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CERTAIN ASPECTS OF AUTOWAVE TRANSITIONS FROM NUCLEATE TO FILM BOILING REGIMES WITH A CYLINDRICAL HEAT GENERATING ELEMENT INCLINED FROM A HORIZONTAL POSITION

S. A. Zhukov, L. F. Bokova and V. V. Barelko
Institute of Chemical Physics of the U.S.S.R. Academy of Sciences,
142432, Chernogolovka, U.S.S.R.

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Abstract—Certain aspects of the autowave processes on non-horizontally placed heating elements are considered. The rates of film regime propagation are shown to depend substantially on its orientation (in, or opposite to, the gravity force direction) and on the heating element inclination angle. It is shown that on a vertical element (a) the rate of film regime propagation can be twice as high as on a horizontal one and (b) within a certain range of heat loads the appearance of a running pulse is possible, i.e. a localized film regime zone. The results obtained are explained on the basis of the theory of autowave processes.

NOMENCLATURE

d, heater diameter;
I, current strength in heaters;
n, dimensionless parameter characterizing the boiling curve shape;
q, q_{cr}, heat flux and maximum heat flux at which nucleate boiling is possible;
T, heater surface temperature;
U, voltage applied to heating element;
u_1, u_2, the speed of propagation of film-mode waves initiated near the positive and negative electrodes, respectively;
α_1, α_2, heat transfer coefficient in nucleate and film boiling regimes, respectively;
δ, front width;
θ, dimensionless parameter;
λ, thermal conductivity;
φ, inclination angle of heat generating element ($\varphi = 0$, horizontal position; $\varphi = 90°$, vertical position).

INTRODUCTION

HE BASIC trends in the phenomena of autowave insitions from a nucleate to film regime of boiling ve been described theoretically and confirmed experi- entally [1, 2]. The physical model was a cylindrical at generating element (HGE) placed horizontally in volume of working liquid. The choice of precisely this nd of model in the first stage of the studies was ctated by the desire to simplify the problem and clude from consideration the nonuniformity of the ternal parameters, which inevitably accompanies the pearance of a free-convective component of medium otion along the axis of a cylindrical heat generating ement when it is declined from a horizontal position. owever, from a practical point of view considerable terest is attached to the data on vertical cylindrical GE's since these kind of elements are more frequently encountered in actual vapour-generating apparatus. The objective of the present work was to elucidate the specific features of autowave transition processes occurring during boiling on a cylindrical heat generator when its axis is declined from a horizontal position.

The apparatus used was an open temperature-controlled vessel. The temperature of the working liquid was fixed by means of electric heaters placed directly in the bulk of the working liquid, while a servo system allowed it to be maintained within 0.1°C.

The heat generating element, an electrically heated $100\,\mu$m diameter, 7 cm long platinum filament, was held stretched by special spring clips. The manner in which they were designed made it possible to set and fix the filament at certain angles of inclination to the horizontal. As in ref. [2], the working liquid was distilled water, the temperature of which in all experiments was 97°C. The element was fed with DC through a stabilizer with a current maintenance accuracy on a 4-fold change in the load impedance of 10^{-3} A (5×10^{-3}%), and a speed of response of about 10^{-3} s. The maximum output current was 20 A. The wave was initiated due to local superheating of the surface by an air jet supplied to a portion of the element through a narrow metal capillary.

It was expected that for a non-horizontal element the location of the superheated portion, where the wave was initiated, would exert a substantial effect on the trends in the film-mode wave propagation. Figure 1 shows the wave velocity plotted versus the angle of filament axis inclination to the horizontal for two cases of wave initiation: from the lower end of the filament (curve 1) and from the upper end (curve 2). In both cases the strength of the current passing through the filament was fixed at 2.88 A. As is seen, the curves differ markedly in character.

