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Behavior of vapor masses on a vertical flat surface of comparatively large height near critical heat flux conditions in saturated pool boiling

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Abstract—With the object of clarifying the fluid behavior in pool boiling at high heat fluxes on a vertical heater surface of comparatively large height, a study has been conducted with a simulated method employing a rectangular nozzle (100 × 10 mm) stretched with a 600-mesh gauge at the exit section through which air is discharged into the surrounding water. First, the propriety of this method to simulate the fluid behavior in pool boiling at high heat fluxes is examined carefully, and then the sequential state of fluid behavior is observed with video for both horizontal and vertical positions of this rectangular nozzle, providing effective information throwing light on the mechanism to cause CHF on a vertical heater surface of comparatively large height.

1. INTRODUCTION

THE THEME of the present paper is concerned with the phenomenon of critical heat flux (CHF) in saturated pool boiling on a heated surface of comparatively large size. In spite of a number of existing studies, the fundamental mechanism of the onset of CHF in pool boiling has not yet been clarified enough, because there is an undeniable fact that, among the two basic systems of pool boiling, that is, boiling on a horizontal surface and that on a vertical surface, the latter system has not yet been provided with any affirmative primary model of CHF.

As was mentioned in ref. [1], two primary models of different nature have been presented for the onset of CHF in saturated pool boiling on an upward-facing infinite horizontal surface. One is the so-called 'hydrodynamic instability model' originated by Zuber [2, 3], which, on the supposition of steady-state vapor escape passages distributed over the heated surface like Fig. 1, assumes the Helmholtz instability on the vapor/liquid interface to cause CHF; and the following correlation equation of critical heat flux q_{cz} is derived analytically (see ref. [3]):

$$q_{cz} = (\pi/24)H_{fg}\rho_v[g(\rho_L-\rho_v)/\rho_v^2]^{1/4}. \qquad (1)$$

Then, mainly through adjustment of the diameter as well as the spacing of the foregoing vapor escape passage, Lienhard and Dhir [4] succeeded in deriving correlation equations of CHF for several finite heaters of comparatively small height.

Another one is the so-called 'macrolayer dryout model', which, on the supposition of vapor masses repeating the growth, hovering, and removal in each unit region of an infinite horizontal surface like Fig. 2, considers the dryout of a macrolayer underlying each vapor mass to create CHF. This is a model depending on experimental observations such as those of refs. [5–10]; and Haramura and Katto [11] derived correlations for the initial thickness of macrolayer δ_c, and the hovering period of vapor mass τ_d, respectively, as:

$$\delta_c = 0.00536[\sigma\rho_v/(q/H_{fg})^2](\rho_v/\rho_L)^{0.4}(1+\rho_v/\rho_L) \qquad (2)$$

$$\tau_d = (3/4\pi)^{1/5}\{4[(11/16)\rho_L+\rho_v]/[g(\rho_v-\rho_L)]\}^{3/5}v_1^{1/5} \qquad (3)$$

where v_1 is the vapor volume generation rate per unit heater area (hence, $v_1 = q\lambda_{TD}^2/\rho_v H_{fg}$ in case of Fig. 2 when heat flux is q). Then, based on equations (2) and (3), a correlation equation of CHF can be derived

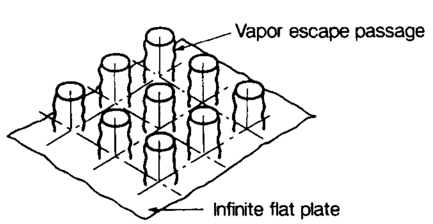

FIG. 1. Hydrodynamic instability model.

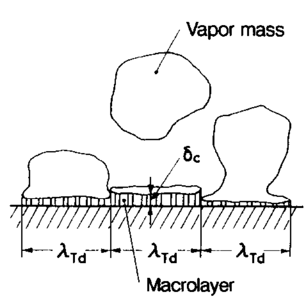

FIG. 2. Macrolayer dryout model.

