# SOME PECULIARITIES OF HEAT TRANSFER CRISIS IN ALKALI METALS BOILING UNDER FREE CONVECTION

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**Abstract**—The experiments described are carried out at low pressures from 0·01 to 2·4 bar in boiling caesium, potassium and benzene under free convection. Existence of a new mode of heat transfer crisis is distinctly found, which consists in a direct transition from a regime of usual "single-phase" heat convection to film boiling missing nucleate boiling. Critical heat fluxes in stable and unstable nucleate boiling are determined. The transition from unstable boiling to film boiling via free "single-phase" heat convection is found possible. Wall temperatures of the working section and heat fluxes were measured experimentally and boiling of metals was visualized by the X-rays examination.

## NOMENCLATURE

$q_{cr}$, critical heat flux;
$p$, pressure;
$t$, temperature;
$\Delta T$, wall–liquid temperature difference;
$r$, latent vaporization heat;
$\gamma'$, specific weight of a liquid;
$\gamma''$, specific weight of a vapour;
$\sigma$, surface tension coefficient;
$g$, acceleration of gravity.

## INTRODUCTION

IN RECENT years a number of works on experimental determination of critical heat fluxes with boiling of metals under free convection (sodium [1–4], potassium [2, 4], caesium [4, 5], rubidium [2]) have been published in the U.S.S.R. and U.S.A. In this case a considerable scatter of the data $q_{cr}$ is observed which may be attributed to different surface conditions at working sections, the effect of admixtures and possibly to the difference of the procedures used.

In [4*, 5] it was found that values of critical

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* Recently the monograph "Heat Transfer in Boiling Metals under Free Convection" has been published which summarizes the results obtained by a team guided by V. I. Subbotin. Therefore, the references are not made to their original papers but we mention here their book.

heat fluxes for metals depend on the boiling regime (stable or unstable) preceding formation of a vapour film. Transition from stable nucleate boiling to film one occurred at $q_{cr}$ essentially greater than at transition from unstable nucleate boiling to film one.

The study of critical heat fluxes in boiling organic liquids under vacuum has revealed the possibility to form a vapour film at the heated surface immediately after natural convection regime without nucleate boiling [6–8]. However, no systematic studies of this phenomenon have been carried out, although it may be supposed that it should also take place with metal boiling [5]. We performed the experiments on transition from one-phase convection to film boiling for a group of alkali metals and benzene.

## EXPERIMENTAL APPARATUS

Critical heat fluxes with boiling of caesium and potassium are determined on horizontal tubes from 9 mm to 14 mm dia, whose active length varied from 80 mm to 100 mm. The case of the first-type working section was made of stainless steel with the wall thickness of 0·5 mm. The thermocouples were embedded into grooves (0·6 × 0·6 mm) of a copper tube with a hot

junction caulked flush with the generating line, and the whole device was pressed-in into the case. The thermocouples embedded in such a way allowed satisfactory record of temperature fluctuations of the working section wall, but a comparatively low melting-point of copper limited a heat regime range. In the second-type section the thermocouples were embedded into the grooves of electrically insulating carbo-nitride boron bushes and pressed-in into the molybdenum case of the section whose wall thickness was 1 mm. Such embedding of thermo-couples allowed coarse scale fluctuations and averaged temperature of the inner wall of working section case to be recorded and experiments over a wide temperature range of boiling metals to be performed. For the first-type working sections thin-wall molybdenum and graphite tubes served as heating elements and for the second-type ones, graphite tubes. All the sections were heated by direct current. Carbo-nitride boron bushes served as an electrically insulating medium between heaters and cases of sections. The inner cavity of working sections was filled with high-purity helium.

All the experiments were carried out at the experimental apparatus, whose schematic diagram and detailed description are given in [9]. Rectangular boiling tanks had the sizes 280 × 180 × 80 mm and 280 × 180 × 140 mm.

The boiling metal volume was X-rayed, and the X-ray pattern was transferred to the screen of an electronic–optical converter used for visualization of the boiling process. A heat transfer crisis was fixed by a sharp increase (by hundreds of degrees) in a surface temperature of a working section. In this case power supply was automatically switched off. Metal boiling took place under pressure of proper vapors, the effect of a dissolved inert gas being practically excluded. After metal was in contact with the working section during fourteen to one hundred twenty days, the regular tests on determining $q_{cr}$ were carried out.