When the film regime is initiated from below, the wave velocity along an inclined filament first decreases with an increase in the inclination angle ($\varphi < 10°$) and then shows a slight increase in a wide range of the φ values ($10° < \varphi < 70°$). Rotation of the element through more than 70° is accompanied by a sharp increase in the speed of autowave motion. The velocity of the wave induced from below on a vertical filament ($\varphi = 90°$) is substantially higher than that on the horizontal one. Thus, the data presented in Fig. 1 should be thought of as indicating the existence of a new (compared with that studied earlier [1, 2]) high-rate mechanism of film regime self-propagation occurring in boiling on inclined HGE's at inclination angles close to 90°. Qualitatively, the nature of its appearance can be explained as follows. When the element is declined from a horizontal position, the mechanisms underlying the displacement of the lower and upper boundaries of a vapour "sleeve", which is formed in the zone of film regime initiation on the filament, differ markedly. While the lower boundary moves following the heat conduction mechanism (just as in the case of a horizontal filament [1]), the motion of the upper one is caused substantially by the buoyancy mechanism which drives the vapour "sleeve" upwards along the filament.

From an analysis of the experimental data (Fig. 1, curve 1) the buoyancy-induced motion is seen to be of a critical nature, i.e. it occurs when a certain parameter (here the inclination angle φ) attains a threshold value. Such a critical angle is $\varphi \sim 70°$. At $\varphi < 70°$, the axial component of the buoyancy force is balanced out by the forces holding the vapour film on the filament, and the film regime zone boundaries broaden due to conductive heat transfer through the element from the film to the nucleate regime zone. At $\varphi > 70°$, one observes the commencement and rapid acceleration (with an increase in φ) of the buoyancy-induced rise of the vapour film, which is accompanied by the successive involvement of the element patches (lying above the upper boundary) into the film boiling regime. As a result, the rate of the film-regime wave motion increases sharply, and at large inclination angles of the element the conductive mechanism of the autowave process is completely replaced by the free-convective mechanism.

When the wave is initiated from above, the rate of film regime propagation is determined by the motion of the lower boundary of the vapour film, as a result of which heat conduction remains the sole mechanism of the autowave process at all angles (Fig. 1, curve 2). However, it has been established experimentally that a not very marked (as in the first case) but yet large enough increase in the wave velocity with φ occurs, although a decrease in the velocity was expected in view of the retarding effect of free convection on the motion of the boundary. An explanation for this peculiar behaviour has been found from an analysis of inclination angle effect on the temperature of the element encompassed entirely by the fim boiling regime. It has been established that an increase in φ leads to an increase in the temperature of the element at a fixed heat load. As is seen from Fig. 2, the vertical element turned out to be hotter by about 350°C than the horizontal one. This deterioration of heat transfer from the surface of an inclined element in a film regime results from a change in the way the vapour is driven away from the element into the liquid volume: in the case of a horizontal filament the vapour does not remain on the surface long, but, by surmounting the surface tension forces of the vapour film around the element, soon accumulates into buoyant vapour plumes densely distributed over the element; when the element is inclined, the vapour is partially detained at the element surface and, before entering into the liquid volume, it moves over the surface vapour film, "swelling" the latter. The larger φ, the higher is the intensity of vapour flow over the film and the stronger is its deformation. A decrease in the heat transfer coefficient in the zone of film boiling regime on inclined elements is responsible for the experimentally observed increase (with φ) of the rate of the autowave process when

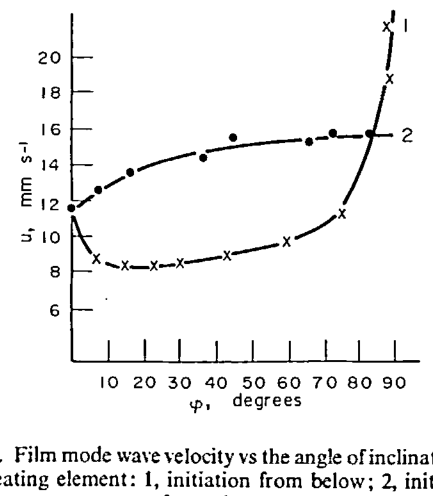


FIG. 1. Film mode wave velocity vs the angle of inclination of the heating element: 1, initiation from below; 2, initiation from above.