NOMENCLATURE

a	acceleration parallel to the heated surface [m s^{-2}]
D	diameter of disk heater [m]
D'	$= D/[\sigma/g(\rho_L-\rho_v)]^{1/2}$
g	gravitational acceleration [m s^{-2}]
H	height of vertical rectangular surface [m]
H'	$H/[\sigma/g(\rho_L-\rho_v)]^{1/2}$
H_{fg}	latent heat of evaporation [J kg^{-1}]
p	pressure [kPa]
q	heat flux [W m^{-2}]
q_c	critical heat flux [W m^{-2}]
q_{ch}	q_c value measured on horizontal heater [W m^{-2}]
q_{cv}	q_c value measured on vertical heater [W m^{-2}]
q_{cZ}	q_c value predicted by Zuber equation (1) for infinite horizontal heater [W m^{-2}]
$q_{c\phi}$	q_c value measured on heater tilted at angle ϕ with respect to horizontal [W m^{-2}]
v_a	velocity of air flowing out of the nozzle [m s^{-1}]
v_c	vapor volume generation rate per unit heater area at CHF [m s^{-1}]
W	width of vertical rectangular surface [m].

Greek symbols

δ_c	initial thickness of macrolayer [m]
λ_{Td}	dominant wavelength of Taylor instability [m]
ρ_L	density of liquid [kg m^{-3}]
ρ_v	density of vapor [kg m^{-3}]
σ	surface tension [N m^{-1}]
τ_d	hovering period of vapor mass [s].

through the foregoing condition of the dryout of macrolayer, resulting in the same equation as that of equation (1). Besides, correlations of CHF on a horizontal cylinder and a vertical surface of comparatively small height were derived in ref. [11] by taking the effect of the heater curvature into account.

Two primary models mentioned above are both based on Taylor instability, through which an infinite horizontal surface is divided into unit regions causing vapor removal motion perpendicular to the heater surface, respectively. Accordingly, one feels a difficulty in extending these models to the case of CHF on a vertical flat surface of comparatively large height. In the present study, therefore, the characteristics of CHF value and the fluid behavior in pool boiling on vertical surfaces are studied to find a clue to the foregoing question.

2. CHARACTERISTICS OF CHF VALUE

2.1. *Experimental data of CHF for vertical surfaces*

Many experimental studies have so far been conducted on the effect of heater inclination on nucleate boiling heat transfer. Among them, however, the studies of refs. [12–15], for example, did not attain to the level of heat flux near CHF. Meanwhile, there are some existing studies of CHF in pool boiling on vertical heaters, conducted by Adams [16], Katto *et al.* [8], Bewilogue *et al.* [17], Bui and Dhir [18], Guo and El-Genk [19], and Githinji and Sabersky [20]; and they are listed in Table 1 together with their experimental conditions. It is noticed in Table 1 that the test fluid (substance and pressure), the heated surface (material, geometry, and size), and the acceleration a/g parallel to the vertical heated surface are full of variety. Symbols H' and D' in Table 1 designate the dimensionless height of vertical rectangular heater and the dimensionless diameter (equivalent to height) of vertical disk heater, respectively, defined as

$$H' = H/[\sigma/g(\rho_L-\rho_v)]^{1/2} \quad (4)$$

$$D' = D/[\sigma/g(\rho_L-\rho_v)]^{1/2}. \quad (5)$$

The CHF data of Guo and El-Genk [19] listed on the fifth line in Table 1 were those measured under the unsteady quenching condition, accordingly they must be somewhat different in magnitude from CHF data obtained under the ordinary condition of steady boiling. However, it is expected that the difference is not so great as to exert serious effects on the result of a rough comparison of CHF value between the horizontal and the vertical surface as attempted in the next section. Finally, a study of Githinji and Sabersky [20] conducted for CHF in 'subcooled' pool boiling is listed on the bottom line in Table 1 for information only.