Three experimental series with boiling of caesium and potassium were made. After each series the working section was replaced, and the working volume was filled with a fresh liquid metal.

The tests with benzene boiling were performed on the device described in detail in [10] with the only difference that the working volume was placed into a thermostat. The surfaces of working sections were ground with the Goya paste to the finish corresponding to the class 10 according to All-Union State Standard 2798–59. Before filling the device with a liquid the working volume and working section were carefully rinsed with benzene, and the working section was then calcinated in vacuum up to 600°C. After the device was filled with benzene, degassing was performed by means of vacuum treatment. Temperatures of the working section, liquid and vapour were measured by chromel–alumel thermocouples. The hot junction of a thermocouple was embedded into the middle part of the working section. All measurements were made at a saturation temperature. D.c. current was supplied to the working section. Load to the working section was supplied smoothly. The moment of film boiling onset after convection was fixed by a temperature jump and visually.

### CAESIUM TESTS

Caesium boiling was performed in the first-type working sections, 80 mm length and 11 mm dia. The first experimental series was carried out in the working section of approximately 6 Class finish at pressures from 0·04 to 1·7 bar. Unstable boiling, alternation of unstable boiling and natural convection were observed. In this case a new mode of a heat transfer crisis in liquid metals, viz. formation of a vapour film directly after a natural convection regime is revealed, that is similar to that observed earlier with boiling of organic liquids under vacuum [6–8].

The transition from a single-phase free convection regime to film boiling may be carried out both directly with no bubble boiling phase

and after unstable boiling regime. In the latter case unstable bubble boiling attenuates at some value of $q < q_{cr}$, there occurs heating-up of the heat releasing surface and adjacent liquid layers under conditions of single-phase free convection, then film boiling begins. Figure 1
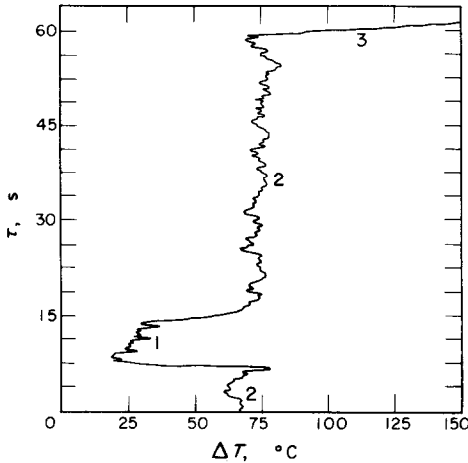


FIG. 1. Record of wall–liquid temperature difference for caesium boiling $t_{sat} = 690°C$.
1. boiling
2. free convection
3. crisis

shows a temperature diagram for second-type transition.

Figure 2 gives the results of the second experimental series on $q_{cr}$ (Curve 1). As is seen, in this case no noticeable dependence of a critical heat flux upon a pressure is observed.

The second experimental series on $q_{cr}$ was conducted in the same working section as in case of the first series with the only difference that artificial vapourization centres (two on the upper generating line and one on the lower one) were created at its surface. These centres ensured stable boiling over the whole pressure range investigated. The geometry of an artificial vapourization centre was chosen according to
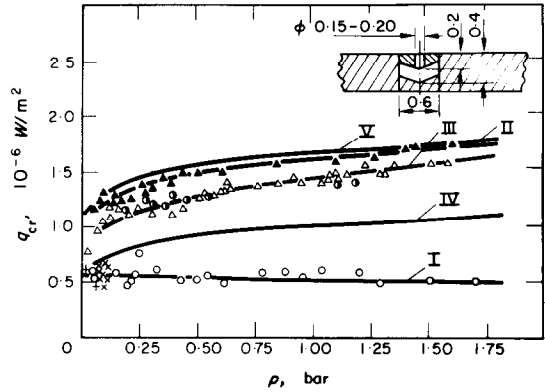


