

THE BOILING MECHANISM IN SUPERHEATED FREE JETS

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Abstract—The phenomenon of boiling is investigated in a superheated water jet. Using this method, the influence of the walls on the boiling process, especially the activation of the wall nuclei, is avoided. Pressurized water heated above 100°C is discharged through short, circular nozzles into ambient air. Thus the water pressure is suddenly reduced to atmospheric pressure, and the water jet becomes superheated. The delay time of boiling commencement, the bubble growth and the mean bubble frequency are measured as functions of the fluid state before the pressure drop, the flow conditions, the jet diameter, the nozzle shape and the gas content of the fluid. In this metastable jet two different mechanisms of bubble formation are observed. One of the boiling mechanisms is independent of the nozzle shape and the jet velocity but depends on the overexpansion of the jet; this mechanism seems to be caused by activated nuclei in the water. The second mechanism is strongly dependent on the nozzle shape and diameter, and on the flow conditions. The first mechanism can be interpreted by using theoretical models, the second can be described only approximately. With the knowledge of these different boiling phenomena it is possible to design nozzles with which highly superheated free jets can be generated for which there are interesting technical applications.

Key Words: onset of boiling, free jet, superheated jet

1. INTRODUCTION

When pressurized water with a temperature exceeding the saturation temperature at atmospheric pressure is discharged into the ambient air through a nozzle, normally no jet flow is formed—the water leaving the nozzle in a two-phase flow with critical mass flow. In this case, the onset of boiling is induced by the pressure drop in the nozzle, and by nuclei in the liquid and on the wetted nozzle wall. In especially short nozzles with small diameters, a jet can be formed and maintained; the jet released from the nozzle evaporates only on its surface, while the core of the jet remains superheated, and the liquid phase in the core is in a metastable condition. In such superheated jets, two further mechanisms of boiling are observed which are described here. By using short nozzles with a length-to-diameter ratio of < 1 , the wall boiling mechanism can be avoided, because the pressure drop to saturation is reached in these nozzles when the liquid is no longer in contact with the wall. The observed boiling mechanisms have completely different causes, and occur at different fluid states; they can to some extent be examined independently. One of the two mechanisms is originated on small suspended particles and depends directly on the size of the activated nuclei, which are the decisive factor for bubble generation during the pressure drop in the nozzle. Mostly these bubbles are created within the jet. The other mechanism depends on the state of flow and on the jet velocity, and occurs exclusively on the surface of the jet. In this paper, these two boiling mechanisms shall be referred to as “particle boiling” and “surface boiling”; to date they have not been recognized or treated as separate mechanisms.

The results are relevant for pressure drop processes, boiling in flowing liquids and for cavitation processes, and they can be directly applied in judging processes with small cracks in boilers and tubes. The knowledge of how to prevent boiling in highly superheated free jets, which only burst when impinging on a solid surface, opens up a whole range of new applications for spray, cleaning, combustion and other technologies.

The experiments answer questions such as: the course of boiling processes in superheated free jets, and what they depend on; where the bubbles have their origin—in the bulk jet or on the jet surface, in the nozzle or at a certain distance from the nozzle; the amount of developing bubbles; the size and velocity of bubble growth; the distribution of the boiling time delays in the free jet; the influence of the nozzle geometry; the influence of the fluid state before the nozzle; and the gas content in the fluid.

The experimental results were subsequently interpreted on physical grounds, and the boiling phenomena theoretically described. A detailed description of this investigation is presented in Wildgen (1985).

2. EXPERIMENTAL PRINCIPLE

Subcooled pressurized water of state A in a boiler is expanded in a short especially designed nozzle to state B (see figure 1). The sudden pressure drop from p_0 to the ambient pressure p_∞ crossing the saturation pressure p_{sat} abruptly causes a superheated state which is maintained and collapses only locally by the formation of bubbles. In the case of incompressible liquids, the isotropic expansion is almost an isothermal one ($T_A \approx T_B$). Superheating, $\Delta T = T_B - T_{\text{sat}, \infty}$, or overexpansion, $\Delta p = p_{\text{sat}} - p_\infty$, of the free jet is adjustable by changing the boiler temperature at the constant pressure p_0 ($A \rightarrow A'$). The flow condition can be adjusted by varying the boiler pressure ($A \rightarrow A''$) and by using different nozzles. Where bubbles develop within the jet, the metastable state of liquid B changes locally into the two-phase state (C' and C'').

In figure 2, the process of bubble formation in a superheated free jet is presented schematically. After the water leaves the nozzle, a free jet is formed and contracts further to a cylindrical shape with a diameter smaller than the nozzle diameter. The term "time delay" refers to the development of bubbles in the free jet. Most of the bubbles are not created in the centre of the jet, as is shown here. In a 1 mm dia jet they can grow to 5 times the size of the jet diameter (figure 8). As soon as the bubbles have grown too far beyond the free jet, they burst and create sequential bubbles. If the superheating of the jet is insufficient, the bubbles can also condensate on the jet surface, which is cooled by evaporation. By unsteady-state calculation it can be demonstrated that only a very thin layer of the jet surface is cooled, the jet surface temperature drops to saturation just after the nozzle. The bulk centre, however, is kept at the initial level of superheating. The boiling formation is always within the breakup length before the jet begins to disintegrate.

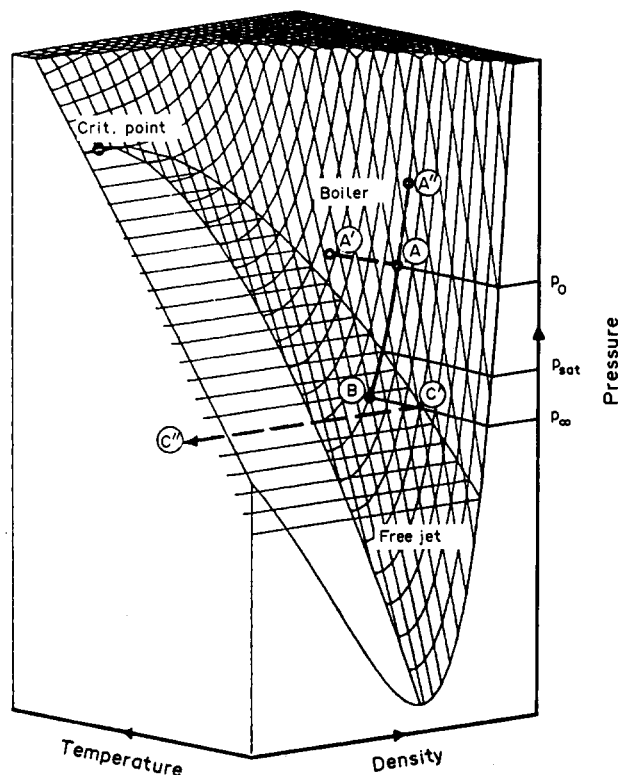


Figure 1. Schematic three-dimensional diagram of the change of the liquid state in the nozzle. The expression p_0 is the initial boiler pressure, p_{sat} is the saturation pressure at the initial temperature $T_0 = T_A$ and p_∞ is the ambient pressure.

