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Photographic Study of Saturated Free Convection Stable Film Boiling*

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Experiments were carried out on the saturated film boiling of water and sodium oleate solution, using three kinds of nichrome wire, 0.6, 0.8 and 1.0 mm in diameter and platinum wire, 0.5 mm in diameter. The bubble dynamics in stable film boiling was studied. The product of bubble diameter just leaving the vapor film and the frequency of bubble formation takes constant value, if the radiation heat flux exceeds (1~2) % of total heat flux, showing nearly the same numerical value as in case of nucleate boiling, but it decreases with the drop of radiation heat flux below the above-mentioned one. In other words, the behaviors of bubble generation in film boiling present different aspects according to the difference of emissivity of heating surface, even if the total heat fluxes remain the same. Though the results from the experimental values of heat transfer coefficient show fairly good agreement with Bancho's equation, the experimental points are somewhat lower than Bancho's equation below the heat flux in which the product of bubble diameter and frequency of bubble formation becomes constant. It will be, therefore, necessary to introduce a correlating equation, taking the vapor film stirring effect of generating bubbles into consideration.

1. Introduction

The film boiling was formerly studied by Nukiyama⁽¹⁾ who elucidated the characteristic curve of boiling. Farber and Scoriah⁽²⁾ studied the effect of pressure on boiling, while Bancho and others⁽³⁾ studied the effect of the dimensions of heating wires. Bromley⁽⁴⁾ proposed a theoretical formula, while Bancho⁽⁵⁾ presented an empirical formula. In these studies, measurements were made on the coefficient of heat transfer in stable film boiling. On the other hand, Westwater et al⁽⁶⁾ elucidated the aspects of formation of vapor films and bubbles. Thus, they undertook to clarify mechanism of film boiling.

Westwater and his co-workers carried out experiments, using a high speed camera. The author used in the present experiment a special method⁽⁶⁾ he had already adopted to study nucleate boiling, and could determine fairly accurately various phases of bubble formation. The present investigation covers both nucleate boiling and film boiling. In this paper, considerations have been focused mainly on the phase of bubble formation in the domain of stable film boiling.

2. Experimental method

Since it is required that a great heat flux is applied to the heating surface, a small wire such as used in the earlier studies was employed. The heating surface was heated directly by electric current. The heating wire was placed horizontally in a beaker filled with a test liquid. The beaker was closed with a rubber lid. In order to prevent heat loss through the side wall of the beaker, it was placed in another vessel of greater size or a thermostat, which contained water of the same temperature as that of the boiling liquid. This thermostat has a glass-window on both sides for internal observation.

Fig. 1 shows the experimental apparatus diagrammatically. The heat flux through the heating surface was calculated from the voltage and the current through the heating wire and the temperature of the heating surface was determined by using the heating wire itself as a resistance thermometer.

The maximum diameter of bubbles just leaving the vapor film formed around the heating surface as well as the frequency of bubble formation was determined by means of an apparatus shown in Fig. 1. A light source was placed behind the

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heating apparatus. The images of bubbles leaving the vapor film were magnified by a convex lens and was projected on an optical box of an electromagnetic oscillograph. The light passed through a slit and the images of bubbles that appeared in succession were recorded continuously on an oscillograph paper wound around a rotating drum. The opening of the slit was adjusted lest the maximum diameter of bubbles should be screened off. The magnification of the photographs was determined by photographing a rod that had been finished precisely with a diameter of 10 mm in the same manner as adopted for the bubbles. The magnification in the present experiments was about 2.5. In addition, the state of things around the heating wire was photographed by means of a movie camera of 16 mm and 64 frames.

Three nichrome wires measuring 0.6, 0.8 and 1.0 mm in diameter and a platinum wire of 0.5 mm in diameter were used for heating. Distilled water and 50 p.p.m. sodium oleate solution were used for the boiling liquid. The heat flux ranged over $(2 \sim 9) \times 10^5$ kcal/m²hr.

3. Appearance of formation of bubble and vapor film

Fig. 2 is the reproduction of some photographs of the environment of the heating surface taken with a movie camera. It shows the transition from nucleate boiling to stable film boiling. Figs. 2 (a) and (b) show pure nucleate boiling. The distance between the points of bubble formation is irregular. The number of vapor columns depended to a great extent upon the condition of the heating surface.

