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Research Article

Investigation of the critical heat flux in small-diameter channels*

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Abstract

The paper describes experimental studies into the hydrodynamics and heat exchange in a forced water flow in small-diameter channels at low pressures. The timeliness of the studies has been defined by the growing interest in small-size heat exchangers. Small-diameter channels are actively used in components of compact heat exchangers for present-day engineering development applications.

The major difficulty involved in investigation of heat-transfer processes in small-diameter channels consists in the absence of common methodologies to calculate coefficients of hydraulic resistance and heat transfer in a two-phase flow. The channel size influences the heat exchange and hydrodynamics of a two-phase flow as one of the determining parameters since the existing internal scales (vapor bubble size, liquid droplet diameter, film thickness) may become commensurable with the channel diameter, this leading potentially to different flow conditions. It is evident that one cannot justifiably expect a change in the momentum and energy transfer regularities in single-phase flows as the channel size is reduced for as long as the continuum approximation remains valid.

The authors have analyzed the experiments undertaken by Russian scientists to investigate the distribution of thermal-hydraulic parameters in channels with a small cross-section in the entire variation range of the flow parameters in the channel up to the critical heat flux conditions when the wall temperature increases sharply as the thermal load grows slowly. The experimental critical heat flux data obtained by Russian and foreign authors has been compared.

Keywords

Experimental facility, test section, heat delivery and removal, critical heat flux, boiling boundary, experimental investigation results

Introduction

Evaporation of liquid, in which vapor generation is accompanied by the formation of new phase interfaces in a liquid volume, is called boiling. Volume, surface or mixed boiling may occur in thermophysical plants (equipment). In the process of pool boiling, the heat flux density q in excess of the critical density value q_{cr} leads to a sharp rise in the surface temperature. In this case, q_{cr} depends largely on the liquid and vapor properties which are defined by pressure. The same quantity is used also for the case of a forced flow in channels. Bubble boiling on the heating

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surface involves the formation of a large number of isolated vapor “bubbles” which separate from the liquid and detach from it after reaching a particular size. They disintegrate the liquid’s viscous sublayer that is immediately adjacent to the heating surface and creates the main thermal resistance for convective heat transfer during bubble boiling of liquids. That is why heat transfer during bubble boiling is intensive, e.g., for water with p = 1 bar, $\alpha \leq 5 \times 10^4$ W/(m^2×K) and $q \leq 1.25 \times 10^6$ W/m^2 where α is the heat transfer coefficient, and q is the heat flux density.

The nature of the critical heat flux in conditions of a forced flow is affected by a much greater number of parameters than for the case of pool boiling.

A critical heat flux is a rapid deterioration of heat removal from a heat-transfer surface accompanied by a jumping growth in its temperature. This is presumably explained by a decrease in the amount of the liquid contacting the heat-transfer wall as the result of which the wall starts to be overheated. For a subcooled liquid flow, an increase in the heat flux density leads to near-wall bubble boiling and then film boiling. In this case, the vapor film screens the wall from the main liquid flow, this leading to a rapid deterioration of heat transfer.

Let us consider the mass rate of the vapor phase formation (ρ”w) on the heating surface and the greatest possible mass rate of the vapor removal from the heating surface under given boiling conditions. With a growth in the heat flux density q, the mass rate of the vapor formation on the heat-transfer surface also increases, and a layer with increased void fraction forms near the heating surface when this value starts to exceed the vapor removal mass rate. This layer makes the surface more difficult to cool. Therefore, with a fixed heat flux density, the surface temperature increases, and the residual liquid in the two-phase layer evaporates as the heating surface is covered with a vapor film. We shall refer to this phenomenon as the critical heat flux of the first kind during surface boiling. So, the value of the first-kind critical heat flux density depends on the rate of the vapor removal from the heating surface and, therefore, on the flow rate of the boiling liquid, the form and size of the boiling liquid volume, and other factors which are external with respect to the viscous sublayer.