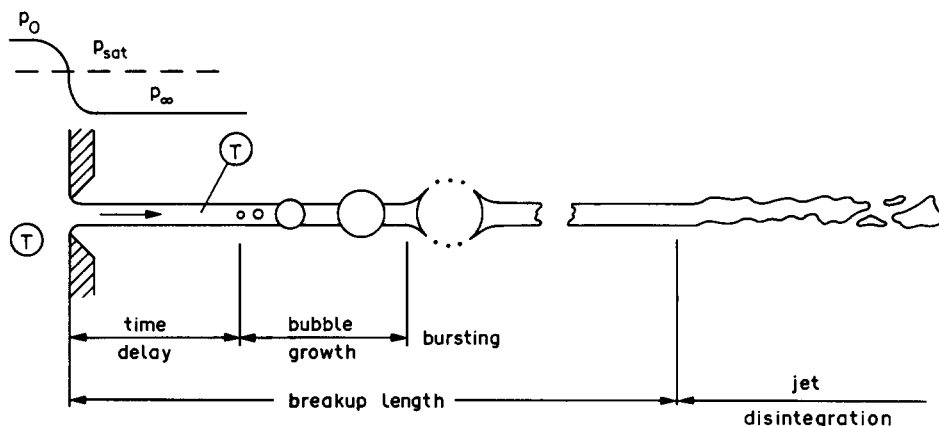


Figure 2. Schematic presentation of the events in a superheated free jet after the expansion.

3. EXPERIMENTAL EQUIPMENT

Demineralized water is heated in an electrical boiler beyond the saturation temperature corresponding to the boiler pressure. The hot water flows from the lowest point in the boiler into the calm region before the nozzle through a flexible tube passing the valve v_0 (figure 3). The pipes have a diameter of 13 mm and are designed so as to avoid diameter reductions, in order to prevent boiling before the nozzle caused by a pressure drop in the pipe. With the speeds involved, the drop in the static pressure in the supply tube is negligible.

In the following theoretical treatment of the boiling behaviour, the term "boiler state" refers to the state in the calm region before the nozzle. All parts are corrosion resistant and equipped with thermal insulation. The length and diameter of the calm region were determined on the basis of extensive preliminary tests, as they can influence the boiling process substantially. The calm region is mounted on a slide, and can be moved in the direction of the free jet by a motor. The distance between bubble detection and the nozzle was determined using a motion pickup. Pressure and temperature were measured before the nozzle in the calm region. The water flows through a short nozzle of brass (the shape and dimensions of the nozzles are given in table 1), expands to the ambient pressure and forms the superheated free jet. After the measuring section of about 1 m, it is caught in a jet condenser. A small part of the water from the boiler is tapped after the valve v_0 , cooled and used to measure the gas content. After the heating period, the boiler pressure is adjusted by a nitrogen pad. It was ascertained that this nitrogen pad only influences the gas content in the upper surface layer of the boiler water and in no way affects the water of the jet coming from the lower section of the boiler. The number of bubbles in the free jet was measured using the light reflection method. A laser beam crosses the free jet at an angle of 45° (figure 3). The light reflected back from the bubbles is registered by a photomultiplier and evaluated by a counter. Without bubbles the jet, whose surface is not totally even, scatters the light in all directions but does not reflect it back to the photomultiplier. With this arrangement, the bubble frequency along the jet—from the exit at the nozzle to the disintegration of the jet—can be measured. All analogue and digital measuring signals are processed by a process-control-computer. With a high-speed drum camera and a nanolight flash, pictures were taken of the jet so that the different bubble formations and their growths could be registered.

4. THE NOZZLE SHAPES

Apart from the boiler state and environmental conditions, all measurements are influenced by the nozzle shapes depicted in table 1. Two nozzle shapes were tested: nozzles with a round inlet marked with r, and nozzles with a sharp-edged inlet marked with s. The number refers to the approximate nozzle diameter in mm. The boiling behaviour was found to be independent of the axial length of the sharp-edged nozzles. The free jet leaves the nozzle wall at the sharp-cornered

