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AN EXPERIMENTAL STUDY OF CRITICAL HEAT LOADS AT BOILING OF ORGANIC LIQUIDS ON A SUBMERGED HEATING SURFACE

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Abstract—Data of experiments for the determination of critical heat flows at boiling of methyl alcohol (P = 1–64·5 atm) and normal propyl alcohol (P = 1–46 atm) on a submerged heating surface are deduced in the present paper. The treatment of experiments is given in relative co-ordinates. The influence of different factors on the values of critical flows is shown.

Résumé—Cet article présente des données expérimentales sur la détermination des flux de chaleur critiques au cours de l'ébullition, sur une surface chauffante submergée, de l'alcool méthylique (P = 1–64,5 atm) et de l'acool propylique normal (P = 1–46 atm). Le dépouillement des expériences est donné en coordonnées relatives. L'influence des differents facteurs sur les valeurs des écoulements critiques est mis en évidence.

Zusammenfassung—Es werden Versuchsergebnisse über den kritischen Wärmestrom beim Sieden von Methylalkohol (P = 1–64,5 at) und Normal-Propylalkohol (P = 1–46 at) an eingetauchten Heizflächen mitgeteilt. Die Ergebnisse sind in bezogenen Koordinaten angegeben. Der Einfluss verschiedener Grössen auf die Werte des kritischen Wärmestroms wird gezeigt.

Аннотация—В статье приведены данные опытов по определению критических тепловых потоков при кипении метанола (P = 1–64,5 ата) и н. пропанола (P = 1–46 ата) на погруженной поверхности нагрева. Дана обработка опытов в относительных координатах. Показано влияние различных факторов на величины критических потоков.

THE value of critical heat load q_{cr-1} at boiling on a submerged heating surface depends on a number of factors, the most important of which are the physical properties of the substance, pressure, conditions of vapour removal from a heating surface, the state of a heating surface and the incomplete heating of a liquid up to the saturation temperature. The influence of the physical properties of a liquid and of pressure was investigated in a number of works. The results given in [1] present the most extensive experimental investigation for some organic liquids in a wide range of pressure variations. The dependence of the critical load variation on pressure obtained in the work mentioned above is typical for some other liquids as was shown by the latest investigation [2]. However the errors of method encountered in the investigation [1] brought to considerable scattering of experimental points, and lowered the numerical value of the experimental results.

The dependence of critical loads on conditions of heat removal from a heating surface was studied in [3] and [4]. Boiling on ni-chrome plates at atmospheric pressure has been investigated in [4]. These experiments showed the qualitative influence of the conditions of vapour removal from a heating surface and made it possible to come to a conclusion that a plate with a surface turned upwards serves as a standard for boiling in a large volume.

The influence of the state of a heating surface on the value of critical loads was found in [1] and in some other works. More detailed investigations [3] showed that the approach of the crisis on rough heating surfaces is delayed and is going on at higher heat loads than on smooth ones.

The same writer [3] investigated the influence of the incomplete heating of a liquid on the value of critical loads. This investigation showed that the incomplete heating of liquids up to the temperature of saturation increases the significance of critical loads, while the influence of the incomplete heating decreases with the increase of pressure.

The brief account of the problem reveals the necessity of further experimental study of the influence of the conditions of vapour removal from a heating surface on the critical heat loads at pressures exceeding atmospheric pressure, and the influence of the physical properties of new liquids.

The present article deals with the experimental results given by the investigation of the boiling crisis of methyl alcohol and normal propyl alcohol on a submerged heating surface.

These liquids find an application in industry, their physical properties are investigated in a wide range of temperature variations, and they differ appreciably from the properties of most of the liquids applied before for the investigation of critical loads. Until now, experiments were not carried out with methyl alcohol and normal propyl alcohol for the determination of critical loads at a wide range of pressure variations. These considerations determined the choice of the investigated liquids.

The methyl alcohol used in experiments was chemically pure, normal propyl alcohol had a technical purity. The chemical compound of the used liquids corresponded to the demands of GOST, as was ascertained both by the data supplied with the chemicals and by an additional chemical analysis.

The viscosity of liquids and the elasticity of vapours at saturation points were determined for the investigated substances. The viscosity of methyl alcohol was determined in the temperature range from 23·5° to 238°C and that of the propyl alcohol from 18·5° to 257°C.

The elasticity of vapours was determined in the pressure interval ranging from 1 atm to the critical pressure.

The obtained data on viscosity and elasticity of vapours agree satisfactorily with the data given in [5, 6, 7, 8, 9].

