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Heat transfer under high-power heating of liquids. 2. Transition from compressed to supercritical water

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ABSTRACT

The peculiarities of heat transfer in water in the course of rapid transition from the state of compressed fluid to supercritical state along the isobar has been studied experimentally. The constant heating power mode for the technique of controlled pulse heating of a wire probe was used. The characteristic heating time was of the order of milliseconds, the characteristic heating layer thickness was of the order of micrometers. The pressure range was from $1p_c$ to $2p_c$, where subscript “c” corresponds to the critical point of water; the heat flux density through the probe surface was of the order of 10 MW/m^2. A sharp decrease in the heat transfer intensity for supercritical water with respect to that of subcritical one uncharacteristic for well-known stationary measurements has been revealed.

1. Introduction

Physics of critical phenomena has been the focus of attention of the researchers [1,2], although one and a half century has passed since the fundamental experiments performed by Andrews [3]. Our experimental approach deals with a study of heat transfer of a substance in the course of its rapid transition from the state of compressed fluid to supercritical state along the isobar. The characteristic heating time is of the order of milliseconds, the characteristic heating layer thickness is of the order of micrometers. This mode of heat transfer, namely, heating mode with a nearly zero mass flux, but with high heat flux density is of practical interest, since supercritical fluids (SCFs), primarily water under supercritical conditions, are widely used in power engineering [4]. The peculiarity of heat and mass transfer pattern in SCFs and, as a consequence, the difficulty of experimental data interpretation became a serious obstacle for the application of supercritical water in nuclear power engineering, see [5] and references therein. Attention should be drawn to limitations in the studies of this pattern. Indeed, the vast majority of experiments on the study of heat transfer in SCFs in the interests of power engineering were performed in quasi-static conditions [5]. In this regard, a mode of high-power heat release under short characteristic times scale and confined spatial scale remains poorly known so far. Studying such a limiting case of heat transfer, a good approximation for practically conductive mechanism can significantly supplement the understanding specificity of heat transfer in SCFs [5–7]. Moreover, knowledge of the heat transfer parameters proved to be useful for revealing the trends in thermophysical properties of SCFs with respect to the reduced pressure of a substance.

This approach, if applied to organic liquids has already given nontrivial results [8]. In the course of pulse isobaric heating of compressed fluid (thermostat temperature was essentially below than critical one), we revealed that the transition to supercritical temperatures was accompanied by a significant decrease in the heat transfer intensity. The present paper concerns with the study of heat transfer in compressed and supercritical water in the case of a high-power local heat release.

2. Background

While on the subject of peculiarities of heat and mass transfer pattern in SCFs, we shall briefly touch upon the problem of measuring the thermal conductivity in the vicinity of the critical point (CP). The thermal conductivity measurements in the near supercritical region were performed mainly by stationary methods [9]. Characteristic perturbation in indirect signal parameters has been revealed in this region. Such a result is usually associated with critical thermal-conductivity enhancement. It’s explanation looks like this. The thermal conductivity value is represented by the sum; one summand is the background thermal conductivity, which would be in the absence of fluctuations, and the second term is interpreted as the result of large-scale fluctuations of density in this region of parameters [10]. It is known that the contributions caused by molecular collisions (background thermal conductivity)

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and the presence of fluctuations (thermal-conductivity enhancement) have significantly different characteristic times, see, for example, [2].

According to hypothesis [11], the thermal-conductivity enhancement originates from the motion (in the direction of the temperature gradient) of "excess density regions", i.e., macroscopic objects with respect to individual molecules. Then, in what does this phenomenon differ from convection? Indeed, a number of authors involved in thermal conductivity measurements do not exclude a possibility of the presence of the convective component in their experiments. Thus, the discussion of the critical thermal-conductivity enhancement can hardly be considered as finalized. Generally, performing experiments in the critical point vicinity requires improved capabilities of a technique (especially if it was initially developed for a continuous medium) and a "healthy skepticism" in assessing the impact of specific factors that may affect the interpretation of the results of voltage drop measurements [12].

Discussing the results on thermal conductivity, it is important to consider the experiments with SCFs under the conditions of orbital flight [13,14]. In these experiments, in addition to the detection of previously unknown effects (e.g., piston effect, see [13,14] and references therein), the strong convective instability of SCFs was revealed. This circumstance resulted in the development of convection flows under the action of vanishingly small perturbing factors. Such a behavior of SCFs was previously observed in experiments on heat transfer at free convection. It has been noted that, to obtain a true picture of heat conduction in SCFs, one should take into account or suppress the convection that easily appears near CP [11].

