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Towards the Direct Numerical Simulation of a closely-spaced bare rod bundle

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ABSTRACT

The aim of the present research work is to design a numerical experiment for a closely-spaced bare rod bundle in order to perform a DNS, which will serve as a reference for the verification purpose. The considered geometric design is based on the well-known Hooper experiment, which contains a bare rod bundle with pitch-to-diameter ratio of P/D = 1.107. However, performing a DNS computation corresponding to the Hooper experiment requires a huge amount of computational power. Hence, in this article, a wide range of unsteady RANS study has been performed to calibrate and optimize the Hooper case for the targeted DNS study. As a first step, the Reynolds number of the original Hooper case is scaled down in such a way that the overall phenomenology of the flow field remains the same, i.e. the very existence of the axial flow pulsations. Afterwards, the calibration of the computational domain with the respective boundary conditions is performed to obtain an optimized Hooper case, which is feasible for the available computational resources. In addition to the flow field, a parametric study for four different passive scalars is performed to take into account the heat transfer analysis, which was not included in the original Hooper case. These passive scalars correspond to the Prandtl numbers of three different working fluids, i.e. air, water and liquid metal fluids. The heat transfer of these three fluids has been studied in combination with two different boundary conditions at the walls, i.e. a constant temperature and a constant heat flux. Accordingly, the final DNS will yield in an extensive verification database for flow and the thermal fields representing different reactor coolants.

1. Introduction

The coolant flowing through the channels within the fuel assembly removes the heat generated by the nuclear fission. In an ideal scenario, the temperature distribution through the fuel assemblies should remain uniformly distributed under normal operating conditions of a nuclear reactor. However, in reality this does not happen and accordingly it leads to inter-subchannel mixing phenomena. A detailed knowledge of flow and temperature in a fuel assembly has always been a major factor in the design and reliable operation of existing and new nuclear systems.

Rod bundles form the basic configuration for most of the fuel element designs used in the existing and future nuclear reactors. These rod bundles are mainly characterized by their geometric arrangements, i.e. triangular or square. Rod spacing is one of the main design characteristics of the fuel rod assemblies. The spacing between the rods is mostly defined as the pitch to rod diameter ratio (P/D). Depending of the P/D, the axial coolant flow in a bare rod bundle, which contains translational symmetry in the streamwise direction due to the lack of spacer grid, exhibit large scale vortices, i.e. so-called gap vortex street (Tavoularis, 2011). These vortices are formed on both sides of each gap region between two adjacent fuel rods and they are transported along the fuel rods. These vortices are beneficial for the heat transfer since they enhance mixing between the adjacent sub-channels. However, the coherent flow structures cause periodic pressure pulsations, which may result in a fatigue of structure materials in the rod bundle. An accurate prediction of the flow distribution inside fuel rod bundles is required for both design and safe operation of innovative as well as conventional nuclear system. The unsteady axial flow pulsations/structures, which appear in the bare rod bundle configuration, have been investigated (experimentally and numerically) over the last 50 years and remain a topic of interest up to the present time.

Trupp and Azad (1975) investigated a fully developed turbulent flow in triangularly arrayed rod bundles using a wind tunnel. The measurements have indicated the presence of secondary flow

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and identified its influence with respect to momentum/kinetic energy transfer. In 1980, Hooper (1980) found out that the turbulent flow structure strongly depend on the P/D ratio. Subsequently, Hooper and Rehme (1984) showed that for a turbulent flow through parallel rod bundles, the azimuthal and the axial turbulence intensities in the rod gap region increased strongly with the decreasing rod spacing. In the same year, Hooper and Wood (1984) found out that the mean secondary flow has a negligible influence on flow parameters. However, in 1988, Vonka (1988a) for the first time measured the secondary flow directly in two subchannels of a four rod bundle with a triangular arrangement. Although, the investigated average secondary vortex velocity components turned out to be extremely weak, they can play an important role as a transport mechanism in turbulent flows (Vonka, 1988b). Krauss and Meyer (1998) carried out experimental studies on turbulent flow and heat transfer through rod bundles. The experiments revealed the existence of flow oscillations, which in turns caused temperature oscillations. In addition, the intensities of temperature fluctuations were found to have larger values than those measured in central channels: the maximum values were observed in the gap region between two heated rods. The existence of large-scale periodic flow oscillations in the tightly spaced rod bundle configuration has been also shown by Guellouz and Tavoularis (2000a, 2000b), Möller (1991). Periodic oscillations are responsible for the high inter-subchannel momentum and heat transfer. (Lexmond et al., 2005) proposed that the large-scale oscillations are connected to interactions between eddy structures of the turbulent flow in adjacent subchannels. Although, the majority of studies of flow and heat transfer inside the fuel rod bundles have been performed experimentally, most of them are conducted on the simplified/idealized geometries and under conditions that are not the same as in normally operating reactors. Moreover, the measurement of the flow properties was very often limited to a single plane or several line traverses.

