UK Heat Transfer Conference 2021

17th UK Heat Transfer Conference (UKHTC2021)
4-6 April 2022, Manchester, UK

HIGHLY TURBULENT NATURAL CIRCULATION IN AN ENCLOSED BUNDLE WITH CONVERGING AND DIVERGING RODS

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ABSTRACT

Turbulent natural circulation flow in an enclosed pressure tube vessel with distorted rods is studied in this paper. The distortion is such that the rods initially converge until mid-height and then subsequently diverge back to their starting positions. Such a distortion is relevant to Advanced Gas-Cooled reactors and novel thermal systems. The resulting natural circulation flow is split into two radial regions. An upward interior/central flow with forced convection flow profiles at the rod gaps and an exterior developing downward flow at the containment surface. Comparisons to a straight bundle case reveal that flow at the rod gaps is accelerated by the distortion, while the turbulent kinetic energy levels are appreciably reduced. At the containment surface, the developing boundary layer transitions to turbulence earlier for the distorted rod bundle. This has the effect of shortening the stagnation region close to the top wall, where the vertical temperature gradient is steep. Consequently, the resulting overall peak rod wall temperature is lower for the distorted rod.

1 INTRODUCTION

Buoyant flows are commonly encountered in a wide variety of thermal systems. In nuclear safety applications such flows are typically integral to maintaining safety and ensuring a fault scenario does not escalate. In this paper, natural circulation is investigated for an enclosed rod bundle with distorted rods. The distortion is such that the rods converge until half-height and then diverge back to nominal. This geometry is particularly relevant to Advanced Gas-cooled Reactors (AGRs), as it constitutes one of the damage configurations that can arise in the event of a non-contiguous fuel assembly drop.

Fujii and Imura[1] experimentally investigated buoyancy-influenced flow on a thick plate at arbitrary inclinations. Heat was applied at a single surface, with the orientation (upwards or downwards) influencing the heat transfer and flow patterns. Oosthuizen[2] studied the effect of rod inclination on natural convection. Peak heat transfer occurred when the rod was horizontal, and the heat transfer decreased as the rod was tilted to the vertical. At shallow degrees of inclination ($\approx 3^\circ$ from vertical), the flow was akin to that for a vertical cylinder. While for moderate inclination ($\approx 32^\circ$), the flow would resemble that of a horizontal cylinder. An increase in rod length and decrease in its diameter resulted in even shallower degrees of inclination being needed to change the flow patterns. Arnold et al.[3] investigated the effect of inclination and aspect ratio on the heat transfer for a rectangular enclosure. The highest heat transfer occurred when the enclosure was horizontal and heated from below $\theta = 180^\circ$. Tilting the enclosure from horizontal lead to a decrease of the Nusselt number. Akbari et al.[4], similarly showed the average Nusselt number decreased as the enclosure was tilted from horizontal to vertical. Ammour et al.[5] used Large Eddy Simulation (LES) and Unsteady Reynolds Averaged Navier-Stokes (URANS) to simulate a tilted cavity $\pm 15^\circ$ to the horizontal. LES results were used to validate the URANS models, which performed well for the inclination leading to unstable stratified flow (i.e. hot surface at the bottom). While for stably stratified flow, the three-dimensional flow structures were not well captured. Chinembiri et al.[6] used LES to investigate highly turbulent natural circulation in an enclosed undistorted (straight) rod bundle. The flow and thermal characteristics of the system were strongly influenced

*Corresponding author: k.chinembiri@sheffield.ac.uk by the buoyancy-driven boundary layer on the containment surface. In the highly turbulent region, the flow through the central channels resembled mixed convection, while the exterior channels resembled an asymmetrically heated/cooled cavity.

Studies for natural circulation in unique geometries such as that considered herein are few and far between. The aim of this paper barring the nuclear safety implications is to add to the general body of literature by investigating natural circulation using LES.

2 METHODOLOGY

The open-source finite volume Computational Fluid Dynamics (CFD) solver *Code_Saturne* is used to conduct the simulation. In LES, the standard Navier-Stokes equations are spatially filtered such that the large energy-containing scales are resolved, while the small scales are modelled. The present study uses the Wall Adapting Local Eddy-viscosity (WALE) subgrid-scale model to achieve this. For brevity, the governing equations and constants for the WALE model are not presented herein but can be found in the straight bundle study[6].

