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Large eddy simulation of a randomly stacked nuclear pebble bed

A. Shams [a,*], F. Roelofs [a], E.M.J. Komen [a], E. Baglietto [b]

[a] Nuclear Research and Consultancy Group (NRG), P.O. Box 25, 1755 ZG Petten, The Netherlands
[b] Department of Nuclear Science and Engineering, Massachusetts Institute of Technology (MIT), 77 Massachusetts, Avenue, 24-107, Cambridge, MA 02139, United States

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ABSTRACT

This paper reports large eddy simulation results for a randomly stacked bed of spherical pebbles, using a second-order accurate, cell-centered finite volume method on an unstructured polyhedral mesh. The selected flow configuration represents the core of a high temperature reactor, in which nuclear fuel is embedded in the pebbles. The geometrical arrangement consists of approximately 30 pebbles, which are randomly stacked and in contact with each other. Extensive analyses of flow and thermal fields are performed to derive valuable insights on the flow characteristics. The predicted flow-field is fairly complex and exhibits highly unsteady and three-dimensional turbulent behavior with strong rotational and cross flow regions. The flow, while moving over the pebbles shows attenuation and enhancement in the turbulence levels, and eventually yields to flow separation and its subsequent reattachment. Consequently, a wide range of temperatures over the pebbles is observed; this includes the appearance of hot-spots especially around contact areas. The occurrence of high- and low-velocity streak regions, and the corresponding temperature fields are examined and quantified. The reported analyses can be used for validation of low-order turbulence modeling applications to complex pebble flow configurations.

1. Introduction and motivation

Complex flow fields, encountered in many engineering applications, are highly three-dimensional, unsteady, separated and turbulent in nature. The accurate prediction of such flows is still challenging for current CFD tools. The applicability of direct numerical simulation for such engineering applications is extremely limited, especially for complex geometries. Large eddy simulations (LES) have played an important role in filling the existing gap, for high fidelity numerical solution [35,16]. The significantly reduced computational effort, in comparison to DNS, has made this CFD technique attractive for a growing range of industrial applications. Simulations involving flow over complex geometries have already been attempted using unstructured grid techniques. Moreover, several attempts have been made to show the ability of unstructured methods to accurately simulate flows involving large-scale unsteadiness. The appeal of accurately solving complex real life problems, by means of the efficient cell or element distribution offered by unstructured grids, motivates continued research in this area. Several flow examples for simple geometries, which expose the challenge of simulating complex separated turbulent flows, are also widely adopted in the literature to support the fundamental development of turbulence models and numerical methods. Representative databases available in literature include for example, flow over a backward-facing step, flow around a square prism, flow over a cube, and other bluff bodies such as a circular cylinder, sphere, and spheroid etc. [3,5–7,8–11,14,21,22,26,29–33,36,37,40,41]. Such simplified flow configuration are considered representative of specific flow phenomena developing in realistic complex 3D engineering geometries. The scope of this work is to extend the range of available fundamental databases by delivering reference results for flow in complex pebble bed configurations, which can be used to develop and validate lower order Reynolds Averaged Navier Stokes (RANS) closures. This paper presents results of highly resolved LES simulations for a randomly stacked, spherical shape, pebble bed at a moderate Reynolds number. The geometry consists of 30 pebbles in contact with one and other.

The selected flow configuration is explicitly representative of a typical core for an innovative pebble bed high temperature reactor (HTR). An HTR uses helium gas as a coolant, while the moderator function is performed by carbon in the form of graphite [13]. The fuel is embedded in the graphite moderator and can withstand very high temperatures [18,19], as an important safety feature of HTRs, basically preventing the fuel from melting. Various experimental pebble bed reactors have successfully been operated worldwide [17]. They have shown safe and efficient operation, however questions have been raised regarding the potential occur-

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* Corresponding author. Tel.: +31 224568152.
E-mail address: shams@nrg.eu (A. Shams).

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rence of local hot-spots in the pebble bed, possibly affecting the pebble integrity [25]. Heat transfer around spherical surface varies noticeably for both laminar and turbulent flow regimes and the obvious appearance of the curved flow. The flow passages through the gaps between the pebbles could have concave and convex configurations, and the manifestation of centrifugal forces comes into play in the form of suppression or augmentation of turbulence level [15]. 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 pebble bed flow physics should be performed.

