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Original Article

Analysis of forced convection in the HTTU experiment using numerical codes

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ABSTRACT

The High Temperature Test Unit (HTTU) was an experimental set-up to conduct separate and integral effects tests of the Pebble Bed Modular Reactor (PBMR) core. The annular core consisted of a randomly packed bed of uniform spheres. Natural convection tests using both nitrogen and helium, and forced convection tests using nitrogen, were conducted. The maximum material temperature achieved during forced convection testing was 1200 °C. This paper presents the numerical analysis of the flow and temperature distribution for a forced convection test using 3D CFD as well as a 1D systems-CFD computer code. Several modelling approaches are possible, ranging from a fully explicit to a semi-implicit method that relies on correlations of their associated phenomena. For the comparison between codes, the analysis was performed using a porous media approach, where the conduction and radiative heat transfer were lumped together as an effective thermal conductivity and the convective heat transfer was correlated between the solid and gas phases. The results from both codes were validated against the experimental measurements. Favourable results were obtained, in particular by the systems-CFD code with minimal computational and time requirements.

1. Introduction

Constructed between 2006 and 2007, the High Temperature Test Unit (HTTU) was an experimental set-up to conduct separate and integral effects tests of the Pebble Bed Modular Reactor (PBMR) core in an annular configuration [1].

The HTTU was one of several experiments [2,3] that were a part of the High Temperature Test Facility (HTTF) which was hosted by the North-West University in South Africa and funded by PBMR (Pty) Ltd. These experiments, as well as the Pebble Bed Micro Model (PBMM), were applied towards the Verification & Validation (V&V) qualification testing [4] for licensing of the PBMR design.

The annular core of the HTTU experiment consisted of a randomly packed bed of approximately 25,000 uniform graphite spheres [5], not containing any fissile material. Firstly, for integral effects tests the core had two configurations: (i) forced convection with an open bed allowing flow to pass upwards through and exit the core, and (ii) natural convection with a closed bed to limit the temperatures of the support structures and allowing only natural convection to take place in the bed.

As part of the integral effects test runs, both natural convection tests using nitrogen and helium, and forced convection tests using nitrogen were conducted. The maximum temperature obtained during natural and forced convection, as well as near-vacuum testing, was 1200 °C.

In order to determine the effective thermal conductivity of the bed through separate effects tests, the experiment was also run under near-vacuum high temperature conditions. The results from the latter tests are described in detail by Rousseau et al. [2].

In the interest of brevity and page limitations, only a brief literature overview is provided here. In previous validation studies the natural convection experiments performed in the SANA experiment [6] were simulated using either a 3D CFD approach [7,8] or a system 1D component network approach [9,10]. The predicted temperature distributions were compared with the experimentally measured temperatures. In all the simulation cases the packed bed was considered as a porous medium.

This study presents the numerical analysis of the flow and temperature distribution in the HTTU under forced convection conditions, using both a 3D CFD and a 1D systems-CFD computer code, and a comparison of the results from both methodologies with the experimental measurements.

Several modelling approaches are possible with the numerical techniques available: from a fully explicit numerical solution to semi-

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implicit method relying on correlations for the associated phenomena. Coupled codes using CFD-DEM have also been used [11]. Due to the complexity and integrated nature of the physics involved in forced convective flow through a packed bed, it is both challenging from a modelling and computational standpoint to obtain a fully explicit solution [12]. With advances in processing and code capabilities it is however possible to perform simulations that were not feasible 15 years ago using 3D finite volume-based CFD running on high performance computer hardware [13].

1.1. Software

Flownex® Simulation Environment [14] is a commercial systems-CFD code which was developed by M-Tech Industrial (Pty.) Ltd. For use in nuclear and thermal-hydraulic system design and analysis. It is developed under ASME NQA-1 standards and is therefore suitable to apply to V&V efforts.

Because of the use of a commercial 1D code, the comparison is made with Siemens Star-CCM + [15] a 3D CFD code which is also used commercially in the nuclear sector. For the comparison, the 3D analysis is performed using a porous media approach, with correlations applied to both the momentum and energy equations.