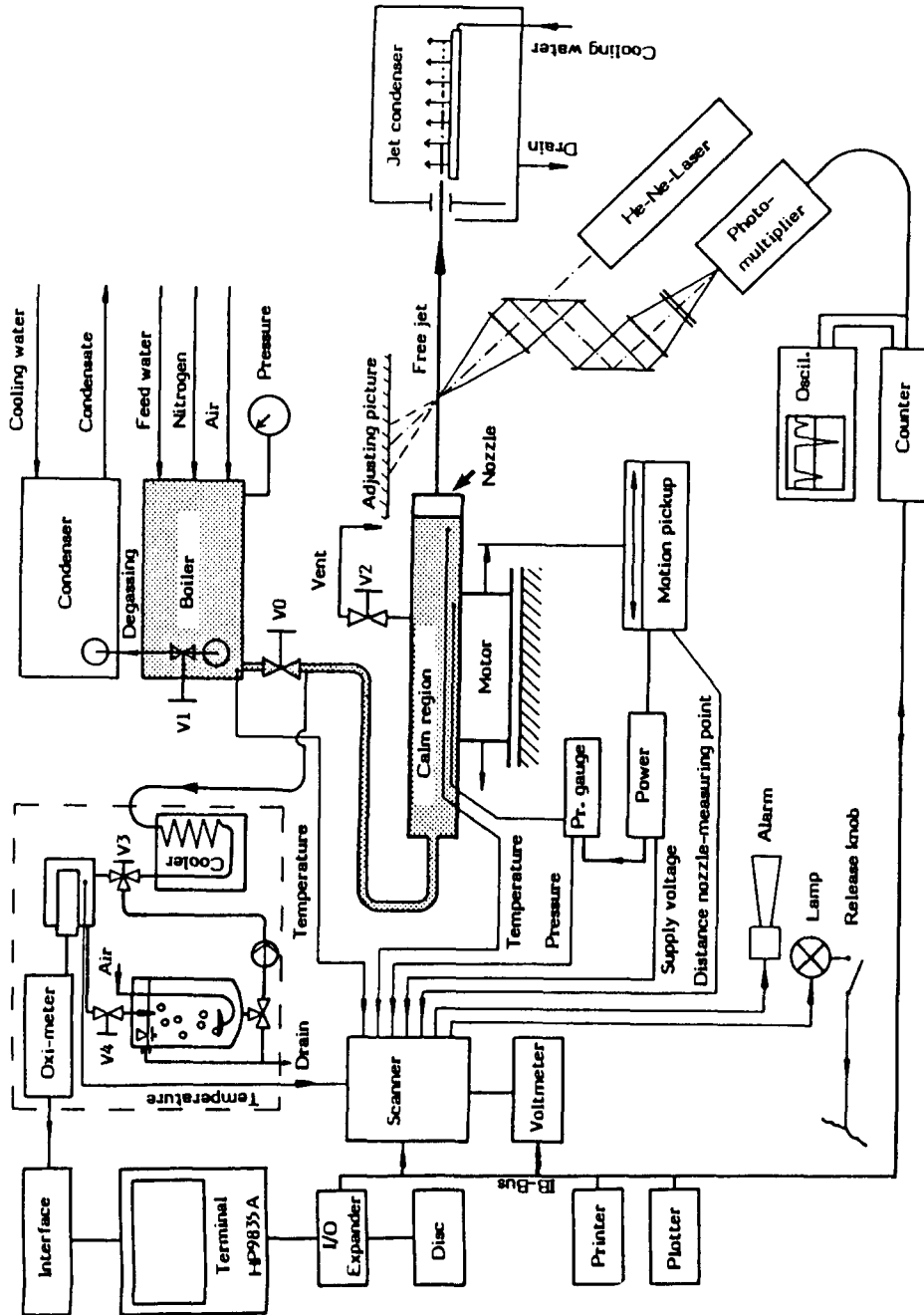


Figure 3. Sketch of the experimental setup.

Table 1. The nozzles used and their dimensions

Nozzle profile:	1r	1.9r	1s	1.3s	2s
d_n (mm)	1.05	1.86	1.05	1.33	2.00
d_f (mm)	1.03	1.81	0.84	1.06	1.57
μ	0.98	0.97	0.80	0.80	0.78
α_1	0.89	0.93	0.59	0.62	0.58
α_2	0.93	0.98	0.92	0.98	0.95

inlet edge and, as pictures of the emerging jet show, the fluid does not touch the nozzle drill hole after that. In the case of the round nozzles, the fluid touches the nozzle drill hole, and detaches itself from the wall at the nozzle outlet. The nozzle length amounts to about 1 mm.

The nozzle 1r has the same nozzle diameter as 1s, however, because of the jet contraction at the sharp-edged inlet, the free jet diameter d_f is about 20% less. The jet contraction μ is the ratio of the free jet diameter d_f to the nozzle diameter d_n . The free jet diameter d_f as well as the jet contraction μ were determined by photography. The r-nozzles produce only a weak jet contraction of about 0.98, the s-nozzles a large contraction of about 0.8. The flow coefficient α_1 , relating to the nozzle diameter, was determined by draining and, neglecting the exact free jet diameter, is only useful for mass flow control. The actual flow coefficient α_2 describes the ratio of the free jet speed to the theoretical speed according to Bernoulli. These flow coefficients were measured as temperature and pressure dependent, and then extrapolated to temperatures above the saturation point, where draining of the jet is not possible. The free jet velocity calculations were verified by high-speed photography.

5. RESULTS

In this investigation, three mechanisms leading to bubble formation within the breakup length of the free jet could be distinguished. We call them: "wall boiling", "particle boiling" and "surface boiling". The mechanisms of these boiling onsets are sketched in figure 4. In the first case, boiling is generated by nuclei on the nozzle wall, and in the second case by nuclei on particles floating within the liquid. Homogeneous nucleation can be excluded, as the degree of superheating or of pressure drop is too small to trigger it off. The steam and gas inclusions in the pores of the wetted

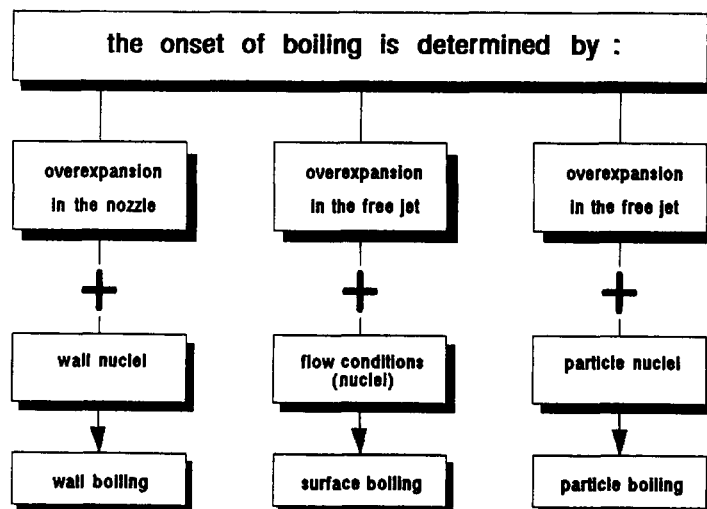


Figure 4. Sketch of the boiling mechanisms of the nozzles.

nozzle walls act as nuclei on the wall, if the wall is in contact with the superheated liquid caused by the pressure drop in the nozzle, and if the pressure in the liquid decreases below the saturation pressure during the period when it touches the wall. However, in the case of the short nozzles used, the overexpansion necessary for bubble formation takes place in the jet contraction region where the wall is no longer in contact with the liquid. With all of the short nozzles used, the overexpansion at the nozzle walls was not enough to induce bubble boiling on the wall nuclei. As calculations of the pressure variations during the pressure drop in the nozzle show, the saturation pressure is achieved beyond the point of wall contact. Wall boiling would occur in a region where the other two mechanisms are too active to allow a separation from the wall boiling phenomenon.

Even though the water is filtered before being filled into the boiler, small particles may be floating in the liquid. Steam and gas inclusions in the pores of these minute floating particles suspended in the liquid act as nuclei. By a process of boiling in the boiler or by the injection of gas, it is possible to "activate" these nuclei to such a degree that their adhesion radius exceeds the critical radius. Due to the pressure balance, these nuclei are activated after the pressure drop in the nozzle. The critical radius depends on the overexpansion in the nozzle, which is in a state of laminar flow $\Delta p = p_{\text{sat}}(T) - p_{\infty}$. The boiling process which can be induced by the regular overexpansion of the free jet is referred to as "particle boiling", it is normal nuclear boiling on a "solid" particle, see figure 8.

