Int. J. Heat Mass Transfer. Vol. 5, pp. 661–666. Pergamon Press 1962. Printed in Great Britain.

NEW EXPERIMENTAL DATA ON CRITICAL HEAT LOADS AT BOILING OF LIQUIDS ON A SUBMERGED HEATING SURFACE

V. G. MOROZOV

Moscow Branch Department of the Polzunov Central Boiler–Turbine Institute

(*Received* 4 *November* 1961)

Аннотация—В статье излагаются результаты экспериментального изучения критических тепловых нагрузок при кипении на погружённой поверхности нагрева этилового спирта, воды и четырёххлористого углерода. Величины критических нагрузок для этанола определены при изменении давления от 1 до 62,6 ата, для воды—от 1 до 36,5 ата. Для четырёххлористого углерода величина $q_{(cr-1)}$ определялась при атмосферном давлении. Данные опытов сопоставлены с опытами других исследователей и обработаны в форме критериальной зависимости.

NOMENCLATURE

- $q_{(cr-1)}$, first critical heat load, kcal/m² h;
- P_{cr}, critical (in a thermodynamic sense) pressure, atm;
- P, pressure when testing, atm;
- T_s, saturation temperature, degK;
- r, latent heat of evaporation, kcal/kg;
- C_p, heat capacity of a liquid at constant pressure, kcal/kg degC;
- γ, specific weight of a liquid, kg/m³;
- γ'', specific weight of vapour, kg/m³;
- σ, surface stress, kg/m;
- ν, kinematic viscosity, m²/s;
- g, acceleration of gravity, m/s².

Subscripts

- cr, critical;
- evap, evaporation.

THE results of an experimental investigation of the effect of various factors on values of critical heat loads ($q_{(cr-1)}$) at boiling of methanol and n-propanol on a submerged heating surface were given in a recent publication [1]. Later on, critical loads for ethanol (ethyl alcohol), water and carbon tetrachloride were investigated. The results of this investigation are given in the present work.

Experiments for determining $q_{(cr-1)}$ were carried out according to the methods described in detail in [1]. Boiling of a liquid proceeded on horizontal, gauged ni-chrome plates placed on a fin. The working length of the plates was equal to 80–90 mm. Heating of the plates was carried out by direct current fed from a low-voltage dynamo. The presence of a rheostat in the exciting winding of the dynamo gave a smooth increase of heat load on the plates. The approach of critical flow was determined by a sharp change in electrical resistance of the plate where it was superheated by two zero-galvanometers connected by a balanced-bridge scheme. The method adopted determined the start of a boiling crisis with great reliability. In our experiments, the correction for measuring critical loads did not exceed ±7–10 per cent.

RESULTS OF EXPERIMENTS

Experiments with rectified ethanol (95 per cent alcohol) were carried out in the pressure range from 1 to 62·6 atm. The purity and chemical composition of ethanol satisfied all the demands of GOST. Before critical heat loads were investigated, the vapour-pressure curve for ethanol was obtained experimentally on a saturation line.

Results obtained for the dependence of saturation temperature upon pressure agree with tabulated data satisfactorily. Boiling of ethanol was carried out on experimental plates 5 × 0·5 mm in section. Results of experiments are illustrated in Fig. 1. At heat loads higher