FIG. 2. Plot of $q_{cr}$ vs. pressure for caesium.
I—○ First series of runs. Transition from free convection to film boiling
II—▲ Second series of runs. $q_{cr}$ with stable boiling. Caesium level is 60 mm
III—△ Second series of runs. $q_{cr}$ with stable boiling. Caesium level is 30 mm
IV— Prediction by formula (1) $C = 18$
V— Data of [4] with stable boiling
◑ Third series of runs
+, × Some data of [4] with unstable boiling

the recommendation in [11] and is shown in the upper right-hand corner of Fig. 2. The experimental results on artificial vapourization centres for caesium above the working section at a distance of 60 mm are shown in Fig. 2, Curve II and at a distance of 30 mm, Fig. 2, Curve III. As is seen, in case of stable boiling critical heat fluxes increased 2–3 times, as compared to the values of a regime following a natural convection regime. Figure 2 gives Curve V averaging the experimental data of [4] for $q_{cr}$ with stable caesium boiling at a disc 38 mm dia. The agreement of the results is quite satisfactory.

The data of [4] obtained in case of unstable boiling fall above Curve I and below Curve III. Some test points fall to our Curve I, that is shown in Fig. 2. The authors of [4] proposed the following design formula for $q_{cr}$ with pool boiling of alkali metals:

$$k = k_0 \left[ 1 + \frac{C}{p_{cr}} \left( \frac{p_{cr}}{p} \right)^{0.4} \right]. \qquad (1)$$

Here

$$k = \frac{q_{cr}}{z\sqrt{(g\gamma'')^4}\sqrt{[\sigma(\gamma' - \gamma'')]}}$$

is the criterion of hydrodynamic stability of a boiling boundary layer [12], $k_0 = 0.14$ is the value of this criterion under ordinary conditions, $p$ and $p_{cr}$ are instantaneous and critical values of a pressure. For stable boiling it is recommended that $C = 45$ bar and for unstable boiling $C = 18$ bar. Curve IV in Fig. 2 is the prediction by formula (1) for unstable boiling, and the predictions by formula (1) for stable boiling fairly coincide with Curve V. The comparison with the formulae of other authors is omitted since it is given in [4].

The third series of our tests is performed in a working section with grooves 0.1 mm long over the whole surface at the level of caesium of 60 mm. As is seen, the grooves stabilize boiling somewhat worse than the centres in the second series of the tests.

## POTASSIUM TESTS

In the first series of the tests boiling occurred in the second-type working section, 14 mm dia. and active zone, 100 mm long. The surface finish corresponded to Class 5. The tests were carried out over a pressure range from 0.01 to 1.45 bar. In this series of the tests unstable boiling and natural convection preceded the onset of a crisis. In this case stable boiling was not observed.

As follows from visualizations, in an unstable boiling regime there appear coarse vapour bubbles with a low frequency of departure (from 1 c/s and less), that results in large wall temperature fluctuations.

Curve II in Figure 3 shows experimental results obtained with unstable boiling of potassium. As is seen from the chart, the values of $q_{cr}$ increase approximately to 0.2 bar, with a further increase in a pressure, $q_{cr}$ does not increase. Curve I exhibits the values of $q_{cr}$ which correspond to a transition from natural convection to film boiling, i.e. the values of $q_{cr}$ of
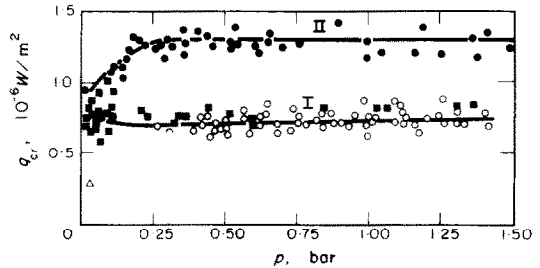


FIG. 3. Plot of $q_{cr}$ vs. pressure for potassium.
I  ■  $q_{cr}$ after free convection
   ○  $q_{cr}$ after cessation of unstable boiling
II ●  $q_{cr}$ with unstable boiling
      $q_{cr_2}$ for transition from film boiling to nucleate boiling

that mode of a crisis which was earlier found in the caesium tests (Curve I, Fig. 1). As in case of caesium, this transition may take place under the following conditions: (a) after a natural convection regime without boiling in the working section (b) after cessation of unstable boiling with subsequent heat removal by natural convection whose duration time varies from very short (some seconds) to very long (up to some tens of seconds) periods. Figure 4 gives wall temperatures in cases (a) and (b).
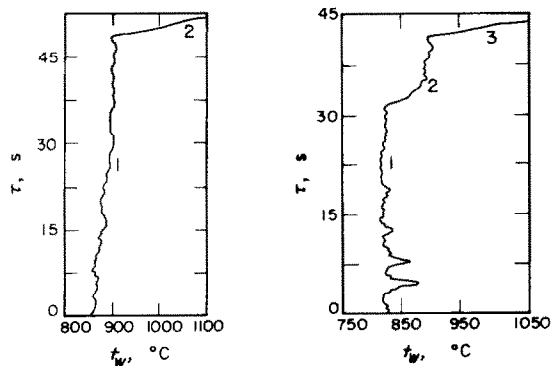