At high jet velocities a type of boiling was observed just on the surface of the jet, see figure 11. The origin of this boiling mechanism is as yet not completely understood. The short nozzles cause a slim flow boundary layer with high velocity gradients on the jet surface. These high gradients may induce turbulent fluctuations with local pressure fluctuation, which is added to the pressure drop in the nozzle, and effects an increase of the local overexpansion, and may yield to an activation of nuclei on the jet surface. Jones (1980) attributes the boiling phenomenon in the free jet to these turbulent pressure fluctuations and the resulting higher local expansion. However, these pressure fluctuations are only minor, so this explanation seems doubtful. Another explanation may be that just before the sharp edge of the nozzle, where the flow is accelerated, small vortexes are generated. At higher velocities these vortexes detach themselves, and flow with the jet through the nozzle. The rotation of the vortexes is maintained, and gas or vapour can be inserted below the jet surface and may act as nuclei for bubble generation. Even this is a hypothesis to explain the observed "surface boiling", but in any case it is certain that this mechanism depends on flow conditions such as the jet velocity and the diameter of the nozzle. Almost all experiments described in literature were performed with nozzles with dia > 2 mm. At such diameters, the surface boiling mechanism starts at a very low degree of superheating so that particle boiling was never recognized as an independent mechanism. Comparing figure 8 with figure 11, the difference between the phenomena of particle boiling and surface boiling is evident, and these two mechanisms can be easily distinguished by photographs and by the measured bubble frequency.

Figure 5 shows the ranges of boiler states with these three boiling mechanisms for the nozzle 1r. Plotting the boiler pressure vs the degree of superheating of the free jet facilitates the comparison

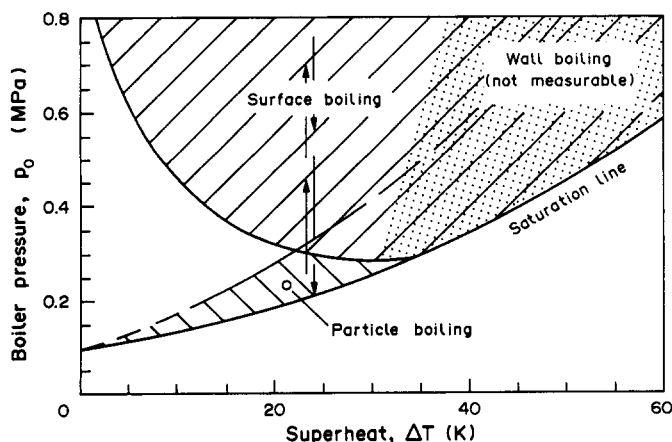


Figure 5. Experimentally determined boiling region for nozzle 1r.

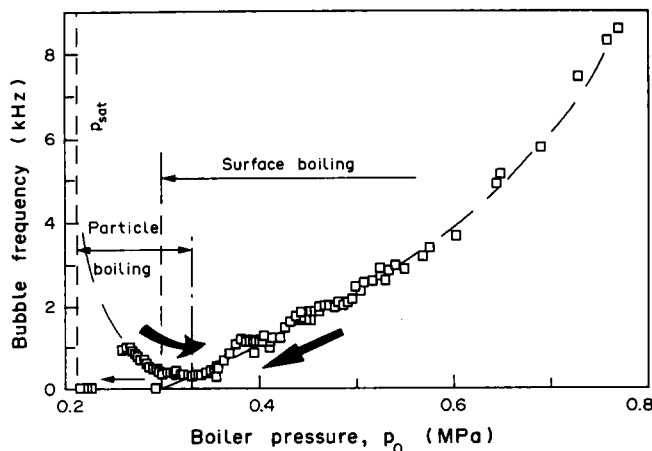


Figure 6. Bubble frequency for particle boiling and surface boiling at the same superheat $\Delta T = 23.8$ K vs boiler pressure (nozzle 1r).

between measurements at different air pressures p_∞ . In figure 5, the process of achieving the bubble frequency pressure dependency of figure 6 (also nozzle 1r) is indicated by arrows. In all tests the boiler water is degasified by 15 min vehement boiling before the test begins. In doing so, the pores of the particle nuclei are filled with steam, and the nuclei are activated; consequently the measurement in figure 6 begins with particle boiling. With increasing pressure, the particle nuclei continuously decrease in size, and in the same way the frequency of bubble generation decreases. With the chosen degree of superheating (figure 5), surface boiling begins before particle boiling has ended completely. The mean frequency of the surface bubbles grows with increasing free jet velocity or with boiler pressure, respectively. No particle boiling is observed in the subsequent pressure reduction to saturation pressure, as the higher boiler pressure renders the nuclei inactive, i.e. the steam nuclei of the appropriate size are flooded so far that they cannot be reactivated by decompression. Surface boiling and wall boiling depend on the flow condition, and hence on the nozzle shapes if the superheating is < 20 K. Between the areas of particle boiling and surface boiling, there is an area in which no boiling is observed indicated by the white field in figure 5. The nuclei are flooded because of the high boiler pressure.

Similar and reproducible results are achieved with the other nozzles. The particle boiling phase is the same but the surface boiling phase is shifted depending on the size and shape of the nozzle.

5.1. Particle boiling

As mentioned above, particle boiling depends directly on the size and the number of the nuclei in the boiler. The bubbles are formed within the bulk liquid of the jet, they are spherical and grow to a size 5 times the diameter of the jet (figure 8). The number of bubbles formed in a certain volume of the free jet is directly proportional to the density of activated nuclei in the boiler. Thus the reaction of the nuclei in the boiler upon changes of the boiler state can be directly studied by measurements of the mean bubble frequency, and of the volume flow. These results allow conclusions with respect to the size, the shape and the behaviour of the suspended nuclei. Particle boiling is best characterized by the nuclei density nd in the boiler or by the density of bubble generation in free jet, respectively. If there is no dissolved gas in the liquid the pressure relation $\Delta p_0 / \Delta p = (p_0 - p_{\text{sat}}) / (p_{\text{sat}} - p_\infty)$ best describes the boiling activation with regard to the state before the nozzle, which is called the boiler state.

In order to explain the mechanism of nuclei activation, the cavity plotted in figure 7 is a proper model. In the literature, the totally smooth cone is most often used as a cavity model. However, in this case the behaviour of the nuclei depends not only on the aperture angle of the cone but also on the contact angle. If the walls of the cone are rough in comparison with the idealized model, the influence of the unknown contact angle is negligible in the cavity shown in figure 7. We assume with this model that particle boiling depends only on the adhesive radius r_a of the nucleus, and then the observed pressure behaviour of the bubble formation can easily be described.

