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Investigations on the propagation of free surface boiling in a vertical superheated liquid column

P. K. DAS, G. S. BHAT and V. H. ARAKERI
Department of Mechanical Engineering, Indian Institute of Science, Bangalore 560 012, India

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Abstract—Some experimental studies on boiling propagation in a suddenly depressurized superheated vertical liquid column are reported. The propagation velocity of this phase change has been measured using an optical method. This velocity is strongly dependent on liquid superheat, liquid purity and test section size. The measured velocities of less than $5\,m\,s^{-1}$ are significantly lower than the sonic velocity. Present observations suggest that the dominant mechanism for boiling propagation is convection.

1. INTRODUCTION

IN MANY practical situations like liquid cooled nuclear reactors and some chemical plants, liquids at high pressure and temperature flow in pipes. If a break or leakage occurs in these pipes, the inside pressure may be reduced to a value well below the saturation pressure corresponding to its initial temperature. Under such conditions, the resulting flow is two phase, i.e. a mixture of liquid and its vapor bubbles. In the numerical models employed to describe and predict such cases, it is usually assumed that as soon as the pressure decreases below the saturation value, boiling will start. This assumption need not hold good in all cases, especially in vertical pipes when the pressure fall is sudden enough and if the pipe walls and the bulk of the liquid are free from any nucleation sites. In such cases, boiling starts at the open end or free surface and propagates down into the liquid at a finite velocity, uncoupled from the rarefaction wave travel. The movement of this phase change boundary into the vertical liquid column is termed boiling front propagation (BFP). Actually, the phase change boundary is highly irregular and terming it as a boiling front is not very appropriate. Observations show that phase change across a horizontal cross-section is very fast and that is why the term boiling front has been used.

In the early 1960s, Terner [1] conducted experiments in gas driven vertical shock tubes containing a liquid column. His observations showed that as the expansion wave proceeded from the open end into the liquid, a boiling front or a vaporizing front followed it. He reported that the boiling front propagated with a much slower velocity compared to the sonic velocity in the liquid. He concluded that the BFP is uncoupled from the rarefaction wave and is closely dependent on the mechanism of heat transfer and bubble formation.

Grolmes and Fauske [2] have reported on experimental investigations on flashing in water, methyl alcohol and refrigerant-II in vertical glass test sections of different diameters. Stationary liquid was suddenly depressurized by breaking a diaphragm resulting in an initial liquid superheat in the range 25–100°C (difference between the initial temperature and the saturation temperature corresponding to the applied pressure). The average velocity of BFP in the refrigerant was 1.06 fps and they showed an inverse relationship between the test section size and the threshold superheat below which flashing could not be sustained. However, no quantitative information was given on the dependence of BFP velocity on liquid superheat. Peterson *et al.* [3] conducted similar experiments with refrigerant for very low superheats. Using Mach–Zender interferometer and high speed photography, the liquid–air interface was examined. They observed that as a result of depressurization below the saturation level, instabilities in combination with rapid evaporation resulted in a convective motion being initiated at the top layer.

In this study, BFP velocity has been investigated experimentally. Two types of experimental arrangements were used: (a) a stainless steel test section (50 mm diameter) to study the effect of liquid superheat and (b) glass test sections of different diameters, primarily for visually observing this phenomenon and to study the effect of diameter. A convective model has been proposed to explain boiling front propagation.

2. EXPERIMENTAL METHODS

Figure 1 shows a schematic diagram of the experimental set-up with the stainless steel test section. It consists of a stainless steel pipe (diameter 50 mm, length 600 mm and 10 mm thick) internally polished using very fine emery cloth in the middle, a 4 kW electrical heater section at the bottom and a large air chamber at the top. The test section was provided with pairs of 15 mm diameter flat-glass windows