FIG. 4. Record of a wall temperature in runs with potassium.
(a) 1—free convection; 2—critical regime $t_{sat} = 720°C$
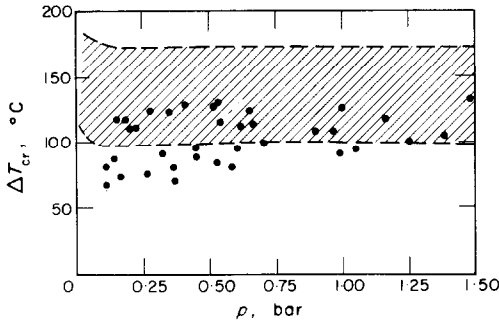(b) 1—boiling; 2—free convection; 3—critical regime $t_{sat} = 772°C$

FIG. 5. Plot of $\Delta T_{cr}$ vs. pressure for potassium.

In Fig. 5 the hatched band shows a domain of superheatings $\Delta T_{cr}$ occurring at a transition from natural convection to film boiling, that corresponds to Curve I, Fig. 3. Critical superheatings with unstable boiling are designated by dots and located in the lower part of the hatched region.
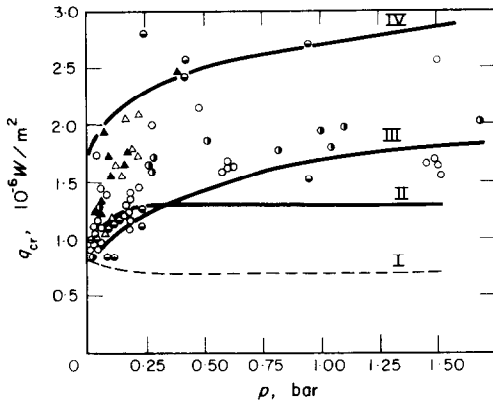
The second series of tests was performed with



FIG. 6. Plot of $q_{cr}$ vs. pressure for potassium. ▲—second series of our runs; △ —third series of our runs; ◯—data of [2]; two series of runs of [4] I, II—averaging lines of our runs of first series (transition from free convection and unstable boiling to film boiling); III—prediction by formula (1) with unstable boiling; IV—prediction by formula (1) with stable boiling

boiling of potassium in the first-type working section over a pressure range from 0·035 to 0·4 bar. The values of critical heat fluxes in this series are given in Fig. 6.

Some experimental points are obtained after natural convection, some with unstable boiling and only two points with stable boiling.

In the third series use is made of the first-type section, 9 mm dia., where some conic grooves, 0·02 mm depth, were made. The results of this series are also presented in Fig. 6. The tests were carried out over a pressure range from 0·1 to 0·2 bar. From visualizations only two points are obtained with stable boiling, and the remainder, with unstable boiling and immediately after a natural convection regime.

### BENZENE TESTS

A transition from natural convection to film boiling for benzene was studied on stainless steel tubes, 5 and 2 mm dia., and nickel ones, 1·5 mm dia., with an active length of 60 mm.

Figure 7 gives experimental results on heat fluxes occurring in formation of a vapour film after a natural convection regime for a section, 0·5 mm dia. Here, for comparison the values of $q_{cr_1}$ according to data of [8] are presented. As is seen, the critical heat fluxes corresponding to formation of a vapour film after natural convection are some times less than those with developed bubble boiling and decrease as the pressure increases.

The values of a wall temperature of the working section occurring in transition from natural convection to film boiling are given in Fig. 8; over a pressure range from 0·1 to 0·4 bar the growth of this temperature is observed; at pressures more than 0·4 bar this temperature is practically constant. Here for comparison the limiting superheating temperature of benzene for homogeneous ebullition [13] is given.

