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Pre-pressurization effects on initiation of subcooled pool boiling during pressure and power transients

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Abstract—Evidence is presented demonstrating effects of pressure–temperature history on conditions for initiation of nucleate pool boiling in water under a range of conditions. Boiling phenomena were studied using platinum-wire heating elements. Element temperature, pressure or heat flux, and boiling initiation time were monitored during both increasing-power and decreasing-pressure transients. It was found that, if the system were subjected to highly subcooled (over-pressure) conditions prior to a transient, nucleate boiling was significantly suppressed. Results agree qualitatively with predictions of a model based on contact-angle hysteresis in movement of the liquid–vapor meniscus in a boiling nucleation site.

1. INTRODUCTION

EVIDENCE of the suppression of nucleate boiling as a result of pre-pressurization has been found in studies of subcooled and saturated nucleate boiling during pressure and power transients. Boiling inception from horizontal cylinders in the form of platinum wires has been investigated under pressures ranging from atmospheric to 1.4 MPa, saturation temperatures of 100, 150 and 195°C, and subcoolings of 5, 10 and 30 K. In studies of pressure transients, the heat flux from the cylinder was held constant, initially under conditions of natural convection heat transfer, while the pressure was descreased exponentially at periods ranging from 3.6 to 7.2 s. In studies of power transients, the pressure was held constant while the heat flux was increased linearly with time at "ramp" rates ranging from 0.008 to 8.0 MW/m^2 s.

In certain cases, a substantial overpressure was applied briefly prior to the transient. In these cases it was found the boiling initiation was inhibited, i.e. that boiling initiation occurred at substantially greater cylinder surface temperature and heat flux than was the case in the absence of pre-pressurization. Observed effects were in qualitative agreement with predictions of a model based on the concept of contact-angle hysteresis, i.e. on the difference between the contact angle made by the vapor–liquid interface as the interface advances over a previously unwetted surface or recedes over a previously wetted surface.

This paper deals first with a review of prior work on boiling initiation during transients, effects of pre-pressurization, and effects of contact angle hysteresis. A specific model is developed to relate pre-pressurization and contact-angle effects. Description of apparatus and experimental procedure is followed by discussion of results and comparison of results with model predictions.

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2. REVIEW OF PRIOR WORK

There have been many investigations of boiling phenomena which, although not necessarily designed to that end, provide information on inception of boiling during transient increase in heat flux or decrease in pressure. In the following discussion, the term "superficial heat flux", sometimes called "applied heat flux", refers to the thermal power delivered to a heating element divided by the surface area through which heat is being transferred to surroundings. In many studies, the variable reported is the superficial heat flux which may be substantially greater than the actual heat flux because of sensible-heat effects in the heating element. In the following, T_s denotes saturation temperature, T_a ambient liquid temperature, and T_w heater element surface temperature. Superheat, or ΔT_s is $T_w - T_s$, and subcooling, or ΔT_{sub} is $T_s - T_a$. Exponential changes in heat flux or pressure are characterized by the e-fold period τ. Only boiling in water is considered in this paper.

A. *Boiling initiation during power transients*

In step application of power to a heating element in subcooled or saturated water, the greater the superficial heat flux, the greater is the superheat at boiling initiation. This was observed by Cole [1] and confirmed by Ngheim *et al.* [2], Ciampi *et al.* [3], Tolubinskiy *et al.* [4] and Derewnicki [5]. Using very high superficial heat fluxes, Ebrardt and Vernier [6] observed surface temperature increase at rates as high as 2.5×10^6 K/s and superheats at boiling initiation approaching 200 K in water at 20–25°C and atmospheric pressure. Derewnicki and Hall [7] applied a superficial heat flux of 1.13×10^8 W/m^2 to water at

NOMENCLATURE

- a empirical factor, equation (1)
- b empirical factor, equation (1)
- k thermal conductivity (W/m K)
- p pressure (Pa)
- q heat flux (W/m^2)
- r radius of curvature of vapor space (m)
- r_c radius of cavity (m)
- s radius of meniscus line of contact (m)
- T temperature.

Greek symbols

- β half angle of cavity apex
- θ contact angle
- λ latent heat of vaporization (J/kg)
- ρ density (kg/m^3)
- σ surface tension (J/m^2)
- τ time constant (s).

Subscripts

- a advancing (contact angle); ambient (temperature or pressure)
- b temperature condition at boiling initiation
- d pressure condition at boiling initiation
- m maximum
- o initial
- r receding (contact angle)
- s saturation
- sub subcooling (temperature)
- v vapor (pressure or density)
- w heating element (temperature).

20°C and atmospheric pressure and observed surface temperature increase at a rate of 4.3×10^6 K/s and boiling initiation at the homogeneous nucleation temperature, 310°C. A consistent observation is that, with exponential or ramp application of power, the greater the rate of increase in superficial heat flux, the greater the superheat at boiling initiation. This was observed by Rosenthal and Miller [2], Hall and Harrison [8], Tolubinskiy *et al.* [4, 9], Johnson [10], and Sakurai and Shiotsu [11].

As subcooling increases, superheat at boiling initiation increases. This was observed in step applications of power by Lurie and Johnson [12] and Tolubinskiy *et al.* [4, 9], and in ramp or exponential applications of power by Hall and Harrison [8], and Johnson [10]. As pressure increases, superheat at boiling initiation decreases, as observed by Tolubinskiy *et al.* [4, 9] and Schultz *et al.* [13] in step application of power, and by Johnson [10] in exponential application of power.