2.2. *Characteristics of CHF value on vertical surfaces*

The CHF column in Table 1 represents the ratio of the CHF value measured in pool boiling on vertical surfaces, q_{cv}, to the CHF value in pool boiling on horizontal surfaces, q_{cZ} or q_{ch}. First, q_{cZ} designates the magnitude of CHF calculated by Zuber's equation (1), and the result of $q_{cv}/q_{cZ} = 0.9$ shown on the first line in Table 1 is the relationship derived by Lienhard and Dhir [4] for the experimental data obtained by Adams [16] in a range of $H' = 6$–30. Next, q_{ch} designates the magnitude of CHF measured on horizontal surfaces. In experiments by Katto *et al.* [8] as well as by Bewilogue *et al.* [17], CHF was measured by holding an identical heater surface in a vertical and a horizontal position, respectively, under common conditions, so the magnitude of q_{cv}/q_{ch} can be obtained directly from their experimental data. In particular,

Table 1. Experimental data of CHF in saturated pool boiling on vertical surfaces

Data source	Fluid	Heater ($H \times W$, or D)	p(kPa)	a/g	H' or D'	CHF	State of boiling
Adams [16]	water	graphite (50.6 × 7.1 mm)	≈ 101.3	2–82	$H' = 6$–30	$q_{cv}/q_{cz} = 0.9$	steady boiling
Katto *et al.* [8]	water	copper (D = 10 mm)	3.03–46.5	1	$D' = 3.7$–3.9	$q_{cv}/q_{ch} = 1$	steady boiling
Bewilogue *et al.* [17]	helium	copper (D = 25 mm)	6.83–205	1	$D' = 55$–190	$q_{cv}/q_{ch} = 0.73$	steady boiling
Bui and Dhir [18]	water	copper (103.4 × 63.5 mm)	101.3	1	$H' = 41$	$q_{cv}/q_{cz} = 0.82$	steady (dirtiest)†
Guo and El-Genk [19]	water	copper (D = 50.8 mm)	101.3	1	$D' = 20$	$q_{cv}/q_{cz} = 0.72$	quenching
Githinji and Sabersky [20]	isopropil alcohol	Chromax (3.2 × 102 mm)	101.3	1	------	$q_{cv}/q_{ch} = 1.22$	subcooling of 56 K

† Transient modes and other surface conditions were also tested.

the experiment of Bewilogue *et al.* [17] was conducted for various angles of the heater surface ϕ with respect to the horizontal level; and their results can be correlated as:

$$q_{c\phi}/q_{ch} = (1-\phi/190)^{1/2} \quad (0^\circ \leqslant \phi \leqslant 165^\circ) \qquad (6)$$

where $q_{c\phi}$ designates CHF measured at the angle of inclination ϕ. Of course, the magnitude of q_{cv}/q_{ch} on the third line in Table 1 is given by equation (6) with $\phi = 90^\circ$.

Then, it is concluded from the results of Table 1 that, when H' or D' is higher than 6 (that is, when the vertical surface is comparatively large in height), CHF on the vertical surface takes magnitudes about 70–90% of CHF on the horizontal surface. Roughly speaking, therefore, the difference of CHF value between the vertical and the horizontal surface is not so great, and there seems a possibility of finding some kind of resemblance of the CHF mechanism between the vertical and the horizontal surface.

3. FLUID BEHAVIOR IN BOILING ON VERTICAL SURFACE

Visual observations of fluid behavior near the vertical heated surface in saturated pool boiling at high heat fluxes near CHF are quite limited in number; and two examples are cited below.

First, as an example of the observation based on 'still photographs', there is a study of Ishigai and Kuno [21], in which the behavior of a vapor mass was observed near the heated surface in saturated nucleate boiling of water at atmospheric pressure on a vertical cylindrical heater of comparatively large size (80 mm height; 40 mm diameter). According to their paper, a sequential state of vapor mass in nucleate boiling at high heat fluxes is as follows: (1) a vapor mass becomes large enough to cover the entire surface of the heater, (2) after the vapor mass moves upward and leaves the heater surface, there occurs an instance of vaporless condition on the heater surface, and (3) at the next moment, a succeeding vapor mass begins to grow again on the heated surface.

Second, as an example of the observation based on 'high-speed photography', there is a study of Katto *et al.* [8] observing fluid behavior in nucleate boiling of water at high heat fluxes on a vertical disk heater of small size (D = 10 mm). Figure 3 is the successive state of pool boiling observed in this case at interval of 10.6 ms, representing the behavior of a vapor mass growing and rising simultaneously until it leaves the heater surface.