M: motor, *G*: generator, *H*₁: nichrome-wire heater, *H*₂: base heater, *H*₃: cast-in heater, *R*_z: heating wire, *R*_B: variable resistance, *R*_C: manganese-wire resistance, *R*_A: fixed resistance, *g*: galvanometer, *R*_g: variable resistance, *A*: ammeter *V*: voltmeter, *O*: optical box of electro-magnetic oscillograph, *m*: motor for revolving drum, *L*: light source, *I*₁: condenser lens, *I*₂: magnifying lens, *T*₁, *T*₂, *T*₃: thermometer, *CC*: movie camera, *CA*: camera, *P*: pint glass

Fig. 1 Experimental apparatus

Fig. 2 (c) also shows a case of nucleate boiling. Here, neighboring bubbles coalesced at the heating surface. This phase will be called "the bubble-coalescence region of nucleate boiling." Fig. 2 (d) is a photograph of the first stage of film boiling, i.e., the stage just after the transition from nucleate boiling. Although the heating surface was covered with vapor film, the film was more or less unstable. The regularity of bubble formation was poor compared with that of stable film boiling which will be described below. In this phase, however, bubbles became much greater than those in nucleate boiling. Figs. 2 (e), (f) and (g) represent stable film boiling. The vapor film became stable. Bubbles of greater size were generated in a regular manner from the film surface. The surface of the vapor film made wave motion just like a vibrating string, where the points of bubble formation oscillated to and fro over the film surface. When a bubble at a certain point was leaving the film surface, the vapor film in its neighboring points already showed swelling.

4. The diameter of bubbles and the frequency of bubble formation

The heating surface and the bubbles just leaving the vapor film were photographed by the method described in Section 2. Some of the photographs are reproduced in Fig. 3. In taking these photographs, a slit was placed a little above the heating surface, and bubbles were photographed on an oscillograph paper wound around a rotating drum. Therefore, the bubbles on the right side in the photographs are those generated earlier.

Fig. 3 (a) corresponds to nucleate boiling. It will be seen that bubbles are generated continuously from definite points of bubble generation. The diameter of bubbles and the frequency of bubble formation depended upon the points of bubble generation, but the product of those two quantities was nearly constant. Figs. 3 (b) and (c) show the bubble-coalescence region of nucleate boiling. Bubbles coalesced before they left the heating surface. In this region, even when the heat flux varied, the temperature of the heating surface did not change appreciably. The coefficient of heat transfer was almost proportional to the heat flux. Figs. 3 (d) and (g) show film boiling. As already mentioned, the

diameter of bubbles was much greater than that in nucleate boiling. In addition, the diameter was independent of the points of bubble generation.

Fig. 2 Appearance of bubble formation (water at atmospheric pressure, q =heat flux, kcal/m² hr)

The bubble formation was very regular. The points of bubble generation shifted to and fro, as can be seen very clearly from the photographs. In some cases, bubble coalesced before they left the vapor film.

From the photographs of Fig. 3, the diameter of bubbles just leaving the vapor film and the frequency of bubble formation were evaluated mainly in the domain of film boiling and their dependence upon the heat flux was investigated. In Fig. 4, the

Fig. 3 Photographs of bubbles just leaving the heating surface or vapor film surface (water at atmospheric pressure, q =heat flux, kcal/m² hr)

maximum diameter of a bubble just leaving the vapor film (d_m), the frequency of bubble formation per unit length of the heating wire (F), or the distance between the points of bubble generation on the heating wire (p) is plotted against the heat flux (q). It will be seen that d_m , F and p are constant and independent of the heat flux as well as of the diameter of the heating wires in case of nichrome wire, while d_m , F and p are independent of the heat flux above $q=6 \times 10^5$ kcal/m² hr, and d_m and p increase and F decreases with increase of heat flux below $q=6 \times 10^5$ kcal/m² hr, in case of platinum wire. Furthermore, the difference between water and sodium oleate solution was not found.

The difference of the appearance of film boiling between these two wires seems to be due

	Liquid	Heating surface	
		material	diameter mm
○	water	platinum wire	0.5
●	sodium oleate solution	"	"
△	water	nichrome wire	0.6
▽	"	"	0.8
×	"	"	1.0

Fig. 4 Bubble diameter and frequency of bubble formation

to the difference of emissivity between them. Therefore, plotting d_m , F and p against the radiation heat flux (q_r), it is seen that the data of nichrome and platinum wires do not branch off, varying with q_r below $q_r=10^4$ kcal/m² hr and taking constant value above $q_r=10^4$ kcal/m² hr.