At a "fresh" section the wall temperature and accordingly heat fluxes preceding the formation of a vapour film appeared to be less. As far as a "fresh" section ages the wall temperature and heat fluxes increased and pressure

range involved in transition from free convection to film boiling.* For illustration the experimental data on a "fresh" section are presented
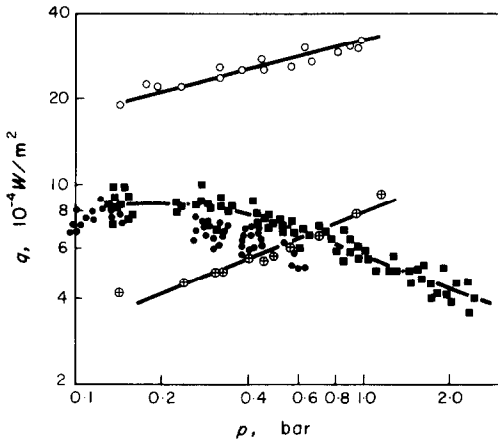


FIG. 7. Plot of critical heat fluxes vs. pressure for benzene.

$q*\begin{cases}\text{aged section} \\ \text{"fresh" section}\end{cases}$

⊕   $q_{cr_2}$

○   $q_{cr_1}$ according to data of [8]

in Figs. 7 and 8. All the remainder of the experimental data are obtained on the "aged" surfaces when further time of operation did not influence the quantities measured.

The formation of a vapour film after free convection at lowered pressures occurs explosively with specific sound. After a stable vapour film is formed, heat transfer deteriorates and a surface temperature sharply increases to 500–600°C at a pressure of 0·1 bar and remains at this level. As far as a pressure increases, the sound accompanying this phenomenon becomes weaker, and forming vapour films are less stable. In the region of unstable vapour films, just after their formation, a wall temperature starts increasing, and then as far as the film
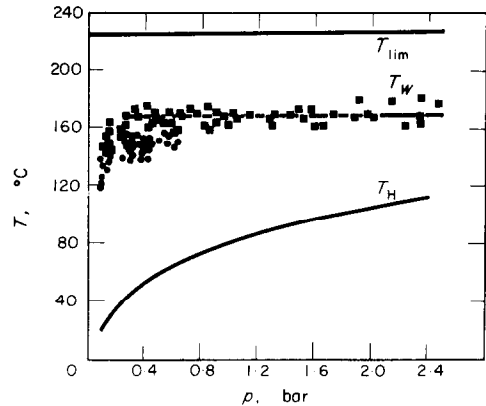
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* In this case the problem on the nature of the aging of a section is not considered here.



FIG. 8. Plot of wall temperature vs. pressure for benzene. ■—aged section; ●—"fresh" section; $T_{lim}$—limiting heating temperature for benzene according to the homogeneous theory; $T_{sat}$—saturation temperature

destructs, it decreases to a quantity corresponding to bubble boiling. The formation of a vapour film as a burst after a convective regime is apparently explained by large initial liquid superheats. Thus, for a section, 5 mm dia., the wall temperature in this regime was 170°C, that corresponded to a pressure of 11 bars in an equilibrium bubble nucleus.

To reveal the stability regions of a vapour film forming after free convection the heat fluxes were determined involved in destruction of the film. $q_{cr_2}$ is taken as a heat flux of which slight decrease resulted in complete destruction of the film. Experimental results on $q_{cr_2}$ for a section 5 mm dia. are shown in Fig. 7. $q_{cr_2}$ $(p)$ and $q_{cr_+}$ $(p)$ are seen to intersect at $p \approx 0.7$ bar. Here $q_{cr_+}$ denotes a heat flux involved in a direct transition from single-phase free convection to film boiling. It is obvious that at $q_{cr_+} < q_{cr_2}$ the probability of transition decreases essentially.

Figure 9 gives the experimental results on heat release with free convection for a ground working section, 2 mm dia., at pressures of 0·13 and 2·4 bar.