Normally, a critical heat flux during liquid boiling in a channel means a sharp rise in the wall temperature during a slow growth in the thermal load. The existing hypotheses attribute the onset of the critical heat flux to the termination of the liquid contact with the wall for any reasons (a hydrodynamic hypothesis, a hypothesis of the liquid flow stoppage in the film flowing over the channel walls; a droplet diffusion model; a hypothesis of a critical heat flux caused by the channel blocking). With major heat fluxes on the channel wall, high velocities of the subcooled liquid lead to the so-called “rapid crisis”. In this case, the value of the critical heat flux depends largely on the wall-adjacent flow parameters rather than on the flow’s central region conditions. A “slow crisis” is observed predominantly with high void fractions, low weight flow rates, and an annular dispersed flow. The value of the critical thermal load depends in this case on the flow core parameters which are presumably close to the average flow parameters. The conditions in the wall-adjacent region are also defined to a great extent by the flow in the core. High coefficients of heat transfer in a high-velocity flow lead normally to a much smaller and slower wall temperature increase. In some cases, a critical heat flux may occur without the preceding boiling process (Vasiliyev 1971, Kirillov 1996, Belyaev 2018). The cooling of a fast reactor core, high-power radar systems, oscillator valves, and various targets may cause the wall-adjacent liquid layer to be heavily overheated. Even in subcooled liquid cooling conditions, the heat-emitting wall surface temperature becomes much higher than the saturation temperature but, despite this fact, boiling turns out to be suppressed (Vasiliyev and Kirillov 1972, Skripov 1967, Kirillov 1996). This is contributed to by the high velocity of the flow, its hydrodynamic stability, the core subcooling, and minimization of the gas dissolved in the liquid. High liquid velocities and small diameters lead to high heat transfer rates. The heat from the superheated liquid layer is conveyed to the cooled core through intensive turbulence. Especially high superheats are possible with low pressures. So the vapor bubble growth rate during liquid boiling in the wall-adjacent layer turns out to be very high. This process may lead to a vapor plug blocking the channel and a further reversal of the circulation which will cause the cooling termination and the channel failure with continued heat deposition.

The experimental studies on the distribution of thermal-hydraulic parameters in annular small-diameter channels suggested that experiments were to be undertaken in a temperature variation range from indoor values to critical heat transfer modes. In his time, numerous experiments were conducted by V.P. Skripov and workmates to determine the limiting superheats of water, ether, and other liquids (Skripov 1967, 1972). These studies helped describing more fully the thermodynamic state of a liquid-vapor system and identifying the limits of the metastable state regions. In Skripov’s opinion, a thermodynamic crisis is defined by the limit of the thermodynamically possible liquid superheats. The thermodynamic approach gives prominence to the wall temperature t_w as the base determining parameter (with the given external pressure).

Despite a large number of studies to investigate the critical heat flux in channels (Ornadsky and Kichigin 1961, Doroshchyuk and Lantsman 1963, Ornadsky 1963, Levitan et al. 1981, Edelstein et al. 1984, Steiner and Taborek 1992, Kew and Cornwell 1997), many of the phenomenon’s internal mechanisms have not been made clear to date. If a critical heat flux is compared with the pool boiling case, the nature of the critical heat flux with a forced flow in channels affects much more parameters. Here, heat is removed from the surface by two processes: by forced convection and by evaporation. With an increase in the heat flux density, the share of the heat removed by evaporation grows and increases prior to the crisis onset as the pressure grows. Therefore, the heat flux density can be roughly associated with the mass flow of the evaporated liquid:

$$q \approx G \times r, \quad (1)$$

where G is the mass flow rate; and r is the evaporation heat.

Let us consider simultaneously the mass exchange and crisis processes. We shall do it using the example of an annular dispersed two-phase flow which occupies the largest void fraction interval. This flow consists of two regions: a wall moving liquid film with the rate G'_{film}, and the flow core consisting of vapor G'' and liquid droplets G'_d. In a general case, droplets may fall onto the film surface with a certain intensity as they are carried over from the film surface due to the mechanical interaction with vapor E_m and the boiling inside of film E_b. The hypothesis of the crisis onset in an annular dispersed flow is normally associated with the liquid flow stoppage in the film. The mass balance equation looks like

$$dG'_{film} / dz = D - (E_m - E_b) - q/r, \quad (2)$$

where D is the intensity of the droplet falling onto the film surface; q/r is the intensity of the film evaporation; and z is the film height. By integrating equation (2), one can determine z_{cr} in the cross-section of which the liquid mass in the film would be equal to zero, and have it associated with q.