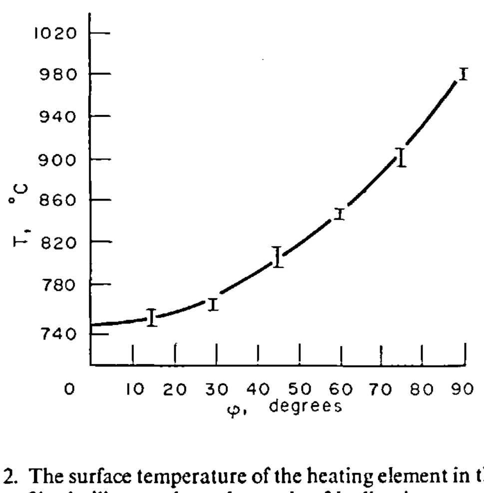


FIG. 2. The surface temperature of the heating element in the film boiling mode vs the angle of inclination.

nitiated from above. This conclusion is drawn directly rom the theory developed previously [1], which uggests that a decrease in the slope of the film boiling ranch of the boiling curve leads to a decrease in the arameter θ (θ is the dimensionless parameter varying vithin $0 \leq \theta \leq 1$ which characterizes the extent of the leparture from q_{cr} [1]), i.e. to an increase in the wave-notion rate.

One other specific feature of the wave processes on nclined elements is that the gas bubbles, rising along he element surface, capture liquid, leading to the ormation of a two-phase flow. This is thought to be he reason for the discrepancy between curves 1 and 2 of Fig. 1 within the range $0 < \varphi < 90°$. In accordance vith the above arguments, the existence of such a flow ahead of the running front should lead to higher heat ransfer in the nucleate regime region, which must entail an increase of the heat transfer coefficient α_1 higher θ), i.e. a decrease in the rate of the film regime vave when it propagates from below upwards. This also seems to explain the existence of the descending part of curve 1.

Striking features of the wave modes of boiling on nclined heat generating elements have been discovered n the region of transition from the film to the nucleate boiling wave. In this region [1], called the region of "indifferent equilibrium", the nucleate and film boiling zones on a horizontal element co-exist in a steady ashion, forming standing waves ($u = 0$)*.

Let us consider the results obtained in experiments for a vertical heat generating element using the data presented in Fig. 3. The figure shows plots of the film-mode wave velocity (positive values) and of nucleate-mode wave velocity (negative values) versus the strength of the current, which heats the element, for the cases when the wave is initiated from below (curve 1) and from above (curve 2). The mechanisms discussed above relate to the region of parameters which corresponds to the interval 1–2 in Fig. 3. The character of curves 1 and 2 within this interval illustrates again the conclusion on the wave process acceleration in the case of its initiation in the lower portion of the vertical filament. The interval 4–5 corresponds roughly to the region of the nucleate regime wave. This autowave process originates spontaneously (without introduction of a local disturbance), which is associated with the existence on the filament of the end patches that are cooler than the remainder portion of the element. The nucleate regime wave on a vertical element always moves from below upwards due to the effect of the buoyancy force. This causes the displacement of the vapour film from the element.

In the interval 2–5, a new type of autowave process has been discovered, a travelling film regime spot which originates on the element in response to local initiation. While in the case of a horizontal filament such a disturbance in the mentioned interval of parameters produces a standing wave (i.e. a hot spot remains stationary on the filament) on a vertical element motion arises under the action of buoyancy forces and it rises up as an entity not detaching from the heater surface. Figure 4 shows a photographic record of this process. As already mentioned, the motion of the lower and upper boundaries of the spot differ in character and, depending on the relationship between the rates of their displacement, the entire region 2–5 can be subdivided into the three characteristic intervals. Within the interval 4–5, the rate of motion of the lower boundary is higher than that of the upper and therefore the spot diminishes in size as it moves along the element and, before reaching the upper end of the heater, it collapses and disappears. With an increase in the strength of the current, the coordinate of the spot disappearance approaches the upper end of the filament, and at the edge of the interval (point 4) the spot disappears, only after having travelled over the entire element, near its end due to a strong conductive heat transfer by the electrode. The interval 3–4 corresponds to an equality between the speeds of the upper and lower boundaries of the spot, and here the spot moves unaffected at, on average, constant velocity. The size of the spot and its velocity increase with the current strength (Fig. 5). Within the interval 2–3, the velocity of the upper boundary becomes higher than that of the lower one. This causes spot expansion during its motion.