2. Background and theory

There is a history of several HTGR core designs utilising a pebble bed geometry [16] starting with the German AVR prototype from the late 1960's, the South African PBMR-400 and more recently the Chinese HTR-PM which has reached the milestone of the first such unit reaching criticality on September 12, 2021 [17]. This makes it the first commercial SMR using a pebble bed core to become operational. The Xe-100 currently under development by US-based X-energy, further confirms the relevance of the continued study of packed pebble bed heat transfer phenomena.

Experimental results from integral effects tests of forced convective flow in pebble beds have previously not been investigated. The HTTU experiment and in particular the Nitrogen forced convection integral effects tests were performed over a continuous period of 14 days in 2009 [1]. In the following sub-sections, the parameters and theory related to this experiment are outlined as background to the numerical studies which are compared with the data from these tests.

2.1. Geometry

The HTTU comprised of an outer pressure vessel with interconnected heat removal equipment, piping and auxiliary equipment as well as internal components. The focus of this study concerns the internal structure that was representative of a reactor core consisting of a randomly packed annular bed of uniform spheres enclosed with walls formed by an inner and an outer reflector. The inner wall was heated by three electric elements in a central column placed behind the reflector and the back surface of the outer reflector was cooled by a water jacket.

A rendered CAD representation of the HTTU installation is shown in Fig. 1. The bed contained mono-sized graphite spheres of 60 mm in diameter. These pebbles were supported by a rigid bottom structure with several flow channels and corresponding openings, designed to provide a uniform bed inlet velocity profile. The open top of the bed was surrounded by two skirts of angled insulation material, to shield against thermal radiation and to induce thorough mixing of the flow before exiting the bed. Table 1 shows a summary of the packed bed dimensions and which were also used in both numerical models.

2.2. Measurements

A total of 144 thermocouples were placed throughout the packed bed. It is not clear if the instrumentation procedure involved contact with sphere surfaces or penetration. The assumption is made that all temperature measurements reported are of the solid surfaces of the spheres at their respective locations. Because the spheres were not internally heated, it can be assumed that the temperature distribution through a sphere would be uniform.

Fig. 2 shows the placement of thermocouples in a cross-section at a tangential angle of 0° of the packed bed, in black on Levels A to E. The

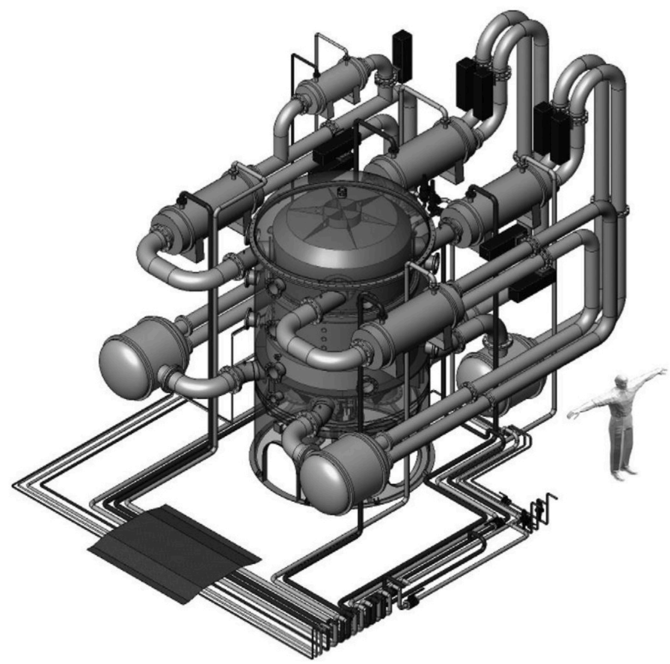

Fig. 1. 3D Rendering of the HTTU installation (taken from Ref. [2]).

Table 1
HTTU annular packed bed dimensions.

