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Heat transfer under high-power heating of liquids. 3. Threshold decrease of heat conduction in supercritical region

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ABSTRACT

The peculiarities of heat transfer in isopropanol in the course of rapid transition from the state of compressed liquid to supercritical state along the isobar have been studied experimentally. The temperature plateau mode, as a specific case of the technique of controlled pulse heating of a wire probe was used. The characteristic heating time was of the order of tens milliseconds, the characteristic heating layer thickness was of the order of micrometers. The pressure range was from $1p_c$ to $6p_c$, where subscript "c" corresponds to the critical point of a substance. A sharp decrease in the heat transfer intensity for supercritical isopropanol with respect to that of subcritical one has been revealed. The similar effect, which was found previously by the technique of constant heating power as well, is uncharacteristic for well-known stationary measurements. A discussion of the origin of discrepancies between the results from pulse and stationary measurements has been initiated by us.

1. Introduction

This paper is the third one in a series of papers concerned with heat transfer in liquids under high-power heat release. In the first paper, we presented an experimental procedure for pulse heating of a wire probe of 20-μm diameter, which is immersed in a studied substance, at the constant heating power mode [1]. A procedure for power control in the course of pulse heating was explained; variables directly measured in the experiment and the values calculated based on them were specified; an approach to the estimation of the temperature dependence of thermophysical properties of the liquid by the results of a single pulse measurement was proposed. In the second paper, by the example of water we discussed the phenomenon of threshold decrease in the intensity of heat transfer in the course of transition of the substance from the initial stable state (with the temperature $T_0 < T_c$ and the pressure value $p > p_c$) into supercritical state ($T > T_c$) along the isobar [2], where subscripts "0" and "c" refer to an initial state and a critical point, correspondingly. This phenomenon was previously revealed for organic liquids as well [3,4]. The penetration into supercritical region was implemented so rapidly (probe heating rate was 10^4–10^5 K/s) that the convective component of heat transfer did not have time "to be switched on" and the parameters of the response signal were reliably reproduced in a series of successive pulses. The characteristic pulse length of the probe heating within the technique of constant power was of the order of milliseconds; the characteristic heating layer thickness was of the order of micrometers [1–4].

The data obtained in [1–4] provide new insights concerning the long-term debate on the nature of the heat capacity peak and excess thermal conductivity of substances in the near-critical region, which are known from the quasi-static measurements (and solely from them) [5–9]. The debate was initiated by the breakthrough experiments performed, in particular, by Guildner [10], Voronel and Sengers (as cited in Ref. [11]), Skripov and Kolpakov, see in the final form in Ref. [12]. In its turn, the generality of our results obtained at the abovementioned heating rates also requires verification at other time–temperature conditions of the short-term experiment. In particular, it is important to find out the boundary from above of the time scale for experiment, in which the phenomenon of threshold decrease in the intensity of heat transfer was revealed. For this purpose, it is important to resolve the appearance of characteristic signs caused by free convection of a substance near the probe surface. In this regard, we have chosen the technique of thermostabilization of the pulse-heated probe at a given temperature value $T_{pl} > T_0$, or, in short, the technique of temperature plateau, see [13,14] and

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references therein. This approach allows for changing the characteristic duration of experiment by orders of magnitude under strictly specified probe temperature, which is equivalent to a "zero" rate of heating at the temperature plateau time period.

In the light of the above, our aims were defined as follows: (1) to compare the results of experiments on the intensity of heat transfer at the rapid isobaric heating of substance, which is carried out by two different techniques with a significant difference in the characteristic times, and (2) to clarify the time boundaries of conductive heat transfer mode (for given values of the pressure and probe temperature) from the pulse heated wire probe to environment. For definiteness, isopropanol (p_c = 4.9 MPa, T_c = 236 °C) was chosen as an object of the study. As in a basic experiment with isopropanol [3], the pressure value p served as a parameter and was varied in the range from 1 to $6p_c$.

2. Experimental

To meet the aims of this study, we have chosen the technique of temperature plateau. This technique, as well as a technique of constant power of heat release, is a specific case of the general method of controlled pulse heating of a wire probe [15,16], where probe combines a heater and a resistance thermometer [17]. Essence of the technique is as follows. Powerful heating pulse is applied to the probe and its temperature (hereinafter, it comes to the average integral temperature T along the probe length [1,17]) starts to rise. Upon reaching the chosen temperature T_{pl} at a certain timing t_1, the heating power $P(t)$ varies so that the probe temperature is maintained constant, $T(t \geqslant t_1) \approx T_{pl}$, $t_1 \sim 0.1$ ms, from that time until the end of the pulse. The prospect of technique is that the T_{pl} value can be selected (and can be changed with an arbitrary step in a series of measurements) in the temperature range that meets the conditions of the tasks, including the region of thermally unstable and superheated states of a liquid [1,13–16]. In accordance with the first aim of our study, the selection of T_{pl} values was made in the areas of both below and above the isopropanol critical temperature T_c and was coordinated with the parameters of basic experiment [3], see Fig. 1.