3.1. *Possibilities of a simulated experiment*

The experimental results mentioned above are not enough for the purpose of the present study, and further experiments are needed particularly for pool boiling on a vertical rectangular surface of comparatively large size. However, since the characteristics of CHF value on vertical surfaces have already

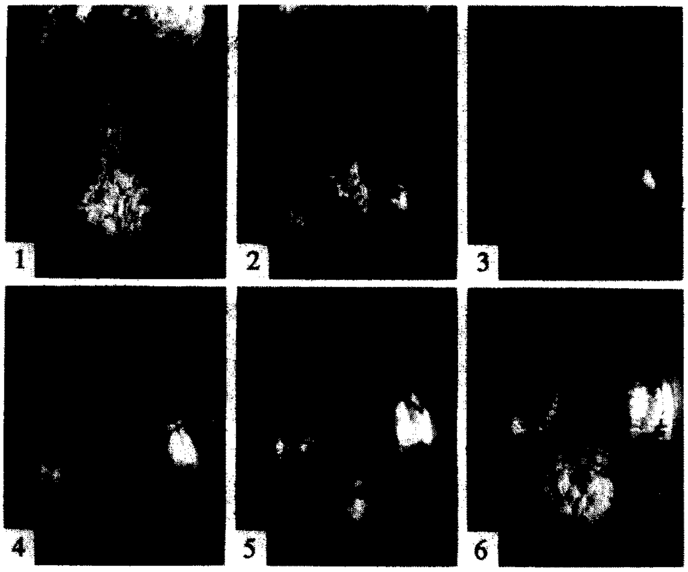

FIG. 3. Nucleate boiling on a vertical disk heater of 10 mm dia. at q = 1.14 MW m^{-2} (interval: 10.6 ms). (Katto *et al.* [8].)

been shown in the preceding section, the most urgent matter at present is to obtain more effective information of the fluid behavior concerned. Under such circumstances, it is convenient of course if the fluid behavior can be studied by means of a simulated experiment discharging air from a rectangular nozzle submerged in water.

For this purpose, however, the propriety of the simulated experiment must be examined beforehand; and it is made as follows by choosing saturated pool boiling of water at atmospheric pressure as a standard condition.

(1) As has been pointed out in ref. [1], fully developed nucleate boiling at high heat fluxes is characterized by a particular feature that its heat transfer is hardly affected by external conditions such as the forced convection of bulk liquid, the depth of liquid above the heater surface, the inclination of the heater surface, and the acceleration perpendicular to the heater surface. This situation is caused presumably by the establishment of a thin, self-regulating nucleate boiling region on the heated surface. Besides, it has been confirmed in refs. [8, 9] that the quantity of heat transferred from the heater surface at high heat fluxes is absorbed entirely by latent heat of evaporation in a thin region adjacent to the heated surface.

(2) Under such conditions of high heat flux boiling, vapor must be generated uniformly over a heater surface if it is heated uniformly. Meanwhile, the density of air at the normal temperature and pressure as well as that of saturated steam at atmospheric pressure takes magnitudes in the order of 1.2–0.6 kg m^{-3}, which are negligibly small compared with the density of water at the normal condition in the order of 960 kg m^{-3}. Accordingly, if air is discharged uniformly from the exit section of a nozzle into water at velocity v_a, and the magnitude of v_a is equal to the vapor generation rate per unit area of the uniformly heated surface at CHF condition v_c, then it can cause the movement of water similar to that in boiling at CHF condition on a uniformly heated surface (note that no condensation of vapor occurs in saturated boiling).

(3) Uniform discharge of air from the exit section of a rectangular nozzle independent of the bulk condition can be attained by stretching a very fine gauge over the exit section so as to cause a great pressure drop of air flow across the gauge. In this case, of course, there remains a difference between the microstructure of vapor generation on the heated surface and that of air flow near the gauge; but this is not a serious matter for the purpose of observing the behavior of vapor mass of much large scale. Finally, it is added here that a simulated experiment of nucleate boiling at high heat fluxes on a horizontal disk heater has been conducted by Kawanishi [22] employing round nozzles of rather small sizes (D = 8–36 mm) and a high-speed cine camera.