Measurement	Value	Unit
Inner Diameter	0.600	*m*
Outer Diameter	2.300	*m*
Bed Height	1.200	*m*
Pebble Diameter	0.060	*m*

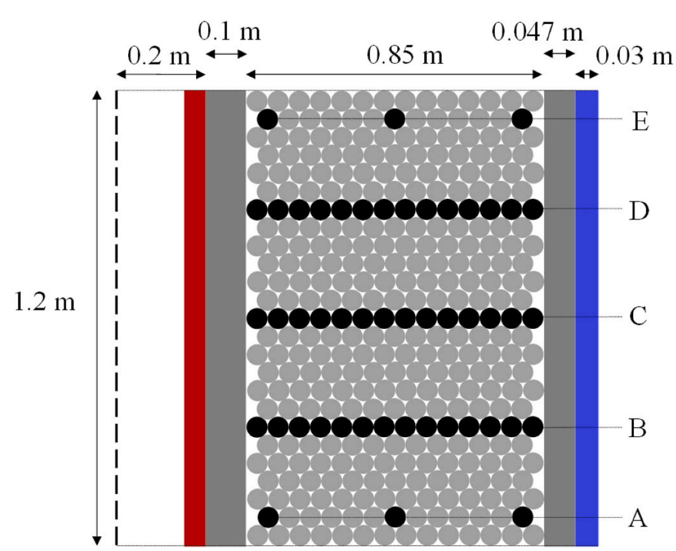

Fig. 2. HTTU core geometry, measurements and placement of thermocouples (in black).

upper and lower levels had 3 thermocouples (A and E) and the middle levels (B, C and D) had 14 thermocouples, each. The same placement was repeated at 2 other sections at tangential angles of 120° and 240°. The radial positions relative to sphere diameters may be inferred from the scale of Fig. 2. The elevation and uncertainty of the axial placement is shown in Table 2.

2.3. Physics

There are several flow and heat transfer phenomena which contribute to the overall heat transfer of a packed bed. Many references are from the chemical industry and the correlations may be simplified when using mono-sized spherical elements in the bed. For high temperature gas cooled pebble beds, there are several references specifically in the nuclear industry such as the SANA experiment [6] (non-nuclear, electrically heated core) conducted at the INR at Karlsruhe Institute of Technology in Germany similar to the HTTU, or the TF-PBEC [18] (non-nuclear, electrically heated) of INET at Tshinghua University in Beijing.

The physics relating to momentum and energy transfer, as well as the correlations, which are applicable to the study are discussed here.

2.3.1. Pressure drop

The large surface area per unit volume, braiding effect and particle roughness will affect the viscous and inertial terms in a numerical calculation of pressure drop. A widely used equation for randomly packed pebble beds to calculate the pressure drop which combines the laminar and turbulent components, is the friction factor (f) correlation is published in the KTA standard for HTGR pressure drop [19] as shown in Eq. (1):

$$f_{KTA} = \left[\frac{160}{\mathrm{Re}_0} + \frac{3}{\mathrm{Re}_0^{0.1}}\right] \tag{1}$$

with the modified Reynolds number:

$$\mathrm{Re}_0 = \frac{\rho v_s D_p}{(1-\varepsilon)\mu} \tag{2}$$

Where ε is the porosity or void fraction of the bed, ρ the density of the fluid, v_s the superficial velocity of the bed without particles, D_p the particle diameter, and μ the dynamic viscosity of the fluid.

A convenient way to describe the superficial velocity when making use of a numerical method is using the gas mass flow rate ($\dot{m}$) and bed cross-sectional area (A):

$$v_s = \frac{\dot{m}}{\rho A} \tag{3}$$

The friction factor is related to the pressure drop (Δp) through the following equation:

$$\Delta p = H\frac{f\rho v_s^2}{D_p}\left(\frac{1-\varepsilon}{\varepsilon^3}\right) \tag{4}$$

With H the height of the pebble bed.

2.3.2. Heat transfer

There are several heat transfer phenomena which contribute to the overall heat transfer of a packed bed. This has been well researched in the nuclear industry.

As illustrated in Fig. 3, the different modes of convective, conductive, and radiative heat transfer may be classified as follows (with respective colours).

