STUDY OF FLOW INSTABILITY DUE TO STREAMWISE INTER-ROD GAPPING

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Abstract The turbulent flow in an annular channel with streamwise inter-rod gapping is computed using Large Eddy Simulation (LES). This fundamental study is carried out with a view to investigate the vortex shedding generated at the end of the fuel rods and its impingement onto the downstream rods. The spacing between the rods is varied to study the effect of the mean flow as well as the turbulence structure revealing two distinct flow patterns analogous to the flow over the *k*-type and *d*-type roughness.

INTRODUCTION

Component failures due to excessive flow-induced vibration in reactor cores and steam generators affect the performance and reliability of nuclear power stations and have been observed in water and gas cooled reactors alike. The fluid-structure interaction between the coolant and fuel rod bundles in nuclear reactors is an important source of excitation for vibrations and has become the subject of increasing attention. Numerous investigations on the axial flow within tube bundles have been performed experimentally [1-3] and numerically [4-6], confirming that the flow is characterised by long-term, large-scale coherent patterns in the streamwise direction. In the unique AGR design, the reactor core consists of over 300 fuel channels and each fuel channel comprises eight fuel elements held together vertically by a tie bar to form a fuel stringer or assembly. Each element contains a bundle of 36 fuel pins housed in a graphite sleeve and each consecutive element within the fuel stringer is separated by a streamwise gap.

The present study aims to investigate a particular mechanism that has been identified as a potential source of vibration, namely, vortex shedding generated at the end of the fuel rods and its impingement onto the downstream rods. To this end, *Code_Saturne*, an open-source, general-purpose industrial Computational Fluid Dynamics (CFD) code developed by Electricité de France (EDF), is employed and the calculations are performed using wall-resolved Large Eddy Simulation (LES). The CFD model comprises two solid rods separated by a gap and enclosed by an outer cylindrical wall, with fluid flowing axially in the annulus between the outer wall and the inner rods, as illustrated in figure 1. This simpler configuration is considered with a view to develop a fundamental understanding of the vortex dynamics and fluid forces in the more complex AGR fuel element configuration.

NUMERICAL METHOD

Two computational geometries have initially been considered with the aim to investigate the effect of the streamwise gap spacing between the rods on the flow phenomena. The first case features a streamwise gap length, L_{gap}, equal to six times the inner rod diameter, whilst the second geometry consists of a shorter gap length equal to two times the rod diameter. In both cases, the rod diameter D_{rod}, is consistent with the AGR fuel rod design; the outer wall diameter, D_{out}, is twice the inner rod diameter and the length of each rod within the annular domain is ten times the rod diameter, as depicted schematically in figure 1. The working fluid is carbon dioxide (CO_2) at a temperature of approximately 500°C and a pressure of 40bar. The Reynolds number based on the inner rod diameter, D_{rod}, and the bulk velocity in the annular region, U_{bulk}, is $Re \approx 12000$.

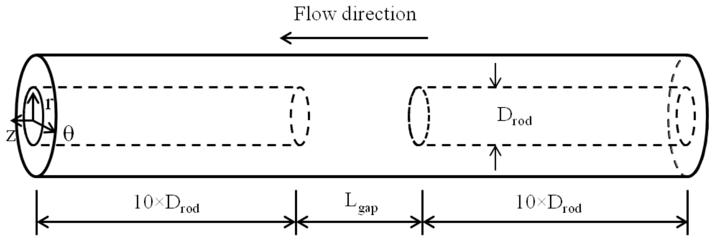

Figure 1. Schematic diagram of computational domain

The calculations have been performed using the wall-resolved LES technique available in *Code_Saturne*. The three-dimensional, filtered Navier-Stokes equations are completed with the Dynamic Smagorinsky sub-grid-scale (SGS) turbulence model based on the Germano identity [7] and the minimization proposed by Lilly [8]. Second-order schemes are used in space and time. Periodic boundary conditions are applied in the streamwise (z) direction and the flow is driven by a constant pressure gradient, which is the same in the two cases considered. No synthetic method is employed to generate the turbulence due to the use of periodic boundary conditions and no wall functions are required due to the use of the dynamic SGS model.

RESULTS

The simulations reveal that, whilst flow recirculation is present in both cases considered, there is a strong interaction between the outer flow and the flow within the cavity only for the larger gap length of six times the rod diameter. In this configuration, the highest turbulence intensities and Reynolds stresses coincide with the end of the recirculation region in proximity to the upstream rod. For the smaller gap spacing of two times the rod diameter, the gap is found to have a reduced impact on the annular flow and the interaction between the main and the recirculation flow is weaker. The separation eddies are largely confined to the gap between the rods and the turbulence intensities appear to increase as the downstream rod is approached. The effect of the gap spacing on the flow structure suggests that the configurations considered represent two distinct flow patterns analogous to the flow over the *k*-type and *d*-type roughness. Such a distinction is likely to have major implications on the inter-rod gapping flow instability and fluid structure interaction.

The three dimensional iso-surfaces of the negative eigenvalue, λ_2, of the instantaneous flow for the larger and smaller gap spacing highlight the major differences exhibited in the flow structures in each case and are presented in figures 2 and 3, respectively. The former shows the vortical structures being ejected as a result of flow separation from the upstream rod and subsequently disappearing well before the downstream rod, where new strong vortical structures are generated as a result of the impinging flow on the rod and ensuing flow separation as the flow re-enters the annular space. By contrast, in the latter, the vortical structures produced upstream impact on the downstream rod overlapping the new structures produced locally.

The full paper will discuss results from further investigations that are being carried out with the addition of eccentricity to one of the rods to study the effect of misaligning one rod with respect to the other. This will provide interesting insights into the turbulent flow structure that is likely to be more realistic in the context of the AGR. Additionally, the end profile of the rods will be modified to observe its effect on flow separation and vortex shedding frequencies. To the best of the authors' knowledge, this is the first detailed study of this important and industrially relevant fluid-structure interaction phenomenon.

Figure 2. Instantaneous iso-surface of λ_2 for $L_{gap} = 6D_{rod}$ at $t = 108\ D_{rod}/U_{bulk}$

Figure 3. Instantaneous iso-surface of λ_2 for $L_{gap} = 2D_{rod}$ at $t = 108\ D_{rod}/U_{bulk}$

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