Fig. 5 shows the result of the product of d_m and F correlated by the ratio of the radiation heat flux (q_r) to the total heat flux (q). The author⁽⁷⁾ has already established the following relations on the bubble formation from different liquids in nucleate boiling.

$$f_s = f \left(\frac{d_0}{d_{0s}} \right)^3 \left(\frac{\gamma''}{\gamma''_s} \right) \left(\frac{r}{r_s} \right) \quad \dots\dots\dots (1)$$

$$\chi_s = \chi \left(\frac{d_0}{d_{0s}} \right)^2 \left(\frac{\gamma''}{\gamma''_s} \right) \left(\frac{r}{r_s} \right) \quad \dots\dots\dots (2)$$

Here, d_0 =the diameter of bubble just leaving the heating surface or the vapor film (transformed to a sphere), f =the frequency of bubble formation, γ'' =specific weight of vapor, and r =latent heat of evaporation. The subscript "s" refers to distilled water, while notations without the subscript refer to any liquid under investigation. If this relation is assumed to hold for the bubble

	Experimenter	Liquid
○	Nishikawa	water
●	"	sodium oleate solution
△	"	water*
▽	"	"
×	"	"
◎	Westwater	methanol

	Heating surface	
	material	diameter mm
○	platinum wire	0.5
●	"	0.5
△	nichrome wire	0.6
▽	"	0.8
×	"	1.0
◎	copper tube	9.5

Fig. 5 Values of $d_m F$ and $d_m f$

formation in film boiling and the data of Westwater⁽⁵⁾ on methanol are converted to the case of distilled water, the double circle points in Fig. 5 will result. Accordingly, the relations (1) and (2) may be presumed to be applicable also to film boiling without modification. Jakob proposed the following equation for the diameter of a bubble just leaving the heating surface in nucleate boiling.

$$d_0 = 1.034 \sqrt{\frac{\sigma}{\gamma'}} \quad \dots\dots\dots (3)$$

Here, σ = the surface tension of the liquid and γ' = specific weight of the liquid. His formula does not seem to hold for the data of the present investigation. Since there is found hardly any literature on the bubble formation in film boiling, except that of Westwater, it is rather a venture for the author to draw a definite conclusion on it. For all that, experimental results obtained by Westwater and the author will justify a conclusion that the relation (3) is not applicable to the case of film boiling.

Next, the value of $d_0 f = \chi$, which was originally a constant for the bubble formation in nucleate boiling, was evaluated for the case of film boiling. Since the relation $f = FP/2$ holds, χ can be evaluated and is plotted against the heat flux in Fig. 5. As seen from Fig. 5, $d_m f$ and $d_m F$ take constant values independent of the kinds of wires above $q_r/q = 0.015$, showing nearly the same numerical values as in the case of nucleate boiling, but decreasing with the drop of q_r/q below the above-mentioned value. In the case of nucleate boiling, $\chi = 111$ mm/sec, whereas in film boiling $\chi = 120$ mm/sec. One reason for this discrepancy seems to lie in the use of d_m

rather than d_0 for the diameter of bubbles. d_m is nothing but the observed maximum diameter of bubbles evaluated from the photographs in Fig. 3. As can be seen from Fig. 2, however, the bubbles generated in film boiling deviated to a considerable extent from a spherical shape. The cross-section was nearly an ellipse. Therefore, the value of d_0 will be affected by whether an ellipsoid or egg shape is assumed in calculating the volume of a bubble. This requires further studies for confirmation. Westwater also dealt with d_m . In this paper this problem is ignored: all the data are treated with d_m . It is therefore impossible to draw a definite conclusion on whether or not the absolute value of χ is different between nucleate boiling and film boiling. And yet, in all cases the relation $\chi = \text{constant}$ is strictly obeyed.

The relation between the diameter d_m of bubbles just leaving the vapor film and the period of bubble generation τ'' is shown in Fig. 6. The relation is in good agreement with the relation⁽⁶⁾ which the present author has established in nucleate boiling.

