Int. J. Heat Mass Transfer. Vol. 7, pp. 187–190. Pergamon Press 1964. Printed in Great Britain

EFFECT OF PRESSURE AND MASS FLOW RATE ON BURNOUT HEAT FLUXES IN A WATER AND STEAM–WATER MIXTURE FLOW IN TUBES

V. E. DOROSHCHUK and F. P. LANTSMAN
All-Union F. F. Dzerzhinsky Research Institute of Heat Engineering, Moscow, U.S.S.R.

(*Received* 17 *June* 1963)

Аннотация—Проведено экспериментальное исследование критических нагрузок в цилиндрических трубах внутренним диаметром 8 мм при течении воды и пароводяной смеси в широкой области параметров рабочей среды.

Установлено, что критические тепловые нагрузки во всех случаях снижаются с уменьшением недогрева воды до температуры кипения, с увелечением паросодержания и с ростом давления. Влияние же весовой скорости на q_{bo} носит более сложный и неоднозначный характер.

NOMENCLATURE

q,	burnout heat flux q_{bo}, wt/m^2;
γW,	mass flow rate of working fluid, kg/m^{2}s;
p,	pressure, bar;
t,	temperature, °C;
t_2,	outlet working fluid temperature, °C;
d,	internal diameter of test tube, mm;
l,	heated length of test tube, mm;
l/d,	relative heated length;
θ,	subcooling of water to boiling point at a given pressure, °C;
i',	heat content of boiling water at a given pressure, kJ/kg;
i_2,	outlet working fluid heat content, kJ/kg;
r,	latent heat of vaporization at a given pressure, kJ/kg;
$x_2 = \frac{i_2 - i'}{r}$,	outlet parameter.

Subscript

bo,	refers to burnout heat flux.

ACCUMULATION of experimental data on burnout heat fluxes (q_{bo}) is of great importance for subsequent generalization and for obtaining reliable calculation methods.

This paper describes experiments on q_{bo} in a water and steam–water mixture flow in a tube 8 mm i.d. at pressure 49–196 bar and flow rates 750–2200 kg/m^{2}s. They were carried out at the All-Union Research Institute of Heat Engineering.

A block diagram of the experimental unit is shown in Fig. 1. Steam was supplied to the rig from a supercritical boiler. Before entering the test section it was throttled and cooled in a surface heat exchanger to the required values of p and t. A test section (6) was a vertical stainless steel tube with the relative length $l/d > 10$. The working fluid flowed through the tube upwards.

It is known that with the straight-through arrangement of the unit, powerful pulsations in mass flow rate and pressure of the fluid in the working section may take place, which cause a significant decrease in burnout heat fluxes [1]. To eliminate the pulsations in the experiments in all the cases the pressure drop in a throttle (2) was maintained at not less than 30 bar.

In experiments with water the basic parameters characterizing the test regime were pressure and temperature of liquid at the outlet of the test section, which were measured by manometer (16) and thermocouples (8, 9), the latter were

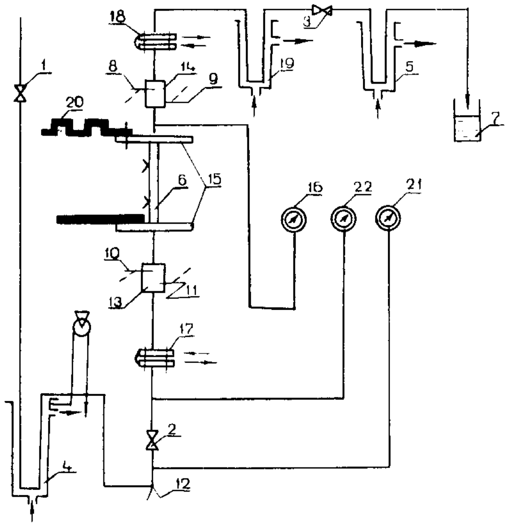

FIG. 1. Block diagram of experimental unit: 1, 2, 3—valves; 4, 5—heat exchangers; 6—experimental section; 7—measuring flask; 8, 9, 10, 11, 12—thermocouples; 13, 14—mixers; 15—current feeding flanges; 16, 21, 22—manometers; 17, 18—current insulating flanges; 19—cooler-calorimeter; 20—normal resistance.