The observation of the mean-integral temperature (resistance) of the heated filament give qualitative information about the dynamics of spot motion.

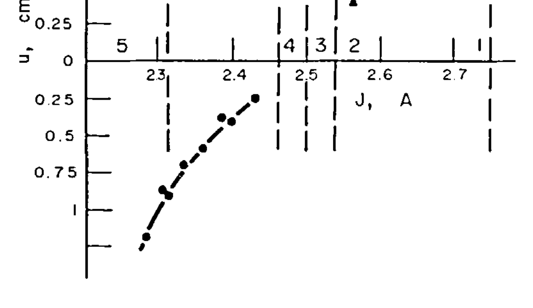


FIG. 3. Dependence of the speed of film ($u < 0$) and nucleate ($u > 0$) mode wave propagation over a vertical heating element on the strength of the current which heats the filment: 1, initiation of the film mode wave from below; 2, initiation from above.

*In ref. [5], the heat flux, which corresponds to this region, s called an "equilibrium" one.

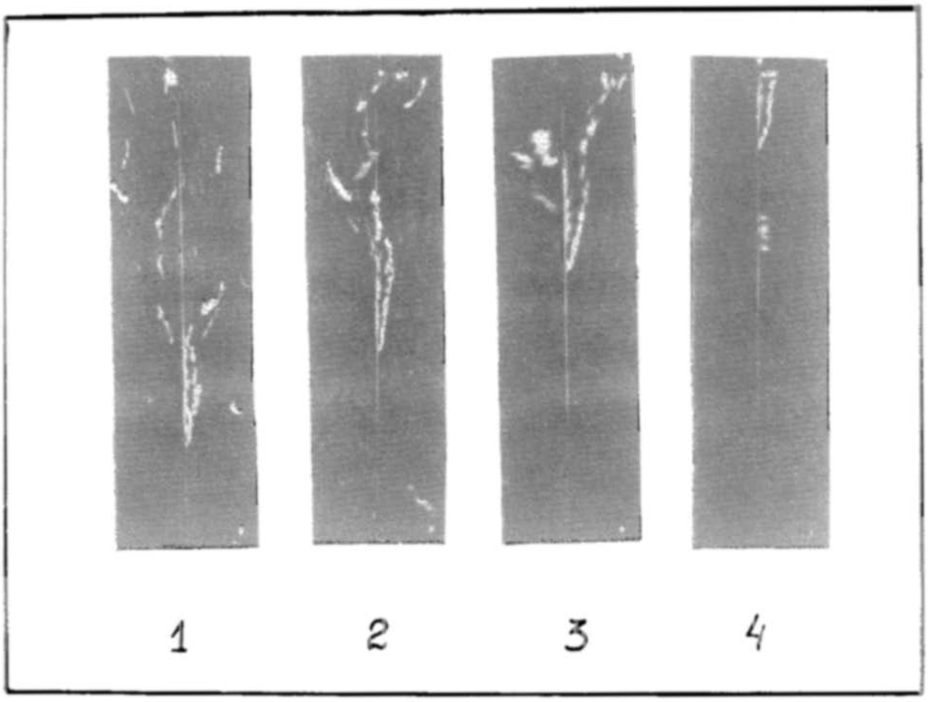


Fig. 4. Photographic record of film spot propagation.