The issue on the properties of SCFs is closely related to the concept of object structure. The presence of large-scale fluctuations in SCFs points to a complex dynamic structure of the object. In this regard, at least in some region of parameters the description of SCF as a continuous medium becomes unsatisfactory [15]. It has been shown that SCF near CP is a fractal cluster; any selected volume of it is half-filled and almost half empty [16,17]. It is not obvious that such a non-homogeneous structure has an increased thermal conductivity. Indeed, experience shows that the values of thermal conductivity tend to decrease with the appearance of non-homogeneity of any type in initially homogeneous system [18,19].

Let us summarize the most important experimental points:

- a peak in the heat transfer coefficient values in the near supercritical region, which is usually associated with the peaks of isobaric heat capacity and volumetric expansion, has been determined;
- thermal conductivity enhancement in the near-critical region, which is related to the effect of large-scale density fluctuations, has been revealed;
- very high ability of SCFs with respect to the formation of convective flows under the action of small perturbing factors has been revealed as well.

Emphasize once again that the known experiments were performed in stationary or close to stationary regimes. Performing experiments under conditions of orbital flight did not save the results from the influence of residual gravity and convection, the two most important factors affecting the interpretation of the results. Transferring the experimental procedures developed for continuous media to SCFs, one should take into account specificity of the object under study.

3. Scientific objective

It is timely to supplement our knowledge of stationary heat transfer in SCFs with the experimental data obtained in the scale of small characteristic times and sizes, namely, under powerful local heat release. Such an approach makes it possible to shift the initial conditions (thermostat temperature) from supercritical part of the phase diagram, characteristic for quasi-static methods, into that of absolutely stable states and observe how the known peaks of thermophysical properties will manifest themselves under conditions of almost total lack of convection effect.

4. Experimental

As in our previous studies [20–22], we used the method of controlled pulse heating of a thin wire probe immersed in the fluid under investigation. The probe serves as a heater and a resistance thermometer simultaneously. The probe is a platinum wire of a 20 µm diameter and a 1–2 cm length. The time-varying voltage drops at the current-measuring resistor and the probe were measured in the experiment. The heating power, probe resistance and weight-average temperature were calculated from these values as time functions. The cell with the probe is placed in a thermostat. The pressure serves as a parameter in the experiment. Controlling unit [20,21] provides a mode of constant heating power over a pulse length with a spread of set power value less than 0.1% in a series of dozens of pulses. In this case the scattering of the heating trajectories did not exceed 0.5 K (Fig. 1), and this value can be regarded as the resolving power of the technique.

This approach makes it possible to change the pressure from pulse to pulse, thus ensuring the implementation of the given heating conditions with sufficient accuracy. As a result, a basis for quantitative evaluation of the changes of heat transfer patterns observed in the experiment at a step change in pressure appears. The weight-average temperature $T(t)$ of the probe at a given value of power P is recorded in experiment. Knowing the length l and diameter d of the probe, we calculated the heat flux density $q = (P - P_{Pt})/\pi dl$ and the thermal resistance $R_\lambda(t) = \Delta T(t)/q$, where $\Delta T(t)$ is the temperature rise, P_{Pt} is the power spent on heating the probe for any instant of time t. Thermal resistance is the principal factor in our experiment, since the usual approximation of temperature-independent properties [23] over the experimental ΔT range ($\sim 10^2$ K) is no longer valid. Since the error in determining the probe area is an order of magnitude greater than the errors of

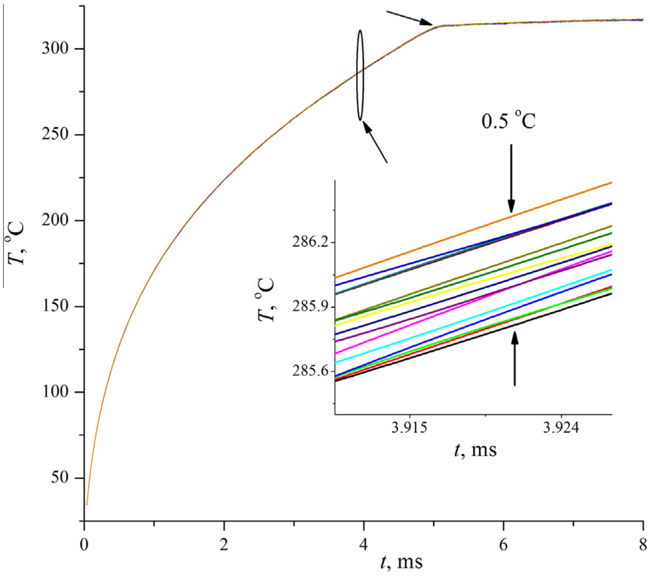

Fig. 1. Characteristic scale of scatter of the actual parameters for the probe temperature curves within one series of measurements on water at the constant heating power mode. The arrow indicates the timing of boiling-up onset.