5. Coefficient of heat transfer

In nucleate boiling the present author's formula⁽⁸⁾ agrees excellently with experiments. However, in the bubble-coalescence region of nucleate boiling the relation approximates to $\alpha \propto q$ rather than $\alpha \propto q^{2/3}$. Thus, for nucleate boiling with a heat flux near the burn-out heat flux, further studies are desirable.

In the domain of stable film boiling, the experimental data were coordinated with the equations of Bromley and Banchemo. Bromley's equation was derived from the similar conception of Nusselt's water film theory for the condensation. In deriving this equation, he assumed that liquid-vapor interface is very smooth and applied the same thermal resistance equation as the flat plate to the horizontal circular tube. The equation that corrected the latter assumption is Banchemo's one. The former assumption is not correct, but interface is wavy as seen from the present experiment. If the stirring of vapor film by the bubbles is independent of heat flux, this assumption will be allowable. However, since $d_m f = \text{constant}$ does not hold in the case where the radiation heat flux is a few percent of total heat flux, it will be necessary that this fact be taken into account in deriving the correlating equation.

Fig. 6 Relation between bubble diameter and generating period

	Experimenter	Liquid	Heating surface	
			material	diameter mm
△	Nishikawa	water	nichrome wire	0.6
×	"	"	"	0.8
▽	"	"	"	1.0
○	"	"	platinum wire	0.5
●	"	sodium oleate solution	"	0.5
□	Nukiyama	water	"	0.15

Fig. 7 Heat transfer in stable film boiling

Fig. 7 shows the result of the experiment. All the data conform to Banchero's empirical equation. Nukiyama's data are also plotted for reference. They also agree with the empirical equation. Banchero modified Bromley's equation taking into account the dimensions of heating surfaces. So far as wires are used as a heating surface, Banchero's correction seems to be adequate.

6. Conclusion

Experiments on saturated boiling were performed using a fine metal wires and distilled water. By means of a special optical equipment, various phases of bubble formation were elucidated mainly in film boiling. However, when wires were used in the experiments of film boiling, the size of bubbles was several times as great as the dimensions of the heating surface. It is therefore doubtful whether the present results are available to guess the phases of boiling using a heating surface greater than the generated bubbles. This point will be studied in future. In nucleate boiling, the coalescence of generated bubbles takes place near the burn-out heat flux and shows a different phases of heat transfer from the case of small heat flux. This requires special attention.

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Discussion

F. TACHIBANA: For the practical purpose, the study of film boiling heat transfer is very useful to make clear the heat transfer of the quenching process, while it is also important as the basic research of the burn-out phenomena.

The author has much experience already in the study of the nucleate boiling in the past, and now he has proceeded into the region of film boiling. I am much pleased to know this, and look forward to his achievements.

When the film boiling starts, the bubble formation becomes very regular as the author also describes. In this case, maximum bubble diameter d_m and the bubble formation frequency f bear the relation $d_m f = \text{const.}$, and also this constant has just the same value as that for the nucleate boiling. I wish to know the physical interpretation of this coincidence.

The maximum diameter d_m seems to have some relation to the vapour film vibration. How

do you think of this relation?

Observed data are plotted versus q_r/q . How shall I interpret the fact that these values vary according to q_r/q , or remain constant?

I. TANISHITA: (1) I think that the transition from nucleate boiling to film boiling or one in the reversed direction is the same as in common problems in dynamics (vibration, buckling, etc.). Is it justified by the experimental results?

(2) In saturated stable film boiling, bubbles with nearly equal size are generated with regularity. Did you measure the relation between the rising speed of bubbles and their size?

This is, I think, the same problem as one of the stability of a liquid drop proceeding through the air. What is your opinion?

N. ISSHIKI: (1) I want to know the values of surface tension of oleic acid solution, and the radiation coefficient of platinum wires and nichrome wire used by the author.

(2) The theories of Zuber and Chang say that the surface tension of liquid plays a major part in the mechanism of transient and film boiling. And on the other hand, I have observed some film-boiling of short piano wires, which leads me to think that the film moves in a kind of standing wave controlled by surface tension.

I want to know the opinion of the author on the role of surface tension.

Author's closure

(1) Either in nucleate boiling or in film boiling, the rule of $d_m f \equiv \chi = \text{constant}$ holds between the diameter of the bubbles just leaving heating surface or vapor film (d_m) and the frequency of bubble formation (f) and the values thereof are numerically equivalent. These facts seem to indicate that the same rule of bubble formation governs all cases, provided that the physical properties of liquid are the same, whatever the conditions of heat flux or heating surface, this is, whether bubbles are generated from solid surface or vapor film, and irrespective of the size of generated bubbles.