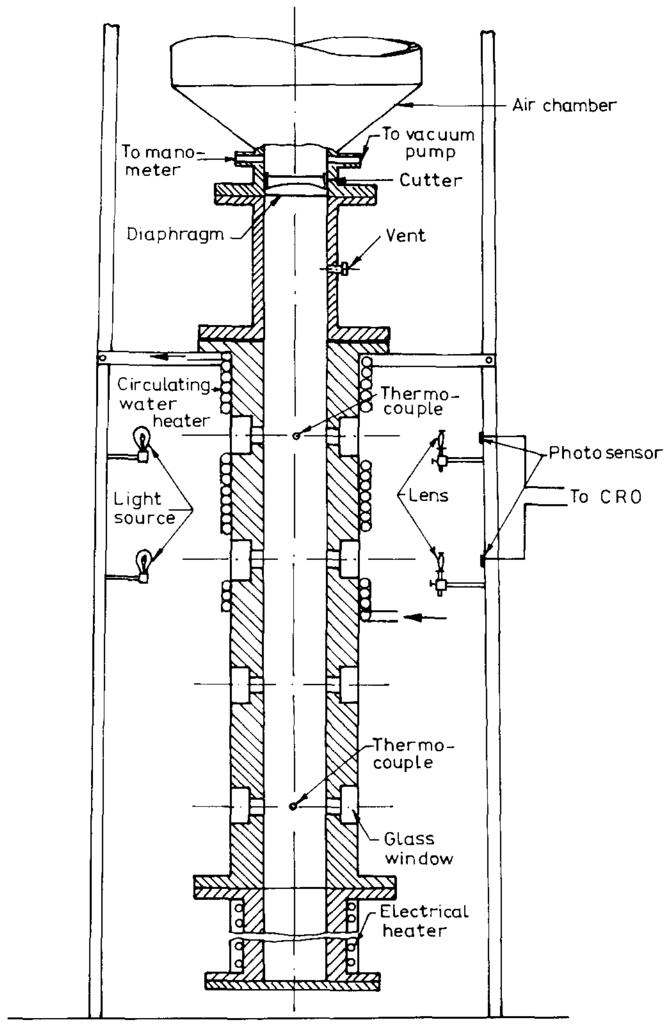

FIG. 1. Schematic diagram of set-up with stainless steel test section.

placed diametrically opposite each other at four axial locations, 165 mm apart. A 0.2 mm thick PVC plastic diaphragm separated the test section from the air chamber at the beginning of each experiment. To burst the diaphragm, a four bladed cutter was placed at the lower end of the air chamber directly above the diaphragm. When the air chamber was evacuated with a vacuum pump, the diaphragm bulged out towards the cutter and at a certain pressure differential it burst. The cutter could be moved vertically to get any desired initial distance between the cutter and diaphragm and this was used to obtain different depressurization levels. The pressure in the air chamber just before the burst was measured with a U-tube mercury manometer. The initial temperature of the liquid was measured with copper–constantan thermocouples. The superheat (denoted as ΔT) was the difference between the initial temperature and the saturation temperature corresponding to the applied pressure.

The BFP velocity was measured using an optical method. Light from a 100 W bulb was passed through the windows and liquid bulk to fall on a photodiode (SI 100). Windows were fully covered except for 1 mm wide horizontal slits that allowed a thin horizontal beam of light across the liquid bulk. When bubbles formed in the bulk across the windows, due to scattering, intensity of the beam reaching the detector dropped with a consequent change in the detector current. The signals were recorded on a storage oscilloscope (Gould model OS4000) and by measuring the time delay between intensity changes at two window locations 165 mm apart, the BFP velocity was calculated. Figure 2 shows photographs of two such signals. The step change in the signal corresponds to the start of boiling across the horizontal slits in the windows.

In the second arrangement, glass test sections with 30, 40 and 50 mm diameter were used. Water was heated in a constant temperature bath and then circulated in the test section. The remaining experimental procedure was the same as for the stainless steel test section.