Such approach is however approximate since the crisis onset is not at all times associated with the liquid flow stoppage in the film for there are modes when the flow rate in the film is not equal to zero during a crisis.

The results of experimental and theoretical studies have shown that different combinations of parameters (such as pressure, mass rate, void fraction, density, etc.) are matched by different processes that define the crisis (Ornadsky 1963, Yagov 1988, Kew and Cornwell 1997, Hamdar et al. 2010). With a low pressure and a small void fraction, the liquid fraction in the film is relatively large. This is defined by the stability of the film due to high surface tension values and a small vapor density. Film evaporation takes place largely due to the carryover of bubbles, and the crisis occurs with the end flow rate of the liquid in the film. With the void fraction being $x > x_{boundary}$, the crisis is caused by the film surface being insufficiently wetted with droplets ($D \approx 0$). As the pressure grows, the liquid fraction in the film becomes smaller due to a smaller stability of the film (due to the fact that the surface tension will be lower and the vapor density higher). In these conditions, the liquid carryover from the film prevails. The crisis occurs in this case when the film is fully exhausted ($G'_{film} \approx 0$).

In all cases, the larger is the heat flux density, the higher is the velocity of the vapor flowing out of the wall. This vapor flow prevents the droplets from falling out, and, with low q values, the wall is wetted with droplets more intensively.

In (Yagov 1988, Kew and Cornwell 1997), the channel diameter was found to influence q_{cr} directly in experiments with water and Freon in a bubble flow and inversely in an annular dispersed flow. Suggestions have been made which can explain such nature: a diameter increase for a bubble flow leads to an improved mass exchange between the flow core and the two-phase wall layer, that is, the bubble outflow from the wall improves which increases q_{cr}. With an annular dispersed flow, a dimeter increase leads to a growth in the liquid fraction in the flow core and, therefore, q_{cr} decreases. This is qualitatively confirmed by the data in Fig. 1 based on direct measurements (Yagov 1988, Serizawa et al. 2006, Sung-Min and Issam 2014).

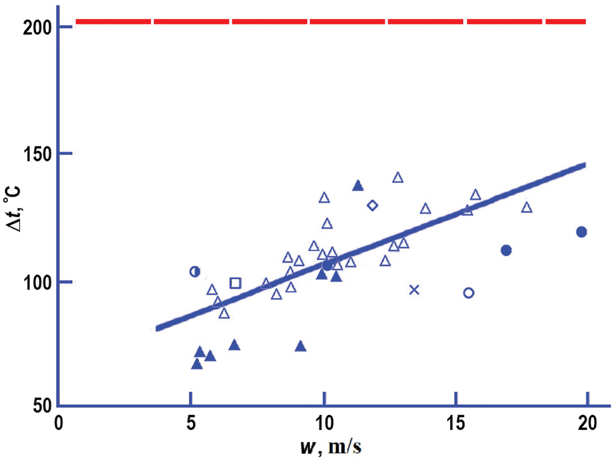

Figure 1. Experimental dependences of limiting superheats on w (p = 1 bar).

The experiments in (Vasiliyev 1971) showed that the surface boiling occurred only with small rates. The boiling was suppressed as the rate and, therefore, the heat load increased. The figure shows the boiling boundaries with p_{out} = 1 atm. Table 1 presents values of the parameters for the experimental points in this figure.

