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TRANSIENT HEAT TRANSFER FROM A HOT NICKEL SPHERE MOVING THROUGH WATER

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Abstract—The object of the work described in this note was to identify the rapidly changing modes of boiling and to correlate these with variations in heat flux, so that any theoretical treatment of transient heat transfer from hot bodies could be founded on a correct physical model.

1. DESCRIPTION OF APPARATUS

NICKEL was chosen as the sphere material because of its high melting point and non-corrosive properties. A 6·35 mm diameter nickel sphere was supported between two parallel 0·56 mm diameter thermocouple wires, the ends of which were flattened and then spot-welded tangentially to the surface of the sphere on opposite ends of a sphere diameter. The sphere was then mounted in the assembly shown in Fig. 1(a). This assembly was fixed to the end of a 0·6 m long arm which was pivoted on top of a Kodak High Speed ciné camera. The camera was mounted on a trolley which could run along a track parallel to a polymethylmethacrylate tank containing water. The arm was spring loaded so that it rested on one edge of the tank and as the camera traversed the track the arm was made to follow a profile which allowed the sphere to enter the water at an angle of 60° to the horizontal and then travel horizontally about 20 mm below the water surface for a distance of 0·3 m before being raised clear of the water again [Fig. 1(b)]. The camera was arranged to have a field of view of approximately 25 mm × 20 mm with the sphere in the field view throughout the length of its horizontal path.

The sphere was heated in free air in an image furnace which consisted of a 200 W quartz iodine lamp set at one focus of an ellipsoidal mirror and the sphere placed at the second focus. Sphere temperatures of 1000°C could be readily achieved by this method. When the sphere had reached the desired temperature, the film transport in the ciné camera was started and the camera trolley was manually pushed along its track. The velocity of the sphere through the water was established from electrical pulses produced by equi-spaced contacts operated by the camera trolley as it ran along its track. These pulses were displayed on a multi-beam oscilloscope along with the thermocouple outputs. In the experiments with a heated bath the water temperature was uniform throughout the bath to within ±0·5°C of the stated temperature.

There was little heat loss from the sphere prior to its entry into the water bath and the temperature recorded by the thermocouple was reasonably assumed to be the average throughout the sphere. On emerging from the bath the temperature reached a steady level within 0·2 s by which time the temperature throughout the sphere would again be nearly uniform.

2. RESULTS

Unless otherwise stated the sphere velocity

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was within the range 1·2–1·5 ms^{-1}. No attempt has been made to analyse the transient temperatures since by themselves they gave no quantitative indication of either the average sphere temperature or the temperature gradients within the sphere.

The difference between the temperature on entry into the bath and the final uniform temperature has been used in the following analysis. An average heat flux has been calculated assuming that the heat transfer is uniform over the whole sphere for the duration of its submerged path. This assumption is not justified on the evidence of the ciné films but the method has been used in order to make comparisons which have been corrected for variations in sphere velocity. A summary of the results is shown in Fig. 2 where the average heat flux is plotted against initial sphere temperature. It should be noted that for initial sphere temperatures of less than 300°C the average heat flux is apparently independent of bath temperature up to 80°C. For initial sphere temperatures above 700°C the average heat flux is constant for a given bath temperature. All these data were obtained with a relatively clean sphere surface. Some further tests were performed to examine the effects of an oxidised surface as well as the effect of sphere velocity upon the heat flux.

2.1 *Effects of oxide layer and sphere velocity*

These tests were done with a bath temperature of 40°C and an initial sphere temperature of 800°C. Tests with a clean sphere were performed first and the sphere was enveloped in an argon atmosphere when it was not in the water bath. Runs were performed at velocities within the range 0·50–1·75 ms^{-1} and then an oxide layer was formed by frequent heating of the sphere in air before performing the second part of the tests. The results are shown in Fig. 3 where it can be seen that the average heat flux with an oxidized sphere is some 30 per cent higher than with a cleaned surface, and the heat flux is almost independent of velocity within the range 1·0–1·75 ms^{-1}. The oxide layer was less than 15 μm thick. The enhancement of heat flux by the presence of an oxide layer has been reported in other experimental conditions (e.g. Bennett [2]). Figure 3 also gives some idea of the scatter of the results.

