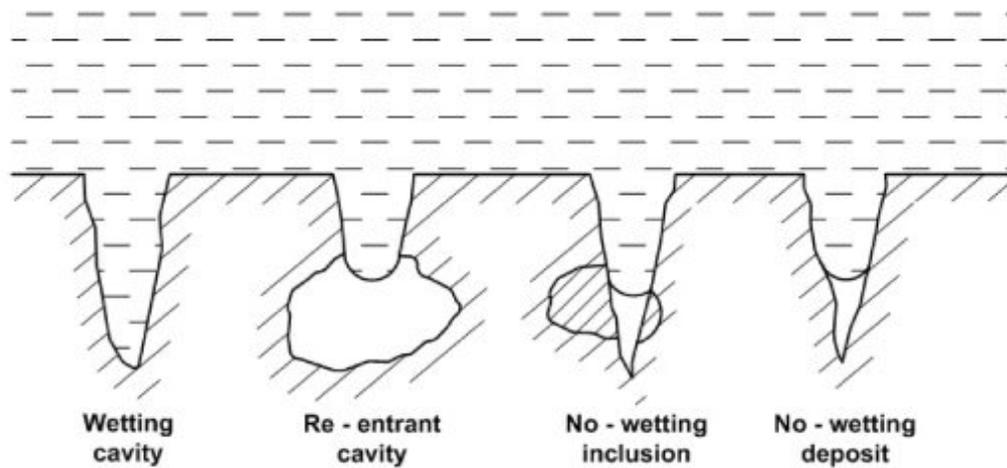


Figure 1. Examples of nucleation sites.

In the case when temperature of liquid is lower than the temperature of the bubble  $T_L < T_G$ , vapor bubbles cannot exist. The range between the minimum,  $y_{\min}$ , and maximum,  $y_{\max}$ , sizes of bubbles corresponds to temperature range where temperature of the surrounding fluid is greater than the vapor temperature inside the bubble. In such a case the bubble can increase its size.