placed in thin wells in a mixer (14). Similar measurements were also made at the entrance to the test section [manometer (22) and thermocouples (10, 11)], in order to correlate heat balance in terms of "electric current" and that on "water". Those runs in which non-balance exceeded 15 per cent were not taken into account. When treating experimental data the heat amount q_{bo} measured by voltage drop over the test section and by the value of electric current was taken into consideration.

In experiments with a steam–water mixture it was not enough to measure temperature and pressure to determine the characteristics of the working fluid in a tube. In connexion with this a supercritical pressure was maintained in front of a valve (2). Pressure and temperature of a single-phase fluid were measured by a thermocouple (12) and manometer (21). This permitted determination of the heat content at the inlet of the test section and at the outlet of it, the latter being possible if heat supplied to the test section is taken into account. In order to correlate heat balance a cooler-calorimeter (19) was placed immediately behind the test section.

The steam–water mixture passing through this cooler-calorimeter was cooled to the single-phase state and its temperature could be measured by a thermocouple. By measuring the heat amount given off to cooling water in the calorimeter (by water flow rate and difference between its inlet and outlet temperatures) it was possible to calculate parameters of the working fluid (x_2, t_2) at the outlet of the test section.

Initiation of the critical condition was visually observed by a local redness of the tube. The experimental results were worked out for the working fluid state at the outlet of the test channel and graphs of $q_{bo} = f(x_2)$ were plotted for various mass flow rates of liquid.

As an example such graphs for $p = 137$ bar and $\gamma W = 750$ and 2200 kg/m²s are given in Fig. 2. For other pressures and velocities the graphs are of the same form.

A similar treatment of experimental data in the co-ordinates q_{bo}, x_2 shows that all the experimental points are satisfactorily fitted by straight lines. Fig. 3 compares the experimental data for six pressures; 49, 78. 98, 137, 167 and 196 bar, obtained when mass flow rates were 750, 1100, 1500, 1750 and 2200 kg/m²s, respectively.

A group of straight lines which intersect either near the vertical straight line $x_2 = 0$, for pressures of 49, 78 and 98 bar or over the range of positive values of x_2 for higher pressures is given for each pressure.

It should be noted that over the whole range of pressures the burnout heat fluxes increase significantly with subcooling of water to boiling

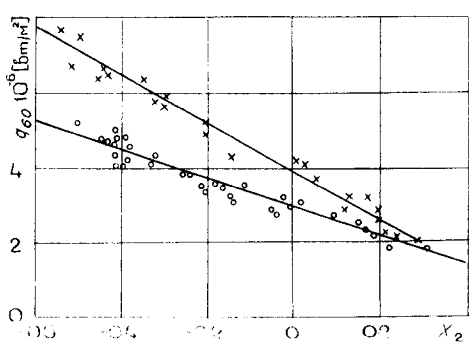

FIG. 2. Relation $q_{bo} = f(\gamma W, x_2)$; $p = 137$ bar; $\gamma W =$ 750 kg/m²s; $\gamma W = 2200$ kg/m²s.