2.2 *Photographic studies*

Seven different modes of heat transfer were identified from the ciné films and examples of these are shown in the selected "stills" from the ciné films shown in Fig. 4. They are identified as:

1. *Laminar film.* In which the vapour film around the front of the sphere is smooth and stable.

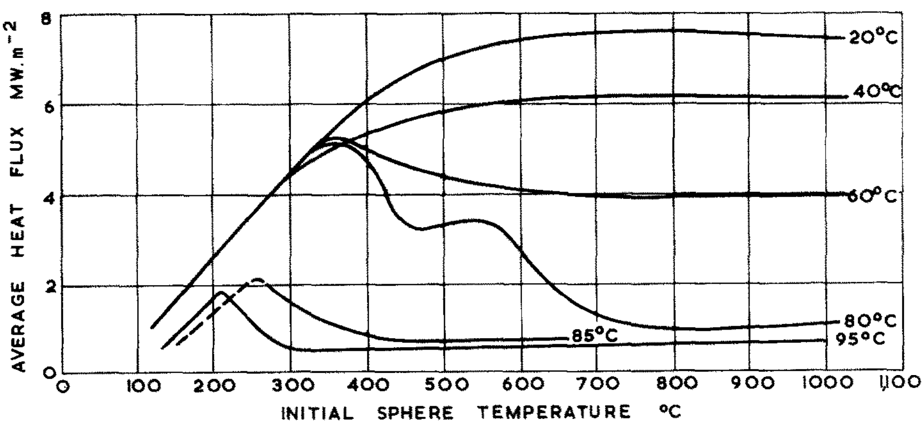

FIG. 2. Average heat flux vs. initial sphere temperature.