Table 1. Values of parameters for the experimental points in Fig. 1

Marker	Capillary diameter, mm	Heated length, mm	Inlet liquid temperature, °C
△	4.0 × 3.0	210	20
●	3.0 × 1.96	210	20
◇	4.0 × 3.0	270	20
□	4.0 × 3.0	331	20
○	3.0 × 1.96	331	20
▲	1.95 × 0.96	210	60
◑	1.53 × 1.2	210	60
×	4.0 × 3.0	210	60

It can be seen that with diameters close to 4 mm it was surface boiling that was largely recorded. Large water flow rates were required for "entering" the boiling region. As we have already said, the boiling was very abrupt. For water with rates of above 9 m/s, the crisis recording circuit had not enough time to respond and the test sections failed. The critical heat flux in the surface boiling region can be considered from the point of view of the "hydrodynamic hypothesis".

The data on the diameter influence on the critical heat flux density was obtained in (Tong 1976, Isachenko et al. 1981, Boltenko et al. 1991, Tran et al. 1996, Kirillov and Bogoslovskaya 2000, Xu et al. 2000, Kawahara et al. 2002, Serizawa et al. 2006), the numerical values being varied in these studies.

Due to this, a series of experiments was undertaken to determine the critical heat flux value in the investigated range of mode parameters. The experiments made it possible to obtain and analyze the distribution of thermal-hydraulic parameters in the channels immediately prior to and after the critical heat flux occurrence.

Far from being complete, the considerations provided in this paper with respect to the influence of different factors on heat transfer during bubble boiling of liquids on the heating surface show this to be a complex phenomenon. This circumstance complicates the investigation of the process and leads to the entire variety of the factors, which affect the heat transfer during boiling, not taken currently into account.

The experimental studies were conducted with annular channels of 1Kh18N10T and 1Kh18N9T steel of the length 120 to 1450 mm with the internal diameters of 0.64 to 4.0 mm. The flow velocities were in the limits of 0.2 to 20 m/s. The outlet pressure ranges were 0.3 to 1 bar. Distilled water (pH = 6.5) was used as the coolant. The flow rate in the circuit was created by the displacement of the liquid from the pressure tank to the drain tank using compressed nitrogen or using a thermocompressor (Fig. 2). The flow rate was measured by volumetric method, as well as using a constant-pressure drop flow meter (rotameter). The circuit flow rate was adjusted using a bypass line and a fine control valve (VT2). A water glass with a reference system not only made it possible to monitor the liquid level in the pressure tank but also served one more flow rate determination technique where experiments were conducted with an outlet pressure of below 1 bar. The displacement system valves provided for the liquid back pumping after the experiment was over.

The power circuit comprised a regulating low-voltage transformer (AOMKT 100/0.5A), an OSU-80 power transformer of up to 100 kW, a control circuit, and instrumentation for determining the power generated in the test section.

The liquid temperature at the test section inlet and outlet was measured using copper-to-constantan and chromel-copel thermocouples, and the channel outer surface temperature was measured using 16 to 20 thermocouples with the thermocouple wire diameters of 0.2 mm. The thermocouples were welded to the test section wall by contact welding with three or four thermocouples installed in the cross-section.

The test channel was clamped in current-conducting busbars using cones and gaskets (Fig. 3). Chambers with takeoff taps were installed in the channel's top and bottom parts for the pressure and temperature measurement and

