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DIRECT NUMERICAL SIMULATIONS OF FORCED AND MIXED CONVECTION FLOWS IN A REACTOR VESSEL AUXILIARY COOLING SYSTEM (RVACS)

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1. ABSTRACT

Direct numerical simulations (DNS) of forced and mixed convection flows in a simplified geometry, representing the Reactor Vessel Auxiliary Cooling System (RVACS), have been conducted using the open-source solver Nek5000 [1]. This study compares the flow and thermal fields, mean flow and turbulent kinetic energy between the two cases, providing insights into the impact of buoyancy. The findings indicate that the mixed convection case is in the recovery regime, with turbulence being enhanced in both downward and upward flows due to the direct effect of buoyancy. Additionally, the buoyancy-driven flow near the inner wall weakens the recirculation flow at the bottom cavity.

2. INTRODUCTION

The RVACS [2] is a key facility for heat removal in the 4th generation design nuclear reactors and it is of critical importance for its design and optimisation to inspect and understand the flow and heat transfer physics within the facility. In this study, we investigate forced and mixed convection flows in an RVACS subjected to a temperature difference of $300K$ between the inner and outer walls. The objectives are to: (i) reveal the flow physics in the complicated geometry and under these conditions and (ii) investigate the impact of buoyancy. Moreover, the DNS dataset is also used as the reference data for a benchmark exercise regarding the Reynolds-averaged Navier-Stokes (RANS) modelling for RVACS, which is organised by the Collaborative Computational Project in Nuclear Thermal Hydraulics (CCP-NTH: https://ccpnth.ac.uk/).

3. METHODOLOGIES

The low-Mach Navier-Stokes solver in Nek5000 is used for the simulations and the governing equations are as follows:

$$\frac{\partial \rho \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \rho \boldsymbol{u} = -\nabla p + \nabla \cdot \tau + \rho g,$$
$$\frac{\partial \rho}{\partial t} + \nabla \cdot \rho \boldsymbol{u} = 0,$$
$$\rho c_p \left(\frac{\partial T}{\partial t} + \boldsymbol{u} \cdot \nabla T \right) = -\nabla \cdot \lambda \nabla T.$$

The coolant fluid is air and variable thermophysical properties [3] are considered in the simulations. A turbulence generator (periodic domain) is used to generate instantaneous, fully-developed turbulence velocity profile for the inlet ($Re_\tau = 180$). At the inner (hot) and outer (cold) walls, convective heat transfer boundary conditions are applied with a heat transfer coefficient = $200W/(m^2 \cdot K)$. The ambient

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temperatures for the inner and outer walls are respectively $700K$ and $400K$, respectively, resulting in a Grashof number of 1.25×10^{11} for the mixed convection case. An adiabatic thermal boundary condition is applied to the solid-baffle walls.

4. RESULTS AND DISCUSSIONS

The instantaneous velocity and temperature fields in the forced convection (FC) and mixed convection (MC) cases on a mid-plane are shown in Figure 1b to 1e. Both velocity fields exhibit flow separation and vortex shedding at the upper-right corner and around the tip of the baffle. Case MC, however, has stronger perturbations in both the left and right channels as well as in the bottom cavity. The temperature distributions of the two cases are markedly different: Case MC exhibits a significantly higher bulk temperature in both the left channel and the bottom cavity, attributed to the enhanced turbulence and heat transfer rate due to the buoyancy.

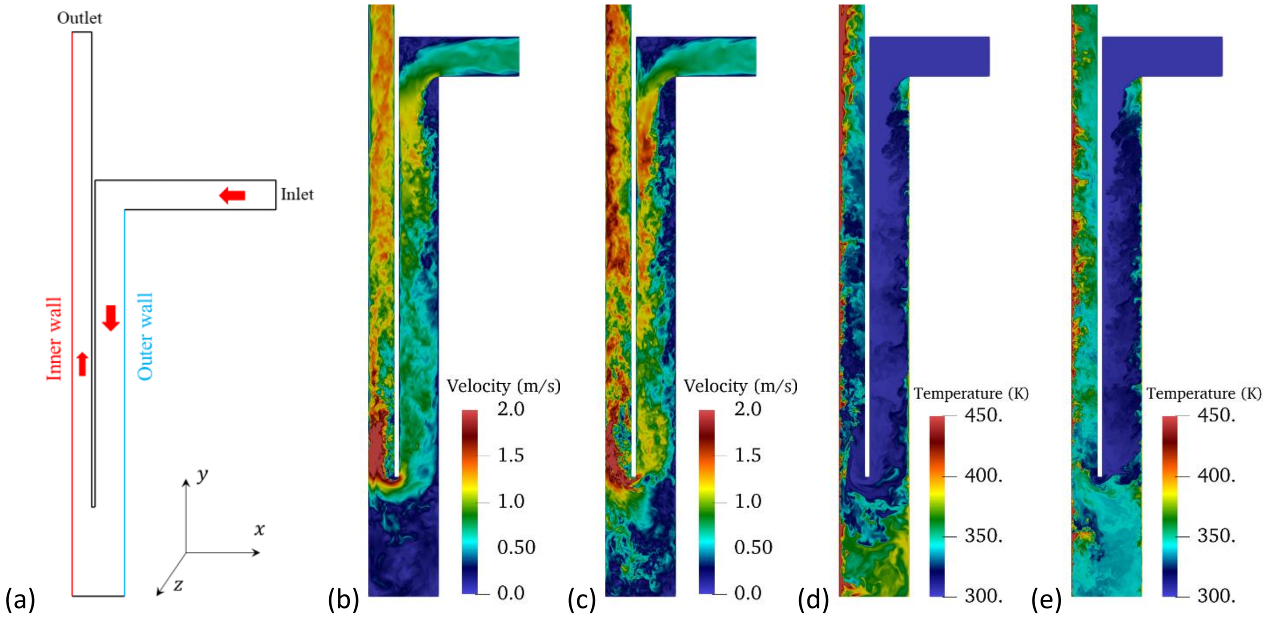

Figure 1. Planar view of the DNS geometry (a) and the instantaneous velocity and temperature fields at the centre-plane of the forced (b & c) and mixed (d & e) convection cases.

