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# Influence of buoyancy on heat transfer to water flowing in horizontal tubes under supercritical pressure

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## HIGHLIGHTS

- An experiment of supercritical water flow in a horizontal tube is conducted.
- Buoyancy effected heat transfer mechanism of SCW flow in horizontal tube is analyzed.
- Different factors effects on heat transfer of a horizontal tube are discussed in detail.
- Petukhov and Jackson criterion are employed to judge the buoyancy effect in the horizontal tube.
- The numerical study of measuring the heat transfer characteristics of SCW has been conducted.

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## ABSTRACT

The present paper was devoted to clarifying the effect of buoyancy on heat transfer characteristics of supercritical pressure water flowing in horizontal tubes. Experiments were conducted in horizontal tubes with inner diameters of 26 mm and 43 mm. Operating conditions included mass fluxes of 300–1000 kg/m$^2$ s, heat fluxes up to 400 kW/m$^2$, and a pressure of 25 MPa. Based on the experimental data, the difference of heat transfer characteristics between the top and bottom surfaces of a horizontal tube was analyzed. It was found that the buoyancy effect makes the low density hot water gather at the top surface of the horizontal tube; hence, heat transfer condition is deteriorated and wall temperature is increased. The effects of mass flux, flow direction and tube diameters on the heat transfer characteristics of water in horizontal tubes were discussed in detail. Jackson and Petukhov buoyancy criterions were selected to judge the buoyancy effect in horizontal tubes. The results showed that when the buoyancy effect is significant, both criterions are able to predict the onset of buoyancy effect. Furthermore, numerical simulations were carried out by using Fluent solver, aiming to extending experimental research on buoyancy effect.

## 1. Introduction

Industrial processes involving flow and heat transfer of supercritical pressure fluids have been taken on considerable importance in the past few decades. At present, the supercritical water (SCW) employed as working fluid in supercritical (ultra-supercritical) pressure fossil-fuel power plants is the largest industrial application of supercritical pressure fluids [1]. Other important industrial applications of fluids at supercritical pressures include new types of nuclear reactors using SCW as coolant (i.e. the supercritical pressure water-cooled reactors (SCWR)), rocket motors using hydrogen as working fluid, and supercritical extraction systems using carbon dioxide as extractant etc. [1]. In order to improve the economics, efficiency and operation safety of the above-listed supercritical apparatus, it is important to investigate the heat transfer characteristics of supercritical pressure fluids in channels at the multitude of conditions that may occur in practical services. Reviews on existing experimental and theoretical studies on flow and heat transfer of fluids at supercritical pressure conditions were published by Polyakov [2], Cheng and Schulenberg [3], and Pioro et al. [4].

Buoyancy effected heat transfer is an important phenomenon of supercritical fluid flows. When the heat flux is high or the mass flux is low, the density difference between the near-wall fluid and the bulk fluid becomes large enough to induce significant buoyancy influence in the flows, and thus increases the complexity of heat transfer characteristics of the supercritical pressure fluids. In vertical flows, differences in heat transfer characteristics of upward

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and downward flows which have the same controlling parameters have been attributed to the effect of buoyancy. Such experiments were first reported by Shitman [5] and Jackson [6]. They found that the heat transfer deterioration occurs in a vertically upward tube but does not occur in a vertically downward tube under the same conditions except for flow direction. Similar results have also been reached by a number of other researchers, including Bourke et al. [7], Shiralkar and Griffith [8], Yamagata et al. [9], Alfertov [10] and Zhou [11]. Based on experimental data and theoretical analysis, Hall and Jackson [12,13] indicated that deterioration of heat transfer in upward flow is caused by the localized laminarization of the flow due to strong buoyancy effects.

In horizontal flows, buoyancy effects may lead to non-uniform local temperature distributions in cross-sections of the experimental tubes. The temperature difference between the top and bottom surfaces ($\Delta T$) of the experimental tubes can be considered as a measure of buoyancy effects in horizontal flows. Shitman [14] studied the buoyancy effects of SCW in horizontal tubes, and proposed to use the product of Grashof number (Gr) and Prandtl number (Pr) as the criterion to judge the effect of buoyancy. Solomonov and Lokshin [15] investigated the SCW flows in horizontal and inclined tubes with an inner diameter of 20 mm, and found that with an increase in the angle of inclination the heat transfer coefficients (HTCs) at the bottom surface decline, whereas the HTCs increase at the top surface. The relative increase in the HTCs at the top surface is larger than the corresponding relative decline of HTCs at the bottom surface. Belyakov et al. [16], Vikrev and Lokshin [17], Yamagata et al. [9] and Krasyakova et al. [18] have experimentally compared the heat transfer characteristics between vertical and horizontal flows. Their research results showed that the effect of buoyancy could cause the temperature and HTC profiles of top and bottom surface for a horizontal tube differ from that for a vertical tube. Direct application of the results obtained from either a vertical or horizontal tube to the other, though very similar in other aspects, may lead to significant error. Recently, Bazargan and Fraser [19,20] systematically studied the effect of buoyancy and acceleration of SCW in a horizontal tube with inner diameter 6.6 mm. They believed that neglecting buoyancy is a primary reason for the considerable disagreement between the predictions offered by available empirical correlations and the experimental data.