In this regard, Computational Fluid Dynamics (CFD) has been considered as an attractive alternative. The most accurate and reliable CFD method is the Direct Numerical Simulation (DNS). In the past, only a few DNS studies have been performed by Mayer and Házi (2006), Ninokata et al. (2009). It is worth mentioning that, these computations were limited to low Reynolds number and the selected computational domain was relatively small. On the other hand, Large Eddy Simulation (LES) approach is computationally less demanding than DNS and it enables to simulate flow at relatively larger Reynolds number and a bigger rod bundle computational domain. Accordingly, numerous researchers have utilized the LES approach to simulate momentum and heat transfer in different rod bundle configurations (Duan and He, 2015; Ikeno and Kajishima, 2010; Mayer et al., 2007; Mayer and Házi, 2006; Merzari and Ninokata, 2011; Mikuž and Tiselj, 2016; Ninokata and Merzari, 2007; Shams et al., 2018; Walker et al., 2014). It is important to realize that a successful prediction of flow pulsations requires relatively long streamwise computational domain, which allows the development of large axial coherent structures. Therefore, most of the simulations aiming to reproduce pulsations in rod bundles applied computationally even less demanding approaches, i.e. Unsteady Reynolds Averaged Navier-Stokes (URANS) simulation. Accordingly, several URANS studies (Baglietto and Ninokata, 2005; Cardoso de Souza et al., 2015; Chandra et al., 2010; Chang and Tavoularis, 2007; Liu and Ishiwatari, 2013; Merzari and Ninokata, 2011; Ninokata et al., 2009; Ninokata and Merzari, 2007; Yan, 2011; Yan and Gu, 2012) have been performed to predict the appearance of flow pulsations in rod bundles, particularly in the closely packed ones. In 2010, Meyer (2010) provided an extensive review of different CFD approaches used in the framework of the rod bundle flows and in particular their prediction capabilities. The author summarized that the URANS modelling approach, particularly based on anisotropic models, is able to predict the overall flow characteristics in closely packed rod bundle. It is worthwhile to mention that these conclusions are mainly related to the flow field prediction, particularly in a closely packed rod bundle. An accurate prediction of heat transfer in rod bundle configuration is an additional issue that needs more attention in terms of numerical studies. Turbulent heat transfer is an extremely complex phenomenon and has challenged turbulence modellers for various decades (Shams, 2017). The modellers have often assumed the possibility that turbulent heat transfer may be predicted only from the knowledge of momentum transfer, in what is known as the Reynolds analogy. Although this assumption is overly simplistic, it has been successfully adopted for the last four decades in the large majority of industrial applications of CFD, which are based on Eddy Diffusivity models (EDM). This success is justified by the fact that, for fluids with a Prandtl number close to unity, this approach has provided reasonable predictions.

Nevertheless, a good prediction of the flow and heat transport inside the rod bundle is a challenge for the available URANS turbulence models and these models need to be validated and improved accordingly. Although the measurement techniques are constantly getting improved, however, the CFD-grade experiments of flow mixing and heat transfer in the subchannel scale are often impossible or quite costly to be performed. In addition, lack of experimental databases makes it impossible to validate properly and/or calibrate the available RANS turbulence models for certain flow situations. In that context, Direct Numerical Simulation (DNS) can be served as a reference for model development and verification. However, despite the advancement in the super computing, performing a DNS for a realistic rod bundle at a high Reynolds number is not foreseeable in the near future. In this regard, a research program has been set-up between Nuclear Research and Consultancy Group (NRG) and National Centre for Nuclear Research (NCBJ) to generate a high quality DNS database for a rod bundle configuration.

The present article is also a part of this research program with an aim to design a numerical experiment for a tight lattice bare rod bundle case using different Prandtl fluids, which will be used in order to generate a DNS reference database. This takes into account the turbulent mixing and the evolution of the temperature distribution for fluid flow. The higher order spectral element code NEK5000 (NEK5000, 2018) is selected in order to perform the high quality DNS computations. The obtained DNS results will serve as a reference database to validate and calibrate/improve the available and commonly used low order turbulence modeling approaches. In this regard, a wide range of URANS simulations are performed to design this numerical experiment and are presented in this article. The details regarding the flow configuration and the description of adopted hydraulic experiment configuration by Hooper (1984, 1980), are given in Section 2. The considered numerical methods and the CFD model are presented in Section 3. The scaling analysis of the flow parameters are extensively discussed in Section 4. In Section 5, the feasibility of the temperature field using different Prandtl fluids is outlined. The optimization of the size of the computational domain suitable for final DNS, as well as assessment of the resolution of the computationally affordable DNS mesh are presented in Section 6. This is followed by a summary in Section 7.

2. The Hooper case

As a starting point, Hooper's hydraulic experiment (Hooper, 1980; Hooper and Rehme, 1984) of a bare rod-bundle is selected, hereafter it will be called as the Hooper case. For the sake of understanding some of the key parameters of the Hooper case are