The value of this χ varies according to the ratio of radiation heat flux (q_r) to total heat flux (q). It might be owing to the failure of heat supply for the bubbles to extricate themselves at $d_m f = (\text{constant})$ that the value of χ decreases at $q_r/q < 0.015$. Isn't it due to the convective heat transfer taking place mostly by the medium of water, in contrast to the directness of radiation heat transfer, that this has to do with q_r/q ?

(2) Between the wave length of wave motion occurring to vapor film (p) and the diame-

ter of bubble (d_m), there holds the relation of $p/d_m = 1.4 = (\text{constant})$, as seen from Fig. 6 of the paper, independent of heat flux. I believe this is because the point of bubble formation depends upon the diameter of bubbles since the surface of vapor film has the same surface condition.

The wave motion generated on the surface of vapor film is generally considered to be subject to both the hydrodynamic condition and the thermal condition. While Chang^(a) or Zuber^(b) seems to be concerned only about the hydrodynamic condition, the author considers that the wave motion which is formed in the region of stable film boiling is strongly governed by thermal condition.

(3) Favorable agreement attained in the experimental points as the result of adjustment given to various measured values by q_r/q is considered to be related with the thickness of vapor film. It is due either to q_r itself calling for consideration or to such value of q that makes q_r become considerably large that the data on the generation of bubbles at $q_r/q > 0.015$ give constant values. It is likely that the value of q_r may hold the key in this, since the experimental points tend to be branched by the difference of emissivity of heating surface even with the same heat flux. According to Bromley's theoretical equation^(c), the thickness of vapor film seems to be subject to convective heat flux, but it seems to be necessary to establish the relation between radiation heat transfer and thickness of vapor film, as Chang^(d) has pointed out. I think that the reason for the data about bubble formation giving constant values above a certain value of q_r/q lies in the fact that there is a certain limit to removal of heat in the form of bubbles and that there is no means for removal of heat at $q_r/q > 0.015$ except for the increase of radiation heat transfer. Since the whole heat flux can be removed in case of $q_r/q < 0.015$ below the limit of power to remove heat by bubbles, it is presumed that the data on the bubble formation come to change. Suggestions made so far are all no more than presumptions, and I must admit the necessity of further study on this subject.

(1) The transition phenomena of boiling in the case of heating by the electric resistance wire become the same as problems of general dynamics,

(a) Y. P. Chang: *Trans. ASME*, Vol. 79, (1957), p. 1501.

(b) N. Zuber: *Trans. ASME*, Vol. 80, (1958), p. 711. N. Zuber and M. Tribus: *Univ. of California Report* 58-5 (1958-1), p. 1.

(c) LeRoy A. Bromley: *Chem. Engng. Progr.*, Vol. 46, (1950), p. 221.

(d) Y. P. Chang: *Trans. ASME*, Series C. Vol. 81, (1959), p. 1.

as you say, for instance, the relation between the load and displacement in buckling (cf. Append-Fig. 1) or that of amplitude and the frequency in non-linear vibration.

Append-Fig. 2 shows the boiling characteristic curve where heat flux (q) is taken for ordinate and temperature difference ($\Delta\theta$) between heating surface and liquid for abscissa. As shown in (a) of Append-Fig. 2, when heat flux is increased in heating while its constancy is maintained, there occurs film boiling in a portion of heating wire as it reaches point B of $q_{\max}$. The vapor film ultimately covers the whole heating surface while the phenomena emerge into the condition of point K from point B , are stabilized at point K , and by raising q further they follow the progress of KE . The solid line of this figure shows the course of the phenomena in the case where q is raised. If q is lowered from point E in the reverse way, the part of vapor film covering the heating surface breaks at point C of $q_{\min}$, the part of nucleate boiling spreads quickly and the phenomena settle ultimately to the condition of point J . Then lowering q further down, there takes place the process of JA and the solid line of Append-Fig.2 (b) will show the transition of the phenomena. If q is converted thus into a variable, the process of BC cannot be realized in general.

However, if heating is carried out keeping $\Delta\theta$ constant as in the case where heat is transmitted from vapor or liquid metal to boiling liquid, polyvalency seems to exist no longer between $q_{\max}$ and $q_{\min}$ and the process of BC can be realized.

