Numerical Modeling of Heat Exchange and Turbulent Flow of Fluid within Tubes at Supercritical Pressure

E. P. Valueva
Moscow Power Engineering Institute, Moscow, Russia
Received October 28, 2010

Abstract—Modes of normal and degraded (with peaks of wall temperature) heat transfer are computed for the turbulent flow of carbon dioxide within a circular tube at supercritical pressure. Computation is based on a set of motion, continuity, and energy equations written under the approximation of a narrow channel. The turbulence model uses the Prandtl formula for the turbulent viscosity. The relationship for the travel length takes into account the effect of variation in the fluid properties and thermal acceleration through the tube section. Computation results for variation in the wall temperature along the tube fit the experimental data. An explanation is given for causes of the appearance of the peak on the wall temperature distribution along the tube in the area, where the fluid temperature is close to the pseudocritical temperature.

DOI: 10.1134/S0018151X12020204

INTRODUCTION

A change-over in nuclear power engineering to coolants at supercritical pressure (SCP) has resulted in enhancing the economy of water-cooled nuclear reactors [1, 2]. However, there is a problem of the reliability of similar reactors. As was justly mentioned in [2], there is a need to improve methods of computation for convective heat exchange in the SCP region especially with the purpose of forecasting modes with the degraded heat transfer.

The local heat-transfer drop is accompanied by the appearance of an abrupt increase (peak) in the wall temperature within some tube section. In practice, problems related to this had appeared in the 1950s, when boilers operating on the SCP water began to put go out of operation. These problems initiated numerous experimental investigations of heat exchange during flow of various SCP fluids. One of the first carried out such works carried out was by the author of [3].

The specific character of heat exchange in the SCP region is caused by the strong and peculiar temperature dependence of the physical properties. The isobaric heat capacity $C_p$ has a pronounced peak at the temperature $T_m$, which is called named pseudocritical. Similar maximums (peaks) were obtained experimentally on isobars of the heat conductivity $\lambda(T)$. Close to the pseudocritical temperatures, the density $\rho$ falls abruptly, the dependence of the coefficient $\mu(T)$ of dynamic viscosity passes the minimum, and temperature dependences of the Prandtl number $Pr(T)$ and the coefficient of thermal expansion reach the maximum. The last circumstance is related to heat exchange processes in the SCP region often proceeding under the effect of thermogravity.

The SCP region includes modes of the normal, degraded, and improved heat exchange [4]. The wall temperature in modes with the normal heat exchange varies monotonically along the tube, and dependences for the Nusselt number can be obtained on the basis of well-known conceptions of regularities of heat exchange under the effect of the variability of the physical properties. The local heat-transfer drop, as mentioned above, is characterized by the presence of peaks of the wall temperature in its distribution along the tube length. Modes with the improved heat transfer appear at high thermal loads when the fluid temperature is lower than the pseudocritical temperature $T_m$ and the wall temperature is above than $T_m$. Similar modes are usually accompanied by pressure fluctuations and acoustic phenomena, i.e., noises and whistles.

The subject of the present work is reproduction by the computation way and forecasting modes with the local heat-transfer drop. For that, there is a need to use a turbulence model taking for certain into account the effect of the strong variability of the properties on turbulent transfer.

REVIEW OF EXPERIMENTAL AND DESIGN-THEORETICAL INVESTIGATIONS

There are a number of review works on the topic under consideration (see, for example, [5, 6]). Analysis of the results of the available experimental investigations gives rise to the conclusion that the local heat-transfer drop can be produced by two causes. The peaks of the wall temperature appear in modes with the a small thermogravity effect at the relatively high thermal loads in the tube section in which the fluid temperature $T_b$ is close to $T_m$. Thus, the heat-transfer drop must be related to the effect of the strong prop-
property variability on the turbulent flow. This conclusion is confirmed also by the fact that heat transfer at small thermal loads has a maximum in the section, where the fluid temperature approximates to \( T_m \). A rise in heat transfer in the given case is explained by an increase in the Prandtl number in the region of \( T_m \), whereas variations in the fluid properties (property changeability) over the section and the length of the tube are not too large.