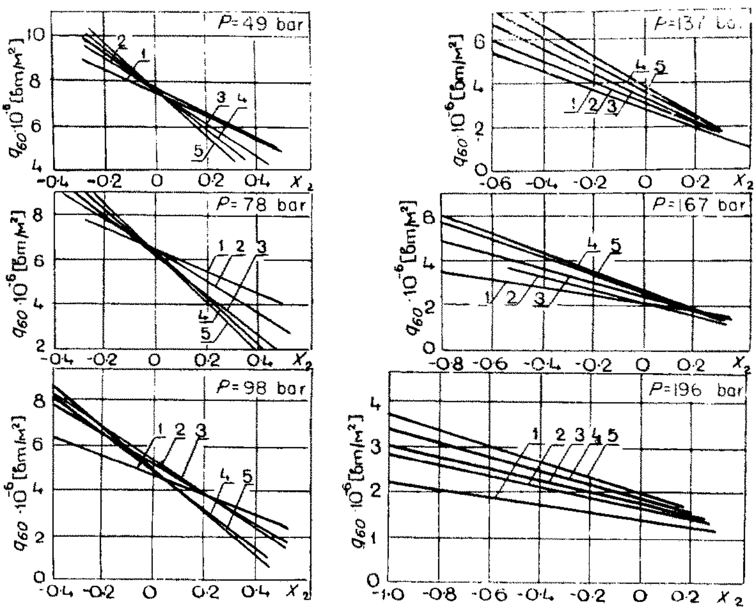

FIG. 3. Relation $q_{bo} = f(\gamma W, x_2)$; 1—$\gamma W$ = 750 kg/m² s; 2—γW = 1100 kg/m² s; 3—γW = 1500 kg/m² s; 4—γW = 1750 kg/m² s; 5—γW = 2200 kg/m² s.

point (θ), in other words, with a negative value of the parameter x_2. Obviously, this is attributed to intensification of heat transfer into the core of the stream due to increase in temperature difference near the outside boundary of the boiling boundary layer.

The effect of the working fluid mass flow rate for pressures up to 98 bar on burnout heat fluxes is somewhat peculiar. In a water flow burnout heat fluxes increase with γW. However, when the water state approaches the boiling one the effect of mass flow rate becomes less noticeable. With transition to the region of positive values of x_2, the reverse effect of γW on q_{bo} is observed. The reason for this phenomenon is attributed to hydrodynamic phenomena in two-phase flow systems. The appearance of the heat-transfer crisis in a steam–water mixture flow occurs due to the disappearance of the water film covering the internal surface of the heated tube [2]. At water pressures $p \geqslant 137$ bar the effect of mass flow rate on q_{bo} seems to be more significant. Moreover, burnout heat fluxes increase with γW in a steam–water mixture.

Such a complex nature of the effect of mass flow rate on burnout fluxes is apparently due to a different mechanism of water vaporization at various pressures and subcoolings of a liquid to boiling. Unfortunately, so far, the detailed investigations into the liquid boiling-mechansim have been carried out only at low pressures [3], and their results cannot be used in full measure at high pressures.

The effect of pressure on burnout heat fluxes for various values of water subcooling to boiling and that of vapour contents are given in Fig. 4.

It is known that the burnout heat fluxes obtained in a large water volume with natural convection over a range 60–80 bar increase with pressure, but with a further increase in pressure they begin to fall, reaching minimum values in a near-critical region of pressures [4]. In contrast to the aforesaid, under the conditions of forced flow the working fluid in a tube over the test range of pressures 49–196 bar q_{bo} they continuously decrease with increase in pressure (according to a linear law for $\theta \geqslant 50$°C).

The above experiments reveal the considerable complexity of the heat-transfer crisis and of many-valued dependence of burnout heat fluxes on working-fluid parameters. This involves