B. *Boiling initiation during pressure transients*

Nucleation from surfaces at the temperature of the surrounding fluid during decompression was studied by Hooper and Abdelmessih [14] who observed that boiling initiation took place at superheat in excess of that expected in steady-state boiling. This was confirmed by Weisman *et al.* [15]. Such excesss was not observed by Kenning and Thirunavukkarasu [16]; however, their study involved decompression to levels well below saturation. Weisman *et al.* also observed increasing superheat at boiling initiation with increasing rate of decompression, in agreement with studies of Lienhard *et al.* [17, 18]. Sakurai *et al.* [19] studied decompression of water at initial pressures from 0.59 to 1.9 MPa and temperatures from 80 to 100°C at exponential periods from 3 to 60 ms. They found superheat at boiling initiation to be sensitive to heat flux but insensitive to decompression period.

C. *Physical models for boiling initiation*

The above observations are generally consistent with concepts and criteria for boiling inception introduced by Griffith and Wallace [20] and further developed by Hsu [21], Bergles and Rohsenow [22], Han and Griffith [23], Madejski [24], and Cole *et al.* [13, 25, 26]. In summary, the superheat and heat flux required for vapor-bubble growth and departure from an active boiling initiation site in the form of a cavity of effective mouth radius r_c are related by

$$T_w - T_s = qar_c/k + 2\sigma T_s/\lambda\rho_v br_c, \tag{1}$$

in which a and b are empirical factors given respectively as 0 and 1 for the Griffith and Wallis approach, 1.6 and 1.25 for that of Hsu, 1.5 and 1.0 for that of Han and Griffith, and 1.8 and 1.67 for that of Sakurai and Shiotsu [11].

If, in the boiling surface, there are active, or vapor-containing sites of all possible radii, then boiling first takes place from a cavity with critical radius $(2k\sigma T_s/\rho_v\lambda b^2 q)^{1/2}$ with corresponding superheat

$$(T_w - T_s)_{min} = (8\sigma T_s q/k\lambda\rho_v)^{1/2}, \tag{2}$$

which is independent of site geometry. However, as is often the case, especially in the laboratory, if the radius of the largest active site r_m is less than the critical radius, then boiling initiation conditions are very dependent on geometry and are given by equation (1) with $r_c = r_m$. For example, in saturated water at atmospheric pressure with a heat flux of 0.5 MW/m^2, the critical radius is about 7 μm at which the boiling initation superheat is about 10 K, whereas, if $r_m = 1$ μm, the superheat is about 30 K.

During a transient, the surface temperature and heat flux are functionally related and governed by conductive or convective heat transfer prior to boiling initiation. The conditions at initiation are thus determined by the intersection of this functional relationship with that given by equations (1) or (2). Analysis of such conditions for transients of various types, accounting for variation of fluid properties with pressure and temperature, leads to qualitative support of the experimental observations cited above.

A more detailed examination of experimental results in the literature reveals ambiguities, uncertainties, and apparently stochastic effects that escape rationalization by simple models. The size spectra of active or potential nucleation sites vary widely with material and with surface treatment. Were the spectra known, that information could be factored into analysis of data. There are, moreover, other and less widely examined complications in the analysis of boiling phenomena. These have to do with the effects of pressure–temperature history, i.e. the influence on boiling initiation of variations in nucleation site conditions as dictated by pressure and temperature pre-conditioning.

D. *Effects of pressure–temperature history on boiling initiation*

Factors affecting boiling initiation, beyond those described above, are the advancing and receding contact angles at the vapor–solid–liquid interface, the degree of subcooling prior to boiling, and, of course, the geometry of nucleation sites. The model described below derives from concepts introduced by Fabic [27], Holtz [28], and Singh *et al.* [29] for cylindrical-cavity sites and the theoretical development by Chen [30] and Apfel [31] for conical-cavity sites advanced and supported experimentally by Winterton *et al.* [32, 33], Cornwell [34], and Eddington *et al.* [35, 36]. The model, as described herein, does not account for the presence of inert gas in nucleation sites. Inert gas can be accounted for readily, as has been done by Winterton [32], the effect essentially being a reduction in the degree of superheat required for nucleation.

Consider a heating element in contact with a fully degassed liquid, both at uniform temperature T, static pressure p, and vapor pressure $p_v \leqslant p$. Potential sites for nucleate boiling, as shown in Fig. 1, are characterized as conical cavities with a range of mouth radii r_c up to a maximum $r_{c,max}$, all with apical half angle β. Mechanical equilibrium requires that the spherical interface between the liquid and any vapor present in a cavity have the radius of curvature

$$r = 2\sigma/(p-p_v), \tag{3}$$

in which σ is the vapor–liquid surface tension. The radius s of the circular line of contact between the meniscus and the cavity wall is $r\cos(\pi-\theta+\beta)$, thus

$$s = 2\sigma\cos(\pi-\theta+\beta)/(p-p_v), \tag{4}$$

in which θ is the contact angle. The largest cavity that could be "filled" with vapor is one for which the meniscus is at the cavity mouth and the contact angle is the advancing contact angle θ_a (Fig. 1b). Call this maximum radius r_c^* which is given by

$$r_c^* = 2\sigma\cos(\pi-\theta_a+\beta)/(p-p_v). \tag{5}$$

Larger cavities contain vapor, but with $s = r_c^*$ (Fig. 1c). In smaller cavities, the meniscus is at the cavity mouth, but $\theta < \theta_a$ (Fig. 1a). Of course, r_c^* cannot exceed $r_{c,max}$ and cavities with $\beta \geqslant \theta_a - \pi/2$ are flooded and inactive.

Suppose that prior to boiling, the system has been subjected to variations in pressure and temperature. Those conditions for which r is minimized determine a minimum or critical value of s, called by Chen the deactivation radius. Consider now several scenarios which begin with a surface conaining many potentially active nucleate boiling sites and conditions of p_0, T_a, and p_{va}, with σ and p_v evaluated at ambient temperature T_a. Various pressure and temperature changes are made leading to boiling initiation.