3.2. *Rectangular nozzle held in a horizontal position*

A plan is then made to use the exit section of a rectangular nozzle (100 mm × 10 mm) covered with a 600-mesh gauge of very fine stainless steel wire. In order to examine the characteristics of this type of nozzle, the fluid behavior is observed first with video by holding the exit section in a horizontal position. Now, if critical heat flux q_c is calculated by Kutateladze's correlation (equation (1) with 0.16 instead of $\pi/24$ (= 0.131)) for saturated pool boiling of water at atmospheric pressure, it gives the vapor generation rate $v_c = q_c/(\rho_v H_{fg})$ = 1 m s^{-1}. The discharge velocity of air is then maintained at the same magnitude as above, that is, v_a = 1 m s^{-1}, when it gives the result of Fig. 4 as to the successive state of air masses generated on the rectangular nozzle at interval of 16.7

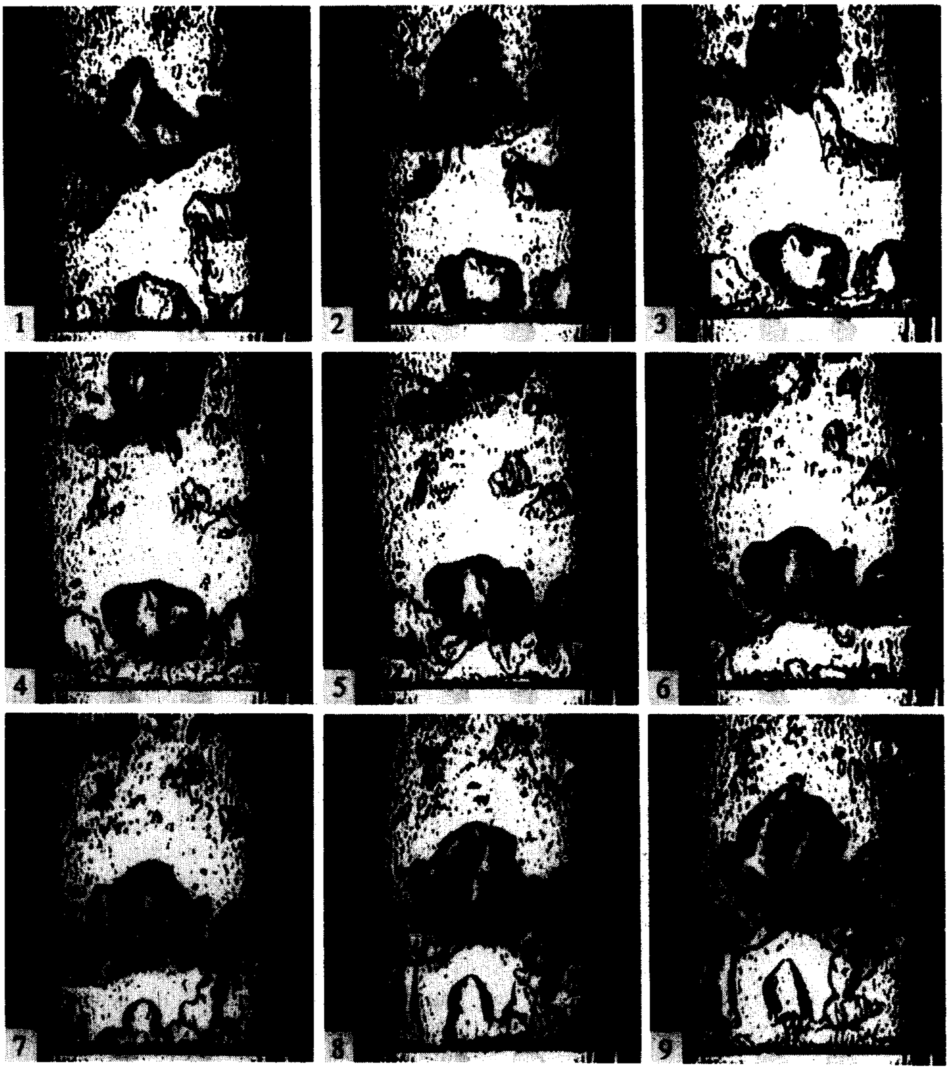

FIG. 4. Discharge of air at $v_a = 1$ m s^{-1} into water from a horizontal rectangular nozzle (100 × 10 mm^2) stretched with a 600-mesh gauge of stainless steel wire.