EXPERIMENTAL APPARATUS AND PROCEDURE

The experiments were carried out on two sets of apparatus—for high and low pressures. Fig. 1 presents a scheme of the experimental apparatus.

Heaters, made out of the calibrated ni-chrome band and ni-chrome wire served as heating surfaces. The length of the heaters was 150 mm.

The edges of plates were covered with brass in order to avoid superheating in contacts and a sharp change of cross section in places. The plates were fastened in plate holders (3a and 3c) of the supporting frame (3e) mounted on the cover of the drum in a horizontal position.

The plate did not bend on heating because the plate holder (3c) had free travel in the supporting frame.

For carrying out the experiments 8–9 l. of liquid were poured into the apparatus, the total capacity of which was 15 l. The liquid was heated to a prescribed temperature by an electric heater (12 and 15) of alternating current. The liquid was kept boiling until the complete removal of air before the valve (6) was set into position "closed". The continuous current, supplied by a low-voltage motor-generator (17) created a heat load on an experimental plate (3). The system of rheostats cut in a network of excitation of the generator gave a smooth increase in heat load. Multivoltmeters (20), connected to the plate by a balanced bridge scheme, immediately fixed the approach of a critical moment due to a sharp change in the electrical resistance of the plate.

The current intensity and the voltage were measured at the critical moment of crisis.

A potentiometer (13) measured the intensity of current through the calibrated shunt (19) to within $\pm 0{\cdot}05$ millivolt. The voltmeter of 0·2 grade measured the drop in voltage on a working section of the plate. The drop in voltage was measured by the wires welded at a distance of 15–20 mm from the plate holders by the method of electrical contact.

The critical heat flow was calculated according to the magnitude of the current intensity and the voltage drop measured on an experimental plate.

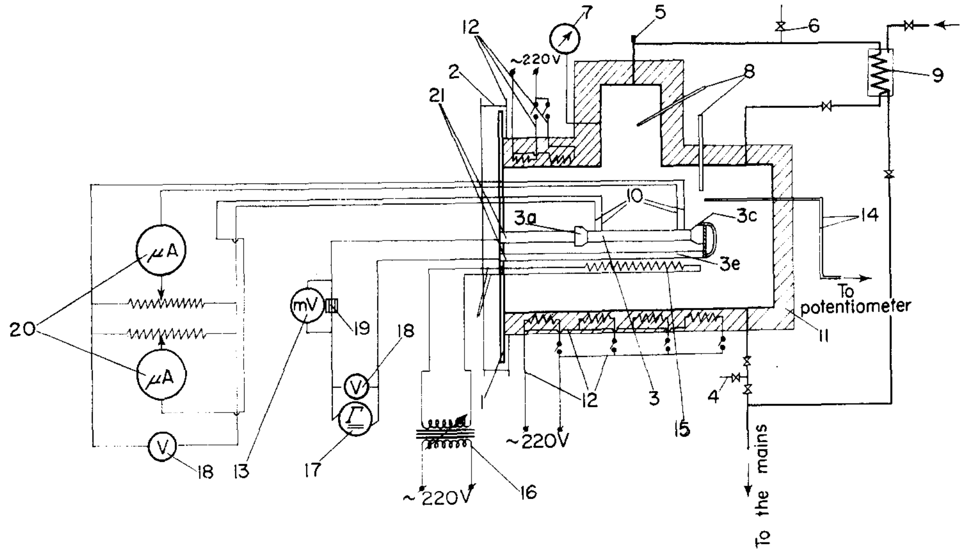

FIG. 1. Scheme of an experimental apparatus of high pressure.
1, drum; 2, protecting cover; 3, experimental plate; 3a and 3c, plate holders; 3e, supporting frame; 4, decantation line; 5, pipe connection for priming; 6, valve; 7, manometer; 8, sleeve with a thermometer; 9, cooler; 10, wires; 11, thermal insulation; 12, electroheaters of external heating; 13, potentiometer; 14, thermocouple; 15, electroheater of internal heating; 16, autotransformer; 17, low-voltage motor generator; 18, voltmeter; 19, shunt; 20, zero-instrument; 21, bushings.

The analysis shows that under given conditions the error of measurement of critical heat flows did not exceed ±7 per cent.

The temperature of a liquid in the tank was measured by the potentiometer of the fine grade with the help of a chromel–alumel thermocouple (14). The reading of the thermocouple (14) was controlled according to the pressure, by thermometers and thermocouples placed in sleeves (8).

The model manometer of 0·02 and 0·35 grades measured the pressure.

During the experiments the constancy of pressure and temperature was maintained by the change of the capacity of electroheaters and by the condensation of vapour in the refrigerator.