Case A. Power transient without prior subcooling. Initially, $r = r_0$, which is given by

$$r_0 = 2\sigma_a/(p_0-p_{va}). \tag{6}$$

It is assumed for the moment that $p_0 - p_{va}$ is

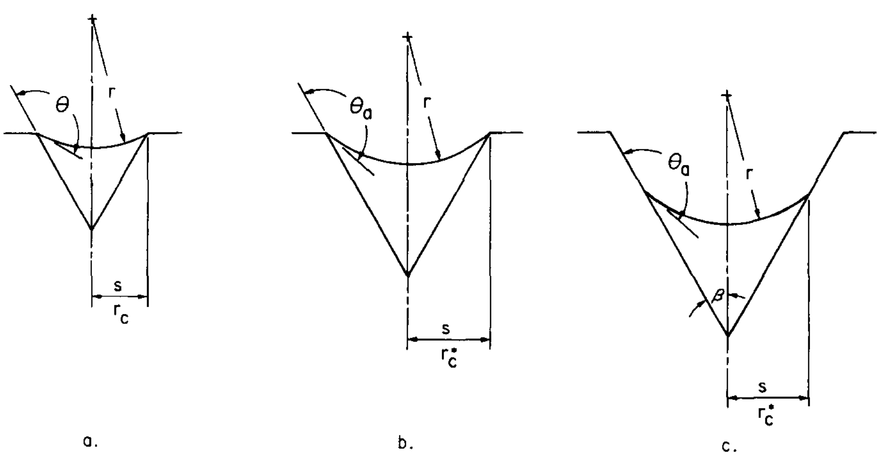

FIG. 1. Potential sites for nucleate boiling approximated as conical cavities of apex angle 2β, mouth radius r_c, and radius s of meniscus line of contact. (a) $r_c < r_c^*$, (b) $r_c = r_c^*$, (c) $r_c > r_c^*$.

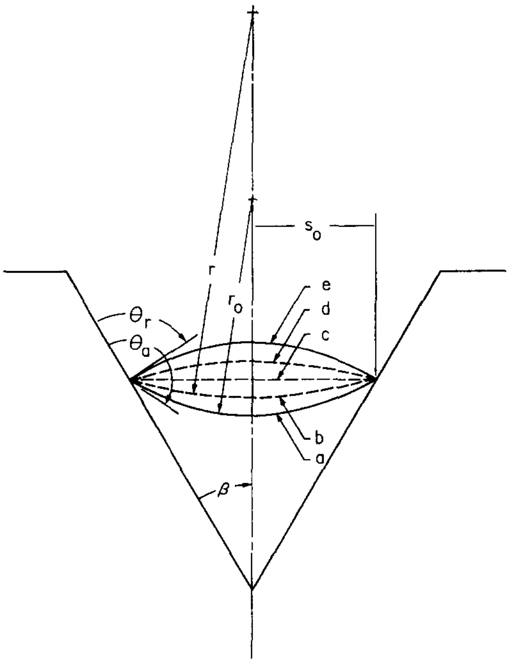

FIG. 2. Meniscus configurations during a power transient. (a) initial condition, $\theta = \theta_a$; (b) $r > r_0$, $\theta < \theta_a$; (c) $r = \infty$, $p_v = p_0$; (d) $p_v > p_0$, $\theta > \theta_r$; (e) boiling initiation, $T = T_b$, $\theta = \theta_r$.

sufficiently large that the advancing contact angle is reached (Fig. 2a), so that the radius of the meniscus line of contact is

$$s_0 = r_0 \cos(\pi - \theta_a + \beta). \tag{7}$$

As T increases further, r increases and θ decreases (Fig. 2b), while s remains constant at s_0, which satisfies both equation (7) and

$$s_0 = r\cos(\pi - \theta + \beta) = 2\sigma_a \cos(\pi - \theta + \beta)/(p_0 - p_v). \tag{8}$$

As T increases, r changes sign (convex–concave transition of the meniscus, Fig. 2c) and then decreases in magnitude. Boiling commences when either $r = s_0$ (hemispherical interface) or when $\theta = \theta_r$ (Fig. 2e), the receding contact angle, and the meniscus is free to recede toward the mouth of the cavity. Here it is assumed that $\theta_r > \beta$. Thus, boiling initiation occurs at temperature T_b, for which

$$s_0 = 2\sigma_b \cos(\theta_r - \beta)/(p_{vb} - p_0). \tag{9}$$

Since s_0 also satisfies equations (6) and (7), it follows that, at boiling initiation, T_b satisfies the criterion

$$p_{vb} = p_0 + \frac{\sigma_b \cos(\theta_r - \beta)}{\sigma_a \cos(\pi - \theta_a + \beta)}(p_0 - p_{va}). \tag{10}$$

† Here it is assumed that $\theta_r < \beta + \pi/2$. As pointed out by Winterton [32], if this is not the case, the liquid will retreat to the cavity mouth prior to nucleation, and nucleation is unaffected by pre-pressurization.

If the meniscus is initially at the cavity mouth, boiling initiation takes place when the radius of curvature is at a minum, i.e. at $r_c^* = 2\sigma_a \cos(\pi - \theta_a + \beta)/(p_0 - p_{vo})$, and boiling initiation is at T_b' which satisfies the criterion

$$p'_{vb} - p_0 = 2\sigma'_b / r_c^*. \tag{11}$$

However, T_b' is greater than T_b and first boiling thus takes place from a partially filled cavity with mouth radius given by

$$r_c^{**} = 2\sigma'_b/(p'_{vb} - p_0) = r_c^* \sec(\theta_r - \beta). \tag{12}$$

If $r_{c,max} \geqslant r_c^{**}$, boiling commences at T_b. If $r_c^* \leqslant r_{c,max} < r_c^{**}$, boiling commences at T_b'. If $r_{c,max} < r_c^*$, boiling commences at T_b'' under which conditions

$$p''_{vb} - p_0 = 2\sigma''_b / r_{c,max}. \tag{13}$$

As a subcase, suppose that prior boiling had left initial conditions such that the advancing contact angle had not been reached. Active sites would be filled and boiling initiation would take place from the largest active site at temperature T_b''.