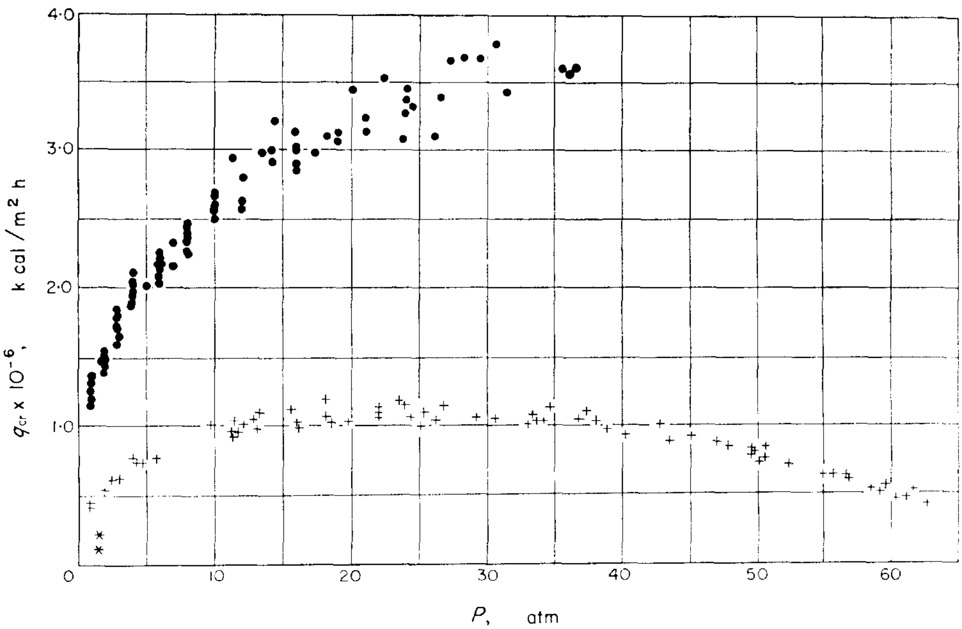

FIG. 1. Experimental data for determination of critical heat loads at boiling on a submerged heating surface.
●—water +—95 per cent ethanol ⁎—carbon tetrachloride

than critical and particularly in the critical pressure region (in a thermodynamical sense), the formation of carbon deposits on the plates was observed.

In experiments repeated on the plates where carbon was deposited, the values of $q_{(cr-1)}$ were usually 15–25 per cent higher than on pure plates. This phenomenon was also noted earlier in experiments with organic liquids [1].

Experiments with carbon tetrachloride were conducted at atmospheric pressure. The carbon tetrachloride used was of Analytical Reagent purity and its chemical composition satisfied GOST and was confirmed by supplied data and an additional laboratory analysis.* The viscosity [11] was also determined. Results for $q_{(cr-1)}$ of carbon tetrachloride are given in Fig. 1. The plates used in experiments were $9{\cdot}8 \times 1$ mm and $3 \times 0{\cdot}5$ mm in section.

Experiments with distilled water (both single and double distillation used) were carried out before the organic liquids were investigated, in order to work out the methods and to verify the reliability of work of an experimental installation working at high pressure.

However, preliminary experiments determined that, during testing, the distillate purity may depreciate considerably, and in this case the initial distillate purity has no great value. The original distillate had a low electrical resistance. Samplings made showed an increase in salt content of the distillate with increasing pressure and time of boiling, and in some cases it was many times in excess of the salt content of ordinary drinking water.

At high salt contents, the electric insulation of the experimental installation became disturbed and work became impossible. An additional investigation showed that the increase of salt content in distillate is caused by washing-out of salts from Paronite spacers. Therefore, in order to prevent this, the Paronite spacers were boiled for a long time in distillate which was replaced every 2–3 hr. Boiling was conducted in a special installation, until the separation of salts from the spacers stopped. Whenever possible Paronite was substituted for mica and plastic.

* Chemical analysis of carbon tetrachloride was made at the Moscow Institute of Chemical Engineering.

The spacers which had undergone this preliminary boiling were used in the experiments with organic liquids.

A number of other experiments were carried out with water in the pressure range 1–36·5 atm; the results are plotted in Fig. 1. Plates (9·6–10) $\times$ 1 mm in section were used.

It had been determined [1] that, with a change in plate height from 3 to 10 mm, values of $q_{(cr-1)}$ (under identical conditions) remain practically invariable. This was confirmed by systematic experiments with water, details of which are not presented herein.

TREATMENT AND COMPARISON OF EXPERIMENTAL DATA

A number of authors have concerned themselves with critical heat loads at boiling of ethanol and water on a submerged heating surface. Cichelli and Bonilla [2] as well as Styrikovich and Polyakov [3] considered a crisis of ethanol boiling.

Cichelli and Bonilla carried out their experiments with 100 per cent ethanol, boiling on a copper-chromed plate. They obtained eleven points, in the pressure range from 1 to 60·1 atm, which were successfully treated, along with experiments on other liquids, in relative coordinates in the form of a dependence:

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

where P_{cr} is the critical (in a thermodynamic sense) pressure; P is the pressure of the experiment.

Styrikovich and Polyakov [3] studied ethanol boiling on a ni-chrome plate at atmospheric pressure.

The cessation of bubbling in boiling water was most widely considered by Kazakova [4] who carried out experiments at boiling on a ni-chrome plate, and for the first time obtained a full curve for water of the dependence of $q_{(cr-1)}$ upon pressure.