3 GEOMETRY, BOUNDARY CONDITIONS, FLUID PROPERTIES AND NUMERICAL METHODS

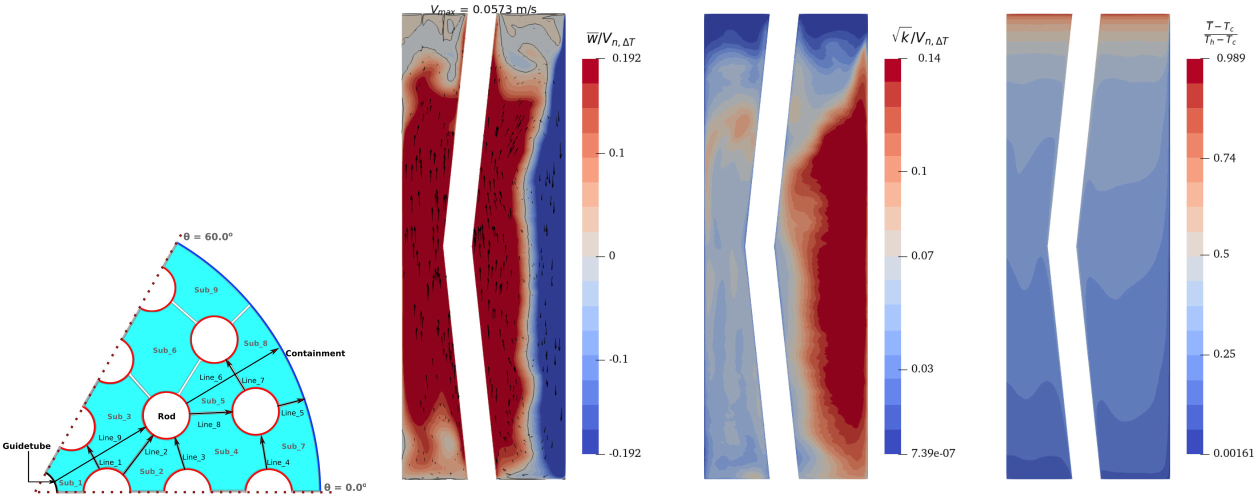
An enclosed rod bundle with converging and diverging rods at $\approx 2.5^\circ$ inclination to the vertical is considered. Figure 1 illustrates this, and Figure 1a has the boundary conditions coloured in. At the rods (coloured in red) a constant heat flux of 289 W/m^2 is applied. The central rod, along with the top and bottom walls (coloured in black) are adiabatic. Cooling is applied at the containment (coloured in blue) using a convective boundary condition with an external temperature of 110 °C and heat transfer coefficient of 700 $W/m^2\,^\circ$C. Radiative exchange between the surfaces is not considered in this study, and all the surfaces are considered smooth walls. The nominal geometry dimensions are typical for an AGR bundle and can be found in the earlier study[6].

Carbon dioxide at a pressure of 3 Mpa is the coolant in the system. Density variation as a function of temperature is modelled using a lookup table populated with data from the NIST database[7]. To study the effect of density in isolation, the remaining properties are fixed, and their values are provided in the straight bundle study[6].

A 60 ° sector is modelled with a mesh density of $\approx$ 108 million cells. The peak y^+ value is 0.58. Grid spacing values at mid-height are $\Delta x^+ \leq 20.38$ (spanwise) and $\Delta z^+ \leq 22$ (streamwise). Discretisation in space and time is second order.

4 RESULTS AND DISCUSSION

Contour plots for velocity, temperature, and turbulent kinetic energy (tke) are shown in Figure 1. The flow in the rod bundle can be clearly split into two lateral flow regions, which are the interior (bundle) region and the exterior (containment) region. In the interior region, away from the top and bottom walls, there is net upward flow at the rod gaps. Close to the top, the flow is constrained to the rod walls due to attenuation by the encroaching end-effects. As a result a stratified temperature field is observed locally here. At the exterior channel, downward spatial boundary layer development is observed from an initially stagnant flow at the top. Immediately after flow transition, we see the formation of two large-scale descending and ascending flow structures. These structures are shown to strongly interact, generating additional turbulence as seen by the tke peaks within this channel.

