

A comparative numerical investigation of the thermal-fluid phenomena between helium and nitrogen cooled pebble bed reactors

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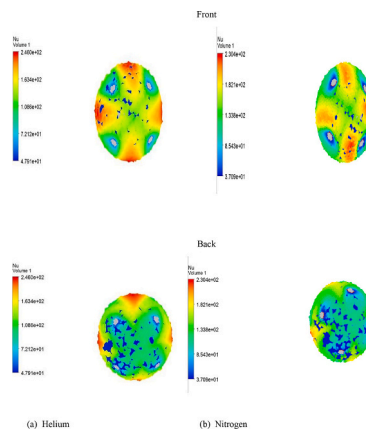
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HIGHLIGHTS

- Thermal-hydraulic performance of two coolants is investigated in a Pebble Bed Reactor.
- A CFD model for a segment of pebbles and another for the whole core are developed.
- Core performance under normal conditions and after reactor shutdown is assessed.
- Temperature distribution, heat transfer coefficient, and reactor power are reported.
- Nusselt number and the stored heat in the pebbles are analyzed.

GRAPHICAL ABSTRACT



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ABSTRACT

The study assesses the thermal-hydraulic performance of a pebble bed type nuclear reactor using nitrogen and helium as coolants. The analysis is done in two separate parts using CFD. First, a segment of the pebbles is modeled and later the whole reactor core. The study assesses the core performance under normal and after reactor shutdown conditions using these two different coolants. The assessment concludes that nitrogen as a coolant candidate for PBR behaves in an acceptable manner in both conditions at a cost of increased pumping power consumption. It is found that under steady state conditions, the heat stored in the pebbles (both for the segment and the whole core) is more in the case of the nitrogen cooled bed compared to the helium cooled bed.

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1. Introduction

The Pebble Bed Reactor (PBR) is a high temperature reactor (HTR) type and is a modern graphite-moderated gas-cooled reactor [14]; it is fueled by spherical elements called pebbles. Each pebble is made of pyrolytic graphite containing about 12,000 microscopic tristructural-isotropic (TRISO) coated fuel particles and it contains only 9 grams of uranium that provide a low power density reactor. The massive graphite core and low power density provide inherent safety features where the preferred coolant selection considered for the PBRs projects has been helium (He₂) [15], but other gases could also be candidates such as nitrogen [30], carbon dioxide [18], and supercritical carbon dioxide [19] among others.

Currently, helium and CO₂ are the only two coolants considered in gas-cooled reactor projects [3,13]. Helium offers neutronic transparency; it is chemically neutral (inert gas), it has optical transparency, and it allows high working temperatures. However, because of its nature it tends to leak through circuit seals and it is also expensive and difficult to store [29]. These are part of the reasons that China have decided to cool the HTR-PM (pebble bed type reactor) with helium and use a steam generator for electricity generation [39]. The use of CO₂ is limited by the fact that it causes graphite corrosion problems at temperatures above 500 °C [3].

Under the above circumstances, nitrogen could be considered as candidate coolant. This concept is not new, but there is lack in the literature of the analysis of the nitrogen cooled pebble bed reactor core numerically. Several efforts have been made to model heat transfer and fluid flow through the PBR core ([4,7,17,19,22,23,27,36]). However, there is no study in which heat transfer and fluid flow inside the nitrogen cooled pebble bed reactor core have been analyzed and even there is no reported information about the performance of nitrogen as coolant in PBRs, at least to our knowledge.

The thermal properties of nitrogen are similar to that of CO₂, as can be seen in Table 1. However, it has a small absorption cross-section that could result in nitrogen activation by neutron capture that could cause an activation problem affecting the PBR core reactivity. Owston [30] has already assessed the possibility of core reactivity effects for nitrogen activation and it has been concluded that these effects are negligible and it does not prevent its use in direct closed Brayton cycles.