ms. Besides, in this experiment, it is found that even if the discharge velocity v_a is increased or decreased considerably beyond the condition of $v_a = 1$ m s^{-1}, the characteristics of fluid behavior in Fig. 4 hardly change.

The result of Fig. 4 reveals the following two matters: (1) the exit section of the rectangular nozzle has been divided into three unit regions, and this corresponds to the situation in primary models of Figs. 1 and 2, where the division of a heater surface into unit regions due to Taylor instability is assumed. (2) Roughly speaking, air masses appearing in each unit region consist of two types: one is an air mass of spherical shape growing independent of the effect of the preceding air mass, while another is an air mass of cylindrical shape which grows under a strong effect of the preceding air mass.

On this point, it is of interest to see Fig. 5 (that is a result obtained in the study of ref. [9] and unpublished so far), showing the behavior of vapor masses in saturated pool boiling of water at atmospheric pressure on a horizontal disk heater of 10 mm dia. (which is expected to act like a unit region). One can notice that there is a close resemblance between Figs. 4 and 5 as to the fluid behavior observed in each unit region, suggesting the propriety of the use of the foregoing rectangular nozzle.

3.3. *Result of simulated experiment of fluid behavior on vertical surface*

Next, the foregoing rectangular nozzle is held in a vertical position in water, when it gives the result of Fig. 6. In each frame of Fig. 6, four small black bars perpendicular to the plane of the exit section are nothing but the elements used to fix the nozzle to the vertical wall of the water reservoir.

The discharge velocity of air in the experiment of Fig. 6 is the same as that in Fig. 5, that is $v_a = 1$ m s^{-1}. The reason why this value is chosen here depends on the fact mentioned in Section 3.2 that the mag-

