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Universal dependencies for the description of heat transfer regimes in turbulent flow of supercritical fluids in channels of various geometries

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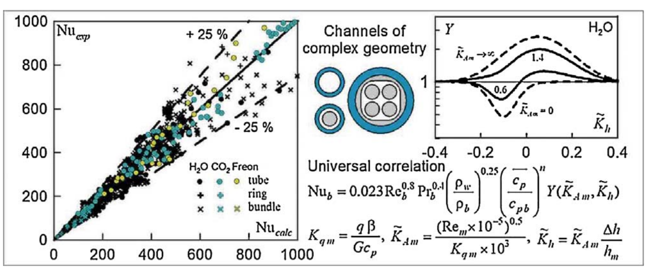
GRAPHICAL ABSTRACT



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ABSTRACT

The paper contains the results of heat transfer regimes analysis in the case of forced turbulent flow of water and modeling fluids in channels of various configurations (round tubes, annular gaps, rod bundles) at supercritical pressures. Two new complex criteria were proposed to describe heat transfer in the pseudo-phase transition region. These criteria take into account the specific features of the influence of inertial and viscous forces on heat and mass transfer processes under conditions of a strong change in fluid properties and when thermally-induced currents arise in the flow. A system of equations suitable for the engineering calculation of heat transfer in fuel assemblies of nuclear supercritical water reactors and in channels of other installations, where coolants are used at supercritical parameters, is presented. The comparison of the calculations of heat transfer coefficient by the proposed method and the predictions of other known correlations with experimental data for the regimes of normal, deteriorated and mixed heat transfer is given.

1. Introduction

The researches of heat transfer of supercritical fluids began to develop intensively in the second half of the last century. The necessity for this was caused by the start of the construction of power units with supercritical water-tube boilers using organic fuel. The main subject of the researches at that time was the study of the temperature regimes of the outside heated round tubes in which supercritical water flows. An important result of these studies was the identification of three heat transfer regimes in the supercritical pressure region, which, at the suggestion by *Petukhov* [1], were called "normal", "deteriorated" and "improved". This terminology was caused by the specific character of the variation in the temperature of the wall along the length of the heated channel, which was observed in some experiments. So, with a certain combination of mass velocity and heat load, regimes of "deteriorated" heat transfer were found, in which temperature peaks appeared on the surface of the pipe (clearly expressed temperature maxima). Regimes with "improved" heat transfer were detected at high heat fluxes and low temperature of the flow at the inlet of tube, in this case in test section there were powerful pressure pulsations,

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Nomenclature

a, b, c	Coefficients in correction function Y
c_p	Specific heat at constant pressure (J kg^{-1} K^{-1})
$\overline{c_p}$	Average specific heat, $(h_w - h_b)/(T_w - T_b)$ (J kg^{-1} K^{-1})
d	Inner diameter of channel (m)
d_h	Hydraulic diameter of channel (m)
g	Acceleration of gravity (m s^{-2})
G	Mass flow velocity (kg m^{-2} s^{-1})
h	Specific enthalpy (J kg^{-1})
K_q	Dimensionless heat flux, $q\beta/(Gc_p)$
$\widetilde{K}_{Am}$	Criterion of thermal acceleration, $(\mathrm{Re}_m \times 10^{-5})^{0.5}/(K_{qm} \times 10^3)$
$\widetilde{K}_h$	Enthalpy criterion, $\widetilde{K}_{Am}(h_b - h_m)/h_m$
N	Number of data points
n	Exponent in Eq. (1)
Nu	Nusselt number, $\alpha d/\lambda$
p	Pressure (Pa)
Pr	Prandtl number, $\mu c_p/\lambda$
$\overline{\mathrm{Pr}}$	Average Prandtl number, $\mu\overline{c_p}/\lambda$
q	Heat flux (W/m^2)
Re	Reynolds number, Gd/μ
St	Stanton number, $q/[G(h_w - h_b)]$
T_b	Bulk temperature (K)
T_m	Pseudo-critical temperature (K)
T_w	Wall temperature (K)
x	Longitudinal coordinate (m)
Y	Correction function in Eq. (2)