To prevent wall nucleation, the liquid in the stain-

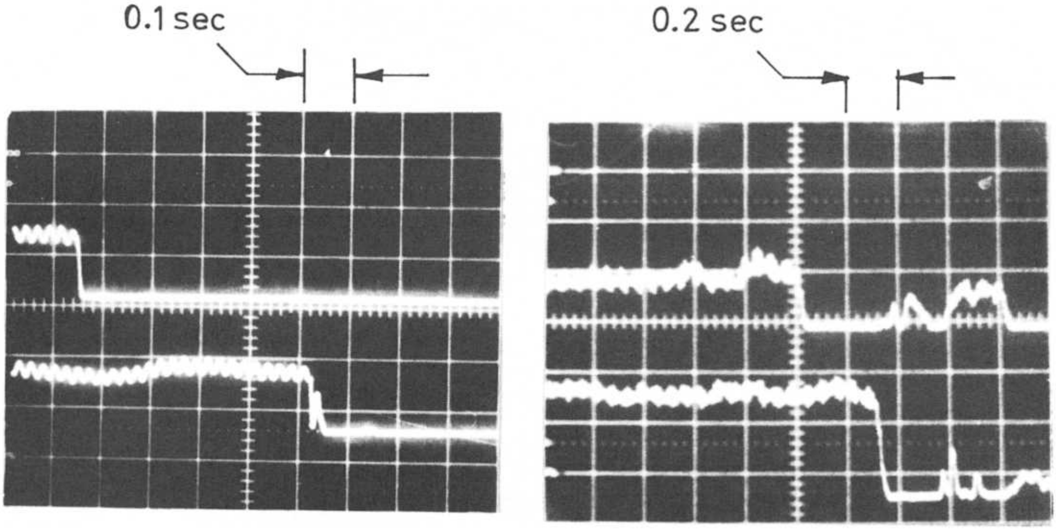

FIG. 2. Typical output signals with tap water.

less steel test section was vigorously boiled continuously for more than 2 h. The water was then cooled to 50° C and then only the top portion was heated using a circulating water heater as shown in Fig. 1 to the desired temperature in the range 80–95° C. This limited observations to the top two windows only; however, from Grolmes and Fauske's [2] findings that boiling propagation velocity does not depend on the axial location, this should not be a severe constraint. For glass test sections, the problem of wall nucleation was minimal and no such special preparation was needed.

3. EXPERIMENTAL RESULTS AND DISCUSSION

The dependence of BFP velocity on the following parameters was examined:

(a) degree of superheat,
(b) purity of test liquid,
(c) diameter of test section.

3.1. *Degree of superheat*

Experiments in glass test sections showed that the extent of superheat governed the vigour of the free surface activity. For values of superheats in the range 2–4° C, there was only evaporation from the free surface and very little waviness on it. This is consistent with the observations reported in refs. [2, 3]. For higher superheats, the top layer was violently disturbed and a phase change front propagated into the liquid.

Figure 3 shows the dependence of boiling front propagation velocity on liquid superheat for distilled water. The scatter in the data is due to the random nature of the process and partly to measurement errors. However, the following two features are clear: (a) boiling front propagation velocity ($\sim 5\,m\,s^{-1}$) is very small compared to the sonic velocity (about $1400\,m\,s^{-1}$) in water, justifying the observation made in ref. [1] that it is uncoupled from the rarefaction wave travel, (b) front propagation velocity increases linearly with increasing superheat.

3.2. *Purity of the test liquid*

Figure 4 shows the dependence of BFP velocity for tap water. Previously mentioned features are prominent here also; however, the front propagation velocity in tap water is observed to be about four times lower than that in distilled water. This difference is due to the presence of a larger amount of impurities, especially the suspended solid particles in tap water as compared to distilled water. This reasoning is based on the observed facts that the presence of contaminants at the evaporating surface reduce the rate of evaporation significantly [4], and that front propagation depends upon the mechanism of heat transfer and bubble formation [1]. Hence it appears that the concentration of impurities has a very significant effect.

3.3. *Diameter of the test section*

Figure 5 shows the dependence of BFP velocity on diameter along with superheat for glass test sections. Here distilled water was used as test liquid. This figure depicts the strong influence of diameter on BFP velocity. Furthermore, the glass test section results for 50 mm diameter are in good agreement with the results presented earlier for the stainless steel test section. This implies that if the surface is smooth enough and if it does not contain nucleation sites then BFP is independent of the wall material.