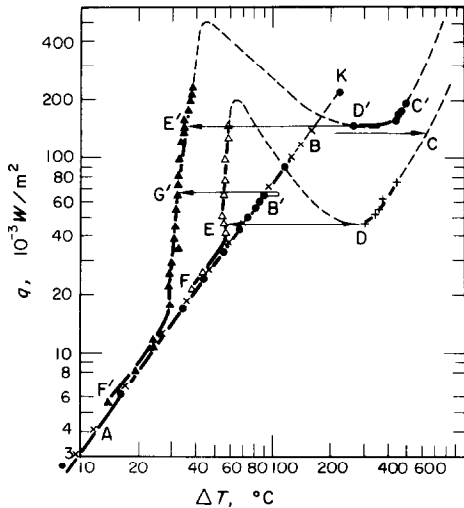At a pressure of 0·13 bar according to curve AB heat is released by convection, at point B

FIG. 9. Heat release for benzene.

$p = 0.13$ bar $\begin{cases} \times \text{ convection} \\ + \text{ film boiling} \\ \triangle \text{ nucleate boiling} \end{cases}$

$p = 2.4$ bar $\begin{cases} \bullet \text{ convection} \\ \blacksquare \text{ film boiling} \\ \blacktriangle \text{ nucleate boiling} \end{cases}$

there occurs formation of a vapour film and step transition to stable film boiling (B → C). When the load decreases (curve CD) such a value of a heat flux is achieved, that corresponds to destruction of a vapour film (point D), and the system transforms into unstable boiling (D → E), a further decrease in the heat flux (curve EF) results in a decrease of the number of bubbles and then in cessation of vapour formation.

At a pressure of 2·4 bar according to curve AB′ heat release is carried out by convection, at point B an unstable vapour film is formed which destructs rather rapidly, and the system transforms into nucleate boiling B′ − G′. To obtain stable film boiling at a moment when unstable vapour film is formed (point B′) the heat flux in the working section was sharply increased, and film boiling heat release (point C′) was set in.

While decreasing, the heat flux (curve CD′) reaches such a value that resulted in destruction of a vapour film (point D′) and the system is transformed into nucleate boiling regime (D′ → E′). A further decrease in the heat flux (curve E′ F′) leads to a decrease in the number of forming bubbles and then to cessation of vapour formation. The arrows in the figures show both the direction of change in the heat flux on the heat releasing surface and that of transitions from one regime to another. Point K on line AB corresponds to a benzene superheat temperature with homogeneous ebullition.

A number of high-speed pictures were taken to study the mechanism of formation of a vapour film just after free convection in benzene.

Figure 10 gives a series of subsequent photographs for the moment of onset of a vapour phase at a surface, 1·5 mm dia., at $p = 0.1$ bar and $q = 10^5$ W/m². On the second frame from above a small dark cloud (spot) is seen which probably consists of a set of first bubbles, that points to the initial ebullition effect. Liquid superheat near the heat releasing surface achieves $\sim 160°$C, that corresponds to a pressure difference $\sim 10$ bar before vapour nuclei begin to grow. The generation and propagation of a vaporization centre has an explosive character and is accompanied by noise. The time interval between frames is $5 \cdot 10^{-4}$ s, and the propagation velocity of the central part of the first cloud during first $3 \cdot 10^{-3}$ s is about 10 m/s. As is shown in Fig. 10, after a rapid growth of a vapour cloud (this stage is not shown since it corresponds to a number of dark photographs due to light absorption by a pulverized cloud) there occur cloud packing and decrease in a volume due to coalescence of finest bubbles (Figs. 11 a and b). Probably, at this moment the surface temperature starts increasing rapidly as a result of heat transfer deterioration due to coalescence of fine vapour bubbles and decrease of liquid interlayers in the vapour cloud. After some time interval (Figs. 11 c and d) the large bubble formed starts departing from the surface and film boiling sites are formed at some part

of the surface. In Fig. 11e it is seen that the vapour film is formed over the whole surface and only at the centre the unstable film boiling section is still visible, which represents a stem of the bubble formed, in Fig. 11f stable film boiling is established over the whole surface. The whole process from generation of a vapour phase (Fig. 10) to a stable film (Fig. 11f) is about 0·12 s, therefore, visualization allows the onset of film boiling only to be recorded, and intermediate stages in developing of the process are not found.

It should be noted that with "ebullition" there are no certain vapourization centres at the surface, and the place of generation of a vapour phase varies from run to run.