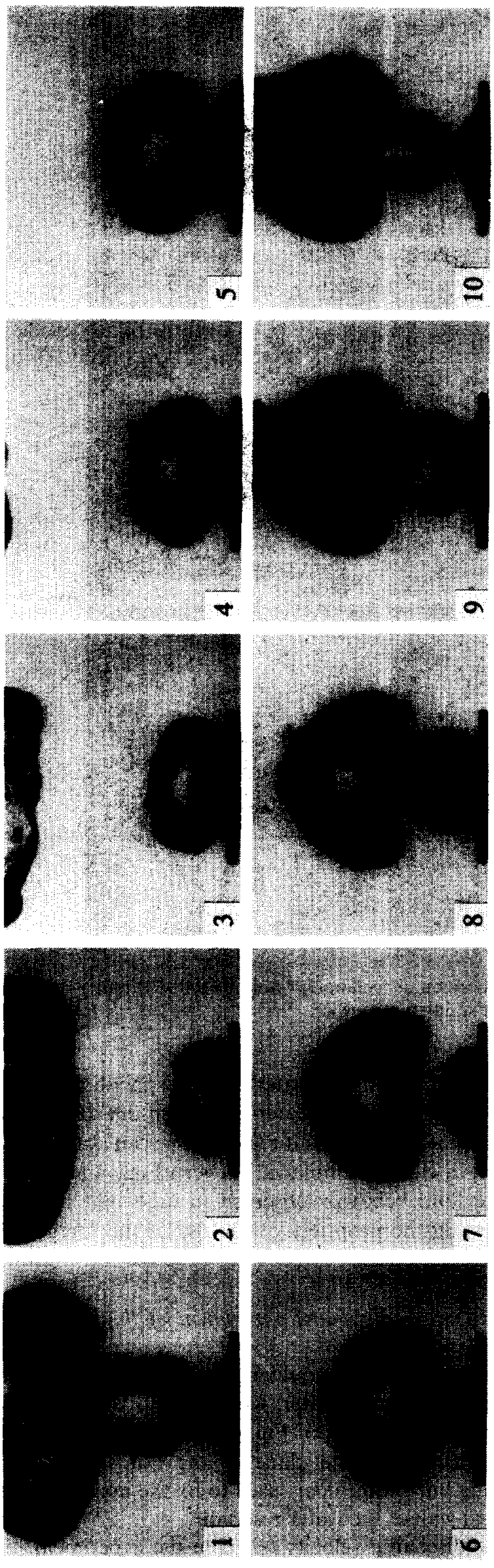

FIG. 5. Behavior of vapor masses in boiling water on a horizontal disk heater of 10 mm dia. at a heat flux near CHF condition (interval: 11.0 ms for Nos. 1–5, and 8.2 ms for Nos. 6–10).

nitude of CHF on the vertical surface is roughly of the same order as that on the horizontal surface, and similarly to the case of the horizontal position, the characteristics of fluid behavior are hardly affected by the considerable change of the discharge velocity from the foregoing value of v_a. In the case of the vertical surface, of course, the static pressure of water exerting on the exit section of nozzle varies with height. However, the pressure drop across the gauge is very high (about 620 mm Aq in this experiment) so that uniform discharge of air can be almost secured independent of the foregoing pressure difference from the top to the bottom end of the exit section (100 mm Aq).

Now, the result of Fig. 6 suggests that air flowing out of the exit section of the nozzle and rising along the vertical surface gathers into an air mass (see the 2nd frame), and the air mass grows moving upward simultaneously by absorbing the entire quantity of discharged air, and finally leaves the top end of the exit section of nozzle.

4. DISCUSSION

The results of Figs. 4 and 6 suggest that nucleate boiling on the horizontal and the vertical surface has a common aspect that vapor generated at high heat fluxes accumulates to form vapor masses and thereafter escapes away from the heater surface. Meanwhile, there is a different aspect that, in the case of the horizontal surface (Fig. 4), the heated surface is divided into unit regions in the order of $\lambda_{TD} \times \lambda_{TD}$ due to Taylor instability, while in case of the vertical surface (Fig. 6), generated vapor is swept away by a vapor mass moving upward along the heater surface (if the heated surface is wide enough, it is presumably divided into unit regions in the order of $H \times \lambda_{TD}$).

As has been mentioned in Section 2.2, there is a possibility of finding some resemblance of CHF mechanism between the vertical and the horizontal surface. If the experimental results mentioned above are considered from this point of view, the generation of vapor mass appears to be a key factor to explain the onset of CHF in boiling on a vertical surface. Then, according to Fig. 6, there must be a location on the heated surface near the top end, where the time for a vapor mass to cover the surface is longest. It must be noted, however, that the situation of Fig. 6 is still involved in some obscure fluid behaviors. For example, the mechanism is not necessarily clear as to how a greater part of vapor generated on the heated surface during a period from the 3rd to the 8th frame in Fig. 6 can be absorbed by an upper vapor mass; and accordingly, some additional studies are needed before the final completion of a definite primary model for CHF based on the macrolayer dryout mechanism.

Nevertheless, Ishigai *et al.* [23] have already reported the periodical generation of vapor mass in pool boiling under a downward-facing disk heater of $D = 25$ and 50 mm; and according to Katto (see p.6 of ref. [24]), the observed characteristics of CHF in this boil-

FIG. 6. Discharge of air at $v_a = 1$ m s^{-1} into water from a vertical rectangular nozzle ($H = 10$ mm, $W = 10$ mm) stretched with a 600-mesh gauge of stainless steel wire.

ing system can be explained by considering the change of the period for a vapor mass to stay under the down-facing heater surface due to the change of heater diameter. Hence, if one takes this into consideration, there seems a possibility of explaining CHF in three basic orientations of a heated surface ($\phi = 0$, 90, and 180°), respectively, on the same principle of macrolayer dryout.