4. A PROBABLE PHYSICAL MODEL OF THE PHENOMENON

Any physical model proposed to explain the mechanism of BFP velocity must be able to explain the

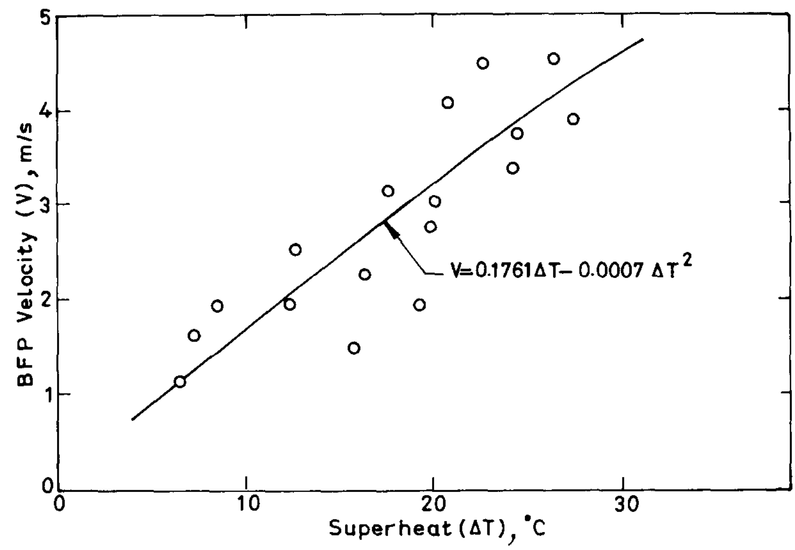

FIG. 3. Dependence of BFP velocity on superheat with distilled water.

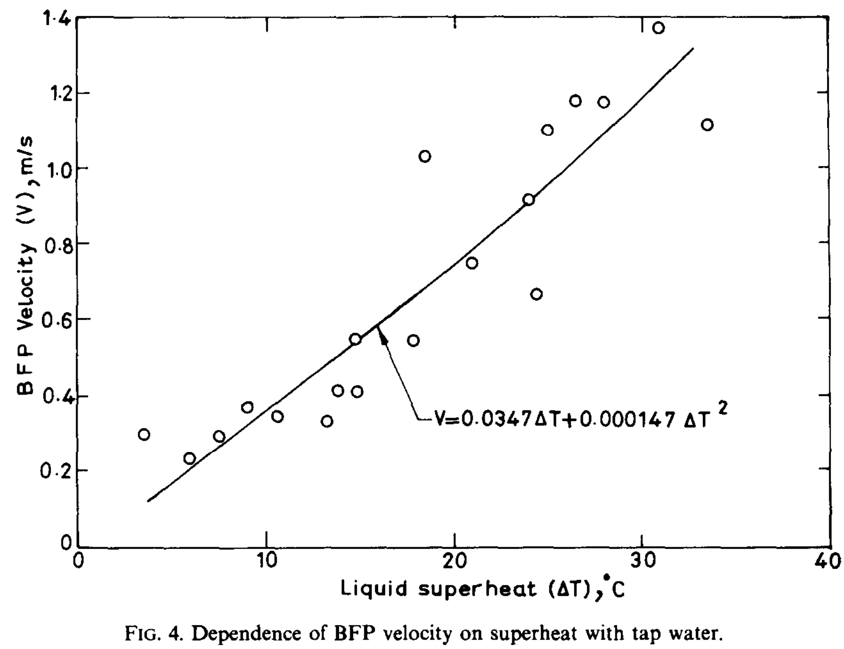

FIG. 4. Dependence of BFP velocity on superheat with tap water.

following features: BFP velocity depends upon the degree of superheat, purity of liquid and the diameter of the test section. Also the material of the wall is not important suggesting that bubbles are formed and grow in the bulk and not on the wall surface. As homogeneous nucleation at these low superheats is not possible, we hypothesize that nucleation bubbles are generated elsewhere and flow into the superheated region by the mechanism.

In order to understand the possible mechanism, a set of still photographs was taken with relatively long exposure times so that the small bubbles acted as markers in the liquid. A typical photograph is shown in Fig. 6. Figure 6 shows that there are vortices in the fluid and small bubbles represented by white lines are carried with these vortices. Based on these observations and earlier results, the following explanation of BFP mechanism is proposed.