In the experiments, histories of the voltage drop across the probe and the standard resistor are recorded (Fig. 2) as described elsewhere [1,4,18]. From these values we calculate the values of probe temperature $T(t)$ and heating power $P(t)$ required for thermostabilization of the probe at the selected T_{pl} and p values. The uncertainties of this calculation are estimated to be 1.0% and 0.65%, correspondingly, as described in details elsewhere [1,18]. As a result, density of the heat flux through the probe surface $q(t)$ in time and, finally, the principal variable in experiments with powerful heat release in the probe [2–4,18], i.e. the actual value of thermal resistance of the sample $R_\lambda(t) = \Delta T(t)/q(t)$ at a chosen values of T_{pl} and T_0, where $\Delta T(t) = T_{pl} - T_0$ is the temperature rise, is deduced. Since the probe surface area is not determined with the required accuracy, comparative experiments are carried out in a relative variant of the technique, i.e. on a single probe, as it was previously [1–4,18].

In accordance with the equation of probe heat balance for the temperature plateau mode (as sited in Refs. [13,14]), samples with a higher value of thermal effusivity require a higher level of power $P(t)$, other variables being equal. In experiments with liquids, increasing pressure at a given T_{pl} value is accompanied by increase in $P(t)$ in accordance with the character of the dependence of thermal effusivity $(\lambda \cdot \rho \cdot c_p)^{0.5}$ on pressure [19]. Given the fact that the pressure serves as a parameter in our experiments, it is convenient to relate the technique sensitivity to the scale of $P(t)$ curve shift along the vertical axis, which is caused by a change in pressure. As an example, the technique sensitivity to pressure variation for maximum T_{pl} value in our experiments is shown in Fig. 3.

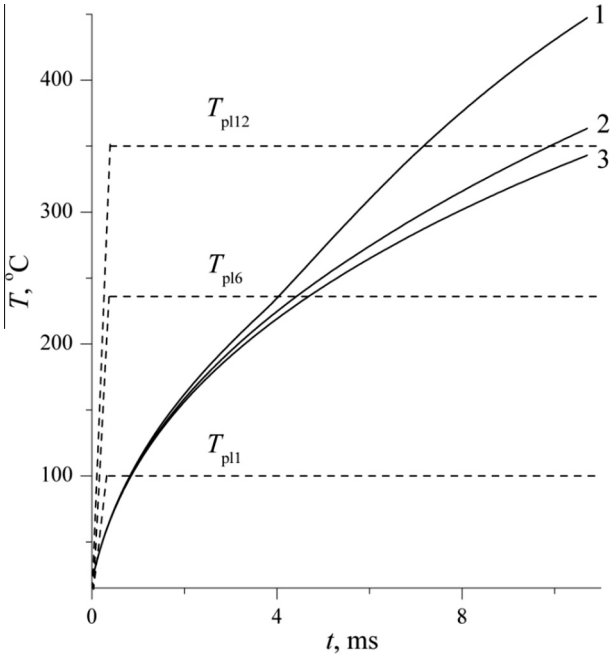

Fig. 1. Pulse heating of isopropanol along the selected isobars (1–3): probe temperature vs. time at the constant heating power mode (solid lines [3]); the reduced pressure p/p_c: 1.01 (line 1), 3 (2) and 6 (3). Schematic heating curves at the temperature plateau mode (dashed lines) show the selected temperature $T_{pl(i)}$ range in the experiment.

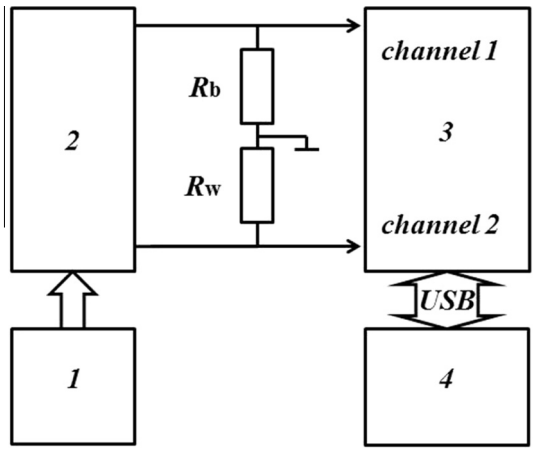

Fig. 2. Block diagram of the device for temperature plateau mode: 1 – voltage pulse generator, 2 – electronically controlled circuit of a wire probe thermostabilization, 3 – analog to digital converter, 4 – computer; R_b – standard resistor for obtaining a current in the probe circuit (low-inductance precise resistor with base error of 0.1% and the rating value of a few ohms), R_w – wire probe.

Let us explain the choice of the criterion for the detection of signs of the free convection onset at the probe surface. Let us increase the length of the temperature plateau portion in step by step manner. It is clear that sooner or later we will initiate "switch-on" of the convective heat transfer mode. According to the specificity of heat exchange of "isothermal" probe with an immovable medium [13], the power values $P(t)$ along a portion of temperature plateau are monotonically decreasing. The process of spontaneous boiling-up at a certain time $t > t_1$ at subcritical pressures is physically reasonable exception [13,14]. Obviously, there is no reason to expect that the signs of convection onset will be as confined in time as signs of boiling-up. In this context, we