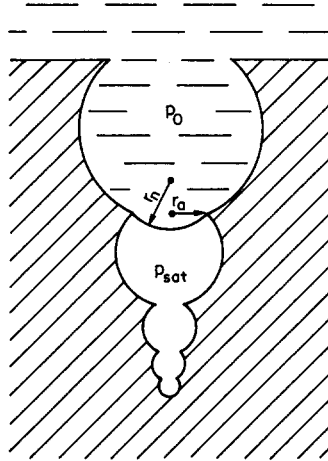


Figure 7. Idealized cavity model as the nucleus for particle boiling.

It is assumed that in the water there are nuclei in suspended particles with adhesion radii r_a . As demonstrated in figure 7, the upper hole of the cavity is flooded with liquid, the lower part is filled with vapour or gas. If the pressure p_0 is higher than the saturation pressure p_{sat} , the liquid forms at the bottle-neck with the radius r_a a convex surface with the radius $r_n = 2\sigma/\Delta p_0$, with $\Delta p_0 = p_0 - p_{sat}$. If the pressure p_0 is increased, r_n will decrease until $r_n = r_a$. The situation in this bottle-neck becomes unstable, and the second hole of the cavity will be flooded with liquid. In this way cavities can be totally or partly flooded, and can be made inactive for bubble formation. If such nuclei flow with the liquid through the nozzle, the pressure decreases, the vapour with its concave surface grows and the radius r_n increases. Reaching the saturation pressure, the radius r_n becomes infinite, the surface between the vapour and liquid becomes flat. If the pressure is lowered beyond the saturation, the surface shape of the vapour nuclei changes to a convex surface and the radius $r_n = 2\sigma/\Delta p$ with centre on the vapour side decreases with increasing overexpansion $\Delta p = p_{sat} - p_\infty$. If the hole radius r_a is smaller than r_n , the nuclei remain stable, and no bubble is generated. But if r_n is decreased to r_a , the nuclei radius reaches its minimal value and becomes unstable, and a bubble develops. The nuclei are activated if $r_n = r_a = 2\sigma/\Delta p$.

If the boiler pressure is raised above the saturation, all nuclei with adhesion radius larger than $r_a = r_n = 2\sigma/\Delta p_0$ are flooded. Bubbles are not generated in the free jet if $\Delta p_0 \geq \Delta p$, i.e. if $r_n \geq r_a$ (see figure 9).

The pressure range Δp_0 in which particle boiling was observed is shown in figure 9. Maximum nuclei density nd_{max} occurs if the initial boiler pressure is close to the corresponding saturation temperature where the overexpansion Δp corresponds to the superheat ΔT . At a certain boiler temperature the nuclei density $nd = 0$, specifically when the initial boiler pressure p_0 is of a magnitude that $\Delta p_0 = \Delta p$. All nuclei with radius $r_a \geq 2\sigma/\Delta p$ are flooded and cannot be activated by the overexpansion Δp . To activate nuclei with smaller radii, a larger overexpansion or superheat would be necessary. This result was observed for all nozzles used, and was always reproducible in the large number of experiments which were carried out; it confirms the nuclei activation model described above.

Further observations of this boiling type are summarized in an abbreviated form:

- The bubbles of particle boiling are smooth, spherically shaped, and can grow up to 5 times the size of the jet diameter (see figure 8).
- Particle boiling has no time delay, bubble growth starts immediately after the pressure drop in the nozzle.
- In particle boiling bubbles occur in the total cross-section of the jet depending on

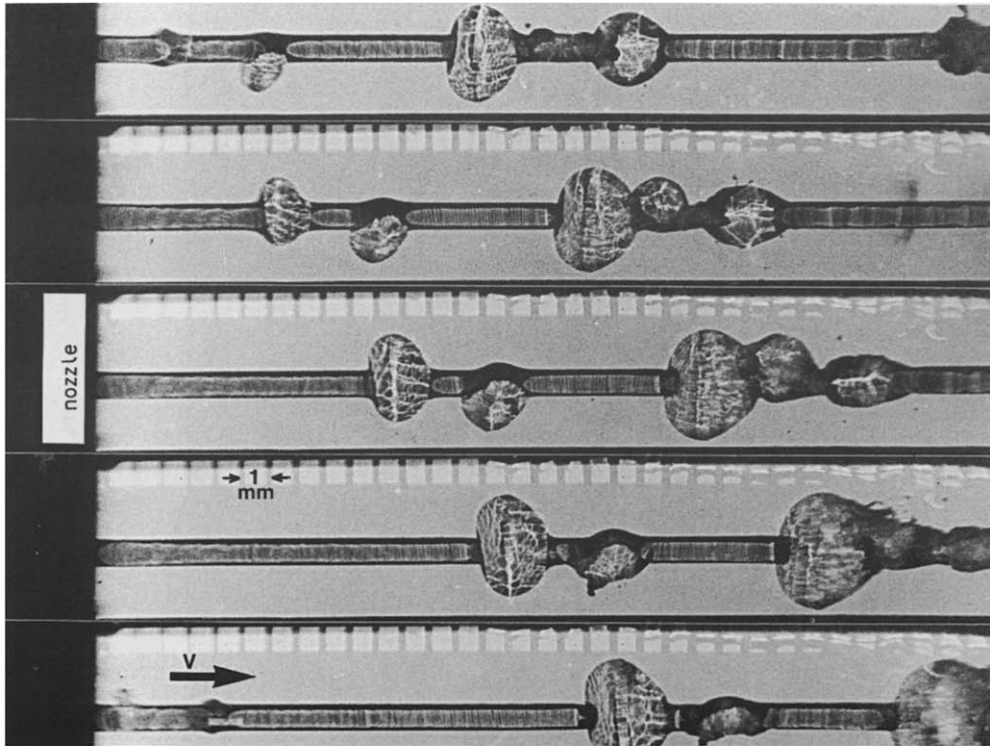


Figure 8. Photographs of particle nuclei induced bubbles in the free jet ($\Delta T = 20.3 \text{ K}$; $v_r = 14.4 \text{ m/s}$; $d_r = 1 \text{ mm}$; time between picture sequences = 0.26 ms).

the location of the nuclei, except near the jet surface where the degree of superheating is reduced by the evaporation on the surface. Immediately after the jet is released from the nozzle, the surface temperature is rapidly reduced to the saturation temperature, the temperature profile in the jet is developed by unsteady conduction.

- Particle boiling depends only on the density of activated nuclei before the nozzle, it is independent of the nozzle shape or of flow values.
- The nuclei can be activated by a boiling process or by gas injection into the boiler. If the boiler pressure is not increased after such a procedure, the nuclei density remains constant.