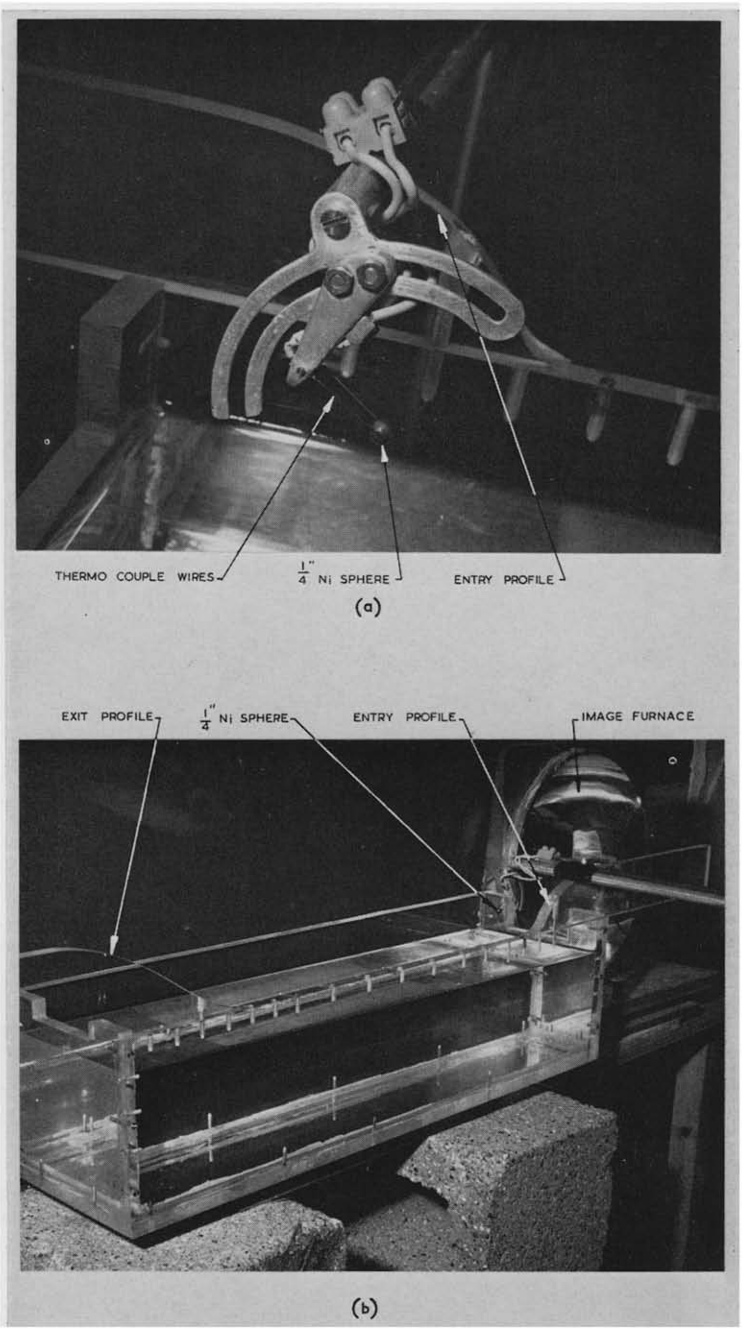

FIG. 1. Close up and general view of the apparatus.