When a rarefaction wave hits the free surface, instabilities occur and distort the free surface considerably. This may trap some air in the liquid as small bubbles. Due to the superheated state of the liquid, some of these bubbles grow in size reducing the amount of superheat available for other smaller bubbles and preventing their growth. As a result of their bigger size, grown bubbles start rising in the liquid due to bouyancy forces. This will initiate a kind of vortex motion, which will carry smaller bubbles into the superheated liquid below. These bubbles will grow in size, form a cluster, and rise as before

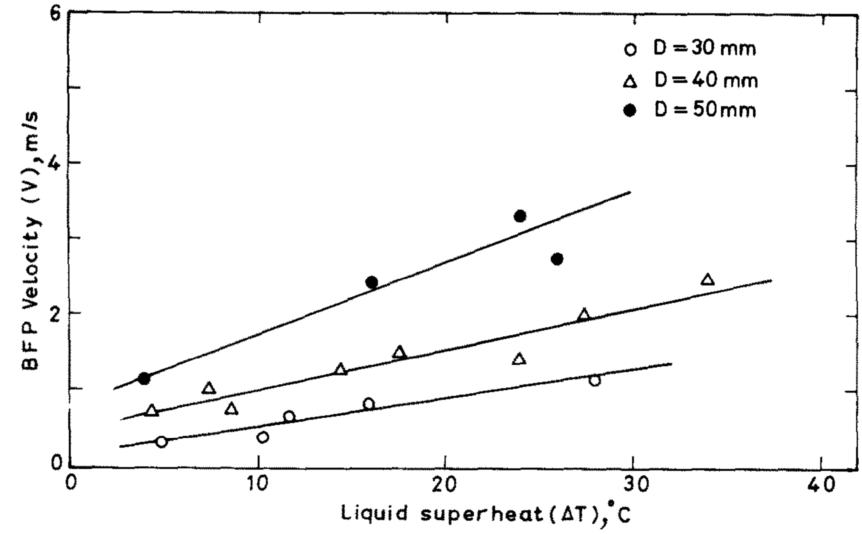

FIG. 5. Dependence of BFP velocity on superheat for different diameters with distilled water.

maintaining the vortex motion. However, due to relatively high velocities and drag, some large bubbles may break down into smaller ones generating fresh nucleation centres. Thus a self-sustaining boiling front is created. This mechanism is depicted schematically in Fig. 7.

The speed with which bubbles grow depends largely on the evaporation rate which is a function of temperature and quality of the liquid. Evaporation is faster at higher superheats and lower contamination levels. Both promote a faster growth of bubbles which in turn increases the recirculation speed. Higher circulation speed increases the frequency and size of nucleation centres entering the superheated region. Thus at higher superheats and lower contamination levels, the boiling front propagates faster. Friction at the walls reduces the recirculation velocity. The frictional forces increase with decreasing diameter and hence for smaller diameters, BFP velocity is smaller. The above explanations are qualitative in nature and they agree with the observations. Obtaining a functional relationship is very difficult, especially the one that links BFP velocity with the degree of superheat and the purity of the liquid. However, under the following assumptions, a relationship between BFP velocity and diameter can be obtained.

(1) The boiling front propagates because of the eddies that carry small bubbles down into the superheated liquid. BFP velocity is proportional to the circulation speed of the eddies.

(2) Eddies are formed by the upward motion of large bubbles.

(3) The circulation speed of the eddies is proportional to the rise velocity of large bubbles.

(4) For high void fractions, the expressions valid for steady state slug flow can be applied to the rise velocity of a swarm of bubbles.

(5) Even though this is a transient case, relations of steady state flow can be used.

(6) Frictional forces dominate the flow.

Observations showed that almost the entire volume was occupied by vapour bubbles. Assuming that most of the superheat goes into bubble formation and that both the liquid and vapour flow at the same velocities result in an estimate for void fraction of 0.97 for a superheat of 10° C at 80° C saturation temperature. So the void fraction is high both from estimates and observations and hence assumption 4 is applicable here. For friction dominated slug flow, the rise velocity v_∞ of bubbles in steady state is given by [5]

$$v_\infty = K\frac{gD^2(\rho_f - \rho_g)}{\mu_f}$$

where K is a constant, g the acceleration due to gravity, D the diameter of the pipe, μ_f the fluid viscosity, ρ_f the density of liquid, and ρ_g the density of vapour. In the range of superheats studied, the value of $(\rho_f - \rho_g)/\mu_f$ does not vary much. Therefore

$$v_\infty = \text{const.} \cdot D^2.$$

From assumptions 1 and 3 it follows that

$$\text{BFP velocity} \propto D^2.$$

To verify this relationship against experimental data, experimental BFP velocity is plotted as a function of D^2 for three different superheats in Fig. 8. For all three superheats, the data points lie close to straight lines through the origin. Considering the nature of the experiment and errors involved, this agreement is really good and implies that the assumptions made in deriving the functional relationship are reasonable. The value of the constant is a strong function of superheat.