(i) Conduction through pebbles (yellow)
(ii) Contact heat transfer, including the gas in the narrow gap surrounding a contact region (light orange)
(iii) Conduction through stagnant gas (orange)
(iv) Convection heat transfer between solid surfaces and gas (red)
(v) Radiation between spheres and to or from walls (purple)

Due to proximity and similarity in form of these local modes, the overall heat transfer such as the sphere contact (ii) and stagnant gas conduction (iii) may be lumped together, for example, and such a method has been proposed by Bahrami et al. [20]. For packed beds in general it is often convenient to make use of the simplified concept of the effective thermal conductivity (k_{eff}) which takes the conductive and radiative heat transfer modes (i), (ii) and (v) into account, such as the Zehner-Schlünder and Bauer-Schlünder model as adapted by Breitbach and Barthels [21]. The heat transfer by convection (iv) consists of the convection from the surfaces of the pebbles as well as the advective heat transfer due to continuous flow of gas. The convective heat transfer may be correlated to the characteristics of the bed, namely porosity and interaction area density (surface area per unit volume), such as the Kugeler and Schulten correlation [22,23].

Table 2
Thermocouple placement in the HTTU.

Level	Elevation	Uncertainty	Unit
A	0.030	±0.015	*m*
B	0.120	±0.030	*m*
C	0.600	±0.015	*m*
D	0.960	±0.015	*m*
E	1.170	±0.030	*m*

3. Modelling approach

3.1. 3D cell-centred CFD

The commercial finite volume CFD code utilized was Siemens Star-CCM + version 17.02.008 [15] using the packed bed geometry flow volume as described represented with a 3-dimensional hexagonal (or directed) mesh and porous medium approach.

The complete inner volume of the HTTU was modelled prior to the work presented here, and a velocity distribution on the inlet of the bed obtained. This step formed part of a larger, yet unpublished study. The obtained distribution was applied as the inlet boundary condition to the

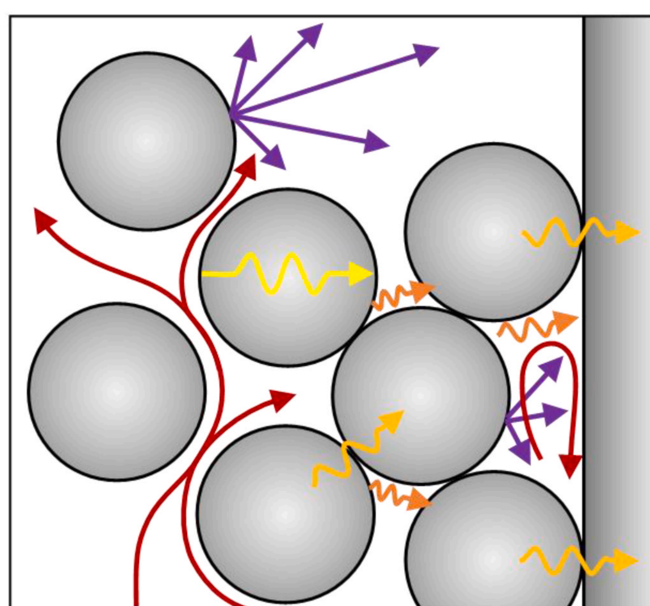

Fig. 3. Different modes of heat transfer in a packed bed.

model described in this study to account for the non-uniform inlet conditions. The top approximately 0.58 *m* of DEM annular packed bed generated by Potgieter and Du Toit [5] was removed to obtain the 1.2 *m* high annular packed bed. Following Potgieter and Du Toit [5], the volume was divided into 4 axial and 5 radial zones and an average porosity value for each determined. The porosities assigned to the mesh are illustrated in Fig. 4 and the values are summarized in Table 3. The thickness of the wall layers is approximately half a sphere diameter, the radial near-wall layers approximately three sphere diameters and the axial near-wall layer approximately six sphere diameters.

The expressions for the KTA [19] inertial and viscous friction factor terms were entered as user functions to be applied in the momentum equation in the porous medium.