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## QUELQUES PARTICULARITES DE LA CRISE DU TRANSFERT THERMIQUE DANS DES METAUX ALCALINS EN EBULLITION SOUS CONVECTION NATURELLE

**Résumé**—Les expériences décrites ici ont été menées sous de basses pressions variant de 0,01 à 2,4 bar dans du césium, du potassium et du benzène en ébullition sous convection naturelle. On a trouvé l'existence d'un nouveau mode de crise du transfert thermique qui consiste en une transition directe entre un régime de convection thermique usuelle "à phase unique" et une ébullition en film et ce sans ébullition nucléée. On a déterminé des flux de chaleur critiques dans l'ébullition nucléée stable et instable. La transition entre l'ébullition instable et l'ébullition en film par la voie de convection thermique naturelle "à phase unique" est possible. Les températures pariétales de la section de travail et les flux thermiques ont été mesurés expérimentalement et l'ébullition des métaux a été visualisée par examen aux rayons x.

## EINIGE BESONDERHEITEN DER WÄRMEÜBERGANGSKRISIS BEIM SIEDEN VON ALKALIMETALLEN BEI FREIER KONVEKTION

**Zusammenfassung**—Die beschriebenen Experimente wurden bei niedrigen Drücken von 0,01 bis 2,4 bar mit siedendem Caesium, Kalium und Benzol bei freier Konvektion durchgeführt. Eine neue Art der Wärmeübergangskrisis wurde deutlich festgestellt. Sie stellt sich dar als ein direkter Übergang vom Regime der gewöhnlichen einphasigen Konvektion zum Filmsieden, ohne Auftreten von Blasensieden. Für stabiles und instabiles Blasensieden wurden die kritischen Wärmeströme bestimmt. Der Übergang