The peak of the wall temperature under the significant effect of the thermogravity is formed close to the inlet into the heated part of the tube (the so-called “inlet peak”) that in which connection occurs only with lifting movement of the fluid. The mentioned peak during downflow is lacking. One can assume that in the given case the cause of the local heat-transfer drop is a decrease in the generation of turbulence energy during heating and lifting movement in the field of the buoyancy force. This is confirmed by the fact that inlet peaks of the wall temperature are found in experiments with the fluid and at the subcritical pressure. In series of experiments, modes with two peaks on the wall temperature distribution along the tube were observed, one of which was located nearby the inlet, and the other, in the region, where the fluid temperature was close to the pseudocritical temperature.

Let us point out several experimental works performed in recent years. Two peaks on the wall temperature distribution along the tube on the wall temperature distribution along the tube in the vertically upward flow were observed in experiments [7] carried out for water. In [8] for the vertically upward flow of carbon dioxide, the modes of the local heat-transfer drop with the wall temperature peaks have also been found; their value and position are subjected to the effect of the shape of the channel cross section (experiments were carried out for a circular tube and channels with the quadratic and rectangular sections). In [9] the modes of normal heat transfer for the vertically upward and downward flow of carbon dioxide within a vertical mini-tube \((d = 0.27 \text{ mm})\) are investigated. The effect of the flow direction on the wall temperature was not observed. Experiments [10] were carried out for the vertically upward flow of carbon dioxide within tubes with the different diameters \((d = 4.4 \text{ mm and } d = 9 \text{ mm})\). They varied the fluid flow, heat-flux density \( q_w \) at the wall, and temperature at the tube inlet. The wall temperature in the region of the peak for the tube with the the greater diameter was found in several modes with the heat-transfer drop distinctly higher than for the tube with the lesser diameter. In [11] for the vertically upward flow of water, they studied the effect of pressure, fluid flow, heat-flux density at the wall on heat transfer, and distribution of the wall temperature along the tube. The modes of both normal and degraded heat transfer were observed.

In the given review of design-theoretical investigations, we set aside works in which turbulence models taking into account the effect of density pulsations of the field of the buoyancy force on turbulent transfer are proposed. The effect is taken into account by means of various corrections in turbulence models meant first of all for computation of the turbulent flow of a fluid with the substantial variability in the physical properties, which is characteristic for the SCP region. The semiempirical turbulence model can be divided in two classes, i.e., algebraic models of the turbulent viscosity and more complex models based on differential equations for various averaged characteristics of turbulence, particularly for kinetic turbulence energy \( k \) and its dissipation \( \varepsilon \). For example, the model proposed in [12] is related to the first class. It is noteworthy that comparison with the experiment in this work is carried out for the normal mode of heat transfer. In [13, 14] it is shown that the use of well-known models of the turbulent viscosity (Deisler, Goldman, Van Driest, et al.) does not provide satisfactory results during reproduction of experimental modes with a local heat-transfer drop.

The turbulence models related to the second above-mentioned classes were used in [9, 15–18]. Computations in [15] were carried out on the basis of the \( k-\varepsilon \) turbulence model as applied to experiments [19] run for the vertically upward flow of water. The wall temperature in these experiments varied monotonically along the tube, and the heat-transfer coefficient \( \alpha \) under relatively small loads had the a maximum in the region of \( T_w \approx T_m \). As \( q_w \) rises, the divergence between computational and experimental data increases. Authors The authors of [16] investigated 11 various models and concluded that a better agreement of computational and experimental data [19] for modes of normal heat transfer is achieved by the standard and low-Reynolds \( k-\varepsilon \) turbulence models, which give almost equal results. One of the variants of the low–Reynolds \( k-\varepsilon \) turbulence model was used in [17]; modes with the local heat-transfer drop were not computed in this work. In [18] the computational (with attracting several turbulence models) and experimental [19] heat-transfer coefficients in the region of the pseudocritical temperature were compared, and the conclusion was made that the maximum of \( \alpha \) is reproduced in the best way during the use of the standard \( k-\varepsilon \) model. The local heat-transfer drop was obtained in the computational way; however, comparison of computational and experimental data was not performed for similar modes. The authors of [9] also used the \( k-\varepsilon \) turbulence model; and they obtained the satisfactory coincidence of calculation results for the heat-transfer coefficient for the normal mode with experimental data of the authors themselves.

Work [20] proposed a turbulent viscosity model based on the conception of a the length of the Prandtl immixture path. The model considers in details the effect of variability of the physical properties on turbulent transfer. Application of this model to compute heat transfer in the tube during the turbulent flow of the fluid with the strong variability of the properties, particular in the SCP region, allows in [14, 21] for reproducing wall