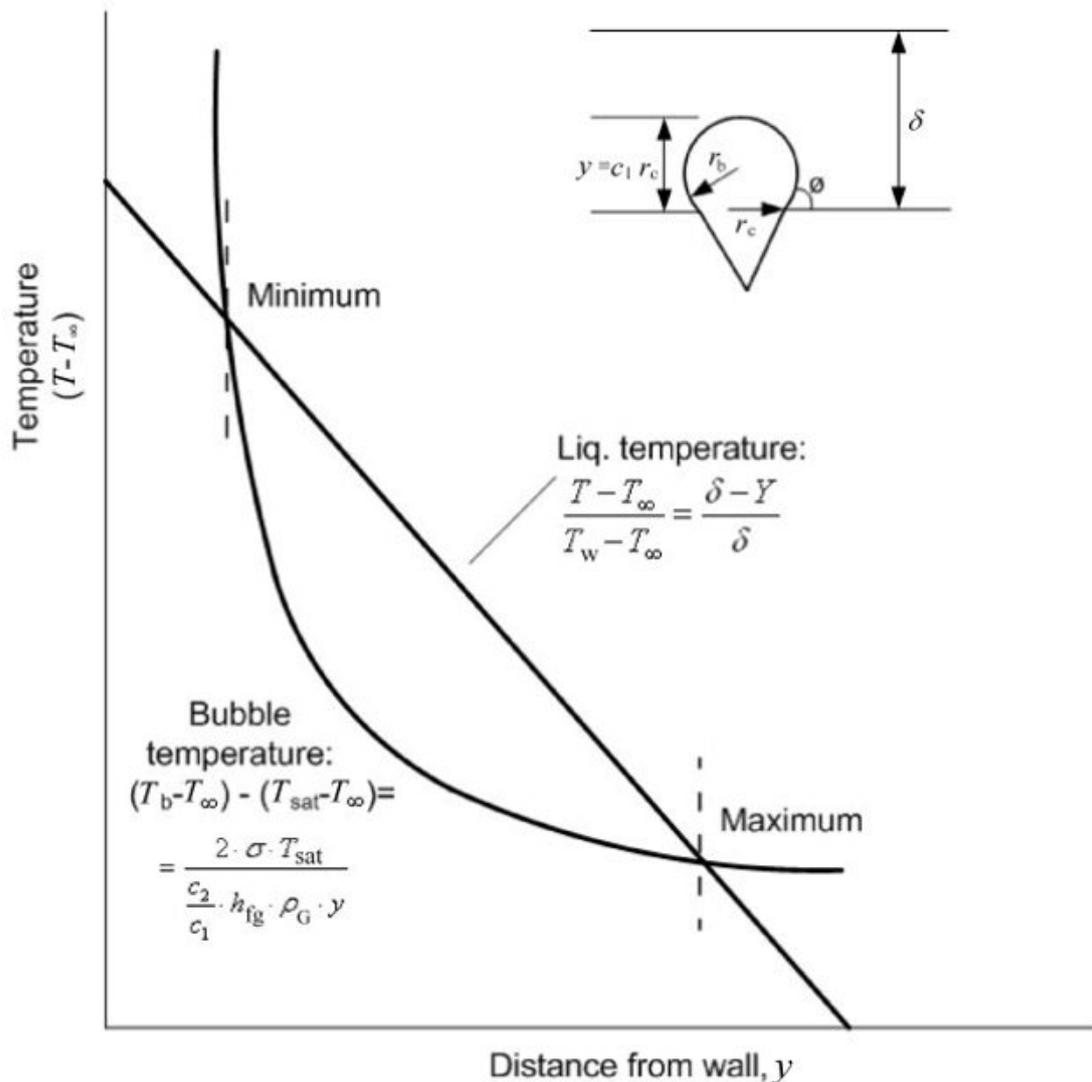


Figure 2. Active size range of nucleation sites.

There is a “waiting period” between the time of release of one bubble and the time of nucleation of the next at a given nucleation site. To predict the waiting period Hsu and Graham (1976) proposed a model based on heating of the liquid by transient conduction. When the size of a bubble nucleus formed in a liquid exceeds that of thermodynamic equilibrium the bubble will grow. During the initial stage of growth, the inertia of surrounding liquid and the surface tension forces control the growth process. At a later stage of bubble growth, heat diffusion effects control its growth.

The bubble contact with a heated surface is sustained by the force balance, see Fig. 3. This balance includes surface forces, buoyancy, liquid inertia due to bubble growth, viscous forces, and forces due to the liquid convection around the bubble. For a horizontally heated surface the maximum sitting bubble size can be determined as a function of contact angle, surface tension, and liquid-vapor density difference. Fritz (1935) found the bubble diameter, just before leaving the surface:

$$D_b = C_d \phi \left( \frac{2\sigma}{g(\rho_L - \rho_G)} \right) \quad (6)$$

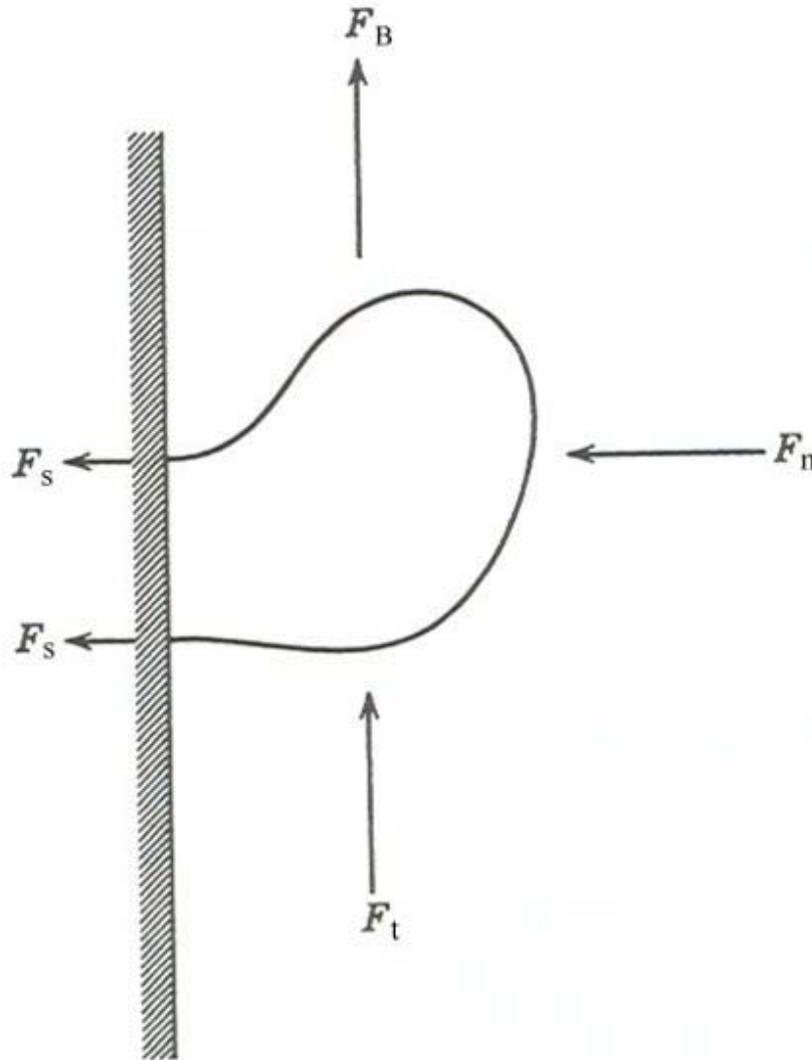


Figure 3. Active size range of nucleation sites;  $F_s$ -surface tension force,  $F_B$ -buoyancy force,  $F_n$ -inertia force due to bubble growth,  $F_t$ -flow resistance force

The constant  $C_d = 0.0148$  and the contact angle  $\phi$  is in degrees. When a bubble starts to grow on a heating surface a time interval  $t_d$  is required for it to depart from the surface. As mentioned before, the time interval  $t_w$ , i.e. the “waiting period”, is required to heat the new liquid layer in order to promote nucleation. If  $t_d$  represents the time of departure,  $t_w$  the waiting period, the frequency of bubble departure  $f_b$  is then defined as  $1/(t_w + t_d)$ . The increase of heat flux activates more nucleation sites, thus increasing the bubble population and reduces the time and size of departing bubbles. There is a

correlation between the departure size and departure frequency, which according to Jakob (1949) reads:

$$D_b f_b = 0.59 \left[ \frac{\sigma g (\rho_L - \rho_G)}{\rho_L^2} \right]^{\frac{1}{4}} \quad (7)$$

The velocity of bubble rise in a gravitational field is:

$$V_b = D_b f_b \quad (8)$$

Heat is transferred into bulk liquid by the motion of bubbles away from the wall (latent heat transport). The bubbles also transport some superheated liquid around each bubble, or by turbulent transport in the liquid. When the bulk of liquid is subcooled the bubbles in contact with the subcooled bulk liquid condense and collapse.

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### Biographical Sketches

**Jarosław Mikielwicz**, born in Vilnius, Poland, 10 April 1941. **Education:** received all the academic titles from the Gdansk University of Technology, Poland, namely the MSc in Mechanical Engineering in 1964, Ph.D. (Mechanical Engineering) in 1968 and Doctor of Science (habilitation) in 1972. The title of Professor was awarded to him in 1979 by the President of State Council of Poland. He received the honorary Doctor of Engineering degree from the Technical University of Cracow in 2004. He has been elected a Corresponding Member to the Polish Academy of Sciences in 2002. Currently he is the President of Editorial Board of the international journal *Archives of Thermodynamics* and the President of Editorial Board of the *Transactions of the Institute of Fluid Flow Machinery PASci*. He served as faculty member at several universities and scientific boards of scientific institutions etc. **Current Position:** Full Professor, Head of the Institute of Fluid Flow Machinery Polish Academy of Sciences, Gdansk and Professor at the Technical University Koszalin, Poland. **Fellowships:** Institute of Thermal Technology of Russian Academy of Sciences, Novosibirsk 1970, American Academy of Sciences in: MIT Heat Transfer Laboratory, University of Delaware, University of Michigan, 1974, Visiting Full Professor, Brown University, Providence RI, USA 1981/1982, German Academy of Sciences (DAAD) in various German Universities 1986. American Academy of Sciences in various American Universities (Rennselear Polytechnic Institute) 1988. Fellowship in McMaster University, Canada 1992. Author or co-author of above 170 papers. **Research Interests:** include nuclear plant safety analysis, heat transfer (flow boiling), fluid mechanics (two-phase flow, thin liquid films), thermodynamics, renewable energy in variety of application areas.

**Dariusz Mikielwicz**, born in 1967. He received his Master of Science degree from the Gdansk University of Technology in the area of Refrigeration Technology in 1990. Subsequently he completed his doctoral education at the Victoria University of Manchester, Great Britain, where he was awarded a PhD degree from the Mechanical and Nuclear Engineering Department in 1994 for the studies on the performance of turbulence models in modeling of mixed convection in tubes. He then joined in 1994 the Nuclear Electric plc, where he was an engineer involved with the development of the safety reactor code Panther. In 1996 he returned to Poland, where he took up employment at the Faculty of Mechanical Engineering of Gdansk University of Technology (FME GUT) at the Heat Technology Department, and where he is still employed. In 2002 he was awarded the Doctor of Science degree (habilitation) by the Board of FME GUT for the studies into modeling of two-phase flows in boundary layers. From 2004 he is

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