Case B. Power transient preceded by temporary pressurization. In this scenario, pressure is first raised to p_m, then decreased to p_0, under constant temperature T_0. Then ambient temperature is increased to T_a. In the power transient, heater temperature is increased until boiling is initiated. There is a threshold for pre-pressurization to affect subsequent boiling. To cause meniscus advance into a cavity, p_m must be sufficient that θ_a is reached in the largest potentially active nucleation site. This threshold value is

$$p_{m,min} = p_{vo} + 2\sigma_0 \cos(\pi - \theta_a + \beta)/r_{c,max}. \tag{14}$$

Application of p_m above the threshold results in a deactivation radius given by

$$s_b = 2\sigma_0 \cos(\pi - \theta_a + \beta)/(p_m - p_{vo}). \tag{15}$$

Subsequent reduction in pressure to p_0 causes θ to decrease and r to increase. Only increased temperature can cause sign change in r. Boiling is initiated when the meniscus recedes from the cavity.† This occurs at temperature T_b, for which the boiling initiation criterion is

$$p_{vb} = p_0 + \frac{\sigma_b \cos(\theta_r - \beta)}{\sigma_0 \cos(\pi + \theta_a - \beta)}(p_m - p_{vo}). \tag{16}$$

Note that according to this approximation, the temperature T_b required for boiling initiation is independent of ambient temperature T_a.

Case C. Pressure transient. In this scenario, pressure is increased from p_0 to p_m. Then temperature is increased from T_0 to T_b. Then pressure is decreased until boiling is initiated. Prior to pressure decrease, the meniscus radius of curvature is $2\sigma_b/(p_m - p_{vb})$ and the deactivation radius is $2\sigma_0 \cos(\pi - \theta_a + \beta)/(p_m - p_0)$. As pressure is decreased, meniscus movement commences, and boiling is initiated at pressure p_d which satisfies the criterion

$$p_d = p_{vb} - \frac{\sigma_b \cos(\theta_r - \beta)}{\sigma_0 \cos(\pi - \theta_a + \beta)}(p_m - p_0). \quad (17)$$

If the meniscus is initially at the cavity mouth, then boiling begins at pressure p'_d which satisfies

$$p'_d = p_{vb} - \frac{2\sigma_b}{r_{c,max}}. \quad (18)$$

Thus, there is a threshold for p_m to affect boiling initiation. If

$$p_m > p_0 + 2\sigma_0 \cos(\pi - \theta_a + \beta)/r_{c,max} \cos(\theta_r - \beta), \quad (19)$$

then p_d depends on p_m.

3. APPARATUS AND PROCEDURE

All experiments were performed using heating elements made of platinum wire (Omega Engineering SPPL-010), 9.6 cm in length and either 0.127 or 0.25 mm in diameter,. The wires were connected to 0.635-cm dia. brass electrodes using high-temperature solder, and were lightly spring tensioned to assure linearity.

The heating element was mounted horizontally and coaxially in an insulated, stainless-steel cylindrical pressure vessel, 10 cm inside diameter and 40 cm long. Quartz windows with 2.54-cm clear aperture allowed viewing and photography of the heating element. The pressure vessel was provided with a 2-kW immersion heater and a copper–constantan thermocouple, together with a control system maintaining system ambient temperature. An external pressurizer was used to maintain the desired system pressure. The pressurizer contained a neoprene diaphragm to isolate nitrogen pressurizing gas from the liquid-filled pressure vessel. Solenoid-operated valves in gas and liquid lines allowed controlled pressurization and depressurization of the system. A (Kistler Model 603A) quartz miniature pressure transducer, with a custom-made cooling adaptor, penetrated the wall of the pressure vessel to provide the means for monitoring pressure during a transient.

The pressure vessel was supported on an optical table along with a (Spectra Physics) 2-W argon ion laser and a (Newport Research Instaview) holographic interferometry system. Mounted external to the table was either a still camera or a (Hycam) cine camera used in recording boiling phenomena on the platinum heater element.

Power to the heater element was provided by two 12-V storage batteries, in parallel, via a custom-made feedback control system. An analog computer generated a reference voltage proportional to the desired time dependence of power dissipation in the heater element. The voltages across the element and a standard resistor in series were sensed and multiplied, the product being proportional to the power dissipation in the element. The product voltage was compared to the reference voltage, and the difference voltage, through a Darlington amplifier, drove four parallel SK3037 power transistors providing current from the batteries.

Prior to any transients, water in the pressure vessel was boiled in bulk for one hour at atmospheric pressure in an attempt to purge dissolved gases,. This was followed by boiling from the heater element for ten minutes in an attempt to activate nucleation sites and purge any non-condensable gases from the sites. Vigorous boiling, at high heat flux, minimized the likelihood of significant inert gas content in even the smaller of the nucleation sites.

During a power transient the voltages across the heater element and the standard resistor were monitored simultaneously and data were stored on floppy disk in a (Nicolet) two-channel digital oscilloscope. These data were then transferred to a microcomputer for processing and analysis. Pressure transients were carried out in two stages. First, data from the pressure transducer were monitored during a sequence of depressurizations to assure reproductibility of the transient. Then, in a final run, voltage data were collected as in a power transient. The voltage data, after processing, led to records of both superficial heat flux and average heating element temperature as functions of time during the transient. With a reference voltage increasing linearly with time, it was found that the superficial heat flux also increased linearly within the precision of the digital oscilloscope, even during vigorous nucleate boiling [37]. Details of the design, construction, testing, and calibration of the apparatus as well as procedures and computer codes for data processing are described elsewhere [38, 39].