Figure 2 shows the mean-velocity and turbulent kinetic energy along several probe lines from h/δ=1 to 11, where h is the height and δ is the full channel height at the inlet. The mean-velocity profiles for the left and right channels are shown in Figure 2.b1 to 2.b6 and 2.d1 to 2.d6, respectively. In the right channel, the flow in Case MC is a downward, buoyancy-opposing flow. Compared to Case FC, deceleration occurs at the outer wall due to buoyancy, while acceleration occurs near the baffle wall due to mass conservation. The recirculation flow in the bottom cavity differs significantly between the two cases, as illustrated by the mean-velocity profile at h/δ=1 (Figure 2.b6): In Case FC, an anti-clockwise recirculation, driven by the main flow above, is indicated by the downward flow near the inner (hot) wall. Conversely, in Case MC, a buoyancy-driven upward flow is observed at the same location, weakening the anti-clockwise recirculation and increasing the turbulence level inside the bottom cavity. The left channel in Case MC features an upward and buoyancy-aiding flow, with local acceleration near the inner wall compared to Case FC. In both the left and right channels, Case MC has higher turbulent kinetic energy compared to Case FC. This suggests that buoyancy is intensive in Case MC and the flow is in the recovery regime, where the direct effect of buoyancy is dominant over the indirect effect.

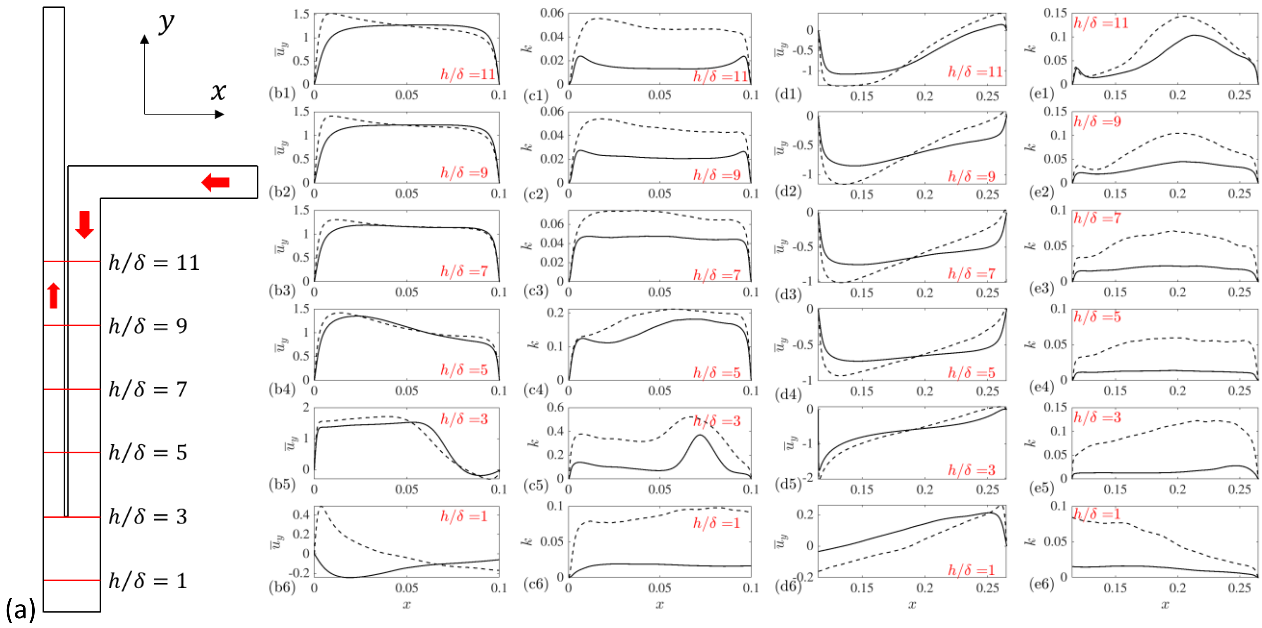

Figure 2. Mean vertical velocity $\overline{u}_y$ and turbulent kinetic energy k in the left ($\overline{u}_y$: b1 to b6, k: c1 to c6) and right ($\overline{u}_y$: d1 to d6, k: e1 to e6) channels in the forced (solid lines) and mixed (dash lines) convection cases.

5. CONCLUSION

In this study, DNS of forced and mixed convection flows in an RVACS were conducted, yielding several important findings from the comparison between the two cases. In Case MC, buoyancy is highly intensive and the flow is in the recovery regime, leading to increased turbulent kinetic energy in both the left and right channels. At the bottom cavity, a buoyancy-driven flow near the inner wall is observed in Case MC, which weakens the anti-clockwise recirculating flow driven by the main flow above.

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