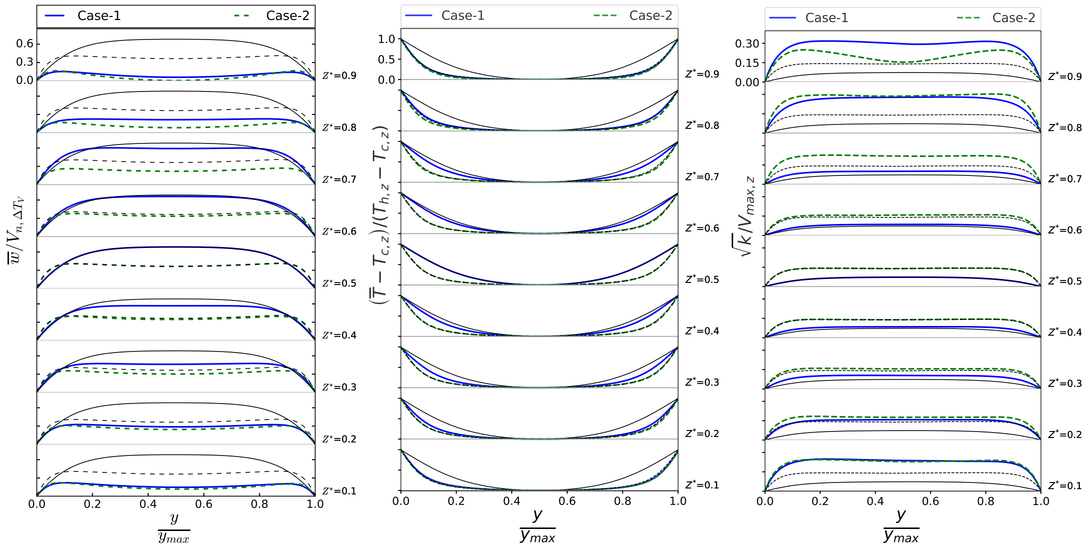


(a) Schematic (b) Velocity (c) TKE (d) Temperature

Figure 1: Schematic and vertical slices at $\phi = 30°$ for Velocity, temperature and Turbulent kinetic energy

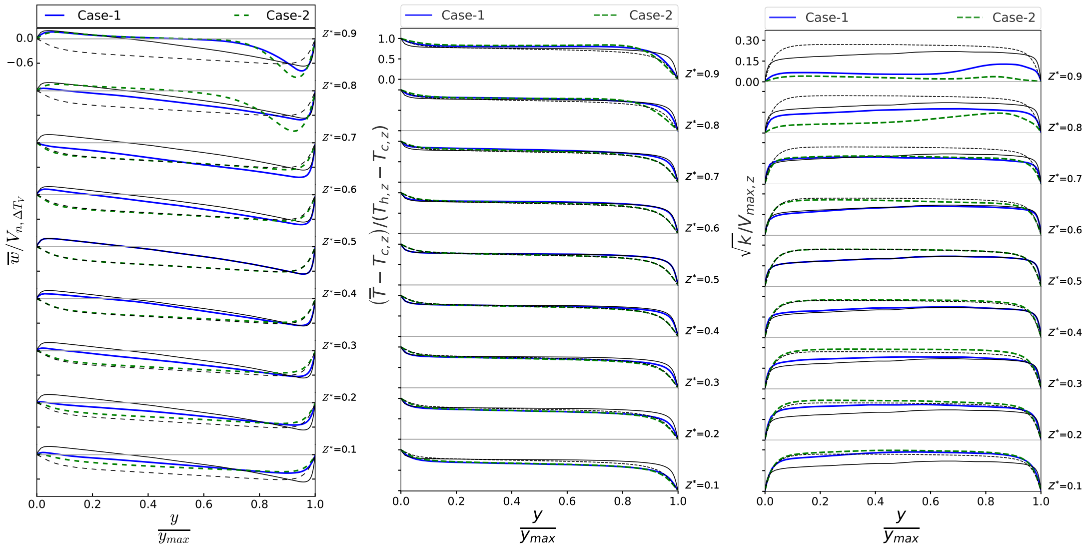
Quantitative plots for variables discussed in the preceeding section are given in Figures 2 and 3. Line_1 and Line_5 are representative of the interior and exterior channels, respectively. An additional case (Case_2) for the undamaged bundle at similar conditions is presented for comparison[6]. Line_1 highlights the absolute increase in peak velocity at the interior region gaps. The flow here is accelerated such that the peak velocities exceed those for the undamaged case at nearly every height. This behaviour is much the same for most of the interior region. Local tke is however conversely higher for the undamaged case. This is until $Z^* = 0.8$ in the interior region and for the exterior region, this switch occurs earlier at approximately $Z^* \approx 0.7$. However, for both geometries, peak turbulence occurs at the gap centres. In the exterior channel, this is due to the secondary shear layer which is formed after transition. While in the interior channel, this is due to the inward transportation of turbulence from the exterior channel. Local non-dimensional temperature profiles show a steeper radial temperature gradient and a progressively thinner thermal boundary layer for the undamaged bundle case at Line_1 until $Z^* = 0.7$. One can discern from this a slightly more effective heat transfer at the rods thus shallower vertical wall temperature gradient for the undamaged bundle (below $Z^* = 0.7$). This is further evidenced in Figure 4, where the vertical peak temperature obtained by scanning all rods at each sampling height is shown. Past this height, the fluid temperature profiles for the two configurations effectively merge and we see the solid wall temperatures flipping with the undamaged case drastically increasing at a lower height. As a result, the undamaged bundle has higher peak temperatures, which occur close to the top wall in the stagnation region.