4. RESULTS AND DISCUSSION

A. *Boiling initiation during power transients with no pre-pressurization*

A number of measurements were made during transients which had been preceded by a period of boiling from the heat element under the same ambient pressure and temperature conditions as those of the transient. This pre-boiling is a common experimental procedure carried out for the purpose of expelling non-condensable gases from nucleation sites and assuring the activation of sites of a wide range of sizes. Each transient began with the heating element at ambient temperature. Then power to the heating element was increased at a uniform rate until the superficial heat flux reached about 0.8 MW/m^2 whereupon the transient was terminated to avoid departure from nucleate boiling. During the transient, the heater temperature and superficial heat flux were monitored electrically and the time of boiling initiation was determined from cine records of the event.

Measurements were made over a period of several years, using a number of heating elements of both

Table 1. Superheat at boiling initiation vs saturation temperature and degree of subcooling. In all cases boiling had previously taken place under the same conditions

T_s (°C)	$T_s - T_a$ (K)	$T_b - T_s$ (K)	
		Single series	Global average
100	0	17±4	25±15
	5	21±4	31±10
	10	19±4	22±5
	30	26±4	26±4
150	5	9±4	14±7
	10	9±4	16±9
	30	15±4	22±8
195	5	10±4	13±7
	10	11±4	18±7
	30	16±4	17±5

0.25 and 0.127-mm dia. platinum, and with transient durations from 0.1 to 100 s. The wide range of durations or ramp rates of increase in superficial heat flux was chosen with the hope of differentiating between boiling initiation during conditions of either conduction or natural convection heat transfer from the heating element. Table 1 shows both global average results for all measurements and results from a single series, namely those for a single 0.25-mm dia. element and a ramp rate equal to about 0.4 MW/m²s (2-s run duration). Because of variations from element to element and other uncontrolled factors, the global results show a great deal more scatter ($1-\sigma$ limits). The 4-degree uncertainty in temperature for the single series is potential systematic error in determination of the very low electrical resistances (about 0.2 ohm of the platinum heater and the associated standard resistor in series. Boiling initiation conditions as a function of ramp rate are summarized in Table 2. Minimum uncertainty in T_b is about ± 4 K.

The results of Table 1 are in general agreement with prior observations that the superheat at boiling initiation increases with increasing subcooling. However, the results of Table 2 are not conclusive. Of the 19 groupings in the table, 7 show an increase in T_b with increasing ramp rate, 4 show a decrease, and 8 show little or no effect.

B. *Pre-pressurization effects on boiling initiation during power transients*

Reported in this section are conditions for boiling initiation during transients which had been preceded by significant pre-pressurization or subcooling. Results are expressed as either superheat, $T_b - T_s$, or vapor pressure excess, $p_{vb} - p_0$. The scenario for the measurements followed Case B of the physical models described above. Prior to a test, vigorous pre-boiling was carried out at the ambient conditions T_0 and p_0. Then pressure p_m was applied. In some cases ambient temperature was then raised to T_a, Then pressure was reduced to either p_0 or to an intermediate value p_a. Measurements of temperature, superficial heat flux, and boiling initiation time were then made during a power transient. One or more additional power transients were then conducted. Since vigorous boiling had taken place under ambient conditions during the first transient, the subsequent transients then followed the Case A scenario of the physical models described above, i.e. a power transient without pre-pressurization or subcooling.

Representative results are shown in a series of graphs relating $T_w - T_a$ to superficial heat flux. Figure 3, for a 0.25-mm heater, illustrates the following conditions: $T_0 = 100$°C, $p_0 = 0.101$ MPa, $p_m = p_a = 0.476$ Mpa ($T_s = 150$°C), and a ramp rate of 3.8 MW/m²s (0.2-s run duration). A second transient immediately followed. For the first, boiling was observed to begin at $T_w - T_a = 34$ K ($T_b - T_s = 29$ K). For the second, $T_w - T_a = 25$ K ($T_b - T_s = 20$ K). Figure 4 illustrates a similar scenario for a 0.25-mm diameter element, with pressurization to $p_m = 1.40$ MPa at $T_a = 95$°C followed by reduction of pressure to atmospheric. The transient was two seconds in

Table 2. Superheat at boiling initiation vs. saturation temperature, degree of subcooling, and ramp rate of increase in superficial heat flux. In all cases, boiling had previously taken place under the same conditions. Heater diameter was 0.25 mm for series 7 and 13, and 0.127 mm dia. for series 14

		$T_b - T_s$ (K)							
		$T_s = 100$°C		$T_s = 150$°C			$T_s = 195$°C		
Series	Ramp rate (MW/m²s)	ΔT_{sub} (K) 0	5	5	10	30	5	10	30
7	7.5			19	17		29	28	
	0.75				27	25	15	22	
	0.075			22	26	24			
	0.0077				27	30			
13	0.36	17	21		9	15		11	16
	0.036	16	24		4	7		10	12
14	0.36	37	43	11	18	22	11	18	21
	0.036	41	44	8	9	31	11	16	20

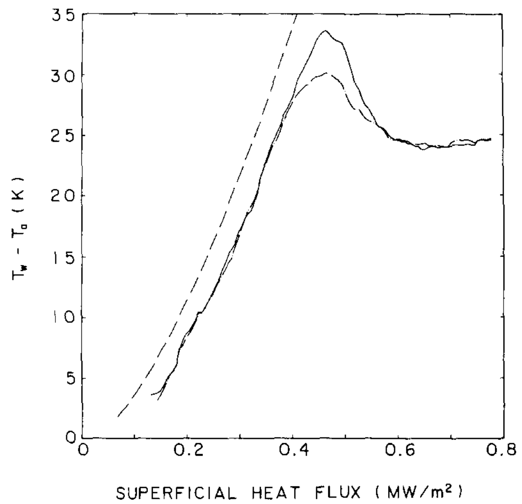

FIG. 3. $T_w - T_a$ vs superficial heat flux for two power transients. For the first (solid line), 0.476 MPa pressure was applied at 100°C ambient temperature. Ambient temperature was raised to 145°C prior to the transient. The second transient (broken line) immediately followed the first. The dashed line represents purely conductive heat transfer for a ramp rate of 3.8 MW/m²s [40].