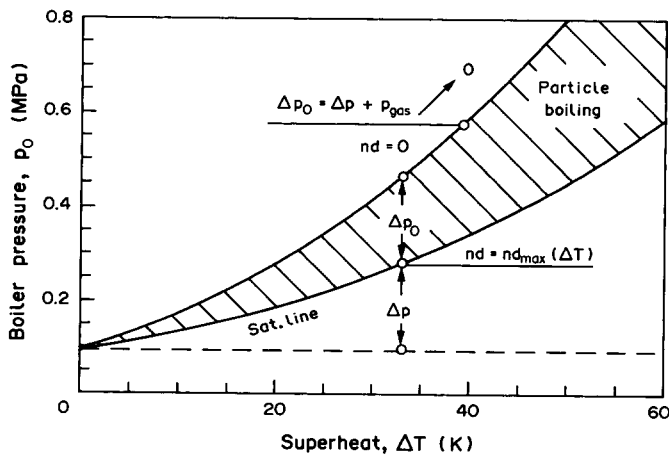


Fig. 9. Range of boiler states for gas-free particle boiling ($\Delta p_0 = p_0 - p_{sat}$).

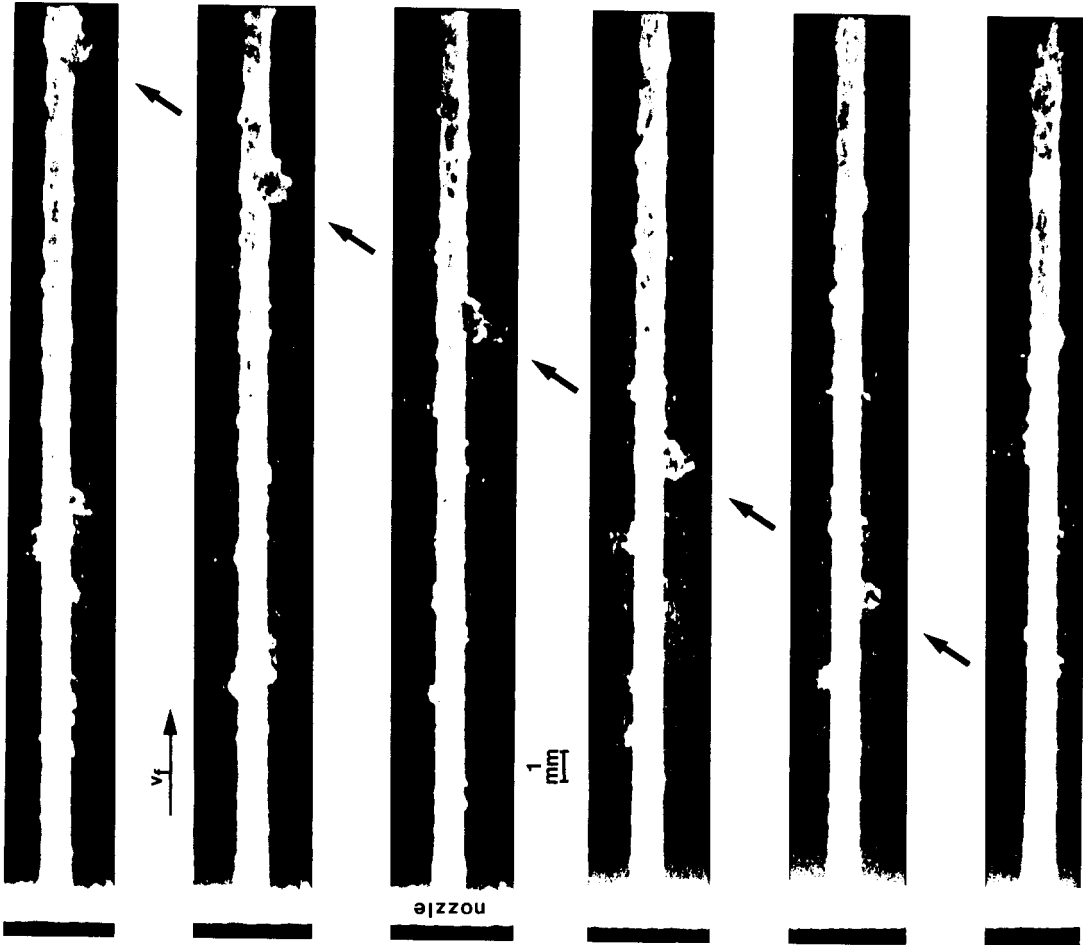


Figure 11. "Surface" bubbles in the free jet (nozzle Ir; $\Delta T = 22.6$ K; $v_f = 36$ m/s; time between picture sequences = 0.12 ms).

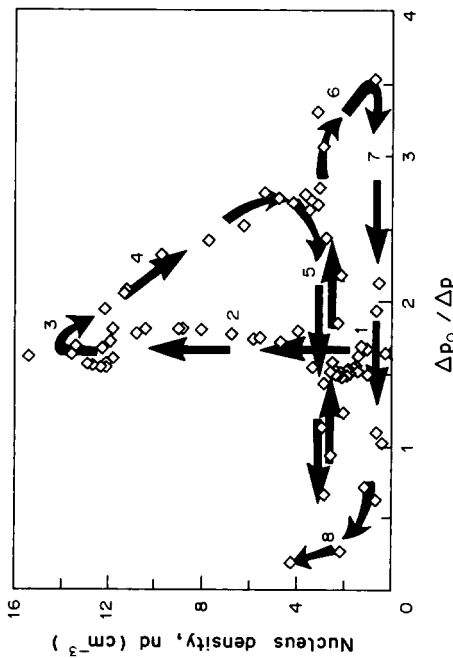


Figure 10. Nuclei density at constant boiler temperature $\Delta T = 32$ K vs pressure variation as indicated by the arrows; O_2 content = 12.8 mg/l. 1—Beginning of gas injection into the boiler. 2—End of injection; the O_2 content and the nuclei density continue to increase at the nozzle because the liquid remains in the supply line for a while. 3—The O_2 content and the nuclei density attain a maximum value and remain constant. 4—Nuclei density decreases with increasing boiler pressure as described, the points indicating steady-state measurements. 5—A reduction of the boiler pressure effects no change in nuclei density, the pressure reduction does not suffice to enlarge the adhesion radii. The nuclei behaviour is identical in degasified liquids; it takes place, however, below $\Delta p_0/\Delta p = 1$. 6—The pressure is increased again. Nuclei density does not decrease before the pressure exceeds higher values than before. 3, 4 and 6 are on one line. 7—A repeated pressure reduction which is reached by increasing the pressure up to $\Delta p/\Delta p_0 = 3.5$. 8—At $\Delta p_0/\Delta p = 0.5$, the liquid is oversaturated with gas and the liquid state is close to saturation. New nuclei are activated, the nuclei density is increasing again.