The effective thermal conductivity values as functions of temperature and porosity assigned to the pebble bed were obtained from a table generated using the Breitbach and Barthels model [21]. The thermal conductivity of the graphite spheres employed in the model was obtained from the correlation proposed by Ren et al. [18].

Lastly the KTA convective heat transfer correlation [23] was applied to obtain the heat transfer coefficient for the interaction between the spheres and the gas.

3.2. 1D systems-CFD

The commercial finite volume 1-D systems CFD code Flownex SE version 8.14.1.4844 was used with its Nuclear Reactor [14] component. It uses a 2D network approach with axial-symmetry and is also capable of including details up to fuel level, coatings and point kinetic core neutronic feedback models. The theoretical background of the model is described by Du Toit et al. [9]. Because no heat was generated in the non-fuel spheres of the HTTU experiment, this functionality was therefore not utilized. The Reactor Geometry Chart specified in the model is shown in Fig. 5.

In the Flownex model, the same porosity zones (yellow regions in Fig. 5) were considered as in the 3D CFD model. The vertical flow region located above the pebble bed zones had a thickness of 0.05 *m* and was assigned a porosity value of 0.7 to represent the top of the packed bed. The pebble bed was given 30 radial and 40 axial increments, respectively.

The KTA friction factor correlation [19] was used in the formulation of the pressure drop in the Nuclear Reactor component. The option to use the Zehner-Schlünder [21] model for effective thermal conductivity was applied. The thermal conductivity of the graphite spheres employed in the model was obtained from the functional relationship given by Rousseau et al. [2]. The Kugeler-Schulten [22] correlation (with dispersion [24] and second order convection) was applied for the convective heat transfer coefficient. The option for dispersion accounts

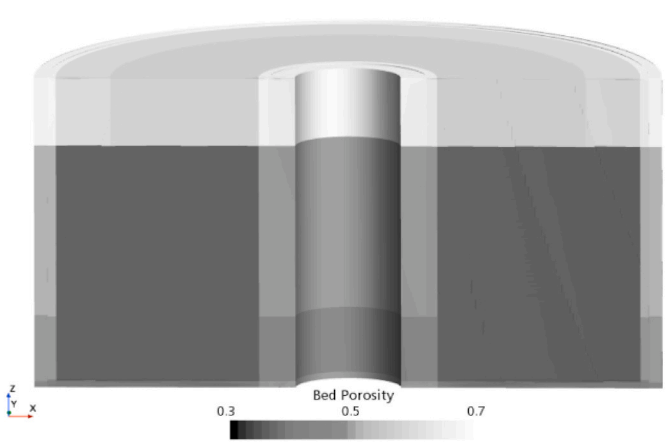

Fig. 4. Porosity distribution in the 3D CFD model.

Table 3
Zonal porosity values.

	Wall	Near-wall	Bulk	Near-wall	Wall
Bulk	0.4948	0.3725	0.3704	0.3735	0.5141
Bulk	0.4948	0.3725	0.3704	0.3735	0.5141
Near-wall	0.4833	0.3689	0.3637	0.3694	0.4929
Wall	0.4935	0.4606	0.4599	0.4722	0.4863

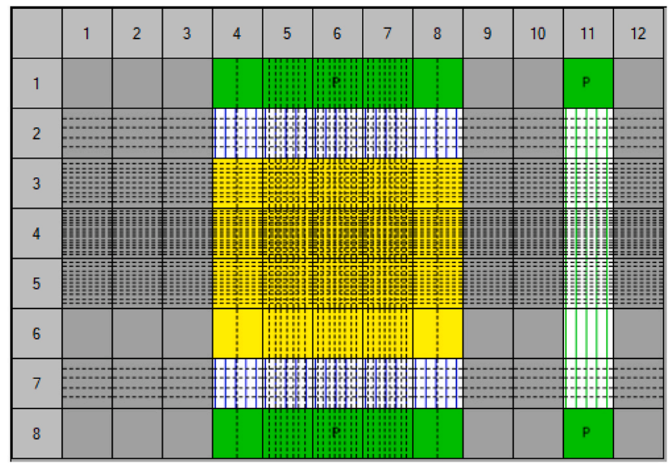

Fig. 5. Reactor geometry chart of the HTTU (not to scale).

for transverse flow mixing by modifying the molecular thermal conductivity of the gas in the direction perpendicular to the axial flow direction.