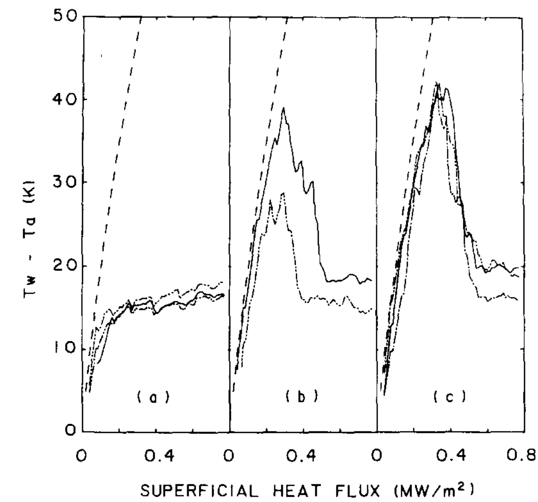

FIG. 5. Effect of p_m on the course of boiling during a power transient. Boiling curves display $T_w - T_a$ vs superficial heat flux for 20-s duration transients with $T_a = 100$°C and $p_0 = 0.101$ MPa. (a) $p_m = p_0$ (no pressurization), (b) $p_m = 0.79$ MPa, (c) $p_m = 1.5$ MPa.

duration (ramp rate = 0.36 MW/m²s). Boiling initiation was observed at $T_b - T_s = 39$ K. In the immediately following transient, without pre-pressurization, initiation was observed at $T_b - T_s = 21$ K.

Figure 5 illustrates qualitatively the effect of p_m during pre-pressurization on the course of boiling during a power transient. All transients illustrated were of 20-s duration and were for a 0.25 mm diameter heating element. Replicate data demonstrate the day-to-day reproducibility of measurements. In all cases, transients were preceded by boiling from the element at a heat flux of about 0.5 MW/m² for 10 minutes, with $T_a = 100$°C and $p_0 = 0.101$ MPa. Transients described by Fig. 5(a) had no pre-pressurization. For those described by Fig. 5(b), pre-boiling was followed by 10 minutes pressurization to $p_m = 0.79$ MPa. Here it must be acknowledged that, despite efforts at purging non-condensable gases from the bulk liquid, the 10-min pre-pressurization period may have allowed some uncontrolled diffusion of such gases into surface cavities. Pressure was reduced to p_0 immediately prior to the transient. Transients described by Fig. 5(c) were conducted just as those of Fig. 5(b), except $p_m = 1.5$ MPa. Dashed lines in the figures show that results prior to boiling initiation followed the pattern of purely convective heat transfer. Clearly, pre-pressurization can have a profound effect on boiling initiation and the course of transient boiling. Threshold phenomena and effects of even greater pressure or subcoolings are subjects of future investigations.

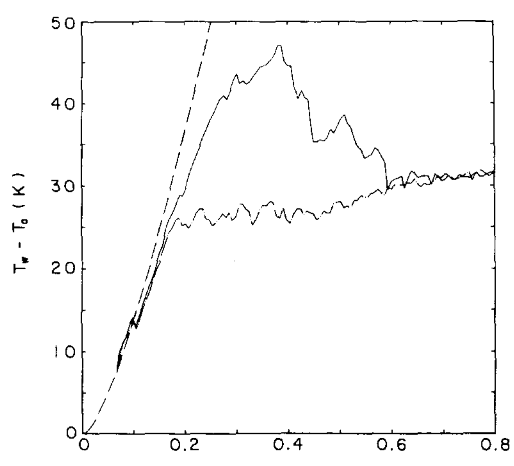

FIG. 4. $T_w - T_a$ vs superficial heat flux for two power transients. For the first (solid line), 1.40 MPa pressure was applied at 95°C ambient temperature. Pressure was reduced to 0.101 MPa prior to the transient. The second transient (broken line) immediately followed the first. The dashed line represents purely conductive heat transfer for a ramp rate of 0.36 MW/m²s [40].

Data for all power transients with pre-pressurization, as well as subsequents transients under the same ambient conditions, are presented in Table 3. Results are presented in terms of the pressure differences identified in equations (10) and (16). These data and the associated figures leave no doubt that the pressure–temperature history of a system can have a profound effect on conditions for boiling initiation. Neither the scope nor the precision of the data allow for a quantitative comparison of results with predictions of the physical models which approximate the effects of contact-angle hysteresis. Equation (16) suggests that the pressure ratio $\sigma_0(p_{vb} - p_0)/\sigma_b(p_m - p_{vo})$ is proportional to the cosine ratio $\cos(\theta_r - \beta)/\cos(\pi - \theta_a + \beta)$. Examination of the data for transients with pre-pressurization reveals that

Table 3. Effects of pre-pressurization on boiling initiation condition during power transients. Heater diameter was 0.25 mm for series 10 and 13, and 0.127 mm diameter for series 14