Figure 6 presents the thermograms that correspond to the cases considered: on curve 1 the initiated spot of the film regime (the moment of initiation is indicated by an arrow) has disappeared not having reached the end of the element; on curve 2 the spot has disappeared after having reached the upper electrode; 3 the spot moves with about constant velocity not changing in size and remains on the electrode after having reached its upper end; curve 4 shows an expanding spot; on curve 5 the process passes over into a stationary wave regime (u = constant) and the entire filament becomes encompassed by the film boiling (interval 1–2, Fig. 3).

The information obtained in the course of the experiments makes it possible to carry out a comparison with the results of a theoretical investigation [1]. The minimum dimension of the isolated stationary zone of film regime is about 0.65 cm. (Fig. 5). Assuming this dimension to be approximately equal to the doubled front width*, we obtain an experimental estimate of $\delta = 0.32$ cm.

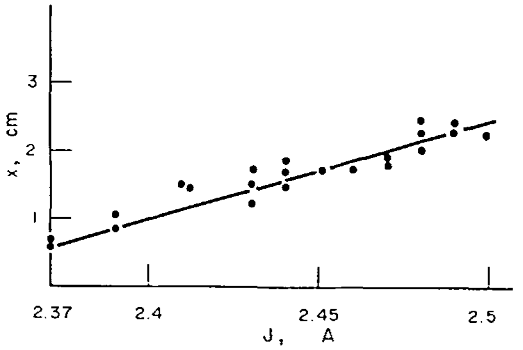


Fig. 5. The size of the moving spot of film mode vs the strength of the current which heats the filament.

An analytical estimation of δ can be made by the formula

$$\delta = \frac{1}{\sqrt{2}} \frac{(d\lambda)^{1/2}}{[\alpha_2 \theta (1-\theta)^2 + \alpha_1 \theta^2 (1-\theta)]^{1/2}}.$$

In the case considered $d = 10^{-2}$ cm, $\lambda = 0.72\ \text{W cm}^{-1}\ \text{grad}^{-1}$, the coefficients of heat transfer in the nucleate, α_1 and film, α_2, modes determined from experimental data, are

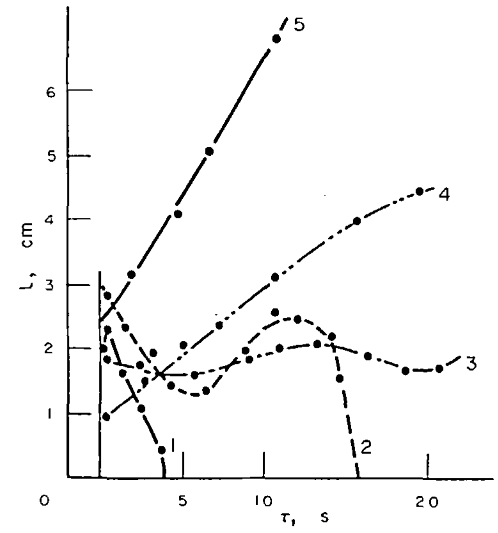
$$\alpha_1 = 3.13\ \text{W cm}^{-2}\ \text{grad}^{-1};$$
$$\alpha_2 = 0.194\ \text{W cm}^{-2}\ \text{grad}^{-1}.$$

In order to determine the parameter θ, we use the fact that motion occurs near the region of indifferent equilibrium, i.e.

$$\theta \sim \theta_{cr} = \frac{n}{1+n}, \text{ where } n = (\alpha_2/\alpha_1)^{1/2}.$$