3.3. Common parameters

The parameters common to both methods are included here for reference and were applied in the appropriate manner in each code. The shared inputs are summarized in Table 4.

4. Results

4.1. Post-processing

Post-processing of the CFD results were necessary in order to extract the temperatures from cells corresponding to the co-ordinates associated with the thermocouple positions as used in the experiment. Three radial lines with increments equal to the number of thermocouples were equally placed and the values at tangential positions of the same radius on a specific height were averaged to a single value. This approach was also used in the processing of the experimental data [25] for which 3 separate tests were completed.

Similarly, the solid material temperatures of sub-zones were extracted from the Flownex reactor model at corresponding radial positions. Due to the axial-symmetric approach in Flownex these values are already tangentially averaged.

Table 4
Input data for both models.

Parameter	Value	Unit
Mass flow rate	1.000	*kg/s*
Inlet Temperature	40.00	°*C*
Inlet Pressure	100.0	*kPa (abs)*
Heater Power	140.0	*kW*
Water Jacket Temperature	25.00 to 35.00	°*C*

4.2. Comparison

The comparison of the numerical results from Flownex SE and from STAR-CCM + as compared with the corresponding experimental measurements are presented in Figs. 6–8 and represent the radially averaged solid temperatures and thermocouple measurements for the relevant axial level in the bed as shown in Fig. 2. For the 3D CFD results two sets of values are included, firstly for the approach outlined thus far, and secondly when applying only the standard values for thermal conductivity of graphite to the solid in the porous medium. It can be seen that accounting for the heat transfer effects, such as shown in Fig. 3, through implementation of the adapted Zehner-Bauer-Schlünder model [21], have a significant impact on the results.

It can be seen that on average Flownex demonstrated better overall agreement with the experimental results. This is a very favourable result considering the solving speed (several seconds) and relatively low computational resources (high-end laptop or desktop computer) required by the software.

The largest difference between the CFD and experimental temperature values occur at a radial distance between 0.3 *m* and 0.6 *m* on the higher levels of Level C and especially Level D. This corresponds to between 0.5 and 5 ball diameters from the inner wall which therefore comprises mostly of the wall and near-wall but also bulk sections. Because of this occurrence in the higher levels, it is possible that this is due to inadequate lateral conduction and/or thermal dispersion. The authors aim to investigate these aspects further in future work.

Both software packages allowed customization of the applicable correlations and parameters related to this specific case. As Flownex is developed specifically with the commercial nuclear sector in mind, it does include several models implemented and verified already that may be selected based on the specific application.

A spatial visualization of the results in Fig. 9 shows the temperature gradient results of the solid phase from the 3D CFD model. It is important to mention that due to the porous media approach in the CFD the values reported are averaged for that phase in each cell. If the pebbles are modelled discretely or with a two-way coupled CFD-DEM it could offer significant insights into geometric phenomena such as local peak fuel temperatures.

The lumping of radiation effects together with the effective heat transfer coefficient could also introduce errors, which could be quantified if a fully discrete model is evaluated. Such a model would come with a substantial computational requirement and necessitate the use of high-performance computer (HPC) hardware.

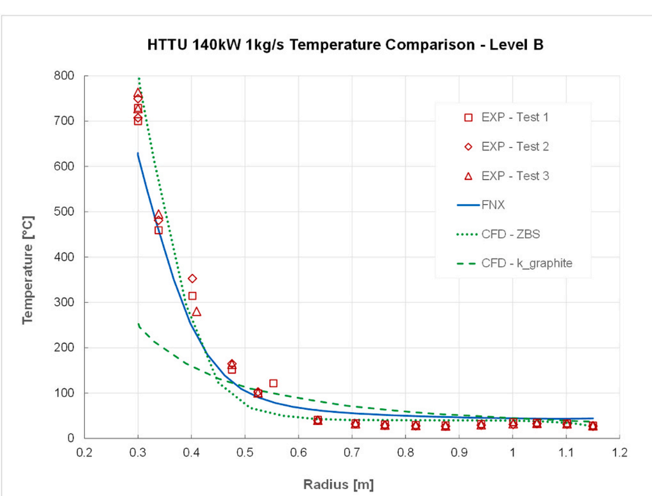

Fig. 6. Results comparison between the CFD, Flownex and Experimental measurements on Level B (experimental results used with permission, copyright PBMR).