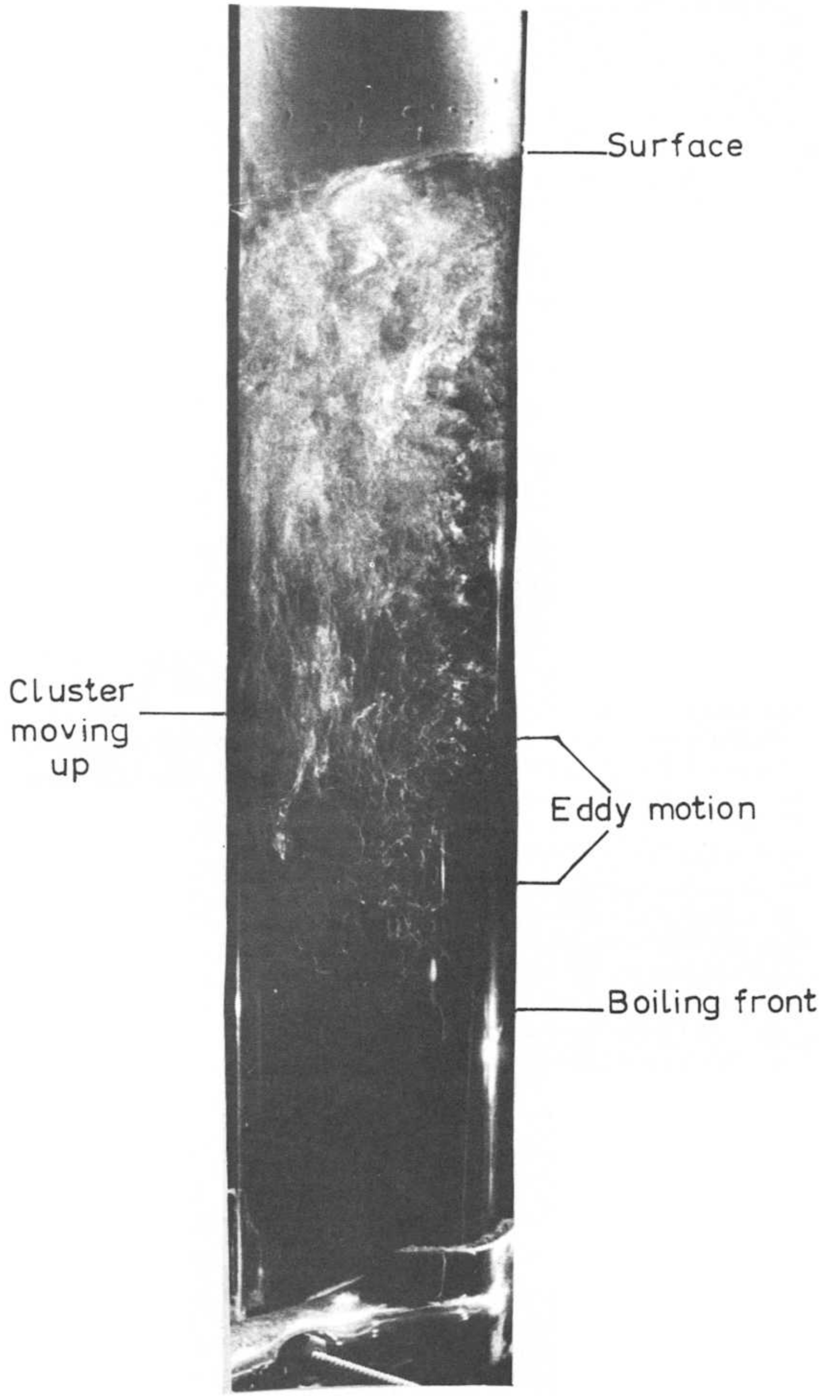

FIG. 6. A photograph of boiling front.

