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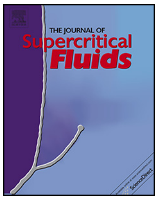

Effect of inclination on frictional pressure drop of supercritical water flows in internally ribbed tubes: An experimental study

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ABSTRACT

Internally ribbed tubes are highly advantageous for heat transfer enhancement in high pressure water flows. But these tubes increase the frictional pressure drop in comparison with smooth tubes. In this paper the frictional pressure drop characteristics of subcritical, near critical and supercritical water upward flows inside the inclined rifled tube with inclinations angles of 5, 20, 30, 45 and 90° with respect to the horizontal plane are studied experimentally. The test pressures were 15, 21.5, 22.5, 25 and 28 MPa, the heat and mass fluxes were kept at 400 kW/m^2 kW/m^2 and 800 kg/m^{2}s. The effect of heat and mass fluxes on frictional pressure drop in inclined tubes was also investigated. The results showed the least frictional pressure drop for both subcritical and supercritical flows occurs at 5°. The effect of mass flux on frictional pressure drop in all water flow conditions was more considerable than the heat flux.

1. Introduction

Studies on supercritical fluids and their related applications have been widely conducted since the 1950′s. These fluids have been used frequently in fossil fuel fired power plants and among these fluids the supercritical water is most common to be used in steam generators [1]. Following early studies during 1960s–1980s many efforts were performed on using supercritical fluids in nuclear reactors especially in former USSR and USA. The advantage of using supercritical water for steam generation is that higher efficiencies could be reach with lower mass fluxes in water wall tubes inside boilers. Also by using supercritical water in the boilers the total generated electricity cost would be decreased as many equipments like steam generators, steam separators, dryers and etc. are being eliminated.

Some other important applications of supercritical fluids flows are in rockets and military aircrafts which are both cooled and being fueled by supercritical fluids. Also some high temperature hot parts like gas turbine blades, supercomputer elements, magnets and power transmission cables are cooled with supercritical fluids. It could be concluded that in order to design any system that works with supercritical fluid, it is important to be able to calculate its' corresponding hydraulic resistance behaviors as well as heat transfer characteristics [2,3].

Tanaka et al. [4] studied the shear-stress distribution in a tube by considering the buoyancy and inertia forces. They found that both forces affect the frictional characteristics of the flow very similarly. They introduced some criteria for the effects of buoyancy and acceleration of shear stresses on the walls. Finally by assuming the turbulent boundary layer as superposition of locally developed layers, an analytical method was suggested by them for calculating the velocities and temperatures along the tube. Alekseev et al. [5] (Institute of Physics and Power Engineering, Obninsk, Russia) prepared an analytical review including 206 papers review of which 55 papers were for Western publications in which they surveyed the previous works on the heat transfer and hydraulic resistance of fluids at supercritical pressures. Due to varying physical properties of the working fluid in supercritical fluid flows, Popov [6,7] developed a method for calculating the hydrodynamic resistance and recovery coefficient for turbulent flow in a circular tube for compressible fluids. They performed some calculations for the hydraulic resistance of turbulent flow in a circular tube with different fluids of water, air, and nitrogen during heating and cooling. They showed that these one dimensional flow models are not enough to evaluate local values of the frictional resistance coefficient for supercritical liquid flow conditions. Also they presented the results of numerical calculations of the hydraulic drag in a turbulent flow of Helium in a heated circular tube at supercritical pressures. Again a

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Nomenclature

c_p	Specific heat at constant pressure, J/(kg°C)
d_e	Hydraulic diameter, *m*
d_s	External diameter, *m*
E	Heating voltage, V
G	Mass flux, $kg/(m^2 s)$
h	Heat transfer coefficient, $W/m^2\,°C$
H_f	Specific enthalpy of bulk fluid, *J/kg*
$\varDelta H$	Added enthalpy, *J/s*
I	Heating current, *A*
L	Length of test section, *m*
L_i	Inlet length, *m*
Nu	Nusselt number
P	Pressure, *MPa*
$\varDelta P$	Pressure drop, *kPa*
$\varDelta P_{lo}$	Frictional pressure drop in single-phase, *MPa*
$\varDelta P_{tp}$	Frictional pressure drop in two-phase zone, *MPa*
P_{cr}	Critical pressure, *MPa*
q	Inner wall heat flux, W/m^2
Q_E	Heating power, *W*
Re	Reynolds number
T_f	Bulk fluid temperature, °*C*
T_{in}	Inlet fluid temperature, °*C*
T_{out}	Outlet fluid temperature, °*C*
u_i	Inlet velocity, *m/s*
u_o	Outlet velocity, *m/s*
x	Vapor quality
DNB	Departure from nucleate boiling