Series	Conditions during pre-pressurization p_m (MPa)	T_0 (°C)	Conditions during transient p_0 (MPa)	T_a (°C)	Boiling initiation conditions: With pre-pressurization $p_m - p_{v0}$	$p_{vb} - p_0$	Without pre-pressurization $p_0 - p_{va}$	$p_{vb} - p_0$
10	1.40	100	0.101	100	1.296	0.63±0.26	0.000	0.13±‡
	0.476	100	0.476	147	0.374	0.43±†	0.037	0.19±0.01
	0.476	100	0.476	145	0.374	0.49±†	0.061	0.31±0.01
	1.40	100	1.40	190	1.296	0.55±†	0.143	0.26±0.01
13	1.40	100	0.101	100	1.296	0.18±0.04	0.000	0.07±0.01
	1.40	95	0.101	95	1.313	0.23±0.03	0.017	0.11±0.02
	1.40	90	0.101	90	1.328	0.25±†	0.031	0.09±0.01
	1.40	70	0.101	70	1.366	0.21±†	0.070	0.14±0.01
	1.40	145	0.476	145	0.982	0.20±0.09	0.061	0.09±0.04
	1.40	140	0.476	140	1.036	0.28±0.01	0.115	0.13±0.02
	1.40	120	0.476	120	1.200	0.51±†	0.277	0.23±0.07
14	1.40	100	0.101	100	1.296	0.49±0.06	0.000	0.25±0.02
	1.40	95	0.101	95	1.313	0.50±0.04	0.017	0.29±0.01
	1.40	145	0.476	145	0.982	0.46±0.02	0.061	0.14±0.03
	1.40	140	0.476	140	1.036	0.36±0.22	0.115	0.15±0.03
	1.40	120	0.476	120	1.200	0.64±0.14	0.277	0.45±0.11

† Single measurement.
‡ Range: 0.05–0.55.

the pressure ratio is not constant but instead tends to increase with increasing temperature of boiling initiation. This trend may be due to imperfect removal of inert gases. Its presence initially in nucleation sites or its diffusion to nucleation sites would lead to a reduction in the denominator and an increase in the numerator of the pressure ratio. Alternatively, the trend may be due to variations with temperature of the contact angles. Adamson [42] suggests that the temperature coefficient is on the order of −0.1 degree/K. A decrease of only a few degrees in either or both θ_r and θ_a can lead to a doubling of the cosine ratio.

C. *Pressure transients*

A series of pressure transients was carried out following the Case C scenario of the physical models described above. In all cases, water was boiled in bulk for one hour and pre-boiling was carried out for ten minutes at atmospheric pressure. While ambient temperature was held at 100°C, pressure was raised to p_m. Then, power was applied to the heating element resulting in a superficial heat flux of nominally 0.42 MW/m^2 and an element temperature of 160°C. Pressure was then decreased to atmospheric at an exponential period of nominally 5 s. Measurements and observations during decompression yielded the pressure p_d at which boiling was initiated.

Typical results which relate pressure and heater temperature are illustrated in Fig. 6. Temperature remains constant at 160°C until boiling commences, whereupon a significant reduction in temperature is evident. Data are summarized in Table 4. According to equation (17), p_d should decline with increasing values of $p_m - p_0$. However, sufficiently great pre-pressurization is predicted to result in subatmospheric boiling initiation pressures. Indeed, eqution (17) predicts that boiling may be totally inhibited (negative p_d) by a large p_m. Furthermore, equation (18) predicts a threshold value of p_m below which pre-pressurization does not affect boiling initiation. Figure 7 shows p_d as a function of $p_m - p_0$. The solid line depicts equation (17) with p_{vb} = 0.618 MPa (at 160°C) and the ratio $\cos(\theta_r - \beta)/\cos(\pi - \theta_a + \beta)$ equal to 1.32. This ratio, incidentally, coincides with that chosen by

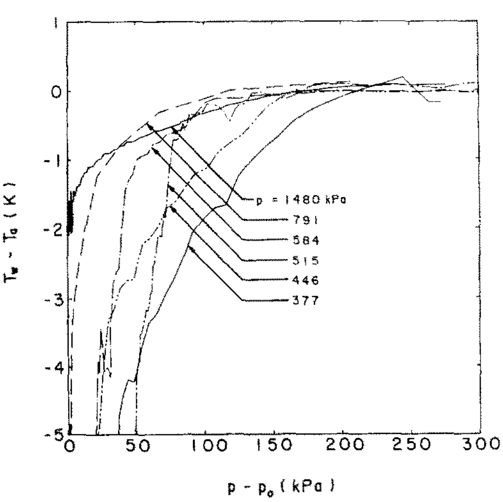

FIG. 6. Temperature drop vs pressure during representative power transients. In all cases, ambient temperature was 100°C. Initial heater temperature was 160°C. Final pressure was 0.101 MPa. Maximum pre-pressurization, p_m, is indicated in the figure.

Table 4. Boiling initiation during pressure transients. In all cases the heating element was 0.25-mm dia. platinum. Ambient temperature was 100°C. Pre-boiling took place at 100°C and $p_0 = 0.101$ MPa. Heat flux was 0.42 MW/m^2. Heater temperature was 160°C ($p_{vb} = 0.618$ MPa) until boiling initiation

p_m (MPa)	p_d (MPa)
0.377	0.35 ± 0.02
0.377	0.29 ± 0.03
0.446	0.26 ± 0.01
0.515	0.20 ± 0.03
0.584	0.22 ± 0.02
0.791	0.13 ± 0.01
1.48	0.11 ± 0.01
1.48	0.13 ± 0.01

Fabic [27], who assumed $\beta = 0$ (cylindrical cavities) and recommended that $\theta_a = 108$ degrees and $\theta_r = 66$ degrees.