*By the width of the front (δ) we mean the ratio between the maximum temperature drop in the front and the maximum gradient in it

$$\delta = (T_{max} - T_{min})/(dT/dx)_{max}.$$

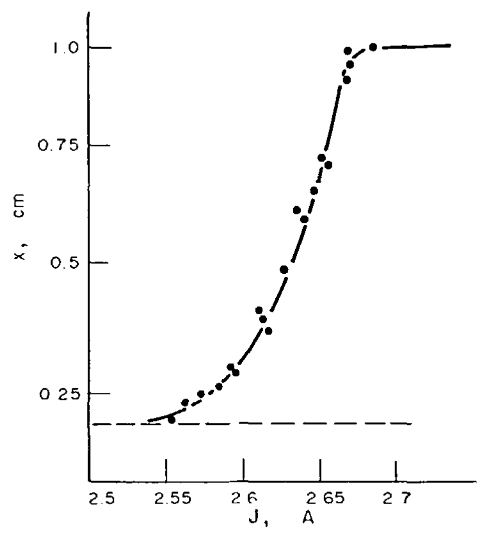


IG. 6. Time history of the film regime spot size: 5, $i = 2.55$ A; 4, $i = 2.52$; 3, $i = 2.48$; 2, $i = 2.37$; 1, $i = 2.28$ A.

Iaving substituted the numerical values into the xpressions for δ, we obtain $\delta = 0.16$ cm.

A unique feature of the process, as compared with utowave transitions on a horizontal filament, is the .ature of steady states that occur on a vertical element t the end of spot propagation within the range of arameters, where the spot, having reached the upper nd of the electrode, does not disappear (Fig. 3, interval -4). It is evident that here that temperature-onuniform steady states are developed: the zone of film regime, having formed on the upper part of the element, coexists steadily with the zone of the initial nucleate regime persisting on its lower portion. However, these steady states differ markedly from the steady states of "indifferent equilibrium" on a horizontal filament [1, 2] in that the relationship between the lengths of the zones and the coordinate of the boundary between them on a vertical element are in a strict one-to-one correspondence with the fixed value of the parameter (here, with the current strength J). This fact is illustrated in Fig. 7, where the dependence of the relative fraction of the entire element length, occupied by the film regime, on the current strength is shown.

The physical reason for the appearance of these steady states is easy to find from the autowave concepts. To this effect, consider a wave process within the given region of parameters occurring on film regime initiation in the upper portion of the element. For a wave induced under these conditions a characteristic feature is its deceleration terminating in a complete stoppage of the front at a certain (for the given J) cross-section of the element, the coordinate of which is the same as in Fig. 7. The wave moves with a variable velocity because, in contrast to a horizontal filament, the intensity of heat transfer in the zone of nucleate boiling on a vertical element is the quantity which varies over the length of the element: its intensity increases from above downwards due to the presence in this zone of the buoyancy flow of the liquid. Thus, in the system described, each cross-section of the heater differs from the neighbouring one by the form of the boiling curve, i.e. by the position of its nucleate branch. In terms of the theory, the film-boiling wave travelling from above downwards over the vertical element is characterized by a variable, rather than a constant, parameter θ, which is responsible for a decrease in the velocity of the wave and its complete termination on reaching the cross-section with $\theta = \theta_{cr}$. With an increase in the current strength, the coordinate of the cross-section, where the wave front stops (i.e. the cross-section at which $\theta = \theta_{cr}$), shifts to the side



IG. 7. A relative length of the heating element occupied by the film mode.

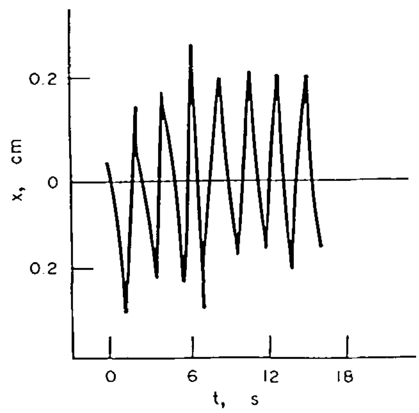


FIG. 8. An example of self-oscillatory instability of the lower boundary of the film spot (vertical heating element).

of the lower end of the filament. Qualitatively, the picture described was observed in the experiment presented in Fig. 7.

