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DIRECT NUMERICAL SIMULATION OF THERMAL STRATIFICATION OF SUPERCRITICAL WATER IN A HORIZONTAL CHANNEL

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Abstract. Direct numerical simulation of supercritical water is carried out to study fundamental characteristics of turbulence and heat transfer in the flow between two parallel plates. The top plate is heated and bottom one cooled to achieve stable thermal stratification. Forced convection and mixed convection are studied to investigate the effects of buoyancy and variable properties in stably stratified horizontal flows.

1 INTRODUCTION

The heat transfer to water at supercritical pressure has been studied intensively since the supercritical water-cooled reactor (SCWR) was selected as one of the Generation IV nuclear systems due to its high thermal conversion efficiency [1]. SCWR operates above the thermodynamic critical point of water ($P_c = 22.1$ MPa, $T_c = 647$ K). Figure 1 displays the thermophysical properties of water at 23.5 MPa, a pressure slightly above its critical value. At this pressure, the pseudocritical temperature T_{pc} is 652.5 K, at which the heat capacity C_p reaches its maximum. Within a narrow temperature range across the pseudocritical temperature, the thermodynamic and thermophysical properties of water experience dramatic variations. Depending on flow development and wall thermal conditions, these large variations of thermal properties can cause significant changes in heat transfer characteristics, especially, heat transfer deterioration, a potential hazard for operation safety. Fundamental research of turbulent heat transfer for supercritical water is highly desirable to improve plant safety and efficiency.

In order to study buoyancy effects for fluids at supercritical pressure with thermodynamic equilibrium, a research group of the University of Manchester [2] designed an experiment on CO_2 flowing through an horizontal plane passage with constant but different wall temperatures at the top and bottom. These experimental results and further data analysis were summarised in [3]. Under such a condition, the final state is a fully developed stably stratified flow with balanced zero net heat input. And the statistically averaged temperature in the streamwise direction is constant after a sufficient distance. As a result, there is no heat advection but only thermal diffusion. Therefore, the effects of variable properties and buoyancy are separated from the intricate effects of the thermal/flow development. However, these conditions are quite difficult to be obtained in real experiments. To better understand the thermal physics in a fully developed flow, a series of numerical tests have been performed to study heat transfer characteristics, including the influence of the location of supercritical temperature relative to the wall and wall temperature differences. In this paper, some preliminary research results are reported, which focus on a stably stratified flow through an horizontal channel.

2 METHODOLOGY AND CONFIGURATION

Direct numerical simulation (DNS) is carried out using the in-house code CHAPSim [4]. It is a Navier-Stokes solver based on a second-order finite difference discretisation of the incompressible flow formulation but with full consideration of temperature dependence of fluid properties.

A sketch of the horizontal channel flow is shown in Figure 2. The channel height 2δ is 3 mm (δ is half of the channel height) and the Reynolds number, based on the channel height and the bulk velocity, is $\mathrm{Re}_0 = 5600$ for an isothermal flow. The working fluid is water at a supercritical pressure of 23.5 MPa with a T_{pc} of 652.5 K. Two cases are designed to have the same bottom wall temperature of 640.15 K (cooled wall) but two different top wall temperatures of 650.15 K (heated wall, below T_{pc}) and 653.15 K (heated wall above T_{pc}), which are labelled as case-1 and case-2, respectively. Forced convection cases, without considering buoyancy force, are also carried out using the same wall conditions as the two mixed convection cases to study the effects of the buoyancy on thermal stratification of the mixed convection flows.

The computational domain for the channel flow is 16δ, 4δ and 2δ in the streamwise (x), spanwise (z) and wall-normal directions (y), respectively. Periodic boundary conditions are applied in the spanwise and streamwise directions. The flow is driven by a constant mass flux, which is 108.6 $kg/(m^2 s)$ for all the cases. The number of grid points in these three directions are 512, 160 and 160, respectively. The grid resolutions are $\Delta x^+ \approx 5.6$, $\Delta z^+ \approx 4.5$ and $0.4 \leq \Delta y^+ \leq 4.4$ based on wall unit of the isothermal flow.

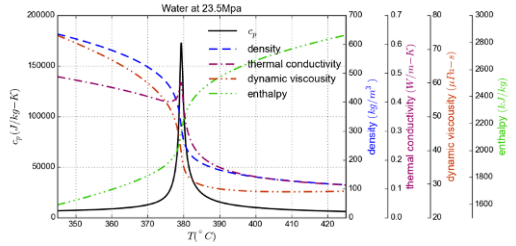

Figure 1: Thermal physical properties of water at 23.5 MPa

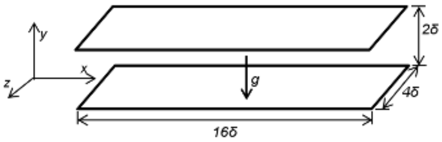

Figure 2: Sketch of the horizontal channel flow

All the simulations are performed in parallel using MPI, on a regional Tier-2 HPC system, *N8 polaris* (now called *N8CIR*). *N8 Polaris* is located in the University of Leeds in the UK, and each node of this system consisted of 16 Intel Xeon processors (Ivy Bridge E5-2670@2.60GHz). In this study, each simulation uses 256 cores, and about 150 hours (elapsed time) are required to obtain statistically converged results.