Finally, Liaw and Dhir [25, 26] have recently performed studies on the effect of heater wettability on heat transfer in saturated pool boiling on a vertical plate heater ($H = 103.4$ mm; $W = 63.5$ mm), including analyses based on a steady-state flow model such as illustrated in Fig. 7. The heater height of 103.4 mm employed in their studies is nearly the same as the nozzle height of 100 mm in the present experiment of Fig. 6; and it is necessary to notice the difference of fluid behavior between the observation of Fig. 6 and the conceptualization of Fig. 7.

5. SUPPLEMENTARY NOTES ON PRIMARY MODELS

Fluid behavior near the heated surface at high heat fluxes is generally very complicated, and hence it is

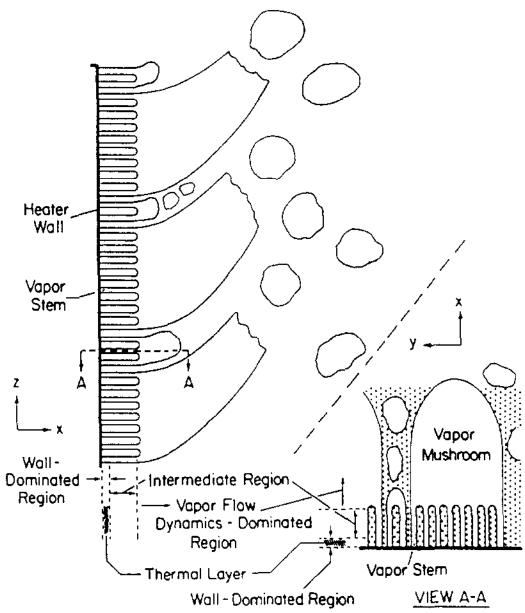

FIG. 7. Conceptualization of pool boiling on a vertical surface in case of contact angle of 90° (Liaw and Dhir [26]).

more or less necessary to idealize the fluid behavior in making a primary model of CHF. For example, the division of a heater surface into unit region due to Taylor instability assumed in the primary models of Figs. 1 and 2 is an idealization, and the comparatively regular behavior of vapor mass observed in Figs. 3 and 5 is also an idealized result relating to the use of a small disk heater of 10 mm dia. which works like a unit region. Similarly, comparatively regular fluid behaviors obtained in Figs. 4 and 6 for the discharge of air from a rectangular nozzle are the results due to the use of a nozzle of 10 mm in width. Accordingly, it is considered important to recognize that experiments under such idealized conditions are very suggestive in devising a primary model of CHF.

In the case of the macrolayer dryout model of CHF on an infinite horizontal surface (Fig. 2), a kind of simplification is also included as to the handling of the periodical behavior of vapor mass. According to experimental results such as Figs. 4 and 5, it is noticed that two different kinds of vapor masses appear successively making a pair in each unit region (see ref. [9] for more details of the behavior of vapor masses). In the macrolayer dryout model, however, only one kind of vapor mass with a spherical shape is assumed to appear successively; and thereby equation (3) of the hovering period of vapor mass τ_d has been derived. Equation (2) also cannot be independent of this simplification, because this equation includes an empirical constant determined relating to equation (3). Accordingly, attention must be paid to these circumstances when the individual magnitudes predicted by equations (2) and (3) are compared with such magnitudes measured through some experimental means.

6. CONCLUSIONS

(1) The state of vapor removal from a heated surface of comparatively large size in pool boiling at high heat fluxes near CHF have been studied through a simulated experiment discharging air from a rectangular nozzle of 100 mm × 10 mm into water.

(2) The vertical and the horizontal surface have a common aspect that generated vapor escapes away from the heated surface taking the form of vapor mass, and there seems a possibility of devising a primary model of CHF in boiling on the vertical surface based on the principle of the dryout of macrolayer. However, the behavior of vapor mass on the heated surface is different between the two orientations, and it needs to reveal the behavior of vapor masses more clearly before the accomplishment of a primary CHF model for boiling on the vertical surface.

(3) In the simulated experiment discharging air from a rectangular nozzle into water, if the discharge velocity is increased considerably beyond the magnitude corresponding to CHF condition, no abrupt change appears in characteristics of fluid behavior. This suggests that CHF in pool boiling is not likely to be a phenomenon created by the instability or any other limit condition of escaping vapor flow.

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