Greek symbols

η	Thermal efficiency of test section
ρ	Density of fluid, kg/m^3
μ	Dynamic viscosity of fluid, *Pa s*
ν	Specific volume of fluid, m^3/kg
φ^2_{lo}	Two-phase frictional multiplier, *kPa/kPa*

great deviation between calculated values and measured values of frictional loss was observed. Petukhov et al. [8,9] developed a computational model which used the simplified equation of turbulent kinetic energy balance to find a turbulent momentum transport coefficient. Their results were compared with experimental data and found to be acceptable for turbulent flow of water and air in tubes under significant influence of gravity. Popov [10] and Popov and Petrov [11] proposed many models to improve the results of numerical simulations of free and forced convection flows and heat transfer in the turbulent flow of supercritical carbon dioxide inside a tube at cooling boundary conditions.

In 1990, P.L. Kirillov, Yu.S. Yur'ev, and V.P. Bobkov [12] published the second edition of “Handbook for Thermal-Hydraulic Calculations (Nuclear Reactors, Heat Exchangers, Steam Generators), in which in some parts they have studied the hydraulic resistance of working fluids at near-critical parameters and the heat transfer at near-critical and supercritical pressures thoroughly investigated. Some new models for simulation of these kinds of flows were suggested by them.

A. Kurganov [13] discussed various areas of heat transfer and pressure drop at supercritical pressures. In 2001 Cheng and Schulenberg [14] presented a literature review of selected papers in which they covered all of the topics of general features of heat transfer at supercritical pressure, experimental and numerical studies, prediction methods, deterioration of heat transfer, frictional pressure drop, and their application to HPLWR.

The considerable issue about supercritical pressures is that at these pressures the flow pattern is very similar to the conventional single-phase flow. No phase change happens but the thermo-physical properties of fluids at these high pressures change drastically during heating and cooling processes. So in these conditions the pressure drop is greatly dependent on the local fluid temperature and the inner wall temperature. This makes the conventional single-phase friction factor correlations unsuitable for supercritical flows [15].

According to rifled tubes there are many researches being conducted to show the effect of internal ribs on heat transfer enhancement [16–20] but few of them spoke about the frictional pressure drop at these tubes and more limited ones investigated these effects in supercritical flow conditions. As it is obvious frictional pressure drop in a rifled tube is far higher than that in smooth tube. Ackerman [21] showed that the frictional resistance in adiabatic rifled tube is 25% higher than that in smooth tube. Kolher and Kastner [22] conducted many investigations on heat transfer at different convective boiling flow conditions in various tubes in Germany and presented some formulas for single-phase and two-phase frictional coefficients. They also found the frictional resistance difference between rifled tube and smooth tube rises with increasing mass flux at operating pressures lower than near critical and supercritical conditions. Zdaniuk et al. [23] studied the frictional resistance characteristics of rifled tube and obtained empirical formulas for frictional coefficient of their tube for subcritical operating pressures of water. Chen et al. [24] performed an experimental investigation on internally ribbed tube supercritical boiling flow. They presented some correlations for calculating the frictional pressure drop for water flow in a rifled tube but they did not study the effect of buoyancy and inclination in their research. Pioro et al. [25] have prepared a literature survey devoted to hydraulic resistance of water and carbon dioxide flows at supercritical pressures. They showed that the most of experimental data were obtained for vertical tubes; some data were obtained in horizontal tubes and just a few of them in other flow geometries including bundles. They concluded that the available hydraulic resistance data are much limited compared to the heat transfer data at supercritical pressures.

In current paper the results of experiments which show the effect of various inclination angles of tube on pressure drop characteristics of subcritical, near critical and supercritical water flows inside a rifled tube are presented. The water flow pressures studied in the experiments were 15, 21.5, 22.5, 25 and 28 MPa which covers the sub, near and supercritical pressures flow range. The mass flux was set at 800 kg/m^2s and the heat flux was kept 400 kW/m^2 for all operating pressures and inclination angles. The studied inclination angles were 5, 20, 30, 45 and 90(vertical) degrees with respect to the horizontal plane in an upward water flow. The results were depicted as frictional pressure drop and two-phase multiplier versus fluid bulk enthalpy and water steam quality. The effects of heat and mass flux on pressure drop are also discussed for two inclination angles of 20 and 90°. Corresponding correlations for single-phase friction coefficient and two-phase multiplier are provided for the utilized rifled tube in the experiments.

2. Test loop & data reduction

The test loop for experiments was set up as it is being depicted in Fig. 1. This experimental set-up is equipped with five valves to control the mass flow and pressure inside the closed system, de-ionized water tank, high-pressure piston pump, filters and de-gasifier, mass flow meter, pressure vessel, pre-heater, condenser, regenerator to recover the energy from out-flow of the test section, data loggers, a computer and an inclination adjustable test section.