- Particle boiling comes to a standstill in degasified liquid if the boiler pressure exceeds the saturation by the overexpansion Δp .
- Particle boiling depends strongly on the gas content. The nuclei density of activated nuclei increases with the gas content.
- In the case of dissolved gas, particle boiling takes place in the range $0 < \Delta p_0 < \Delta p + p_{\text{gas}}$, with p_{gas} being the total pressure of the dissolved gases. Any further increase in the nuclei size by injection of gas is not possible in a gas-saturated liquid.
- Particle nuclei are easily diminished in size and number by increasing the boiler pressure, they are flooded and cannot be reactivated by just reducing the pressure (figure 10). Activation can only be generated by superheating proportional to the adhesion radius, i.e. by a boiling process before the nozzle or by direct contact with steam or gas bubbles.
- Particle nuclei respond slowly to an increase in pressure. The corresponding nuclei density is adapted asymptotically.
- At a degree of superheating of < 5 K no particle boiling was observed. The limit seems to depend on the maximum size of the suspended particles, which means that the degree of superheating would increase by filtration. We have not filtered the water in the supply tubes leading to the nozzle because the nuclei spectrum would be influenced by a pressure drop in the filter due to boiling, and it would be more difficult to study reproducibility. Similar problems occur with feed water pumps in water loops.

The reaction of the activated nuclei density or bubble density in relation to gradual pressure changes (indicated by the arrows) is described in more detail in figure 10. The nuclei density is determined by the measured bubble frequency and by the mass flow rate. The degree of superheating is 32 K, and the O_2 -content after gas injection is 12.8 mg/l. The behaviour of the particle nuclei can be observed particularly well in a gasified liquid; here, the adhesion radii are larger due to the additional gas partial pressure in the nuclei, and due to particle boiling consequently occurring in a wider pressure and temperature range.

5.2. Surface boiling

If one compares the sequence of the high-speed photographs of particle boiling in figure 8 with the bubbles in figure 11, the totally different appearance of these bubbles is noticeable. While in the first instance bubbles are generated in the bulk of the liquid jet, in the second instance they are formed on the jet surface only. They do not have the typical spherical shape and look more like scars on the surface; they are clearly distinguishable from particle bubbles. In order to avoid misunderstanding in the interpretation of the origin of these bubbles, we simply call them “surface boiling”, as mentioned above.

Most of these bubbles burst before having grown to a size of 1 mm. This type of boiling sets in at higher boiler pressures, where the nuclei for particle boiling are flooded and are inactive. It is remarkable that the nuclei density increases with higher pressure, which according to the Bernoulli equation corresponds to higher jet velocities. This contradicts the observation made in particle boiling, where the nuclei density decreases with increasing boiler pressure due to the nuclei flooding process at higher pressure. This boiling mechanism is strongly influenced by the flow conditions, velocity of the jet, form and diameter of the nozzle, and is not, or hardly, influenced by nuclei in the liquid. The essential features of this boiling type are summarized below:

- It seems that turbulence boiling has a time delay.
- Contrary to particle boiling, the amount of bubbles generated (nuclei density) grows with increasing pressure.
- In the primary state this boiling only takes place on the jet surface in the thin boundary layer.

- The mechanism destroying the subcooled free jet in the “turbulent breakup” (McCarthy & Molby 1974; Grant & Middleman 1966) may even be a cause of surface boiling. For example, the pulsating behaviour of the breakup length in the partly turbulent subcooled jet is identical to the behaviour of the bubble frequency at the onset of surface boiling.
- The greater the jet contraction and the smaller the jet diameter, the greater the delay in the start of surface boiling in relation to superheating and boiler pressure (figure 12). These effects disappear at $\text{dia} > 3 \text{ mm}$.
- Surface boiling responds only very weakly to gasification.
- It does not have the nuclei density hysteresis in pressure changes as particle boiling does (figure 10).
- Changes in the boiler state have virtually no effect on the time delay in surface boiling, which seems to be more dependent on pressure than on the degree of superheating.
- It is assumed that the time delay is caused by a creeping growth phenomenon of the bubbles under the jet surface (Lienhard & Day 1970).
- This boiling onset is determined by the flow condition at the point just before the liquid leaves the nozzle wall; this condition can be described by an Re number and an overexpansion Δp_n at that point.

A real physical explanation of the origin of this kind of boiling can not be given yet, but some facts which could have an influence will be discussed below. In the flow towards the nozzle inlet the liquid is accelerated and may become turbulent, thereby producing pressure fluctuations. These fluctuations increase with increasing jet velocity. As soon as the liquid detaches itself from the wall, shear stress ceases and the turbulent fluctuations within the free jet fade away. The turbulent pressure fluctuations will reach maximum values at that point of the nozzle where the liquid detaches itself from the wall. These turbulent pressure fluctuations can locally increase the overexpansion. But, as can be estimated, they are not large enough to induce homogeneous nucleation, i.e. additional nuclei on solid particles, as would be required. However, the usual behaviour of nuclei could not be observed, the production of bubbles increases with higher pressure. Therefore it is doubtful that this may be the reason for this type of boiling. As mentioned above, the sharp edges of the nozzle inlet may produce small vortices which detach themselves from the edge and flow with the jet. These vortices will continue their rotation, and gas or vapour can be sucked in beyond the jet surface, which may act as nuclei for the surface bubbles. Another influence could be the feedback of pressure fluctuations from the jet breakup to the nozzle, even the origin of the bubbles is close to the nozzle and within the breakup length of the jet. It can be argued, against this assumption, that in empirical descriptions of the onset of this type of boiling with the normal jet Re number, the measured data do not fit well.

As mentioned above, there are as yet no strong arguments in favour of any of these suggestions. It is even possible that all three effects—or even one which is not known yet—co-operate and influence each other. However, it is clear that boiling is influenced by the flow and particularly by the flow conditions just before the liquid is released from the wall of the nozzle. Note that a modified Re number and modified overexpansion fits the measured data of the boiling onset reasonably well.