Two general approaches are commonly adopted to model the thermal–hydraulic aspects of a pebble bed, and can be described as porous medium approach on one side and realistic geometry resolution approach on the other. In a porous medium approach, an averaged concept of porosity is applied to simulate the closely packed geometry [19]. In a resolved approach, every pebble is realistically and separately modeled in a simulation using different turbulence modeling methods such as LES, URANS or hybrid URANS/LES [42]. For a reactor scale simulation, presently only a porous medium approach is readily feasible due to the extreme computational requirements of resolving the full pebble bed. Although such porous medium approaches have been developed, for the characterization of local heat transfer requires further improvement and furthermore, a rigorous validation is still pending. In addition to experimental and analytical work e.g. carried out by Van Antwerpen et al. [39,40], Auwerda et al. [1,2], Janse van Rensburg et al. [18], and Wu et al. [42], a numerical approach to a stepwise validation procedure was proposed by Shams et al. [31]. This methodology involves different types of pebble bed distributions as shown in Fig. 1 (right). This validation procedure consists of 4 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. Subsequently, this approach should be applied to derive parameters to incorporate in the porous medium representation in order to enable modeling of the full scale reactor pebble bed.

Step 1 of the CFD triangle has been extensively investigated using quasi-direct numerical simulations. The q-DNS was further utilized to validate LES, hybrid RANS/LES and URANS methods for such complex geometries. The present study is a contribution to the second step of this long journey in order to improve and validate the numerical methods to model a reactor scale pebble bed. Details regarding the flow configuration and the considered numerical tools are given in Section 2. The obtained results of flow and thermal fields are discussed and documented in Section 3. Finally, the summary and conclusions are presented.

2. Flow configuration and numerical strategies

2.1. Computational domain

The selected flow domain is a randomly stacked bed of spherical shape pebbles in a rectangular domain of $x = 0.177$ m, $y = 0.354$ and $z = 0.177$ m, shown in Fig. 2. This flow domain is representative of the core of an HTR. This random pebble geometry is obtained from the work of Pavlidis and Lathouwers [28], and consists of 30 pebbles, and exhibits an average porosity (ε = volume of voids/total volume) level of 0.4. The diameter of the pebbles is 6 cm, consistently with the specification of PMBR-250MWth [23,24], All pebbles are clustered in a cubic domain of 0.177 m per side, while the requirement for inlet and outlet boundary conditions leads to the extension of the computational domain in the y-direction, i.e. 0.0885 m for both inlet and outlet sections. This allows correct description of the inlet and outlet flow behavior where pebbles are fully represented and not truncated in the y direction, as can be seen in Fig. 2. Modeling the contact area between the pebbles also requires particular attention. Straightforward geometrical representation would consider a point contact between pebbles. However, modeling such point contacts is problematic from a meshing view point, which may induce numerical errors to the solution, and is also not representative of realistic reactor cores, where the weight of the pebble bed leads to larger contact areas. Therefore, small area contacts are modeled in the simulations, and are obtained by scaling the pebbles by a factor of 1.034. This gives a maximum radial overlap of $\sim$1 mm between two pebbles. The corresponding contact area is 0.0019 m^2.

2.2. Flow/simulation parameters

In order to mimic the core of an HTR realistically, flow is imposed via an inlet boundary condition at the top of the geometry, and a pressure outlet boundary at the bottom of the domain, as shown in Fig. 2. Following the work of Shams et al. [31–33], helium is considered as a working fluid with an imposed mass flow rate of 0.01607 kg/s. Based on the pebble diameter and the predicted maximum velocity, the estimated Reynolds number is 9753. The inlet temperature of helium is 773 K and constant properties at this temperature are used, as given in Table 1. The

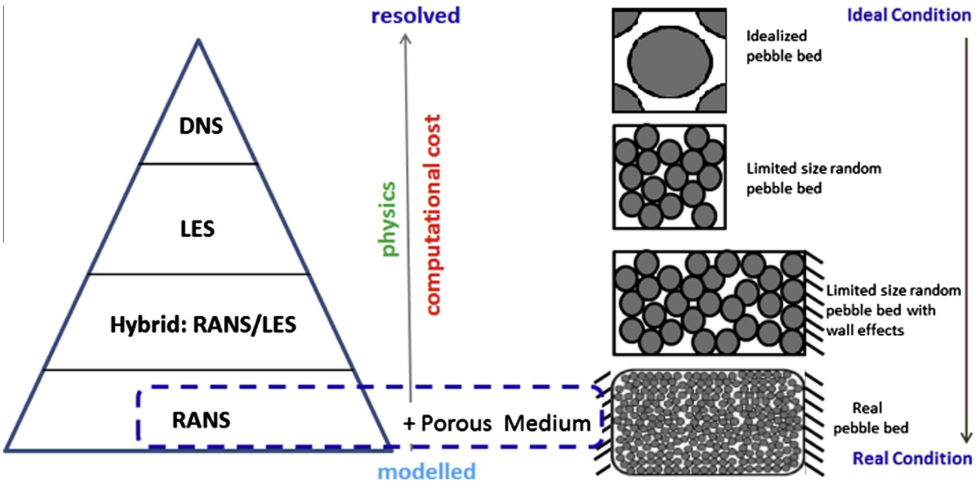

Fig. 1. CFD triangle (left) and different pebble bed distributions (right) [31].