The above-mentioned investigations were conducted under conditions similar to the present author's, and on similar heating surfaces, affording a reliable comparison. A comparison of the present results with those of other authors is presented in Fig. 2 in the form of dependence (1). As may be seen from Fig. 2, the results of the present experiments satisfactorily agree with those of other authors. Experimental data for 95 per cent cent ethanol in dependence (1) show a maximum at $P \simeq 1/3P_{cr}$.

Besides these experiments on water, the investigation carried out by Kutateladze [5] should be noted. It was carried out with water boiling on a graphite heating surface of varying roughness, in the pressure range 1–30 atm, and the present data are in satisfactory agreement with these results.

Cichelli and Bonilla [2] obtained dependence (1) empirically. As is shown in [5], this dependence is a result of approximate thermodynamic similarity between the relative pressure (P/P_{cr}) and physical properties of substances. The more similar the physical properties of the respective substances, the greater the degree of approximation. This fact possibly explains the deviation from a general dependence (see Fig. 2) of experimental data for carbon tetrachloride, physical properties of which considerably differ from those of water and organic liquids; dependence (1) does not reflect the influence of all the factors on values of critical loads.

Some authors [5–8] proposed criterial relations which were obtained as a result of treatment, by similarity methods or dimensionality theory, of a system of mathematical-physics equations describing various general aspects of the process, and of boundary conditions. By these means, formulae with varying degrees of approximation were obtained. In many cases, data, e.g. those of Cichelli and Bonilla [2] and some others, were generalized. The data of Cichelli and Bonilla [2] are described by the dependence proposed by Sterman [8] with a good degree of approximation:

$$(Re_{evap})_{(cr-1)} = f(Ar, Ks) \tag{2}$$

where

$$(Re_{evap})_{(cr-1)} = \frac{q_{(cr-1)}}{r\gamma''\nu}\sqrt{\left(\frac{\sigma}{\gamma-\gamma''}\right)}$$

$$Ar = \frac{g}{\nu^2}\sqrt{\left(\frac{\sigma}{\gamma-\gamma''}\right)}\left(\frac{\gamma-\gamma''}{\gamma''}\right)$$

$$Ks = \frac{r}{C_p T_s}$$

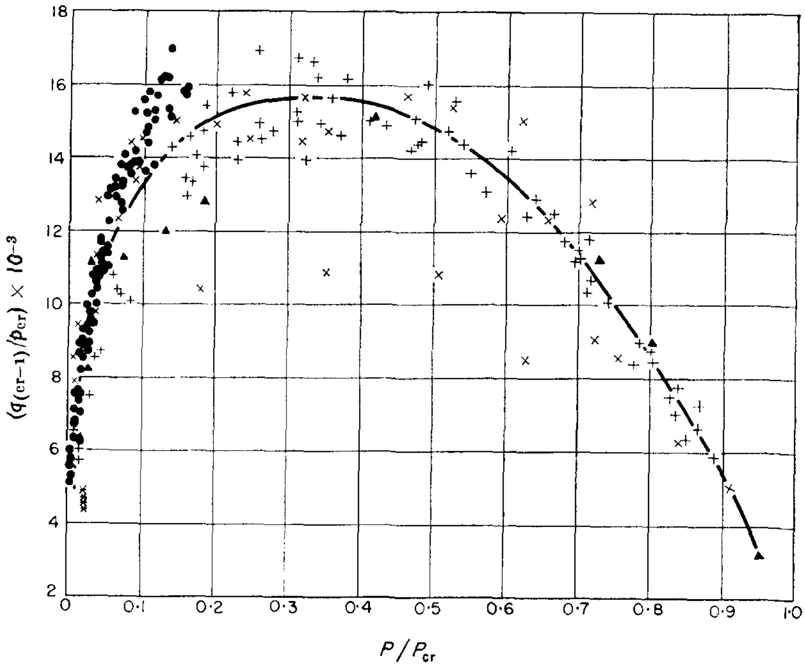

FIG. 2. Treatment of experimental data on critical heat loads in relative co-ordinates.

+—95 per cent ethanol, ⋇—carbon tetrachloride, ●—water: present data
▲—ethanol [2]
■—ethanol [3]
×—water [4]

All the data of the present paper, as well as those obtained earlier for methanol and n-propanol boiling on a plate under atmospheric pressure [1], are treated in the form of dependence (2). Only data obtained on a pure heating surface were considered. Values of critical loads obtained with boiling of methanol and n-propanol under pressures higher than atmospheric in the form of dependence (2) cannot be treated, on account of the lack of data on heat capacity at these pressures.