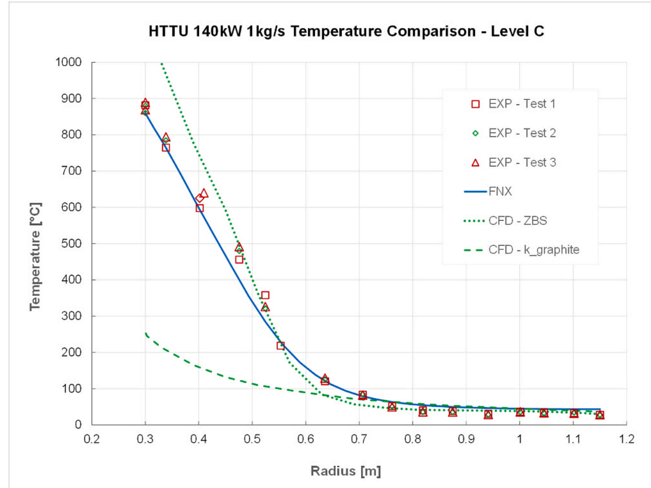

Fig. 7. Results comparison between the CFD, Flownex and Experimental measurements on Level C (experimental results used with permission, copyright PBMR).

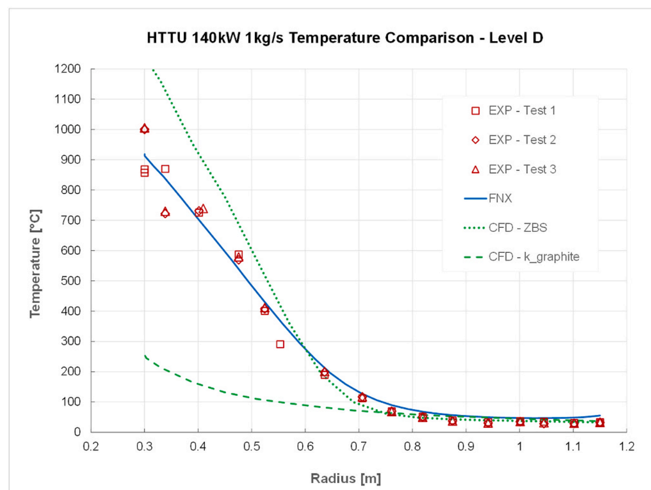

Fig. 8. Results comparison between the CFD, Flownex and Experimental measurements on Level D (experimental results used with permission, copyright PBMR).

4.3. Verification and validation

For validation of the momentum results in both cases, results were compared to the measured pressure drop in the experiment. For heat transfer, the gas outlet temperatures were compared. The heat removed by the water jacket in the experimental set-up could not be obtained.

The final CFD model predicted a 36.3 Pa pressure drop versus 36.9 Pa predicted by Flownex. As the pressure drop formulations in the CFD were implemented similarly to the correlation used in Flownex, the difference can be ascribed the changes made to the permeability of the bed outlet. The detailed geometry downstream of the bed was determined to not influence the upstream results and therefore was not modelled in CFD in order to minimize the cell count.

In the CFD model a reported 2.02 kW was removed by the water jacket, compared to 8.15 kW reported by the Flownex model. As the experimental values are not reported this parameter could not be validated, yet the difference amounts to only 4 % of the overall heat transfer. The sensitivity of this value was analysed in the network-model, and it was determined that it does not have a significant impact on the results.