In conclusion, let us briefly consider one more dynamic feature of the process of boiling on a vertical heat generating element, the self-oscillatory modes of its occurence. They are most pronounced in the region of parameters corresponding to the interval 2–4 in Fig. 3. The phenomenon of the running spot of film regime considered above is characterized by the fact that the rate of its rise involves a periodically variable component actually within the whole interval mentioned. This can be easily observed visually, since the motion of the spot resembles the movement of a caterpillar: first the upper edge of the spot moves upward and then the lower one rapidly pulls itself up. This sequence of stages repeats periodically and is responsible for the oscillatory mode of the spot motion. This fact is illustrated in Fig. 6: curve 3 shows a periodic change in the interval signal which reflects a periodic variation of the rising spot size. On having reached the upper end of the element, the spot, as has been described above, stops, but its lower boundary tends to maintain oscillations about the equilibrium position, the coordinate of which is given in Fig. 7. An illustration of these oscillations is presented in Fig. 8. The self-oscillatory modes were observed on vertical elements also in the region of wave motion (intervals 1–2 and 5–6 in Fig. 3). We think that the mechanism of the observed self-oscillations is based (as in the case of other phenomena considered here) on the interaction between the free-convective and thermal effects. However, this requires further investigations which are beyond the scope of the present work.

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APPENDIX

The problem of the effect of an electric current on the process of boiling has been the subject of previous publications [3, 4]. There the effect of strong electric fields was discovered, and manifested itself in a certain increase in the maximum critical heat flux. However, the literature lacks data on the effect of electric fields on the very process of vapour formation, though, on general grounds (the formation of charged layers of liquid near the conductor surface), this effect might be expected. Hence, before starting experiments on the autowave processes on heat generating elements, a series of tests was undertaken to elucidate the effect of electric current on the speed of film mode wave propagation. Table 1 contains the values of velocities obtained on a horizontal filament at different values of the current passing through it for the cases of wave initiation near a positive (u_1) and negative (u_2) electrodes.

Table 1.

J(A)	2.88	2.90	3.00
u_1 (cm s^{-1})	1.14	1.33	1.60
	1.14	1.33	1.60
	1.00	1.30	1.51
u_2 (cm s^{-1})	0.40	0.66	0.80
	0.44	0.57	0.80
	0.4	0.53	0.77

As is seen from the results of measurements, the velocity is twice as high in the case when the direction of wave motion coincides with that of the current (i.e. from a positive to a negative electrode).

The effect discovered does not depend on the heater position in the vessel and is reproducible on replacement of the filament.

It can be assumed that the nature of the effect observed is associated either with the presence of an electric charge in the gas phase, directly adjacent to the heater surface, or with an ordered orientation of liquid molecules on formation of charged layers near the surface.

Acting on this conclusion, all of the experiments described above were arranged in such a way that the current direction coincided with that of the front motion, which precluded the possible distorting effect of this factor on purely thermophysical trends.

A separate question, outside the scope of the present investigation, was that concerning the pulse motion over an inclined filament. The data obtained made it possible to predict that the electric factor would be yet another mechanism of running pulse propagation in the region of indifferent equilibrium. In fact, at inclination angles less than 70°, when the effect of the buoyancy factor is small, the use of the detected effect allowed pulse starting against the gravity forces, i.e. down the element.

The experiments were carried out on the setup described previously. A voltage stabilizer was used as a current source.

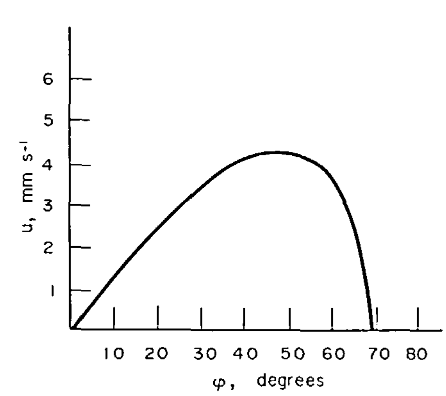

FIG. 9. The film mode spot velocity as a function of the heating element inclination angle.

When the thermal load is supplied in this way, there is a negative current coupling which leads to the formation of a standing wave on film regime initiation. The initial thermal load was chosen in such a way that the size of the film-mode zone was 1–1.5 cm.