vom instabilen Sieden über den Zustand der einphasigen Konvektion zum Filmsieden ist möglich. Wandtemperaturen der Arbeitsstrecke und Wärmestromdichten wurden experimentel bestimmt. Der Siedevorgang der Metalle wurde mit Hilfe von Röntgenstrahlen sichtbar gemacht.
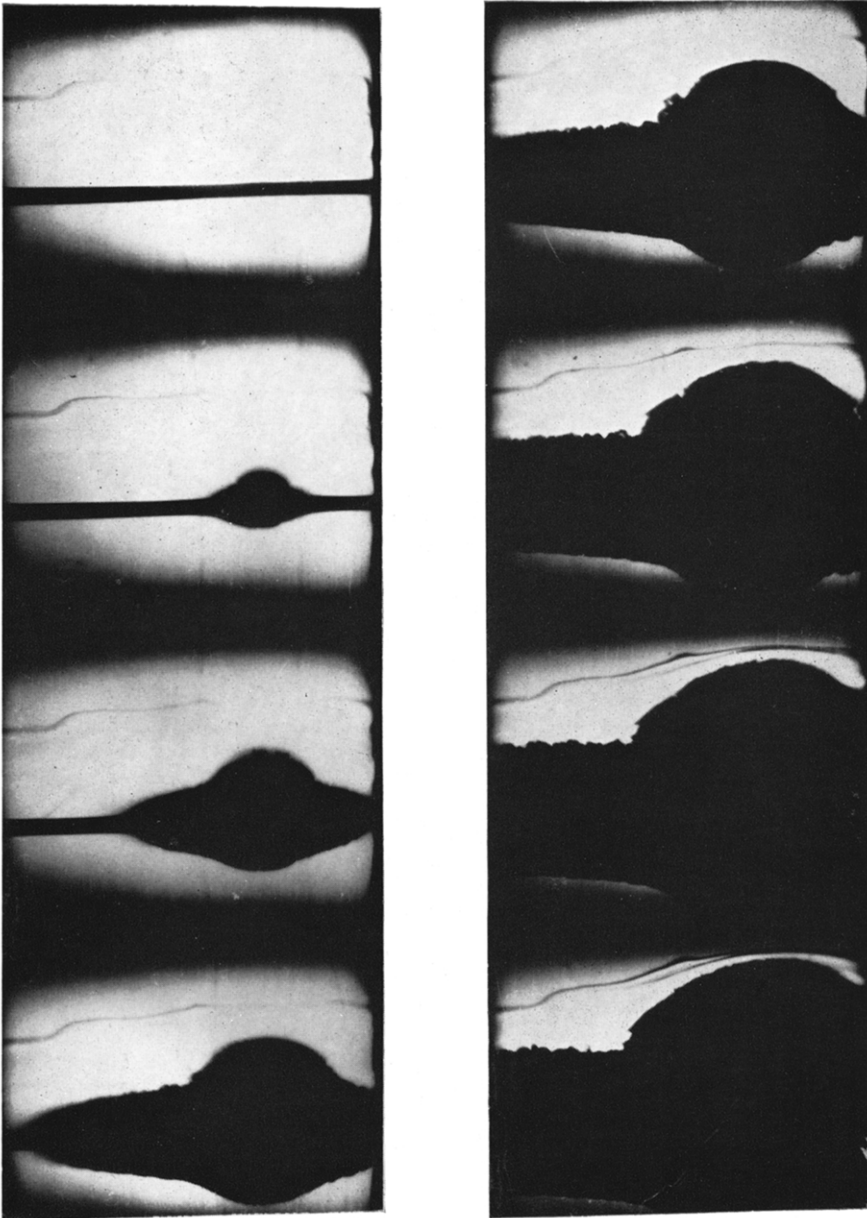
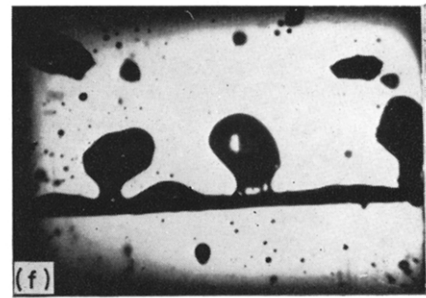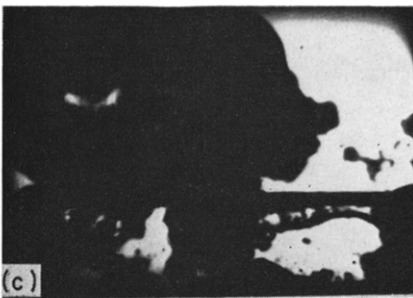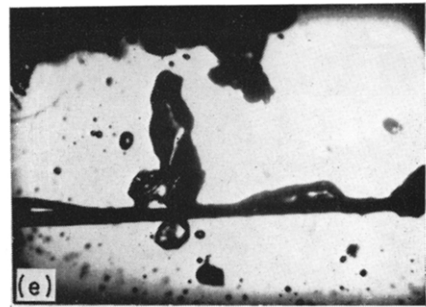FIG. 10. Vapour phase generation. Benzene: $p = 0\cdot1\text{bar}$ $q = 1\cdot5.10^5$ W/m².
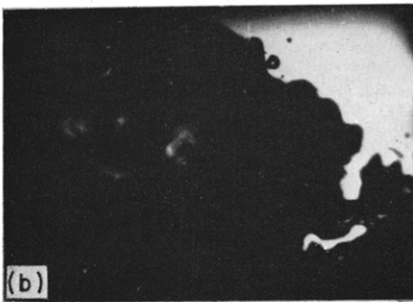
FIG. 11. Intermediate stages of transition from free convection to film boiling.
(a) 0·028 s; (b) 0·055 s; (c) 0·064 s; (d) 0·082 s; (e) 0·110 s; (f) 0·120 s.

# НЕКОТОРЫЕ ОСОБЕННОСТИ КРИЗИСА ТЕПЛООБМЕНА ПРИ КИПЕНИИ ЩЕЛОЧНЫХ МЕТАЛЛОВ В УСЛОВИЯХ СВОБОДНОЙ КОНВЕКЦИИ

**Аннотация**—Описываемые эксперименты проводились при низких давлениях от 0,01 до 2,4 бара при кипении цезия, калия и бензола в условиях свободной конвекции. Отчетливо обнаружено существование нового типа кризиса теплообмена, заключающегося в непосредственном переходе от режима обычной «однофазной» тепловой конвекции к пленочному кипению, минуя режим пузырькового кипения. Определены критические тепловые потоки также в условиях устойчивого и неустойчивого пузырькового кипения. Обнаружено, что возможен переход от режима неустойчивого кипения к режиму пленоуного кипения через режим свободной «однофазной» тепловой конвекции. В опытах проводились измерения температур стенки рабочего участка и тепловых потоков, а также визуальные наблюдения кипения металла в рентгеновских лучах.