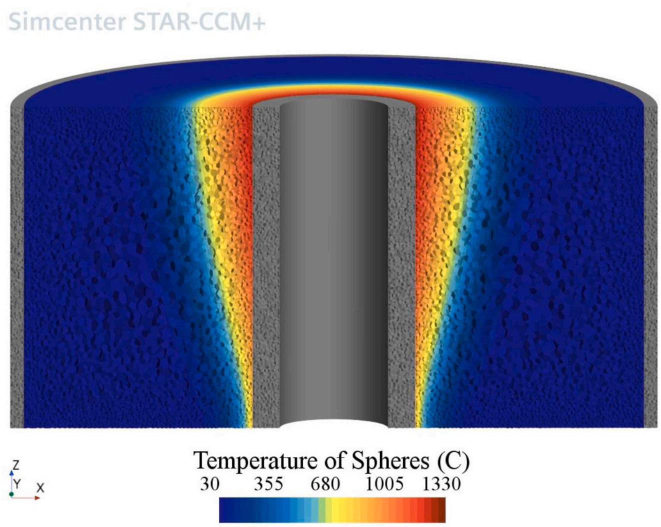

Fig. 9. Solid temperature distribution in 3D CFD simulation.

4.4. Sensitivity analysis

Grid independence was investigated for both the Flownex model (radial and axial incrementing) and the 3D CFD (cell size) and the optimal values were used in both cases.

To ensure there is one-to-one mapping of adjacent cells where the porosity changes abruptly the choice of mesh was important. With the approach used, a polyhedral mesh had to be used in STAR-CCM+ with the alternative to specify a directed hexagonal mesh, where interpolation would be needed, not being feasible. Due to the predominant upwards flow direction and radial heat transfer, an aligned hexagonal mesh could be a better choice for numerical stability, but this was not found to be an issue with the hexagonal mesh.

The experimental uncertainties associated with the temperature measurements are rather small (<3.5 %), such that error bars were not included on the results graphs as it would impair readability. It was investigated which parameters had the biggest effect overall in the results comparison. For the CFD model it was found that the interaction area density (area per volume) had a significant impact especially in the inner regions where a larger convection area transferred more heat away from the solid phase into the gaseous phase. A single value was specified and a recommendation for further improvement is to also make this value a function of porosity, as is the physical case.

A detailed sensitivity analysis was not performed for every parameter of the respective software codes to understand the quantitative influence on the results. Another recommendation is a finer division of local porosities to also include the oscillatory porosity variation in the near-wall regions the effect of which should be investigated to also understand the influence on the local forms of heat transfer.

5. Conclusions

It was shown by De Beer et al. [26] that the effective packed bed thermal conductivity at the near-wall region is dependent on the oscillatory nature of the porosity distribution in this location. As was concluded from the results, that the effect of thermal dispersion and how to improve this in the CFD results need to be investigated. The largest disagreement with results from the CFD was seen in this section of the bed, where the porosity was averaged in the approach used. Implementing a method to correlate the thermal conductivity better to these observations should be investigated. Flownex showed good agreement with the experimental results for the case in this study, where thermal energy is introduced with electric heaters on the inner periphery of the bed and not generated in the bed itself. Further recommended research is to also validate its performance where heat due to fission is also generated within fuel elements and including the corresponding neutronic feedback in the results. This capability is available in the software and requires the reactivity feedback coefficients to be known. Such a solution could be of interest to benchmark tests of future reactors [27], or to be applied as a digital plant demonstrator [28]. Another approach that results from Flownex can be compared to is that of using an explicit bed generated by DEM, coupled to the CFD model which will also allow explicit modelling of particle thermal radiation [29]. In future a comprehensive study will be performed of all HTTU forced convection tests evaluating the effect of a more detailed specification of the porosity and the implementation of other relevant effective thermal conductivity models.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Nomenclature

A	cross-sectional flow area
D_p	particle diameter
ε	bed local or average porosity
f_E	Ergun friction factor
f_{KTA}	KTA friction factor
H	bed height
$\dot{m}$	mass flow rate
μ	fluid dynamic viscosity
Δp	bed pressure drop
Re_0	Modified Reynolds number
ρ	fluid density
v_s	bed superficial velocity

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