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Numerical prediction of flow and heat transfer in a loosely spaced bare rod bundle

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ABSTRACT

A wall-resolved Large Eddy Simulation (LES) is performed for a loosely packed bare rod bundle with Reynolds number of 54,650. The simulation includes heat transfer in a liquid metal with the Prandtl number of 0.016. The rod bundle configuration corresponds to the ALFRED lead-cooled reactor design. The ALFRED design employs nuclear fuel assemblies with triangular arrangement of the fuel rods. In the present study, two important thermal-hydraulics aspects of the ALFRED rod bundle configuration have been analysed. Firstly, the proposed design should not lead to any undesirable vibration issues and, secondly, the heat transport should assure sufficient cooling with no hot spots. The obtained flow and thermal fields are analysed and compared with available data. A detailed investigation of the flow field has revealed the existence of a relatively weak gap vortex street in the loosely packed rod bundle. Hence, this considered configuration is unlikely to cause any vibration issues. In addition, the observed thermal field has shown a specific logarithmic trend, representing the heat transfer in wall bounded flow configurations for a wide range of Péclet numbers. In general, no hot-spots are observed for the considered design parameters.

1. Introduction

Nuclear power plays a significant role in power generation, producing approximately 11% of the total electricity worldwide, and 18% of electricity in OECD countries (NEA, 2015). The rapidly growing energy demand suggests an increasing role for nuclear power in the future energy supply, as the only large scale environmentally sustainable source, as outlined for example in the projections of the World Energy Outlook 2017 (IEA, 2017). Most future energy reports worldwide consider that nuclear fission will play a large role towards a low-carbon energy mix; in connection to this growing role, the IAEA (2014) underlines the importance of the deployment of fast reactors in a sustainable nuclear energy mix. The IAEA (2012) technical report provides a comprehensive overview of the status of fast reactor development; most of the fast reactors technology employ a liquid metal as coolant, which underlines the importance of advancing the understanding and modelling of liquid metal coolants.

The nuclear chain reaction, which is the source of nuclear fission energy production, takes place in the core of a nuclear reactor. Within this core, heat is produced in nuclear fuel and transported to the coolant. Typically, a nuclear core consists of a few hundred fuel assemblies which in turn consist of a large number of fuel rods. Most fast reactor designs employ wire wraps as spacer design, see e.g. (IAEA, 2012). Recently, the Advanced Lead Fast Reactor European Demonstrator (ALFRED) is a lead fast reactor aiming at demonstration in Central / Eastern Europe (Alemberti et al., 2013). One of the important tasks of the ALFRED program is the design of the fuel assembly. If feasible, the application of spacers within the active zone (the heated region) of the fuel assembly should be avoided. From the thermal-hydraulic point of view, it is very important that such design does not lead to any undesirable vibration issues. In addition, the heat transport in the fuel assemblies of the core is also a very important aspect to be considered for the design and safety analyses. Therefore, this is the topic of this study.

It has been observed that flow in a bare rod bundle, which contains translational symmetry in the streamwise direction due to the lack of spacer grid, exhibits a single dominant frequency of turbulence (Rowe, 1973; Rowe et al., 1974; Hooper and Rehme, 1984). This frequency was an evidence of flow pulsations, which turned out to strongly depend upon the P/D ratio, i.e. rod pitch to rod diameter ratio. Strong pulsations have been reported for tightly packed rod bundles (i.e. $P/D < 1.2$) and they gradually decrease with increasing P/D ratio. The spectrum of the fluctuating velocity was obtained by Möller (1991, 1992), who also proposed a model, which explains these pulsations as a symptom caused by a vortex street that is generated in the gap regions between the rods. This model was an important step forward in understanding

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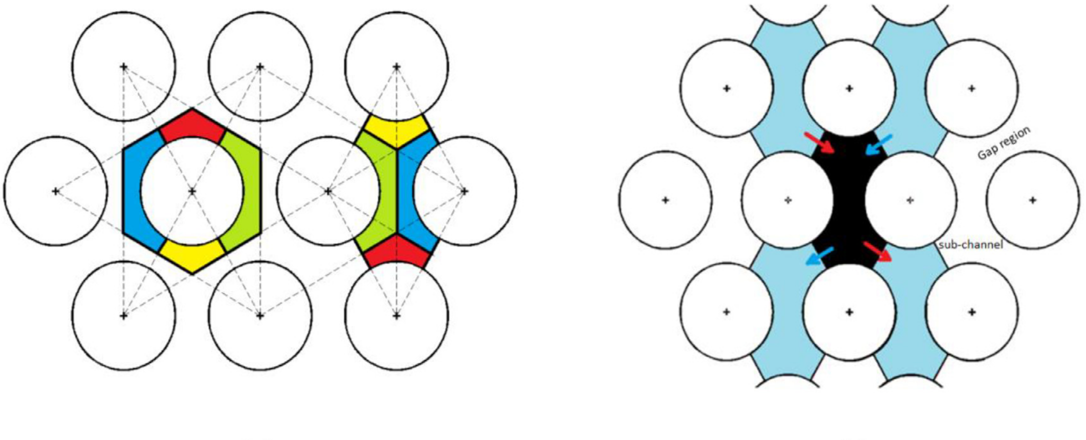

(a) (b)

Fig. 1. Two possible choices for the same fluid domain volume within infinite rod bundle array (a) and the applied computational domain with its periodicity (b).

the flow pulsation phenomenon, however, later on it turned out not to be entirely correct. In Krauss and Meyer (1996, 1998) investigated pulsations in a heated 37-rod bundle with a $P/D = 1.12$ and proposed a so-called double vortex train model, where pulsations are caused by vortices, which develop on both sides of the gap regions between the rods. An extensive review on this phenomenon is given by Meyer (2010). According to Meyer (2010) the origin and nature of the flow pulsations inside gaps is still disputed.