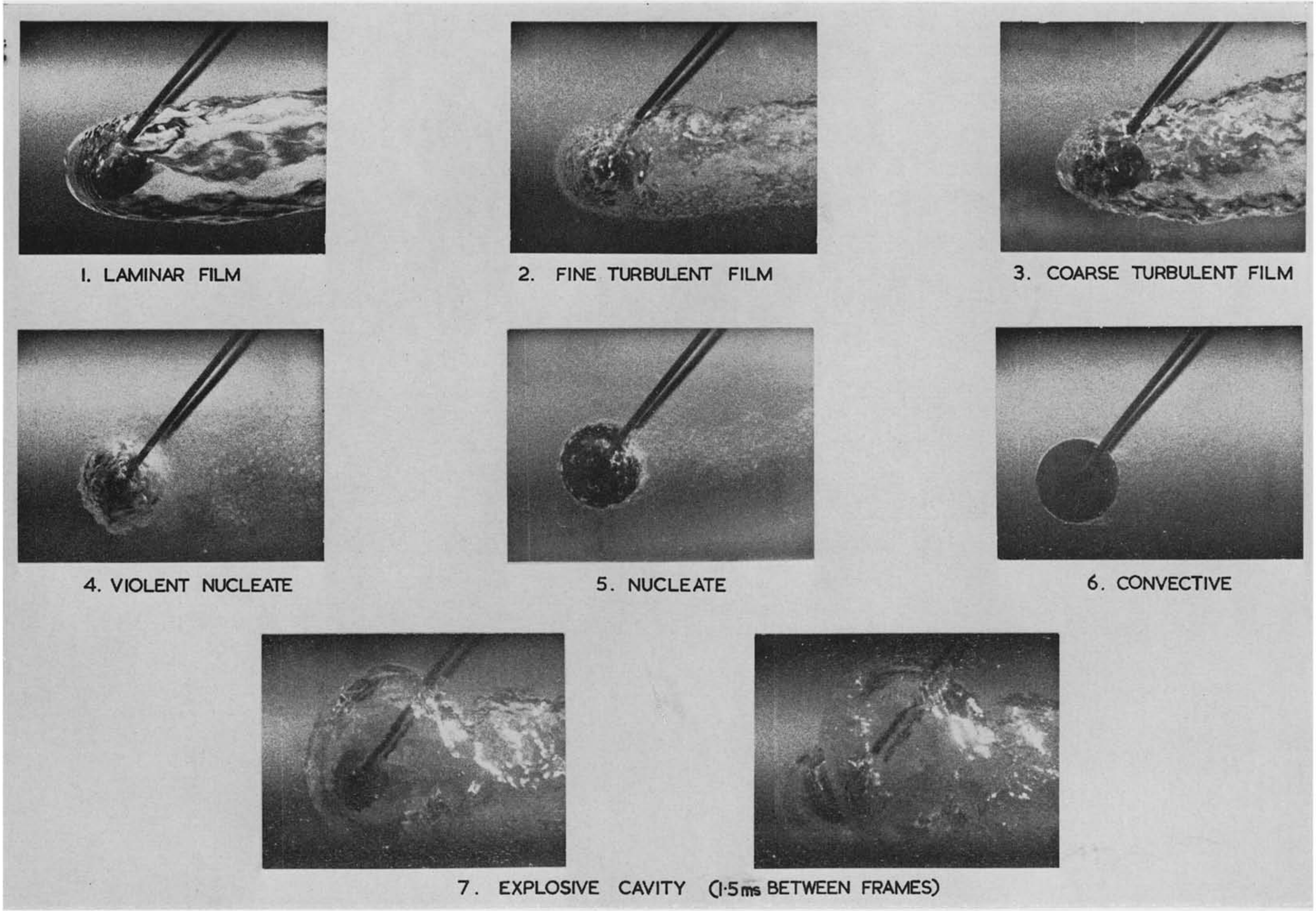

FIG. 4. Photographs of heat transfer regimes.

The wave formation on the film surface is thought to be standing waves produced by the thermocouple junction disturbing the laminar flow around the sphere. In some tests this laminar film later changed to:

2. *Fine turbulent film*. In which the vapour layer became opaque and the standing waves disappeared. The vapour film was less than 15 μm thick on the front of the sphere. As the sphere cooled still further the quality of this vapour layer became more uneven and this is identified as:

3. *Coarse turbulent film*. In which larger disturbances on the vapour–liquid interface can be clearly seen. The disturbances grow larger as the sphere cools further and the vapour cavity which trails behind the sphere collapses as regime 4 is reached.

4. *Violent nucleate boiling*. Where relatively large bubbles are formed rapidly and there is still apparently an almost continuous vapour layer surrounding the sphere and a trail of vapour bubbles behind it.

5. *Nucleate boiling*. This occurs initially on the front of the sphere while the rear is still in regime 4. The vapour bubbles are clearly discrete cavities with wetting of a large area of the sphere.

On further cooling all boiling ceases on the front of the sphere and:

6. *Convective heat transfer* occurs.

7. *Explosive cavity*. This condition was produced only with an initial sphere temperature of less than 500°C and in water at 80°C and 95°C when it was found that a large spherical vapour cavity was produced around the sphere. The sphere progressed through this cavity until it contacted the vapour–liquid interface when another cavity was rapidly formed. Figure 4 shows two frames from this condition in which the time interval between them is 1·5 ms. The newly formed cavity grew to be as large as the preceding cavity (20 mm diameter) and the cycle was repeated with a period of 5–10 ms. This oscillatory phase sometimes lasted for the complete duration of the run and sometimes developed from regime 3.

It is appreciated that identification of the regimes is not very precise. For example: *Laminar Film* may be identical with the well known stable film boiling condition and the *Fine Turbulent Film* may correspond to the unstable film condition. Likewise, *Coarse, Turbulent Film* may in fact have been a nucleate boiling condition.