The experiments were carried out at atmospheric pressure on the low-pressure apparatus which is an open tank with a capacity of 19 l.

For all cases the experimental methods were the same.

The presence of windows in both sets of apparatus made it possible to observe both the heating surface and the process of transition from one régime to another.

Besides the constant observations of the heating surface through a window, periodical control surveys were made on the high-pressure apparatus, when the cap of the drum or the hatch was opened after the carrying-out of experiments.

RESULTS

The value of critical load, as was mentioned above, depends on conditions of heat removal generated on a heating surface. The heating surface turned upwards is the best for removal of vapour. The highest values of critical loads correspond to the given conditions of vapour removal. The creation of high thermal loads on a heating surface turned upwards and the carrying out of an experiment involve great technical and method difficulties.

Due to this fact there arose the necessity of choosing another type of heater, with the help of which one could imitate the boiling on a plate.

For this purpose methodical experiments were carried out at atmospheric pressure on low pressure apparatus. Heaters made out of a band with cross sections of 10 × 1; 10 × 0·5; 5 × 0·5; 3 × 0·5 mm and of a wire of 1 mm in diameter were used in these experiments. All the heaters were placed horizontally; the heaters made of plates were put on a fin and on a wide edge. When placed on a wide edge the lower surface was screened with Paranite and Teflon and the boiling was going on only on the surface turned upwards. The lower surfaces of plates placed on a broad edge in some experiments were not screened and the boiling was going on along the whole perimeter of the heater.

The methodical experiments carried out at $P = 1$ atm showed that the critical loads obtained at boiling on a surface turned upwards and on heaters (from 3 to 10 mm high) placed on a fin are practically the same. On a wire the values of critical loads were obtained higher than on a surface turned upwards while on non-screened heaters placed on a broad edge they were respectively lower.

Thus it was determined that the critical load does not depend on the geometrical peculiarities of the surface at boiling on a heating surface turned upwards and on heaters from 3 to 10 mm high placed on a fin.

Consequently the conditions of vapour removal generated on horizontal heaters of a smaller size (3–10 mm) are the same as on the plate of a larger size, by the upward turned surface and the boiling on a plate can be reproduced on such heaters.

Six series of experiments were carried out at different pressures in order to determine the influence of pressure and of the conditions of vapour removal from a heating surface on the values of critical loads.

The first series of experiments was performed at boiling of methyl alcohol on heaters set on a fin. The cross sections of heaters were of 10 × 1; 10 × 0·5; 5 × 0·5 and 3 × 0·5 mm. The pressure was changed from 1 to 64·5 atm.

The second series of experiments was carried out at boiling of methyl alcohol on a heating surface turned upwards. The heaters were used with cross sections of 5 × 0·5 mm, the lower surface of them was screened with Paranite. The pressure was changed from 2·75 to 10·35 atm.

The third series of experiments was carried out at boiling of methyl alcohol on a wire 1 mm in diameter. The pressure was changed from 1 to 58 atm.

The fourth series of experiments was performed at boiling of normal propyl alcohol on heaters with cross sections of 5 × 0·5 and 3 × 0·5 mm set in a fin position. The pressure was changed from 1 to 46·65 atm.

The fifth series of experiments was carried out at boiling of normal propyl alcohol on a surface turned upwards. The cross section of heaters was of 5 × 0·5 mm. The Paranite and Teflon were chosen to screen the lower surface of heaters. The pressure was changed from 1 to 43·4 atm.

The sixth series of experiments was performed on heaters with cross section of 5 × 0·5 mm set on a wide edge. The lower surface was not screened. The pressure was changed from 6·75 to 41·8 atm. The results of the 1st, 2nd, 3rd, 4th and 5th series of experiments are given in Fig. 2 in a form of the dependence $q_{cr-1} = f(P)$. The experiments of the 6th series are given by the same dependence in Fig. 3.

The analysis of the experiments of the 1st, 2nd, 3rd and the 4th series (Fig. 3, curves 1 and 2) shows that there exists a similarity of the critical load relative to the conditions of vapour removal from a heating surface in a wide range of pressures up to the critical pressure. Here as well as at atmospheric pressure the values of critical loads at boiling on surfaces turned upwards and set on a fin are equal under the compared conditions.