5. SUMMARY

Sudden decompression of a hot vertical liquid column, in the absence of nucleation sites initiates free surface instabilities and boiling. This propagates into the liquid as a phase change front. The velocity of the front increases linearly with the superheat, proportional to the square of the diameter and decreases with the impurities in the test liquid. The proposed convective model of the phenomenon is consistent with the observations.

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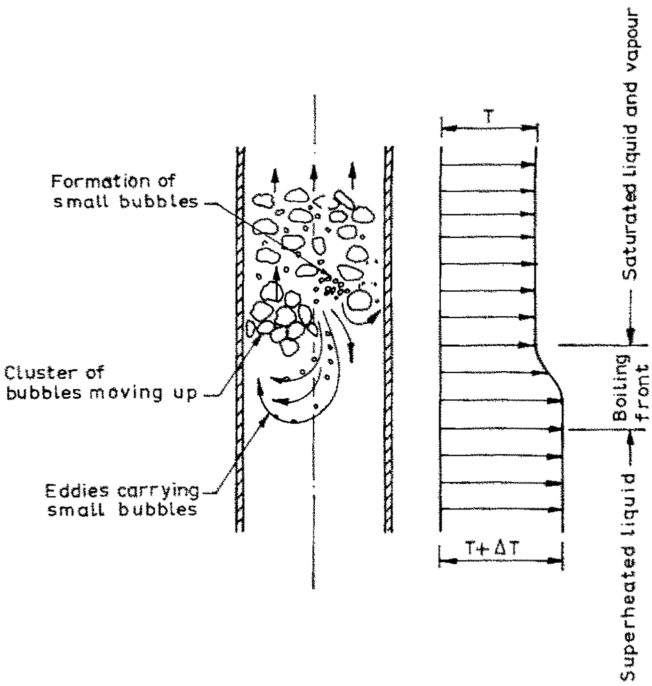

FIG. 7. A schematic diagram of the mechanism for boiling front propagation.

