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Improved delayed detached eddy simulation of a randomly stacked nuclear pebble bed

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ABSTRACT

The high temperature reactor (HTR) design concept exhibits excellent safety features due to the low power density and the large amount of graphite present in the core which gives a large thermal inertia in the event of an accident such as loss of coolant. However, the possible appearance of hot spots in a pebble bed core design may affect the integrity of the pebbles and the fuel. This has drawn the attention of several scientists to understand this highly three-dimensional complex phenomenon. To obtain accurate predictions based on techniques such as DNS and LES, for a realistic (even for a small size) pebble bed flow, is still computationally too expensive and not foreseeable in the near future. On the other hand, the prediction capabilities of turbulence modelling approaches such as RANS and hybrid RANS-LES methods for such complex flow regime have not yet been rigorously evaluated. In this paper, numerical simulations of a limited sized randomly stacked bed of spherical pebbles are performed by using improved delayed detached eddy simulation (IDDES). The pebble bed configuration analysed consists of approximately 30 pebbles, which are randomly stacked to represent the core of an HTR. The obtained results are compared (qualitatively and quantitatively) with the available reference LES for validation purposes. The results show that the selected IDDES based on the SST k-ω model is able to reproduce the overall flow topology. The mean flow and thermal fields are found to be in good agreement with the LES. However, the second order statistics have shown significant disagreement. Nevertheless, these results are explicitly discussed in detail to understand the flow and thermal fields appearing in this complex flow configuration.

1. Introduction

High temperature reactors (HTR) are being considered for deployment around the world. An HTR uses helium gas as a coolant, while the moderator function is accomplished by graphite. The fuel is embedded in a graphite moderator and can sustain extremely high temperatures [7,8], basically preventing the fuel from melting. An important feature associated with the HTRs, is the high coolant temperature that can be achieved and therefore the high efficiency of the thermodynamic cycle. The high coolant outlet temperature also leads to optimal suitability for coupling the reactor to an industrial process requiring heat. The core can be designed using a graphite pebble bed. Some experimental and demonstration reactors have been operated over the world using this design [3] which have shown safe and efficient operation, however questions have been raised about the occurrence of potential local hot spots in the pebble bed, possibly affecting the pebble integrity [15]. Heat transfer around a curved surface shows a complex behaviour, which can be affected by both laminar and turbulent flow characteristics and by the effect of flow curvature. The narrow flow passages through the gaps between the pebbles can have concave and convex configuration which will cause augmentation or suppression of turbulence level [2]. In addition, pressure gradients strongly affect the boundary layers. Transition from laminar to turbulent, wake, flow separation and its respective reattachment make this flow configuration very complex, therefore a detailed evaluation of the pebble bed flow physics needs to be performed.

Computationally, thermal-hydraulic aspects of a pebble bed configuration can be predicted either by a porous medium or by realistic geometry-resolving approaches. In case of a porous medium approach, an averaged concept of porosity is applied to simulate the closely packed geometry [8], whereas, in a realistic approach case, every pebble is accurately and separately modelled in a simulation, using direct numerical simulation (DNS), large eddy simulation (LES), Reynolds averaged Navier–Stokes (RANS) calculations or hybrid RANS/LES methods. However, applying a realistic approach to a reactor scale simulation is still computationally expensive and not foreseeable at an industrial scale. On the other hand porous media models are computationally efficient and represent a practical

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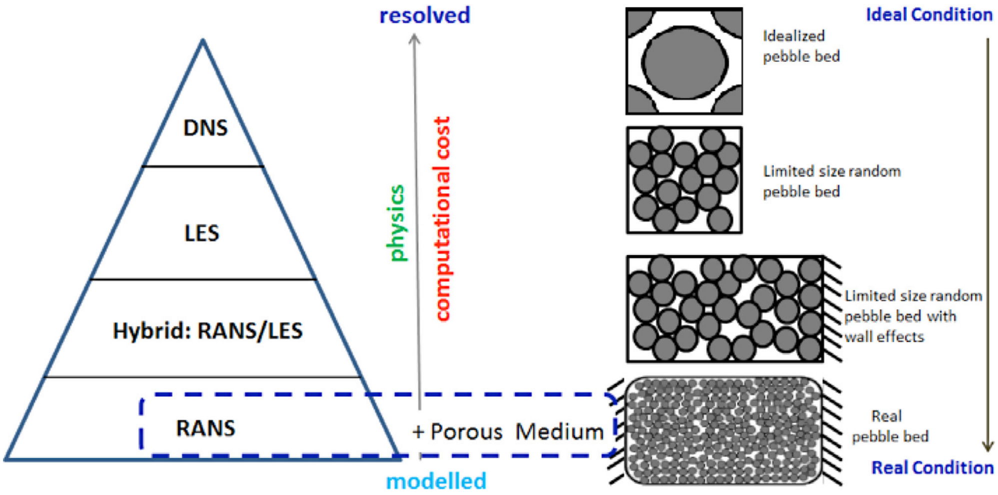