Boiling was not totally inhibited in these experiments, even with p_m as great as 1.4 MPa. Instead, boiling is greatly delayed and does not occur until well after complete decompression has taken place. This is consistent with the observation of Gallagher and Winterton [33] that nucleation sites recover from pre-pressurization effects in time. Recovery phenomena, while possibly introducing additional uncertainties, were not specifically addressed in these studies.

The lower dashed line in the figure represents the final pressure of 0.101 MPa after decompression. The solid line of equation (17) does not extend to p_{vb}. Equation (19) predicts a threshold of 0.18 MPa for $p_m - p_0$, based on the cosine ratio of 1.32 and $r_{c,max}$ equal to 0.5 μm. This is the maximum cavity radius estimated from electron microscopy of the heating elements [39]. As indicated in the figure, this threshold implies a limiting value of p_d equal 0.48 MPa at boiling initiation. Saturation temperature at this pressure is 150°C. This implies limiting superheat at boiling inception of 10 K, a value consistent with data of Tables 1 and 2.

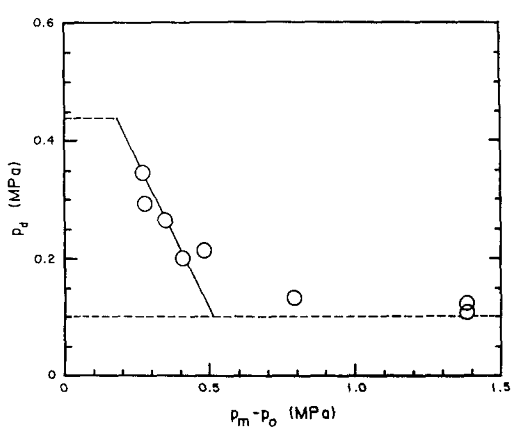

FIG. 7. Pressure at boiling initiation vs $p_m - p_0$ during pressure transients.

5. SUMMARY

Two series of boiling-initiation measurements were carried out using platinum-wire heaters in water at saturation temperatures of 100, 150, and 195°C and subcoolings as great as 30 K. Power transients involved uniform (ramp) rates of increase in heat generation within wires. Pressure transients involved decompressions at exponential periods of five seconds.

The first series, all power transients, had the goal of investigating effects of ramp rate and subcooling on superheat at boiling initiation. In this series, vigorous pre-boiling from a wire was undertaken just prior to a transient. No significant effect of ramp rate was found. As observed by others, increased subcooling tended to increase boiling-initiation superheat.

A second series, both power and pressure transients, had the goal of investigating effects of pre-pressurization. These measurements revealed a distinct suppression of nucleate boiling. Results were consistent with predictions of a contact-angle-hysteresis model for meniscus movement in a boiling initiation site.

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EFFETS D'UNE PRE-PRESSURIZATION SUR L'APPARITION DE L'EBULLITION NUCLEEE PENDANT UN REGIME VARIABLE

Résumé—On montre les effets de l'histoire pression–température sur les conditions de la naissance de l'ébullition nucléée en réservoir dans l'eau soumise à un certain domaine de conditions. Des phénomènes d'ébullition sont étudiés en utilisant des éléments de chauffage avec fil de platine. La température, la pression ou le flux chaleur, et le temps d'apparition de l'ébullition sont monitorés pendant à la fois un accroissement de puissance et une décroissance de pression. On trouve que si le système est sujet à un grand sous-refroidissement (suppression), les conditions favorables à une ébullition nucléée variable sont significativement supprimées. Les résultats s'accordent qualitativement avec les prévisions d'un modèle basé sur l'hystérésis de l'angle de contact dans le mouvement du ménisque dans un site d'ébullition nucléée.

EINFLÜSSE DER VORVERDICHTUNG AUF DAS EINSETZEN VON UNTERKÜHLTEM BEHÄLTERSIEDEN WÄHREND DRUCK- UND LEISTUNGSÄNDERUNGEN

Zusammenfassung—Es wird nachgewiesen, daß die Vorgeschichte von Druck und Temperatur—unter bestimmten Voraussetzungen—Einfluß auf die Bedingungen zum Einsetzen des Blasensiedens im Wasser hat. Siedephänomene wurden unter Benutzung von Platindraht-Heizelementen untersucht. Die Heizelementtemperatur, der Druck oder die Wärmestromdichte und die Zeit des Siedebeginns wurden während positiver Leistungs- oder negativer Druckänderungen beobachtet. Es zeigte sich, daß das Blasensieden deutlich unterdrückt wurde, wenn das System vor den Änderungen starker Unterkühlung (Überdruck) ausgesetzt war. Die Ergebnisse stimmen qualitativ mit Berechnungen nach einem Modell überein, das auf der Kontaktwinkelhysterese bei der Bewegung des Flüssigkeits-Dampf-Meniskus in einem Siedekeim beruht.

ВЛИЯНИЕ ПРЕДВАРИТЕЛЬНОГО СЖАТИЯ НА ВОЗНИКНОВЕНИЕ КИПЕНИЯ В НЕДОГРЕТОМ ОБЪЕМЕ ПРИ БЫСТРОМ ИЗМЕНЕНИИ ДАВЛЕНИЯ И МОЩНОСТИ

Аннотация—Показано влияние изменения давления и температуры на условия возникновения пузырькового кипения в большом объеме воды для широкого диапазона условий. Кипение исследуется с помощью нагревательных элементов из платиновой проволочки. Температура элемента, давление, тепловой поток, время возникновения кипения замерялись как в процессе увеличения мощности, так и уменьшения давления. Найдено, что в том случае, когда система подвергается сильному недогреву (избыточное давление), предшествующему переходному режиму, пузырьковое кипение сильно подавляется. Результаты качественно совпадают с выводами модели, основанной на гистерезисе угла смачивания при движении мениска жидкость-пар в зоне зародышеобразования.