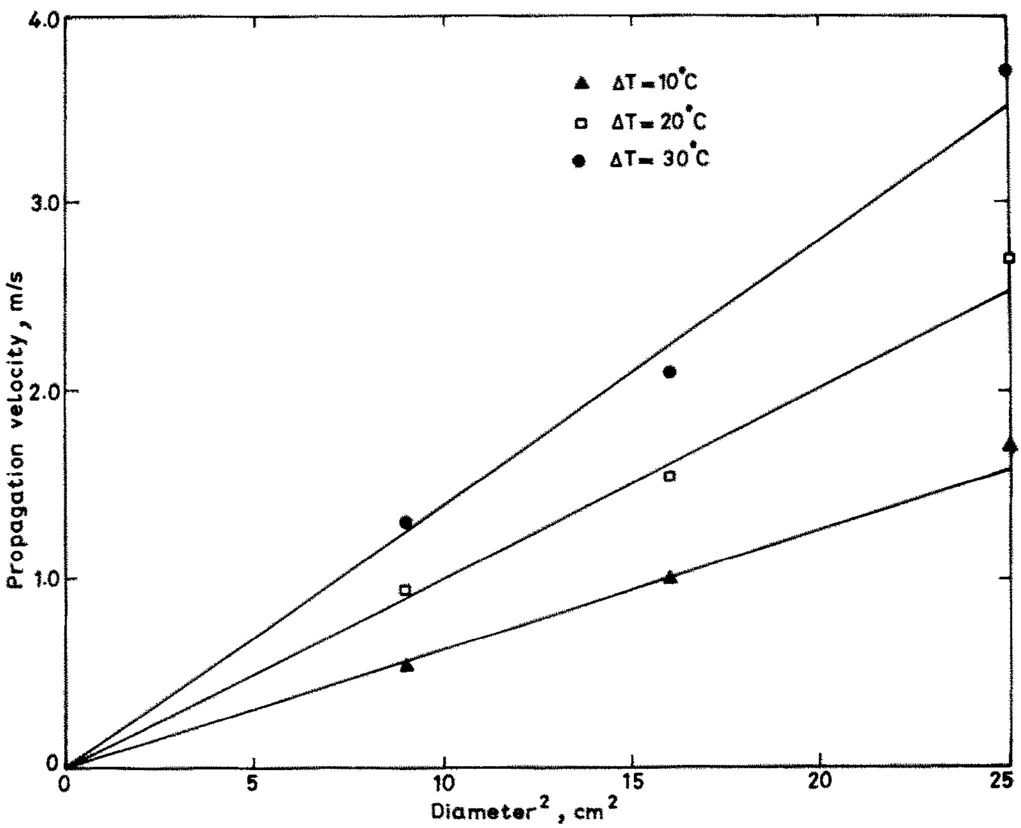

FIG. 8. Plot of diameter^2 vs front propagation velocity for distilled water.

REFERENCES

1. E. Terner, Shock tube experiments involving phase changes, *Ind. Engng Chem. Process Des. Dev.* **1**, 84 (1962).
2. M. A. Grolmes and H. K. Fauske, Axial propagation of free surface boiling into superheated liquids in vertical tube, Fifth International Conference of Heat and Mass Transfer, Tokyo (1974).
3. R. J. Peterson, S. S. Grewal and M. M. El Wakil, Investigations of liquid flashing and evaporation due to sudden depressurisation, *Int. J. Heat Mass Transfer* **27**, 301 (1984).
4. K. C. D. Hickman, Surface behaviour in the pot still, *Ind. Engng Chem.* **44**, 1893 (1952).
5. G. B. Wallis, *One-dimensional Two-phase Flow*, p. 285. McGraw-Hill, New York (1969).

ETUDE DE LA PROPAGATION D'UNE EBULLITION A SURFACE LIBRE DANS UNE COLONNE LIQUIDE VERTICALE SURCHAUFFEE

Résumé—On rapporte des études expérimentales sur la propagation de l'ébullition dans une colonne liquide verticale surchauffée et soudainement en dépression. La vitesse de propagation de ce changement de phase est mesurée par une méthode optique. Cette vitesse est fortement dépendante de la surchauffe du liquide, de la pureté du liquide et de la dimension de la section d'essai. Les vitesses mesurées inférieures à $5\,m\,s^{-1}$ sont nettement plus petites que la vitesse du son. Des observations faites on déduit que le mécanisme dominant pour la propagation de l'ébullition est la convection.

UNTERSUCHUNG ZUR AUSBREITUNG DER OBERFLÄCHENVERDAMPFUNG IN EINER SENKRECHTEN ÜBERHITZTEN FLÜSSIGKEITSSÄULE

Zusammenfassung—Es wird über einige experimentelle Studien zur Ausbreitung des Siedens in einer schnell entspannten, überhitzten senkrechten Flüssigkeitssäule berichtet. Die Ausbreitungsgeschwindigkeit dieses Phasenwechsels wurde mittels einer optischen Methode bestimmt. Die Ausbreitungsgeschwindigkeit hängt stark von der Flüssigkeitsüberhitzung, der Reinheit der Flüssigkeit und den Abmessungen des Versuchsbehälters ab. Die gemessenen Ausbreitungsgeschwindigkeiten von weniger als $5\ m\ s^{-1}$ sind deutlich geringer als die Schallgeschwindigkeit. Die vorliegenden Beobachtungen deuten darauf hin, daß der ausschlaggebende Mechanismus zur Ausbreitung des Siedens die Konvektion ist.

ИССЛЕДОВАНИЕ ЗАКОНА ПЕРЕМЕЩЕНИЯ СВОБОДНОЙ ПОВЕРХНОСТИ ПРИ КИПЕНИИ В ВЕРТИКАЛЬНОМ СТОЛБЕ ПЕРЕГРЕТОЙ ЖИДКОСТИ

Аннотация—Представлены экспериментальные результаты по перемещению свободной поверхности вертикального столба перегретой жидкости при внезапном падении давления. Скорость распространения фронта фазового перехода измерена оптическим методом. Она сильно зависит от перегрева жидкости, ее чистоты и размера экспериментального участка. Измеренные скорости (ниже 5 мс$^{-1}$) значительно меньше скорости звука. Эксперименты показывают, что преобладающим механизмом распространения области кипения является конвекция.