3 RESULTS

A reference temperature T_0 of 645.15 K is used as the reference state and to initialise the thermal field for all the simulations. All the thermal properties shown in this study are normalised based on the reference data at this temperature. Figure 3 (a) displays the temperature distribution along the wall-normal direction. Compared to the forced convection, the mixed convection cases show a larger temperature change near the cooled wall ($y/\delta = -1$) and a smaller temperature change near the heated wall ($y/\delta = +1$), which means a less effective heat mixing near the cooled wall and a more effective heat mixing near the heated wall due to presence of a buoyancy force. This is related to the reduced/increased turbulent shear stress near the cooled/heated wall as shown in Figure 3 (d). From the distribution of the turbulent shear stress, near the heated wall, the increase in turbulent shear stress is significantly higher in case-2 than in case-1, this increase being stronger than the buoyancy effects. This indicates that the large changes in thermal properties near the heated wall in case-2 contribute much more to alter the flow features near the heated wall than the buoyancy does. Actually, the density near the heated wall of case-2 is less than 70% of that in case-1, as shown in Figure 3 (b). Near the cooled wall, the mean flow velocity (see Figure 3 (c)) reduces for both case-1 and case-2, especially for the mixed convection cases. Correspondingly, Figure 3 (d) displays a hugely reduced shear stress near the cooled wall. The reduced shear stress implies the flow laminarisation near the cooled wall. From this analysis, the variable property effects play the most important role near the heated wall with a constant temperature around the pseudocritical temperature in heat transfer and turbulence mixing, and the buoyancy force plays a secondary role. However, near the cooled wall with the same constant temperature in case-1 and case-2, both the buoyancy effect and the variable property effect contribute to the reduction of turbulence shear stress.

The shear stress distribution implies that for the forced convection cases, turbulence suffers from partial laminarisation from variable property effects, which is especially true for case-2 with a top wall temperature above T_{pc}, while the turbulence mixing at the heated wall side is enhanced. For the mixed convection flow, the buoyancy effect further strengthens the flow laminarisation near the cooled wall. Turbulence mixing near the heated wall side benefits less from the buoyancy effect. These phenomena are also confirmed by the instantaneous fluctuations of the spanwise vorticity, as shown in Figure 4.

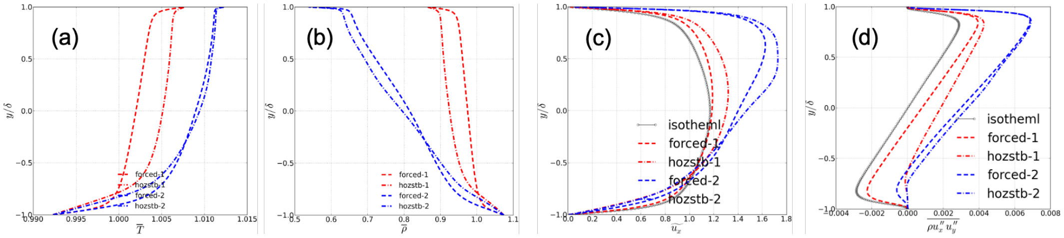

Figure 3: (a) Mean temperature ($\overline{T}/T_0$) distribution, (b) mean density ($\overline{\rho}/\rho_0$) distribution (c) Favre averaged streamwise velocity ($\overline{\rho u}/\overline{\rho}$), (d) turbulent shear stress ($\overline{\rho u'_x u'_y}/\overline{\rho}$)

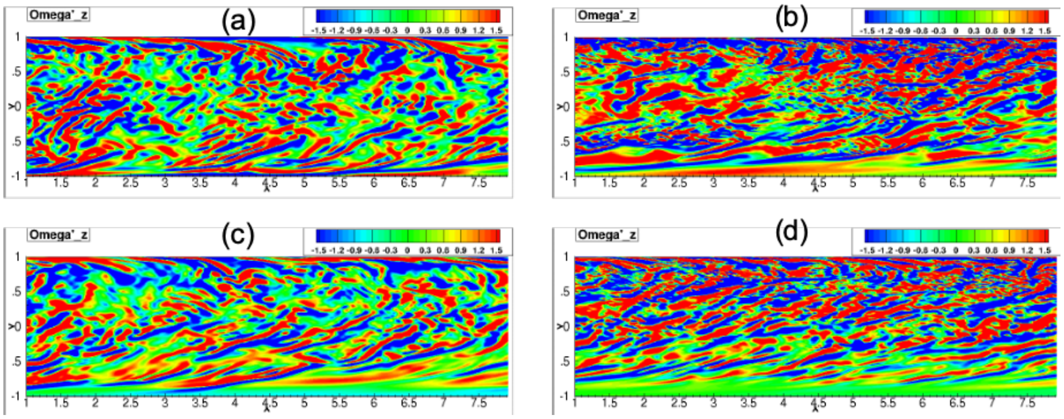

Figure 4: Instantaneous fluctuation of the spanwise vorticity. (a) case-1, forced convection, (b) case-2, forced convection, (c) case-1, mixed convection and (d) case-2, mixed convection

4 CONCLUSIONS

- Supercritical water flow through an horizontal channel is studied using DNS to investigate buoyancy effects and variable properties on stable thermal stratification.
- Flow laminarisation is observed near the cooled wall in both the forced and mixed convection cases, and the buoyancy effect in the mixed convection strengthens these phenomena. Near the heated wall, the turbulence shear stress is dramatically increased for both the forced and mixed convection cases due to variable property effects. The effects of the buoyancy play a minor role in the current configuration.

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