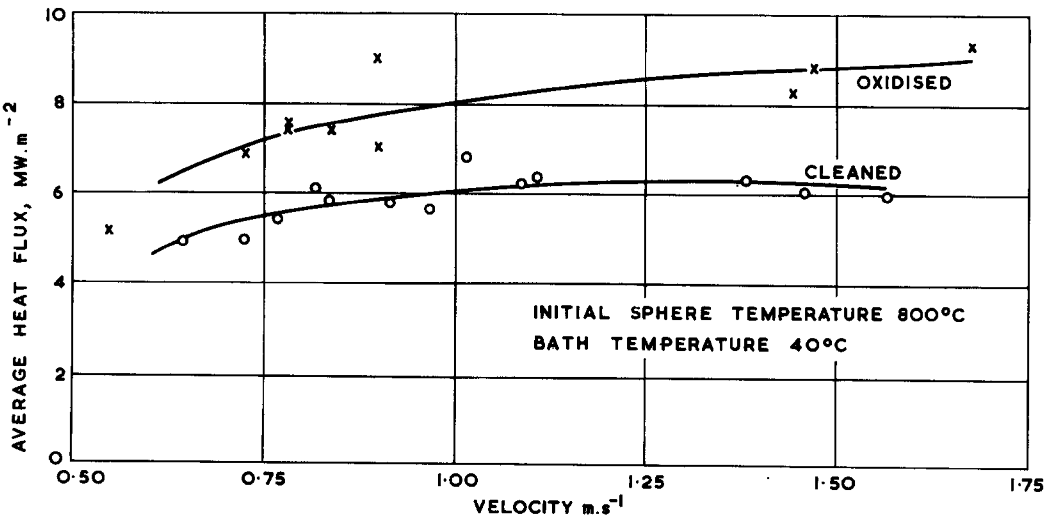

FIG. 3. Effect of velocity on heat flux.

Figure 5 shows the conditions under which each of the above-mentioned regimes existed. The ordinate represents bath temperature and the horizontal bars span the drop in temperature of the sphere during a test. The numbers against each bar refer to the heat-transfer regimes observed in the ciné films. In positioning the numbers along the bars it was assumed that there was a constant rate of fall of average sphere temperature during the run (i.e. the length of a bar occupied by each regime is roughly proportional to the time that the regime existed during the test).

It is most probable that the surface temperature of the front of the sphere had a controlling influence upon which mode of heat transfer existed and it would have been useful to have had a thermocouple embedded in the sphere just below the front surface.

3. COMMENTS ON RESULTS

The largest value of average heat flux from the 6·35 mm nickel sphere was 8·9 MW m^{-2} obtained in a bath of 40°C with an oxidized sphere at 800°C initially. This is somewhat larger than the steady-state burn out heat flux