Fig. 1. CFD triangle (left) and different pebble bed distributions (right) [21].

engineering approach for the simulation of large pebble cores. However porous methods could improve their predictive capabilities by incorporating complex behaviour from higher order simulation methods. To fulfil this gap, experimental studies or validated computational fluid dynamics (CFD) approaches could play a significant role in providing the necessary closure to the coarser porous solution. While a limited number of experimental studies have been performed, the available data are still insufficient in order to support rigorous validation of turbulence modelling approaches [1,12,13]. This limitation is directly related to the difficulty of extracting data from a complex random distribution of pebbles. For such scenarios, high fidelity CFD simulations are possible and/or available, and can be very helpful in quantifying the capabilities and limitations of the available turbulence closures. A large number of modelling attempts ([4–6,10,11]; [14,17,29]) have clearly evidenced the limitations of the adopted RANS methods. This limited success is not surprising, and is related to the intrinsic limitations of the RANS closures, as explained by Wu et al. [29]. Higher order LES based calculations have also been performed to investigate FCC and BCC type pebble bed configurations (see [2] and [11]). Unfortunately, no detailed validation on a reference database was provided in order to verify the accuracy of LES predictions for such complex flow physics.

In 2013, Shams et al. [20] have proposed a stepwise validation procedure involving different types of pebble bed distributions, as shown in Fig. 1. This validation procedure consists of four steps, starting from an idealized pebble bed, via a limited sized random pebble bed, a limited sized random pebble bed with wall effects and finally the reactor scale pebble bed. The purpose of the method is to leverage the first three steps to validate a realistic numerical approach. Afterwards, this approach should be applied to derive parameters to incorporate in a porous medium representation in order to enable modelling of the full scale reactor pebble bed.

As a step 1 of this validation procedure, an idealized face cubic centred pebble bed has been studied extensively. To generate the reference database quasi-direct numerical simulations (q-DNS) for this idealized pebble bed were performed, see Shams et al. [18,19]. The q-DNS was further utilized to validate LES, hybrid RANS/LES and URANS methods for such complex geometries, see Shams et al. [20,21,22]. This extensive validation of step 1 has shown that among the used methods, LES is found to be in excellent agreement with the q-DNS with a maximum difference (for the first and second order statistics) of less than 6%. Hence, it can be said that for complex geometries where performing q-DNS calculations is not possible, LES can be used as a reference to validate the low order turbulence models. Lessons learned from step 1 have been carefully applied by Shams et al. [23] for step 2 to generate a reference database for a limited sized random pebble bed. As a result, a high quality database for flow and thermal fields is obtained by using LES, for details see Shams et al. [23]. In the present study, the prediction capabilities of hybrid RANS–LES methods for this limited sized random pebble bed are evaluated. It is worth mentioning that in the validation procedure for step 1, it was found that among the tested hybrid methods, IDDES based in SST k-ω model performed the best. Hence, the same formulation of IDDES (i.e. IDDES SST k-ω model) was selected for the presented study. Details regarding the flow configuration and the considered numerical methods are given in Section 2. The obtained results of flow and thermal fields and their comparison with the reference LES are discussed and documented in Section 3. Finally, the summary and conclusions are presented.

2. Flow configuration and numerical strategies

2.1. Computational domain

Following the reference LES case [23], the computational domain for the selected IDDES simulation is kept the same. It consists of approximately 30 pebbles with an average porosity (ε = volume of voids/total volume) level of about 0.4. These pebbles are randomly stacked in a rectangular domain of $x = 0.177$ m, $y = 0.354$ and $z = 0.177$ m, which is shown in Fig. 2. This random distribution of pebbles was obtained from [16]. The diameter of the pebbles is 6 cm. In the original geometry configuration, the pebbles were clustered in a cubic domain of 0.177 m per side. However, for the reference LES case, the inlet and outlet boundary conditions needed to be imposed. Hence, the domain was further extended in the y-direction, i.e. 0.0885 m for both inlet and outlet sections. As a result, the appearing pebbles on these sides are not truncated, as can be seen in Fig. 2 (Right). Additionally, in the original geometry the pebbles are in point contacts with each other. Whereas, to model such point contacts is problematic for meshing and consequently may induce numerical errors to the solution. Hence, in order to avoid difficulties, these point contacts are converted into small area contacts by scaling the pebbles by a factor of 1.034. This gives a maximum radial overlap of ~1 mm between two pebbles and the corresponding contact area is 0.0019 cm^2.

2.2. Flow/simulation parameters

Helium is considered as a working fluid with an imposed mass flow rate of 0.01607 kg/s at the inlet section. This is equivalent to the Reynolds number (based on the pebble diameter and the maximum velocity appearing in the computational domain) of ~9753. The inlet