The values of critical loads are obtained 30–40 per cent higher at boiling on a wire than on a surface turned upwards (Fig. 2, curve 3). The visual observations at atmospheric pressure show that vapour bubbles leave the wire more often and they are of smaller sizes than those leaving the plates. The increase of the frequency with which vapour bubbles leave a surface leads to the intensification of heat removal and, apparently, this explains the delay in approach of the crisis. The removal of vapour from the lower surface meets some difficulties when heaters are set in a "fin" position. The crisis of boiling occurs first near the lower surface but not on the opposite surface turned upwards since vapour bubbles lingering near the lower surface form an entire film. Low values of

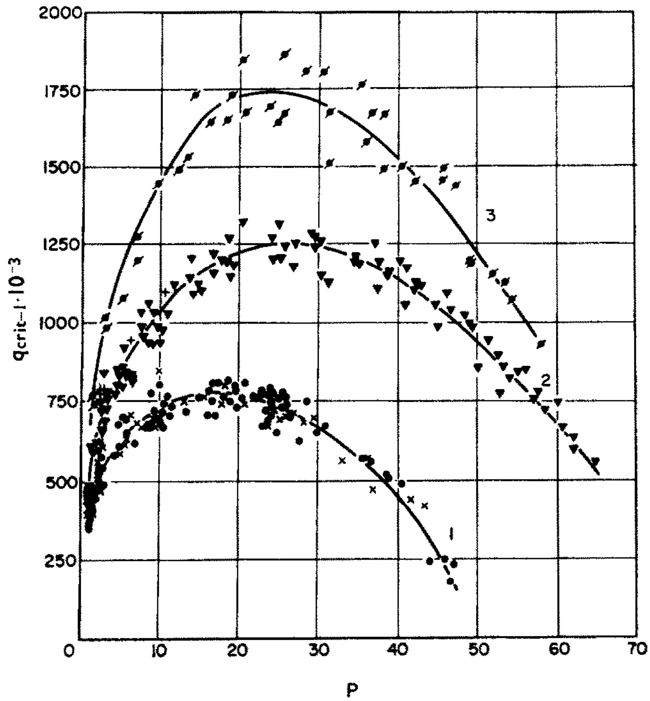

FIG. 2. Experimental data at boiling of methyl alcohol and propyl alcohol on different heaters.
Plate set in a "fin" position
▼—methyl alcohol
●—normal propyl alcohol
Plate with heating surface turned upwards
+—methyl alcohol
×—normal propyl alcohol
Wire 1 mm in diameter
—methyl alcohol

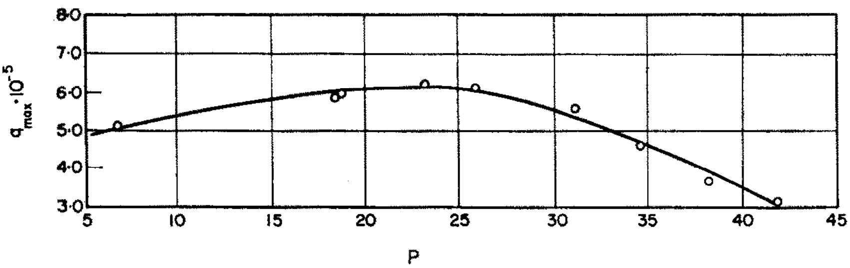

FIG. 3. Experimental data at boiling of normal propyl alcohol on a plate set on a wide edge without screening.

critical loads may be explained by this fact as well. The critical loads were obtained 20–25 per cent lower for the given conditions of boiling than on a surface turned upwards (Fig. 3). The dependence of critical loads change on pressure is one and the same for all types of heaters. The critical load increases up to the pressure which is equal to $\frac{1}{3}$ of the critical pressure, then it decreases till the values are lower than at atmospheric pressure. The same character of the critical load change depending on pressure was obtained in [1] for some other liquids.

The values of critical loads obtained at boiling of methyl alcohol and normal propyl alcohol on a surface turned upwards and set in a fin position were treated in relative co-ordinates of [1]:

$$\frac{q_{cr-1}}{P_{cr}} = f\left(\frac{P}{P_{cr}}\right) \qquad (1)$$

where P_{cr} and P are the critical thermodynamic pressure and the pressure at which the experiments were performed respectively.

boiling of methyl alcohol at atmospheric pressure on a horizontal ni-chrome plate turned by the heating surface upwards [4], on a horizontal copper tube [10] and on a steel surface [11] are plotted in Fig. 4. These data agree satisfactorily with ours.