The results obtained are presented in Fig. 9 as a plot of the pulse propagation rate versus the inclination angle of the heating element. (The film mode was initiated in the upper portion of the element.) The vanishing of the velocity at angles close to 70° is associated with the fact that, as was discovered earlier (Fig. 1), it is at these angles that the effect of the buoyancy forces, acting in the opposite direction, begins to be felt. At angles $\varphi > 70°$, the motion reverses its direction. Affected by the buoyancy force, the spot begins to rise.

In the present paper and in the Appendix we have considered two physical mechanisms leading to the appearance of a running pulse on non-horizontal heating elements. However, this phenomenon is much more complicated and diversified. In particular, it can be assumed that the mechanism of pulse motion over an inclined heat generating element is influenced by a reactive force. However, a detailed discussion of this problem lies outside the scope of the present paper.

CERTAINS ASPECTS DE TRASITIONS D'ONDES DE L'EBULLITION NUCLEE A CELLE EN FILM AVEC UN ELEMENT CYLINDRIQUE CHAUFFE ET INCLINE

Résumé—On considère certains aspects des mécanismes d'ondes sur des éléments chauffés et inclinés. Les vitesses de propagation du régime de film sont dépendants de l'orientation (dans ou opposé à la direction des forces de pesanteur) et de l'angle d'inclinaison de l'élément chauffé. On constate que sur un élément vertical (a) la vitesse de propagation du régime de film peut être deux fois plus grande que sur un élément horizontal et (b), dans un certain domaine de chauffage, une pulsation est possible avec une zone localisée de régime de film.

Les résultats obtenus sont expliqués sur la base de la théorie des mécanismes auto-onde.

EINIGE ASPEKTE DES SELBSTERREGTEN ÜBERGANGS VOM BLASENSIEDEN ZUM FILMSIEDEN AN EINEM, GEGEN DIE HORIZONTALE GENEIGTEN, ZYLINDRISCHEN HEIZELEMENT

Zusammenfassung—Einige Aspekte des selbsterregten übergangs an nicht horizontal liegenden Heizelementen werden betrachtet. Die Ausbreitungsgeschwindigkeit des Filmsiede-Bereiches zeigt eine gewisse Abhängigkeit von der Orientierung (in Richtung der Schwerkraft oder ihr entgegen) und von der Neigung des Heizelements. Es wird gezeigt, daß an einem vertikalen Element die Ausbreitungsgeschwindigkeit des Filmsiede-Bereiches doppelt so groß sein kann wie bei der horizontalen Anordnung und es innerhalb bestimmter Auf heizbereiche zu pulsierenden Übergängen zwischen den Siedezuständen kommt, die an eine bestimmte Stelle des Films gebunden sind. Die Ergebnisse werden auf der Basis der Theorie der Selbsterregung erklärt.

ОСОБЕННОСТИ АВТОВОЛНОВЫХ ПЕРЕХОДОВ МЕЖДУ ПУЗЫРЬКОВЫМ И ПЛЕНОЧНЫМ РЕЖИМАМИ КИПЕНИЯ ПРИ ОТКЛОНЕНИИ ЦИЛИНДРИЧЕСКОГО ТЕПЛОВЫДЕЛЯЮЩЕГО ЭЛЕМЕНТА ОТ ГОРИЗОНТАЛЬНОГО ПОЛОЖЕНИЯ

Аннотация—В работе рассмотрены особенности автоволновых процессов на негоризонтально расположенных нагревательных элементах. Показано, что скорости распространения пленочного режима существенно зависят от угла наклона нагревательного элемента и направления распространения (по и против силы тяжести). Обнаружено, что на вертикальном элементе (а) скорость распространения пленочного режима может в два раза превосходить скорость распространения по горизонтальному элементу, (б) в определенном интервале тепловых нагрузок возможно появление бегущего импульса, т.е. локализованной зоны пленочного режима.

Полученные результаты объяснены с позиции теории автоволновых процессов.