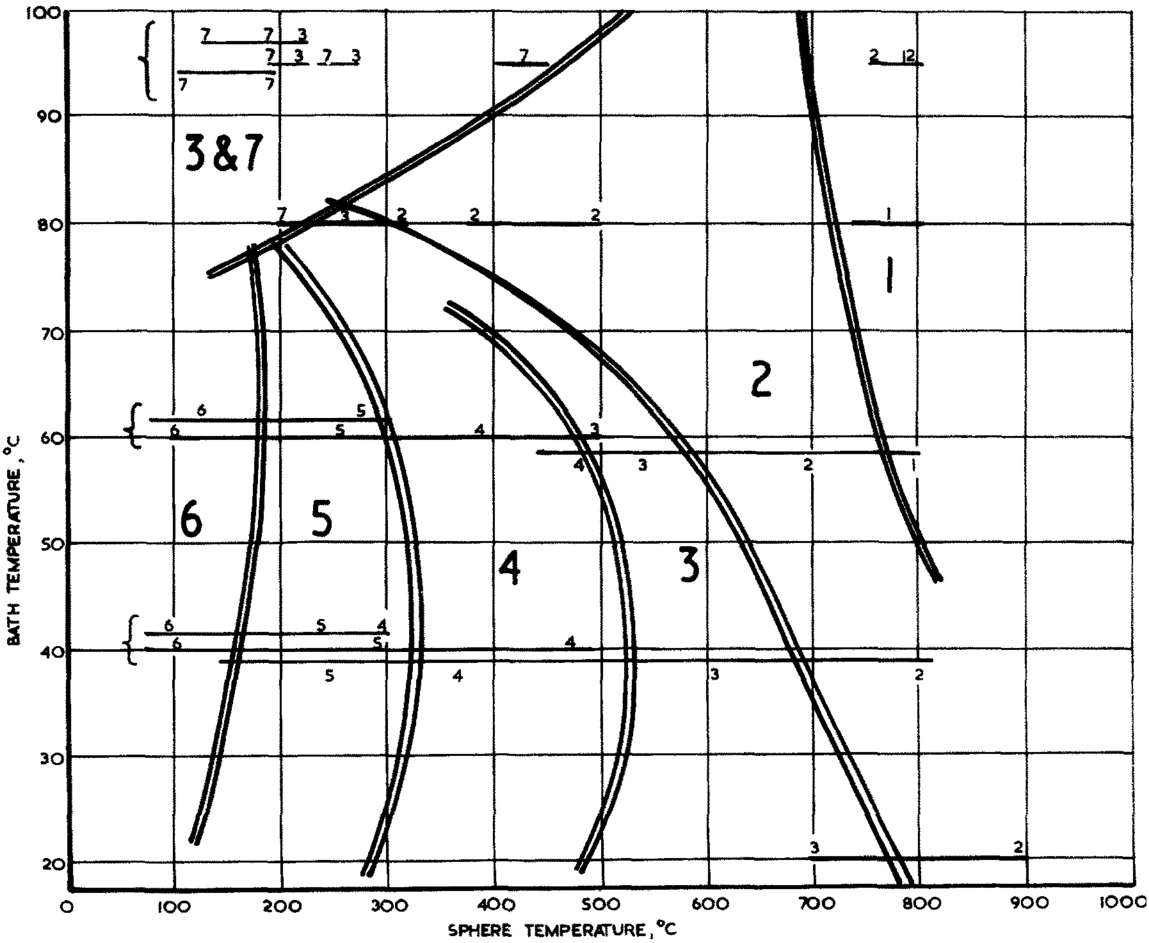

FIG. 5. Summary of heat transfer conditions.
Heat transfer conditions: 1 laminar film; 2 fine turbulent film; 3 coarse turbulent film; 4 violent nucleate; 5 nucleate; 6 convective; 7 explosive cavity.

at this value of subcooling and flow velocity. The measured heat losses are larger than those reported by Ivins and Baker *et al.* [1] who had sphere velocities of 4 ms^{-1}. This is three times faster than most of the tests reported here. Unfortunately it was not easy to modify our apparatus to obtain higher velocities in order to make a direct comparison. Over the range of velocities investigated (0·50–1·80 ms^{-1}) there was little indication that velocity was such a significant parameter.

The maximum heat flux at the front of the sphere will have been larger than the average values given in this note. Test runs done in a darkened room revealed that the rear of the sphere was visibly hotter than the front during the immersion.

The average flux calculated for the condition which produced the explosive formation of a cavity (regime 7) was only about 1·67 $MW.m^{-2}$, but since only a small area of the sphere surface contacted the water for some period less than 1 ms every 10 ms the instantaneous heat flux must have been at least one order of magnitude greater than the average. Similarly with all the conditions where a vapour film was formed the maximum heat flux from the front of the sphere must have been appreciably greater than the average values quoted—since they were calculated assuming a constant and uniform heat flux around the sphere for the entire immersed path length. This means that the local instantaneous heat flux from the front of the sphere was at least one and possibly two orders of magnitude greater than the corresponding steady-state burn out heat flux.

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1. ANL Reactor Development Program. Progress Report ANL7245, July 1966.
2. A. W. Bennett *et al.*, The wetting of hot surfaces in a steam environment at high pressure, *AERE-R*-5146 (1966).

Résumé—L'objet du travail décrit dans cette note était de reconnaître les régimes d'ébullition changeant rapidement et de les corréler avec les variations de flux de chaleur, de telle sorte que n'importe quel traitement théorique du transport de chaleur transitoire à partir de corps chauds puisse être basé sur un modèle physique correct.

Zusammenfassung—Das Ziel der hier beschriebenen Arbeit war es, die sich schnell ändernden Arten des Siedens zu identifizieren und sie in Verbindung zu bringen mit Änderungen des Wärmeflusses. Damitkann jede theoretische Behandlung des instationären Wärmeübergangs von heissen Körpern auf ein korrektes physikalisches Modell gestützt werden.

Аннотация—Целью данной работы является выявление быстро меняющихся форм кипения и их взаимосвязи с изменениями теплового потока так, чтобы теоретический анализ нестационарного теплообмена горячих тел базировался на правильных физических представлениях.