The brief discussion above highlights how integral the containment flow condition/state is to the overall bundle temperatures. Comparisons of the similarity solution by Ostrach[8] against the LES data are given in Figure5. These comparisons reveal that transition to turbulence occurs much earlier at the containment for the WheatSheaf bundle. Once the containment is in a turbulent state, the resulting advection and turbulent mixing with the interior channel corresponds to a shallower vertical temperature increase at the rod walls. Within this turbulent region, in this case, comparing until $Z^* = 0.75$, we note that the wall temperatures at the distorted rods are marginally worse, which is indicative of slightly poor heat transfer (see Figure 4). The behaviour of the rods within this region are also in contrast to the single



(a) Velocity (b) Temperature (c) Turbulent kinetic energy

Figure 2: Profiles extracted at Line_1 for damaged (case-1) and undamaged (case-2) bundle. Black thin lines are for the profile at mid-height.



(a) Velocity (b) Temperature (c) Turbulent kinetic energy

Figure 3: Profiles extracted at Line_5 for damaged (case-1) and undamaged (case-2) bundle. Black thin lines are for the profile at mid-height.

rod bundle observations by Oosthuizen[2], where an increase of inclination from the vertical increases the heat transfer rate. However, care must be taken with the preceding statement, as the local flow at the rods herein is more akin to forced convection. Thus the difference to the observations for this geometry and that studied by Oosthuizen is likely the mixed/forced convection like nature of the flow within the interior channel, compared to the free convection isolated rods they investigated.

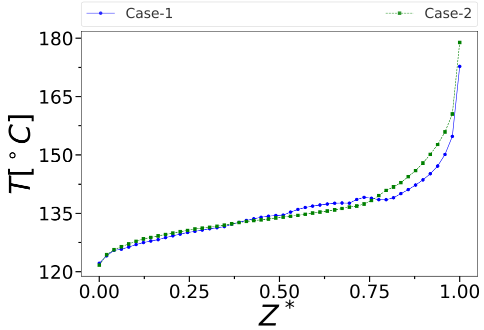
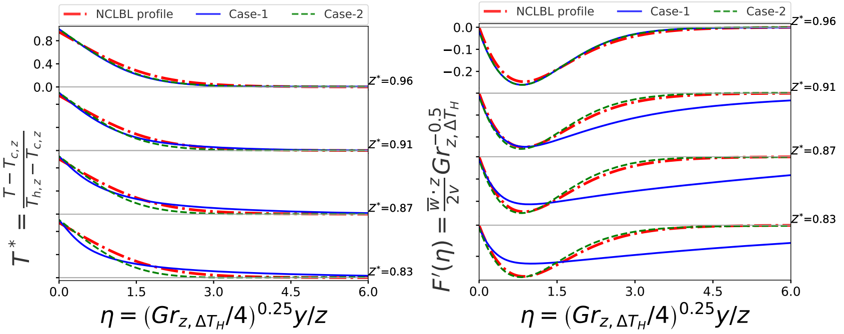


Figure 4: Peak rod temperature varying axial locations represented by the markers



(a) Temperature

(b) Velocity

Figure 5: Comparisons of temperature and velocity against the similarity solution by Ostrach[]. LES data is taken from Line_6.

5 CONCLUSIONS

Turbulent natural circulation in a distorted rod bundle without consideration of radiative heat transfer has been investigated in this paper. The data obtained has furthermore been compared against the straight/undamaged bundle study by Chinembiri et al.[6]. The flow within the distorted bundle can be split laterally into an interior and exterior region, where the flow is akin to a heated pipe and heating/cooling channel, respectively. In the former region, the distortion tends to accelerate the flow at all vertical levels. However, the resulting local turbulent kinetic energy levels are shown to be lower than those of their undamaged counterpart until approximately four-fifths into the domain. Close to the end of this four-fifths vertical region, the rod wall temperatures are marginally higher for the distorted bundle, however the overall peak rod wall temperature occurs in the undamaged bundle. This flip in the location of peak temperature is due to the shorter stagnation region in distorted bundle. The vertical extent of the stagnation region is demonstrated to be heavily influenced by the point of transition at the cooled containment wall (noting that the the flow develops from top to bottom here). In the distorted bundle case, transition to turbulence at the containment is triggered earlier compared to the straight bundle case, and this has been evidenced by comparisons to Ostrach's[8] similarity solution.

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