Despite much work done to find out the mechanism of buoyancy effects on supercritical fluid flows, the issue has not been solved thoroughly. Moreover, the majority of past experimental investigation was performed on vertical flows and the fluids used in experiments were not water, the lack of data for horizontal flows of SCW is evident. Hence, more experimental data with SCW flowing in horizontal tubes which are reliable and systematic may be needed. In the current study, heat transfer experiments of SCW flowing in horizontal tubes are carried out at Xi'an Jiaotong University. Based on the obtained experimental data, the characteristics and mechanism of buoyancy effects on SCW flowing in horizontal tubes were analyzed. The results may provide important references for the proper design of supercritical (ultra-supercritical) pressure boilers and SCWR that use SCW as coolant.

## 2. Thermo-physical properties of the SCW

One of the most important characteristics of SCW is that the physical properties vary sharply with the change of temperature and pressure in regions near the thermodynamic critical and pseudo-critical temperature. Some researchers [21–23] suggested that the thermo-physical properties of SCW change drastically in a so-called large specific heat region (LSHR), where the specific heat of water at constant pressures is generally greater than a value of 8.4 kJ/kg K. When the system pressure is 25 MPa, the LSHR of SCW covers an enthalpy range roughly from 1700 to 2700 kJ/kg. In the present study, for the sake of intuitive analysis of experimental data, the bulk enthalpy is divided into three regimes: (1) Low enthalpy region (LER) (1000–1700 kJ/kg); (2) Large specific heat region (LSHR) (1700–2700 kJ/kg); and (3) High enthalpy region (HER) (>2700 kJ/kg). Fig. 1 shows the thermo-physical properties calculated based on the IFC-67 equation for SCW at a pressure of 25 Mpa.

## 3. Experimental apparatus and procedure

The experiments were carried out in the electrically heated high pressure steam-water two-phase flow test loop established at Xi'an Jiaotong University, Xi'an, China. The schematic diagram of the test loop is shown in Fig. 2. The major controlled and measured parameters included the system pressure, mass flux of the working fluid (deionized water), wall heat flux provided to the working fluid, and the temperatures of the fluid at the inlet and outlet of the test section, etc.

The experiments were generally performed using the following procedures. Deionized water was pumped into the circulation system from a water tank by a high pressure plunger pump, and the pressure and mass flux of the water can be changed accordingly by the valves installed in the main line and the by-pass line of the loop. First, it was heated by the regenerative heat exchanger and main pre-heater to the required temperature of the test, and then flowed into the test section. Finally, the water flowed through the regenerator, condenser and returned to the water tank. During the experiment, the pressure, mass flux, and wall heat flux of the test tube were kept constant, while the electrical power supplied to the pre-heater was increased gradually. Thus, the enthalpy of water at the inlet of the test tube was increased step by step, until it reached the specified value of the test regime. Both the pre-heater and test section were heated electrically by AC power with large currents up to 10,000 A and low voltages. The maximum heating capacities of main pre-heater and test tube were 760 kW and 250 kW, respectively.

Two kinds of smooth tubes were used in the present study. One was a smooth tube with an outer diameter of 32 mm and a wall thickness of 3 mm, while the other was a smooth tube with an outer diameter of 51 mm and a wall thickness of 4 mm. The heating length of both tubes was 2000 mm. Fig. 3 shows the distribution of the wall temperatures measuring points in the horizontal test section. In Fig. 3 the symbols of $T$, $P$ and DP represent the

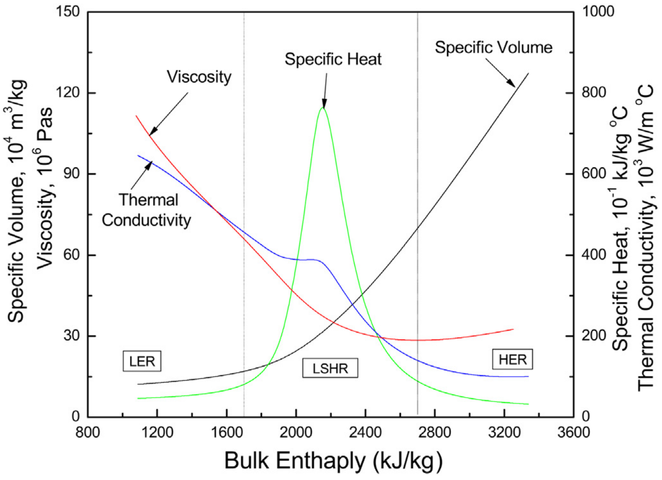

**Fig. 1.** Thermo-physical properties variations of water at 25 MPa.