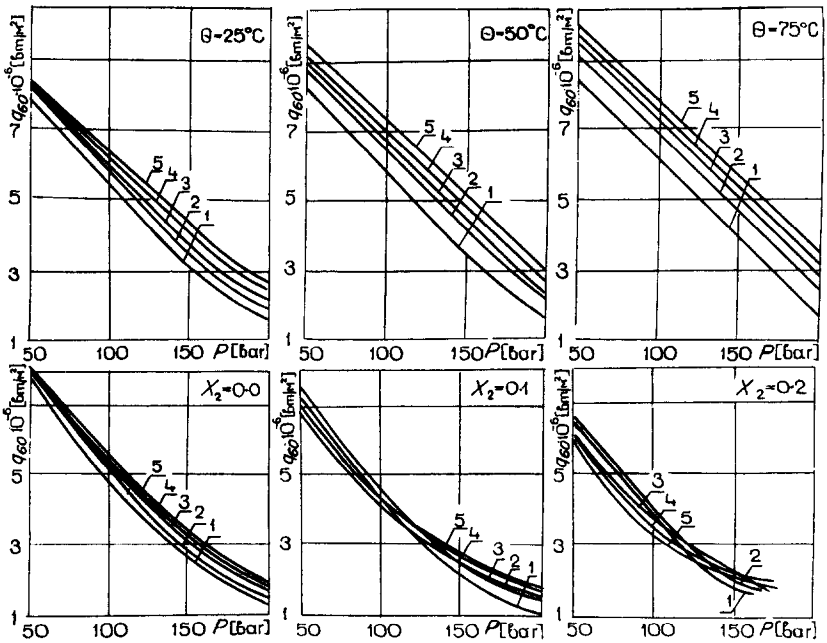

FIG. 4. Relation $q_{bo} = f(\gamma W, p)$; 1—$\gamma W =$ 750 kg/m² s; 2—$\gamma W =$ 1100 kg/m² s; 3—$\gamma W =$ 1500 kg/m² s; 4—$\gamma W =$ 1750 kg/m² s; 5—$\gamma W =$ 2200 kg/m² s.

difficulties in obtaining reliable calculations. It would appear that, in further studies it is necessary to pay much attention to elucidation of the physical nature of the crisis in order to establish a rational model of this phenomenon.

REFERENCES

1. V. E. DOROSHCHUK and F. P. FRID, On the effect of flow throttling and the heated length of a pipe on burnout heat fluxes (K voprosu o vliyanii drosselirovaniya potoka i obogrevaemoi dliny na kriticheskiye teplovye nagruzki), *Teploenergetika* No. 9, 74–79 (1959).
2. K. GOLDMAN, H. FIRSTENBERG and C. LOMBARDI, Burnout in turbulent flow—A droplet diffusion model, *Trans. ASME*, C, No. 2, 158–162 (1961).
3. G. G. TRESCHEV, *An Experimental Investigation Into a Mechanism of a Surface-Boiling Process* (Eksperimental'noye issledovaniye mekhanizma protsessa poverkhnostnogo kipeniya). Sbornik "Teploobmen pri vysokikh teplovykh nagruzkakh i drugikh spetsial'nykh usloviyakh", Gosenergoizdat, Moscow (1959).
4. S. S. KUTATELADZE, *Fundamentals of Heat Transfer Theory* (Osnovy teorii teploobmena). Mashgiz, Moscow (1962).

Abstract—Burnout heat fluxes in a flow of a water and steam–water mixture in cylindrical tubes 8 mm i.d. over a wide range of working fluid parameters were determined experimentally. In all cases burnout heat fluxes were found to decrease with decreasing subcooling of water to boiling point, with increased steam content and pressure. The effect of mass flow rate on q_{bo} is more complex.

Résumé—Les flux de chaleur dissipés dan un écoulement de mélange d'eau et de vapeur, dans des tubes cylindriques de 8 mm de diamètre intérieur ont été déterminés pour un grand nombre de valeurs des paramètres du fluide. Dans tous les cas, les flux de chaleur dissipés décroissent avec le refroidissement de l'eau au point d'ébullition, et avec l'augmentation de la quantité de vapeur et de la pression. L'influence du débit massique de l'écoulement est plus complexe.

Zusammenfassung—Der Burnout-Wärmefluss in einem Wasserstrom und einem Dampf-Wasser-Gemisch in zylindrischen Rohren von 8 mm Innendurchmesser wurde für einen grossen Bereich von Flüssigkeitsparametern experimentell bestimmt. In allen Fällen ergab sich eine Abnahme des Burnout-Wärmeflusses mit der Unterkühlung des Wassers, mit zunehmendem Dampfgehalt und Druck. Der Einfluss des Massenstroms auf q_{bo} ist verwickelter.