It is believed that these vortices result from the interaction of high-speed flow in the middle of sub-channels and low-speed flow in the gap between the rods. It is interesting that the appearance of these flow pulsations is detected not only in turbulent flows. Namely, in the work of Mahmood (2011), the flow pulsations were observed in laminar, transitional and turbulent flow regimes. Moreover, similar phenomena were also observed in other geometries, e.g. in rectangular channels connected with a small gap (Van der Ros and Bogaardt, 1970; Tapucu and Merilo, 1977; Meyer and Rehme, 1994; Lexmond et al., 2005; Mahmood et al., 2009), in a trapezoid-bounded sub-channel containing a single rod (Wu and Trupp, 1993; Guellouz and Tavoularis, 2000a, 2000b; Lee et al., 2013) and in rectangular channels with non-uniform wall roughness (Yan, 2011). Nevertheless, this paper focuses on this phenomenon mainly in the rod bundle configuration.

Turbulent flow in rod bundles has been reproduced by numerous simulations using different turbulence modelling approaches. For example, Direct Numerical Simulations (DNS) have been performed by Mayer and Házi (2006) and Ninokata and Merzari (2007). These DNS studies were limited to low Reynolds numbers and small computational domains. The large eddy simulations (LES) approach is computationally less demanding than DNS and it enables to simulate flows at relatively larger Reynolds number and in a larger rod bundle domain (Ikeno and Kajishima, 2010; Mikuž and Tiselj, 2016a). However, a successful prediction of flow pulsations requires relatively long streamwise domain which allows the development of large axial coherent structures (Ninokata and Merzari, 2007; Ninokata et al., 2009; Chandra et al., 2010; Merzari and Ninokata, 2011; Merzari et al., 2011; Walker et al., 2014). Hence, most of the simulations aiming to reproduce pulsations in rod bundles used computationally even less demanding approaches, i.e. Unsteady Reynolds Averaged Navier-Stokes (URANS) simulation (Chang and Tavoularis, 2007; Merzari et al., 2007, 2011; Ninokata et al., 2009; Chandra et al., 2010; Yan and Yu, 2011; Yan and Gu, 2012; Liu and Ishiwatari, 2013; Cardoso de Souza et al., 2015). These URANS simulations are less accurate but are able to reproduce the appearance of flow pulsations in tightly packed rod bundles. On the contrary, the prediction of weak flow pulsations using URANS approach in loosely packed rod bundles is questionable and not being properly tested.

Existence of flow pulsations are particularly important in bare rod bundles because they enhance mixing between adjacent sub-channels, which is beneficial for heat transfer. Flow pulsation in bare rod bundle including heat transfer has been reproduced by Chandra et al. (2010), Yan and Yu (2011), Yan and Gu (2012) and Cardoso de Souza et al. (2015) using URANS approach. These simulations applied properties of air and water, which corresponds to the Prandtl numbers in a range between 0.7 and 10. The present study deals with the heat transfer in a liquid lead, which is a low Prandtl number fluid. So far, in the open literature no such data is available for heat transfer in rod bundles.

In the present paper, a wall-resolved LES is performed for a loosely packed bare rod bundle in an infinite array with $P/D = 1.32$, which corresponds to the ALFRED design (Alemberti et al., 2013; Frogheri et al., 2013). The simulation is performed for the Reynolds number of 54,650 including heat transfer in liquid metal with Prandtl number of 0.016. The description of the flow configuration and the selection of the numerical methods is given in Section 2. In Section 3, the obtained results of the flow and thermal fields are discussed in details. This is followed by a summary in Section 4.

2. Flow configuration and numerical methods

2.1. Computational domain

Since a wall-resolved LES type simulation requires enormous computational efforts, a careful consideration has been given to the selection of the computational domain assuming a length of 800 mm which corresponds to the heated region (600 mm) of the ALFRED design including the allowance of 100 mm upstream and downstream to place the spacers. As it will be discussed in the next section, a periodic boundary condition has been applied in the streamwise direction for the considered computational domain. Accordingly, a two-point correlation is performed for the selected computational domain to assure that the domain is sufficiently long and the large flow structures are not severely affected by the periodic boundary conditions.

Typically for a rod bundle case, the axial (streamwise) length of the domain should be long enough to capture at least four wavelengths (4λ) of the appearing gap vortex street. Based on the frequency of the gap vortex street predicted in this study (see Section 3.1.2) and assuming the mean fluid velocity as a convective speed of gap vortex street, the axial length of the domain corresponds to approximately 23λ. Fig. 1(a) shows a breakdown of the sub-channels surrounding a bare rod bundle. Clearly, the same fluid volume can be modelled with two slightly different arrangements, which consist of similar fluid domains indicated by red, blue, green and yellow areas. In the present study, the second option (right) is selected and is also highlighted in Figs. 1(b) and 2. The