Greek symbols

α	Heat transfer coefficient, HTC (W/m^2 K^{-1})
β	Coefficient of volumetric expansion (K^{-1})
ζ	Weight coefficient in expression for Y
λ	Thermal conductivity (W/m K^{-1})
μ	Dynamic viscosity (kg m^{-1} s^{-1})
ξ	Coefficient of friction resistance
ξ_i	Coefficient of inertial resistance
ρ	Density (kg m^{-3})
σ_a	Mean arithmetic deviation
σ_{sq}	Mean square deviation

Subscripts

0	At constant physical properties of fluid
b	At bulk temperature
exp	Experimental value
m	At pseudo-critical temperature
n	Normal regime
w	at wall temperature

Abbreviations

GIF	Generation IV International Forum
HTC	Heat transfer coefficient
SCWR	Supercritical water-cooled reactor

accompanied by a characteristic sound (acoustic vibrations). As a result of the analysis and processing of a large number of experimental data for the case of turbulent flow of water, carbon dioxide, helium, and some other fluids in round tubes, the main regularities of the regimes mentioned above were described. A number of dependences for "normal" heat transfer calculation were developed by the end of the last century. The achievements of this early period of research are detailed by *Pioro and Duffey* in their monograph [2].

At present, in connection with the prospect of using supercritical water in nuclear reactors of a new generation – Generation IV SCWR [3], the interest in studies of heat transfer near the critical point has resumed. At the same time, new problems arose from the need to study the features of the heat and mass transfer of supercritical fluids in channels of a complex geometric shape. Due to the difficulties and high cost of setting up and carrying out the experiments with water at high pressures (about 23–25 MPa), some companies began to carry out similar studies with modeling fluids (carbon dioxide, Freon's), the critical pressure of which is much lower. The results of such studies are useful for development and verification of generalized correlations.

This paper presents a new approach, relating to the classification and description of heat transfer modes in supercritical pressure media. Two original combinations of similarity criteria, which take into account the influence of thermal acceleration on heat transfer in narrow channels, caused by thermally induced currents, are proposed. The addition of the traditional system of criteria with the new dimensionless complexes and the assumption of a superposition of transport phenomena under the influence of factors determining the heat transfer rate under given conditions made it possible to construct universal dependences describing the experimental data for the regimes of normal, deteriorated, and mixed heat transfer in water and modeling fluids over a wide range of determinant parameters.

2. Heat transfer regimes at supercritical pressures and methods for their description

The above mentioned classification of heat transfer regimes and the terms concerning the level of the heat transfer coefficient ("normal", "deteriorated", "improved" heat transfer) are widely used in scientific publications dealing with the problem of heat transfer at supercritical pressures. Obviously, this classification is very conditional, and the meaning of the used terms is rather ambiguous. Therefore, in order to avoid contradictions, in the course of the further presentation, the terminology used in this paper will be defined more precisely.

2.1. Regimes of normal heat transfer

According to *Petukhov* [1], the regimes of normal heat transfer are characterized by the fact that the observed dependence of the heat transfer coefficient on the determining parameters (more precisely, the dependence of Nu number on Re and Pr numbers), despite of significant changes of fluid properties, remains approximately the same as for constant properties. For the specified experimental conditions (pressure, fluid temperature at the inlet of the test section, density of heat flux on the heating surface, etc.), the heat transfer coefficient can remain constant along the length of the test section, increase or decrease, pass through a maximum or minimum. Under the conditions of constant heat load, the temperature of the heated wall varies along the length monotonically, without sharp jumps, and depends only on the local enthalpy of the flow in the region of stabilized heat transfer. Under the influence of the variability of the physical properties of fluids near the critical point, the heat transfer coefficients, depending on the combination of the temperatures of the coolant, the wall and the pseudocritical temperature, can be significantly higher or, conversely, lower than the values found from the equations for the case of constant physical properties.

Another treatment of "normal" regimes is contained in *Pioro and Duffey* monograph [2]. In it, the term "normal heat transfer" denotes a