In some experiments the thermal load on a heater increased sharply exceeding to a greater extent the critical load at rapid increase of the

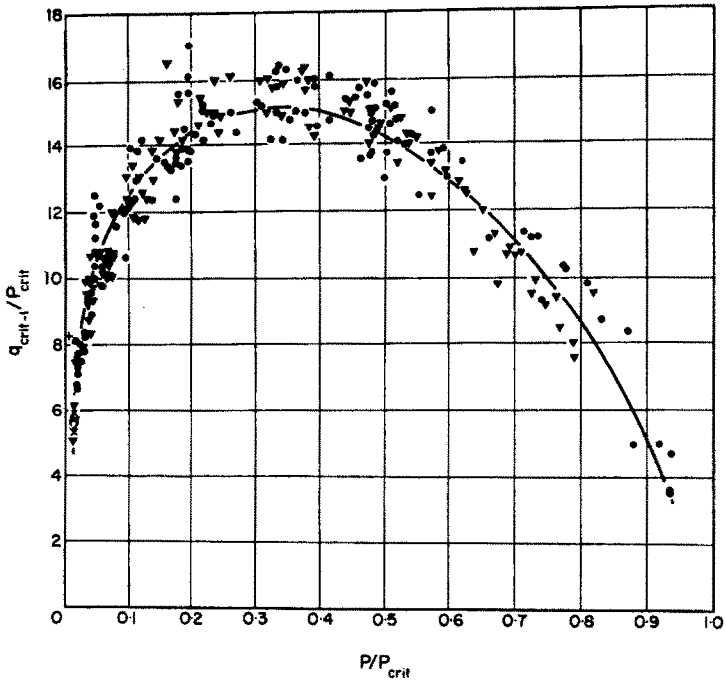

FIG. 4. Treatment of experimental data in relative co-ordinates.

Data given by the author
▼—methyl alcohol
●—normal propyl alcohol
Data given by Styrikovich and Polyakov [4]
+—methyl alcohol
Data given by Weswater and Santagelo [10]
×—methyl alcohol
Data given by Sauer *et al.* [11].
—methyl alcohol

The divergence of a point from the mean line led through the experimental values does not exceed ±20 per cent as can be seen from Fig. 4. However, this dependence does not take into account all the factors influencing the crisis formation process of boiling and with the increase in the difference between the properties of substances this scattering can reach the greater values.

For comparison the experimental data on the

capacity of the current generator. In this case carbon deposit appeared on a heating surface in the form of rough spots. Overstated values of critical loads were obtained at secondary experiments on the same heating surface. This excess depended on the state of the heating surface and fluctuated within 12 to 25 per cent (from the values obtained on a pure surface).

In our experiments carbon deposits provoked the same effect as the artificial roughness created on a heating surface [3]. At work on a heating surface covered by carbon deposits the rise of values q_{cr-1} may be apparently explained by this fact. The experimental points obtained on a surface covered with carbon deposits are excluded from the treatment.

CONCLUSIONS

1. Experimental data are obtained for the critical heat flows at boiling of methyl alcohol and normal propyl alcohol on a submerged heating surface. The pressure in the experiments changed from 1 to 64·5 atm at boiling of methyl alcohol and from 1 to 46 atm at boiling of normal propyl alcohol.

2. The data obtained for methyl alcohol at atmospheric pressure agree satisfactorily with the results of other investigators [4, 10, 11].

3. The character of a change of the dependence of critical flows on the pressure for methyl alcohol and normal propyl alcohol is the same as for other liquids [1]. The maximum of $q_{cr} = f(P)$ is at pressure $\simeq 1/3P_{cr}$.

4. At the change of the height from 3 to 10 mm and of the thickness from 0·5 to 1 mm practically equal values of the critical thermal flows were obtained on heaters set in a "fin" position. The same values of critical flows were obtained at boiling on heaters with the upward turned surface.

5. The critical values are 30–40 per cent higher at boiling of methyl alcohol on a ni-chrome wire 1 mm in diameter, than at boiling on plate heaters. Apparently the increase in the values of critical loads is explained by additional intensification of heat transfer called forth by the increase in frequency of tearing off vapour bubbles, which have lower leaving diameter under given conditions than on a heating surface of larger dimensions.

6. The values of critical flows at boiling of normal propyl alcohol on non-screened heaters set on a wide edge were obtained 20–25 per cent lower than at boiling on a heating surface turned upwards, because of the insufficient vapour removal from the lower surface. In these experiments the pressure was changed from 6·75 to 41·8 atm.

7. Higher values of critical flows were obtained on a heating surface covered with carbon deposits rather than on a pure surface. The increase in values q_{cr-1} results in the intensification of heat emission at the expense of additional roughness created by carbon deposits on a heating surface. The value of critical flows excess depends on the state of a heating surface and fluctuated within 12 to 15 per cent in our experiments. Approximately the same result is obtained in [1].

8. Experimental data are satisfactorily treated in a form of the dependence (1).

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