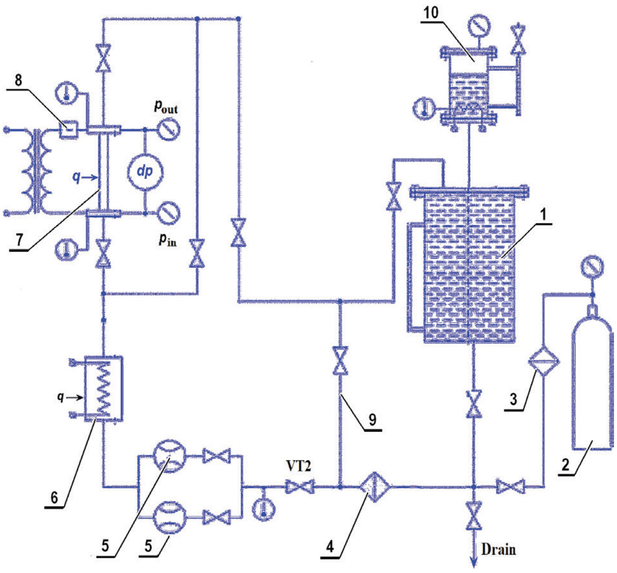

Figure 2. Simplified diagram of the experimental facility: 1 – pressure tank; 2 – nitrogen cylinder; 3, 4 – filters; 5 – flow meters; 6 – preheater; 7 – test section; 8 – current sensor; 9 – bypass line; 10 – thermocompressor.

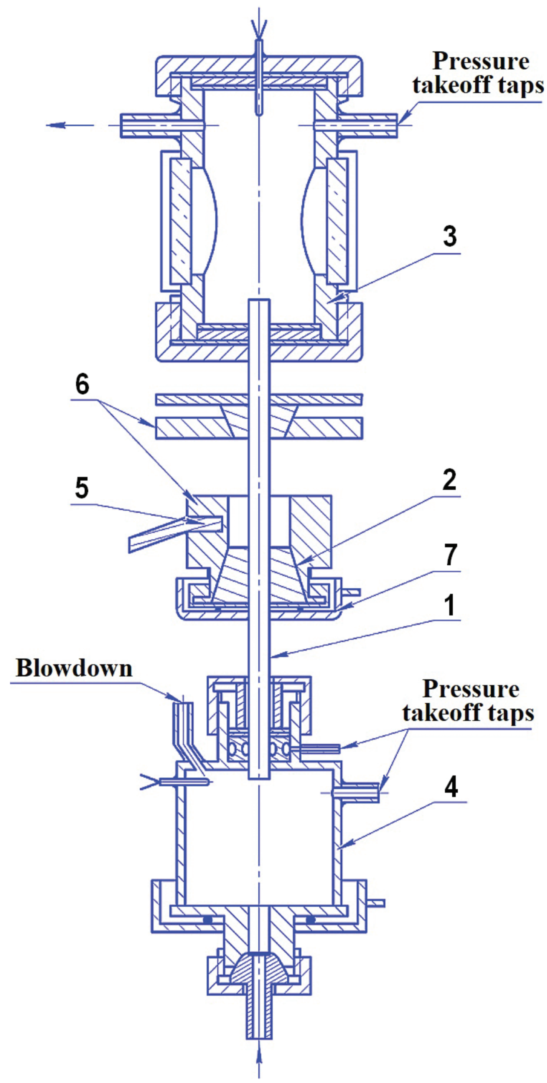

Figure 3. Diagram of the test section: 1 – channel; 2 – cone; 3 – upper chamber; 4 – lower chamber; 5 – lower current lead; 6 – busbars; 7 – liner with springs.