The Re number of the free jet is defined as

$$\text{Re}_f = \frac{v_f \mu d_n}{\nu}, \quad [1]$$

with v_f being the jet velocity, d_n the nozzle diameter, μ the contraction and ν the kinematic viscosity. If one uses this Re number, these data do not fit well. If we assume that the origin of this kind of boiling lies in the flow towards the nozzle, just when the liquid is released from the wall, and if we assume a semi-spherical flow towards the nozzle, the average velocity v_s for an incompressible liquid in a semi-sphere with diameter d_n can be calculated as

$$v_s = \frac{v_f}{2} \cdot \mu^2. \quad [2]$$

A characteristic Re number in this flow section can be defined as

$$\text{Re} = \frac{v_s \cdot d_n}{\nu} = \frac{v_f \mu^2 d_n}{2\nu} \quad [3]$$

In addition to the flow condition defined by [3], a modified overexpansion Δp_n is used in which the normal overexpansion $\Delta p = p_{\text{sat}} - p_\infty$ is reduced by the pressure drop in the range of the pressure difference before and after the jet contraction, this follows for an incompressible liquid from the Bernoulli equation:

$$\Delta p_n = \Delta p - \frac{\rho}{2} v_f^2 (1 - \mu^4) \quad [4]$$

With these two modified quantities an empirical correlation can be found which fits the limit of the onset of surface boiling reasonably well (see figure 12):

$$\text{Re} = (57.5 - 8.5\Delta p_n) \cdot 10^3 \quad [5]$$

Only the nozzle diameter and the jet contraction, which describes the form of the nozzle, are descriptive parameters. Equation [5] cannot be solved explicitly for calculation of the boiler pressure or the degree of superheating of the jet. Therefore the broken lines in figure 12 are calculated by iteration for different types of nozzles. The solid lines are the limits of where the onset of surface boiling was observed under increasing pressure; and being completely reversible, the boiling stops under decreasing pressure. With a further increase in pressure in the hatched area, the bubble frequency increases according to figure 6. The line of [5] and the experimental lines (—) are based on many experiments with different boiler states, i.e. varying pressure and temperature, and the results are reproducible for each of the nozzles used.

6. MAXIMUM SUPERHEAT IN A JET

For superheated jets one can imagine technical applications like fuel injection into a combustion chamber where the highly superheated jet is maintained until it impinges on the surface of a wall where it sprays vehemently. If one knows the behaviour of the different boiling phenomena in the free jet, it is possible to calculate a maximum superheat jet that does not destroy itself by boiling. Therefore, a high-pressure loop was constructed whereby boiler pressures up to 5 MPa could be realized. A sharp-edged nozzle of 0.5 mm dia was used and a superheating of 50–74 K at a boiler pressure of up to 5 MPa could be reached. It must be taken into consideration that with rising boiler pressures or free-jet velocities, and with smaller jet diameters, the jet breakup as observed in the cold jet becomes increasingly important. It can be calculated that in small diameter jets the evaporation of the jet surface cools even the core of the jet so that only a short jet length can be

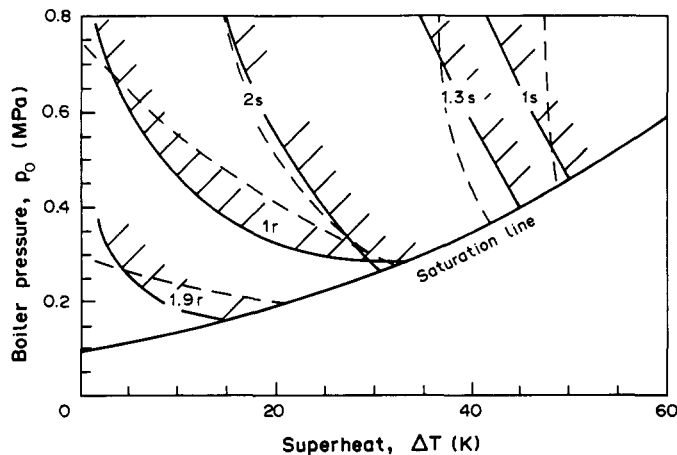


Figure 12. Comparison of the measured boiling limits for different nozzles: —, ▨ experiments; --- calculated with [5].

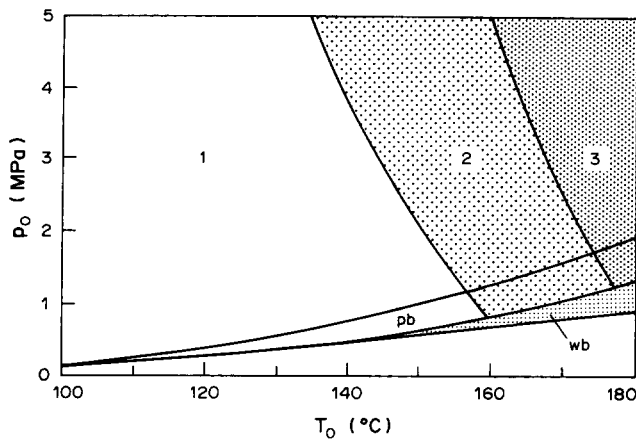


Figure 13. Boiler states of the surface, particle and wall boiling for a nozzle with 0.5 mm dia and a sharp-edged inlet area: (1) no boiling; (2) jet contains single bubbles of the surface type; (3) jet breaks up into a cone flow of vapour and droplets.

used. In the case of using water and a 0.5 mm nozzle, the jet length which could be attained was 40 mm. In figure 13 the boiling areas are shown, depending on the boiler pressure p_0 and temperature T_0 ; the lower curve is the vapour pressure curve. With the boiler states of area 1 no boiling was observed, in area 2 surface boiling occurred in measurable single bubbles and in area 3 the jet broke up into a cone-shaped flow of vapour and droplets. The areas of particle and wall boiling are indicated by pb and wb. Even in this case the experimental results given in figure 13 are in good agreement with the calculated limit for surface boiling [5].

7. SUMMARY

To obtain a highly superheated free jet means shifting the boiler state, where boiling starts (figure 5), to higher degrees of superheating. There are three limits that have to be considered, the limits where particle, surface and wall boiling set in. In order to avoid particle boiling the nuclei in the boiler must not be activated. The boiler pressure must be above the saturation pressure and the liquid must not be oversaturated with gas. For technical applications degassing or filtering of suspended particles is not necessary if the heating of the liquid is accompanied by boiling (degassing), and if the boiler pressure is then kept above the level of $\Delta p_0/\Delta p = 1$. Particle boiling does not depend on the nozzle shape. Surface boiling strongly depends on nozzle size and shape. With decreasing nozzle length, nozzle diameter and jet contraction the boiling is shifted to higher superheating. By using nozzles with sharp-edged inlets, the effective wetting length is reduced almost to zero as the liquid detaches itself at this point. The elevated inlet effects a maximal jet contraction of about 0.8. Reducing the nozzle diameter would theoretically raise the possible degree of superheating.

Calculations have shown that with the use of short nozzles wall boiling usually occurs after surface boiling. Wall boiling also decreases with a sharp nozzle shape but is independent of the nozzle diameter. So wall boiling can be neglected when short nozzles are used.

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