The results of experiments treated in the form of dependence (2), as well as data for methanol [9] boiling on a horizontal copper tube under atmospheric pressure, are presented in Fig. 3. For calculation of the values of criteria of dependence (2), physical constants were taken from [10–13]. The present experiments are covered, to within ±10–12 per cent, by the following formula:

$$(Re_{evap})_{(cr-1)} = 0{\cdot}0365\, Ar^{0{\cdot}57}\, Ks^{-1/3} \qquad (3)$$

This formula was also obtained by Sterman [8] from the experiments of Cichelli and Bonilla [2].

CONCLUSIONS

1. Experimental data on critical heat loads at boiling of 95 per cent ethanol, water and carbon tetrachloride have been obtained. With ethanol boiling, the pressure ranged from 1 to 62·6 atm, with water from 1 to 36·5 atm. Experiments with carbon tetrachloride were carried out at atmospheric pressure.

2. Experimental data obtained for 95 per cent ethanol and water satisfactorily agree with those of other investigators [2–5].

3. The curve $q_{(cr-1)}/P_{cr} = f(P/P_{cr})$ for ethanol has a maximum at $P \simeq 1/3\, P_{cr}$.

4. Experimental data for 95 per cent ethanol, water, carbon tetrachloride, as well as those obtained earlier [1] for methanol and n-propanol boiling under atmospheric pressure, are covered

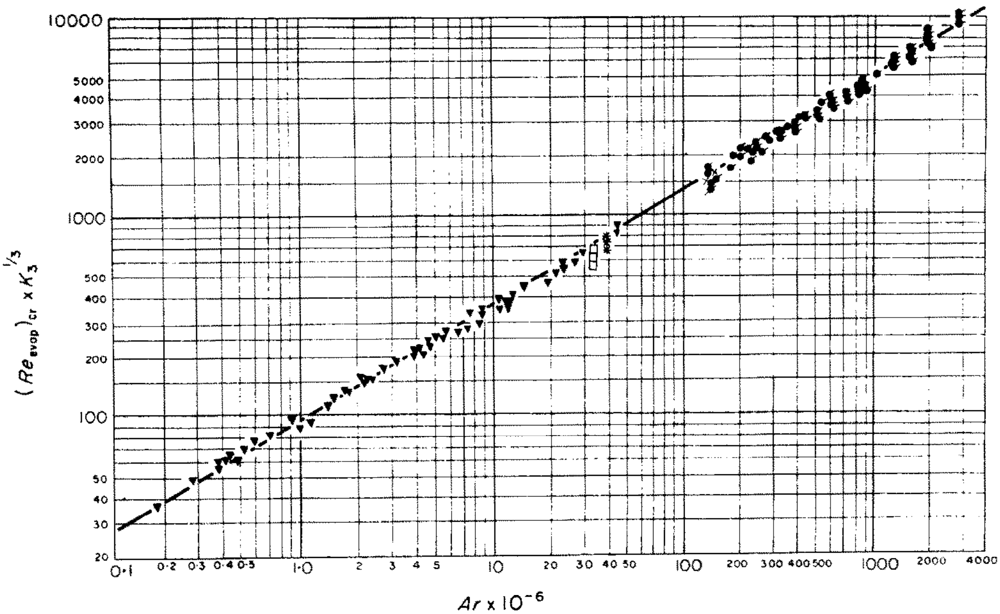

FIG. 3. Generalized treatment of experimental data on critical heat loads.

▼—95 per cent ethanol
✳—carbon tetrachloride
●—water
●—methanol
□—n-propanol
×—methanol [9]
} present data

by equation (3) to within ±10–12 per cent. Equation (3) was earlier obtained by Sterman [8] from the experiments of Cichelli and Bonilla [2].

ACKNOWLEDGEMENT

The author wishes to thank Professor A. A. Gukhman for a number of helpful suggestions.