(2) I have not measured the rising velocity of bubble yet. I believe that rising of the bubbles in boiling is the same fundamentally, as you consider, with the problem of stability of the

Append-Fig. 1 Jump phenomenon in buckling

Append-Fig. 2 Boiling characteristic curve

liquid drop progressing through the air, except that they grow by receiving in the course of their climb from the liquid around them and that there takes place incorporation of bubbles with one another. Append-Fig. 3 is an example of the photographs of external appearance in film boiling, which seems to show the bubbles of such forms as corresponding to the deformation of bubbles discussed in the paper titled "Stability of a Fluid Drop or Bubbles moving through Fluid Medium" by Prof. Tanishita^(e).

(1) The surface tension of liquid has been measured with De Nouy's surface tension tester with the following results.

Liquid	Surface tension kg/m
Distilled water	6.012×10^{-3}
50 p.p.m. sodium oleate solution	3.59×10^{-3}

The distilled water of this table has been obtained as the value for 100°C in the table and the sodium oleate solution has been evaluated at room temperature from the comparative value with distilled water. Since the surface tension of sodium oleate solution has been confirmed not to change very much with temperature, the measured value at room temperature has been also used as it is for boiling condition.

(2) As seen in Figs. 6~9 in the paper, the surface tension has hardly affected the formation of bubbles in film boiling. What Zuber^(b) treated is the transition boiling; he discussed especially the maximum heat flux and the minimum heat flux in transition boiling, where surface tension plays an important role. It seems, however, that Zuber made no reference to the stable film boiling. Also in Chang's^(d) paper on film boiling, there is included no surface tension in the expression of

Append-Fig. 3 Appearance of film boiling on heating wire
(water at atmospheric pressure, $q = 4.78 \times 10^5$ kcal/m² hr, exposure time = 1/1000 sec)

(e) I. Tanishita: *Trans. Japan Soc. Mech. Engrs.*, Vol. 20, No. 96, (1954), p. 521.

Append-Fig. 4 Emissivity of heating surface

the coefficient of heat transfer. He states in it that surface tension wave quickly damps in the region of stable film boiling, and that the effect of surface tension is negligible, proving also that consideration of surface tension in deriving Chang's theoretical equation affects the result very little. It has been confirmed from Westwater's^(f) experiment that the heat transfer in stable film boiling is independent of the effect of surface tension, and the author's experimental results are free from surface tension. Though Chang proposed such equation in which bubble diameter has to do with surface tension, the growth of bubbles after the departure of vapor film is not accounted for in this equation. On the other hand, it seems that the bubble diameter evaluated from the equation by numerical calculation is too small as compared with the measured value (in saturated film boiling of water, bubble diameter just leaving the vapor film is 3.1~2.5 mm when the difference between the temperature of heating surface and saturation temperature is 800~1 600°F).

The surface tension seems to be related with

(f) A.J. Lowery and J.W. Westwater: *Indust. Engng. Chem.*, Vol. 49, (1957), p. 1445.

the thickness of vapor film covering heating surface. According to the author's experiment, however, coefficient of heat transfer in the region of nucleate boiling is larger in the case of sodium oleate solution than in the case of distilled water for the same temperature difference, showing no great difference in both cases in the region of stable film boiling. Since the heat transfer in film boiling is largely subject to the thickness of vapor film, I believe that the effect of surface tension is negligible in this respect. I think Bromley's idea is almost reasonable as far as the mechanism of heat transfer in film boiling is concerned. As already referred to in the paper, however, it will be necessary to account for the fact that the effect of disturbance due to bubbles varies according to the condition of bubble generation, because the gas-liquid interface is wavy.

(3) Emissivity ϵ of platinum wire and nichrome wire has been evaluated from the table instead of measuring it. The value of ϵ used in the present paper is as shown in Append-Fig. 4.

(4) The difference in the interval of the points of bubble generation due to the change of the length of heating wire may be ascribed to the effect of surface tension. However, are you sure that the reduction of the length of wire did not increase the rate of heat loss from both ends and thereby reduced effective heat flux? Are you sure that there was not any considerable change in the temperature distribution of heating wire in longitudinal direction? Unless such thermal conditions are strictly controlled, it will be too hasty to jump to the conclusion from the facts stated in question.

(2) that the effect of surface tension is continuous over the whole length of heating wire.