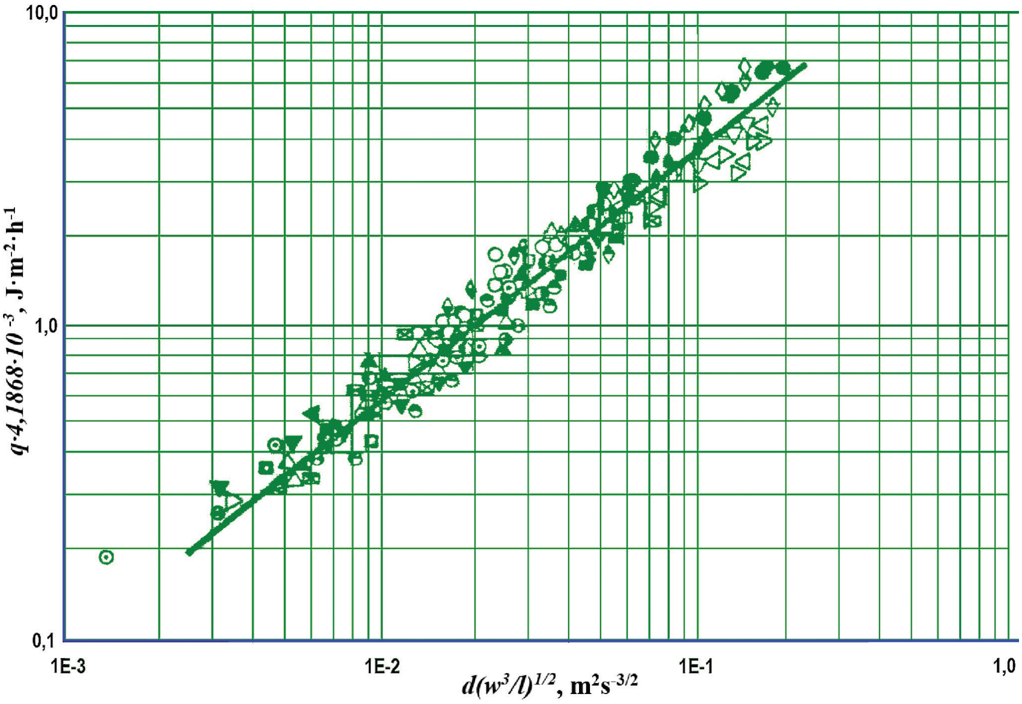

Figure 4. Generalized experimental data for water.

recording. The lower current lead was made movable to make up for the temperature expansions. It was installed in a steel liner with springs.

The experimental procedure was as follows. Prior to the experiment, distilled water was boiled for a long time to be degassed. A pressure of up to 30 bars was created in the pressure tank using a thermocompressor or high-pressure cylinders. A constant flow rate was set using a system of valves, the meters were switched on, and power was then delivered to the test section. Power was delivered in steps (intermittently) to make sure that the boiling process had not yet begun. Prior to the boiling, the power was increased by several watts after which the wall temperature decreased initially to a small extent and then started to rise sharply. With low velocities (of about 5 to 6 m/s), the wall temperature, channel outlet water temperature and flow rate fluctuations were recorded by instrumentation. Pressure fluctuations were recorded by the strain measuring system in the form of roughly sinusoidal oscillations. At the same time, the channel started to take the form of a sinusoid and inhale- and exhale-like hums were heard which were likely caused by the liquid being now delivered to the wall and then fully evaporating. P.L. Kapitsa was of the opinion that the film's wave motion was of a steady-state periodic nature described for any section x by the sinusoidal distribution of the film thickness in time. He obtained that, in the event of a wave flow, the effective film layer thickness δ_{ef} was smaller than δ computed using a Nusselt equation (Isachenko et al. 1981).

A sharp rise in the wall temperature started in the channel's top part; it was there as well that an abrupt blushing occurred which was then spread throughout the channel. A liquid pressure increase was observed at the same time in both chambers. If no supplied power was reduced, the test sections failed at the inlet part. Fluctuations occurred with small velocities and minor wall superheats in excess of the saturation temperature. The results of the experiments to investigate the critical thermal loads during water flowing in channels are presented in Fig. 4 from which it can be seen that the thermal load grows as the channel diameter and the coolant velocity increase.

Conclusions

The paper presents an analysis of the experiments conducted in 1963–2018 in Russia and abroad to investigate the distribution of thermal-hydraulic parameters in channels with a small cross-section in the entire measurement range of the channel flow parameters up to critical heat fluxes. The data obtained for flows in small-diameter channels is not enough to determine an apparent effect of the channel size on the critical heat flux.

The conditions of boiling in a heat exchanger with many channels may differ greatly from the boiling conditions in one channel. Furthermore, channels may differ geometrically. This requires both theoretical and experimental studies to identify the mechanism for the critical heat flux occurrence and to develop its prediction methods for small-diameter channels.

It is necessary to understand the physical meaning of the impact oscillatory processes have on the critical heat flux occurrence in small-diameter channels.

Evidently, the available experimental data on studies for the critical heat flux in small-diameter channels is apparently insufficient to provide a reliable theoretical explanation for the processes under investigation. Such theory is highly timely in the context of developing modern small-size heat exchangers.

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