REFERENCES

1. V. G. MOROZOV, An experimental study of critical heat loads at boiling of organic liquids on a submerged heating surface, *Int. J. Heat Mass Transfer*, **2**, 252–258 (1961).
2. M. T. CICHELLI and C. F. BONILLA, Heat transfer to liquids boiling under pressure, *Trans. Amer. Inst. Chem. Engrs*, **41**, 755 (1945).
3. M. A. STYRIKOVICH and G. M. POLYAKOV, Critical heat load at liquid boiling in a large volume (O kriticheskoi teplovoi nagruzke pri kipenii zhidkosti v bol'shom obyome), *Izv. Akad. Nauk SSSR, Otd. tech. nauk*, No. 5, 652 (1951).
4. E. A. KAZAKOVA, *Influence of pressure on approach of the first critical point at boiling of water on a horizontal plate* (Vliyanie davlenia na vozniknoveniye pervogo krizisa pri kipenii vody na gorizontal'noi plastine). Sbornik Voprosy teploobmena pri izmenenii agregatnogo sostoyaniya veshchestva. Gosenergoizdat, 92 (1953).
5. S. S. KUTATELADZE, Heat transfer with condensation and boiling (Teploperedacha pri kondensatsii i kipenii). *Mashgiz* (1952).
6. V. M. BORISHANSKII, Critical formula for generalizing experimental data on stopping bubble-boiling in a large liquid volume (O kriterial'noi formule dlya obobshcheniya opytnykh dannykh po prekrashcheniyu puzyrkovogo kipeniya v bol'shom obyome zhidkosti). *Zh. Tekh. Fiz.* **26**, 452–457 (1956).
7. G. N. KRUZHILIN, Generalization of experimental data on heat transfer at boiling of liquids under natural convection (Obobshcheniye eksperimental'nykh dannykh po teplootdache pri kipenii zhidkostei v usloviyakh yestestvennoi konvectsii). *Izv. Akad. Nauk SSSR, Otd. tekh. nauk*, No. 5, 701 (1949).
8. L. S. STERMAN, On the theory of heat transfer at liquid boiling (K teorii teplootdachi pri kipenii zhidkosti). *Zh. Tekh. Fiz.* **23**, 341–351 (1953).
9. J. W. WESTWATER and I. G. SANTAGELO, Photographic study of boiling. *Industr. Engng Chem.*, **47**, 1605–1609 (1955).

10. N. B. VARGAFTIK, *Thermophysical Properties of Substances* (Teplofizicheskiye svoistva veshchestv). Gosenergoizdat (1951).
11. N. I. KOPYLOV, An investigation of the viscosity of certain liquids in a wide temperature range. *Inzh. Fiz. Zh.* **3**, 97–102 (1960).
12. *Handbook of Chemistry* (Spravochnik khimika) Vol. 1. Goskhimizdat (1951).
13. G. W. C. KAYE and T. H. LABY, *Tables of Physical and Chemical Constants and Some Mathematical Functions* (9th Ed.). (Russian edition), Izdat. Inostrannoi Literatury (1949).

Abstract—Results are presented of an experimental investigation of critical heat loads at boiling on a submerged heating surface, of ethanol, water and carbon tetrachloride. Values of the critical heat loads are determined, for ethanol, in the pressure range from 1 to 62·6 atm, and for water, from 1 to 36·5 atm. For carbon tetrachloride the value of $q_{(cr-1)}$ is defined at atmospheric pressure. Data of experiments are compared with those of other investigators and treated in the form of a critical dependence.

Résumé—Cet article présente les résultats d'une recherche expérimentale sur les charges thermiques critiques au cours de l'ébullition, sur une surface chauffante, de l'alcool éthylique, de l'eau et du tétrachlorure de carbone. Les valeurs des charges thermiques critiques sont déterminées pour un domaine de pression s'étendant de 1 à 62,6 atmosphères pour l'éthanol et de 1 à 36,5 atmosphères pour l'eau. La valeur de $q_{(cr-1)}$ pour CCl_4 est définie à la pression atmosphérique. Les données expérimentales sont comparées à celles d'autres auteurs.

Zusammenfassung—Die kritischen Wärmestromdichten beim Sieden an einer untergetauchten Heizplatte wurden für Äthanol, Wasser und Tetrachlorkohlenstoff untersucht. Die Werte der kritischen Wärmestromdichte liessen sich für Äthanol im Druckbereich von 1 bis 62,6 atm bestimmen, für Wasser im Bereich von 1 bis 36,5 atm. Für Tetrachlorkohlenstoff ist der Wert von $q_{(cr-1)}$ bei Atmosphärendruck definiert. Die Ergebnisse wurden mit Daten anderer Versuche verglichen und bezogen auf die kritischen Werte wiedergegeben.