The aim of this study is to analyze and compare the thermal-fluid behavior of a nitrogen cooled pebble bed reactor with a helium cooled pebble bed reactor under normal and transient conditions and investigate the effect of the coolant on the reactor core performance after reactor shutdown. In fact the analysis presented here will be two-fold. The first one is the modelling of the heat transfer and fluid flow through the PBR core and the second one is to assess the performance of nitrogen as a coolant for PBRs. In order to study the thermal-hydraulic characteristics of the two gas-cooled pebble bed reactors, CFD methods have been adopted to simulate the flow and heat transfer through the packed pebble beds. Two separate three-dimensional CFD models (one for a segment of pebbles and the other for the whole core) were developed to investigate the thermal-hydraulic characteristics within the packed beds under steady-state and transient conditions.

Several papers in the literature have modeled a segment of the PBR core. However, none of them considered nitrogen as a coolant, Feng and Lin [9] investigated the effects of BCC (body-centred cubic) and FCC

(face-centred cubic) arrangements on the thermal-hydraulic characteristics within pebble beds using CFD. Yu et al. [37] developed a CFD method to simulate a segment of the simplified high-temperature gas-cooled reactor core. In their study, four kinds of arrangements were investigated; namely, the simple cubic (SC), BCC, FCC, and a combination structure of BCC and FCC. Taylor et al. [34] developed a CFD model to investigate the effect of the spacing between adjacent pebbles in a unit cell of a pebble bed, adopting a BCC arrangement of pebbles.

The models employed in the current study examine the effect of the different coolants on the thermal-hydraulic phenomena in the pebble bed reactor core considering the temperature rise over the reactor for the two coolants to be the same, $\Delta T_{He} = Q_T/(\dot{m}C_p)_{He} = \Delta T_{N_2} = Q_T/(\dot{m}C_p)_{N_2}$. In the current study, for the flow and heat transfer simulated in the pebble bed segment and the whole reactor core, several essential fluid flow and heat transfer parameters have been examined, including the temperature distribution, the heat transfer coefficients, Nusselt numbers, the reactor power, and the stored heat in the pebbles.

2. Mathematical modelling

Two separate three-dimensional CFD models were developed to simulate the thermal-hydraulics of the packed pebble beds. The first was an explicit CFD model of a segment of pebbles packed in a BCC arrangement and the second was a porous media CFD model representing a randomly packed pebble bed core.

2.1. Governing equations for a segment of pebbles

An explicit model for the segment of the pebbles, including the thermal flow in the voids, the heat generation in the pebbles, the conduction heat transfer through the fuel pebbles and the convection heat transfer between the pebbles and the fluid, has been developed.

The governing equations used to simulate the thermal-fluid characteristic of a segment of pebbles under steady-state and transient conditions include the equations for the conservation of mass, momentum and energy and the $k - \epsilon$ two-equation turbulence model ([1]. CFX R14.5 User's Guide). The following set of equations are solved using ANSYS CFX 19.1.

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{V}) = 0 \quad (1)$$

Momentum equation

$$\frac{\partial (\rho \mathbf{V})}{\partial t} + \nabla \cdot (\rho \mathbf{V} \mathbf{V}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} + \rho \mathbf{g} \quad (2)$$

where the stress tensor, $\boldsymbol{\tau}$, is related to the strain rate by the following equation:

$$\boldsymbol{\tau} = \mu \left(\nabla \mathbf{V} + (\nabla \mathbf{V})^T - \frac{2}{3} \delta \nabla \cdot \mathbf{V} \right) \quad (3)$$

Thermal energy equation

$$\frac{\partial (\rho h)}{\partial t} + \nabla \cdot (\rho \mathbf{V} h) = \nabla \cdot (\lambda \nabla T) + \boldsymbol{\tau} : \nabla \mathbf{V} + S_E \quad (4)$$

The viscous dissipation term $\boldsymbol{\tau} : \nabla \mathbf{V}$ is always positive, and it models the internal heating by the shear stresses in the fluid and is negligible in most flows. In the case of the solids the velocity is zero.

Despite being a simplification, the thermal energy equation can be used for both liquids and gases to avoid potential stability issues with the total energy formulation ([1]. CFX R14.5 User's Guide). CFX has two options for simulation: total energy equation and thermal energy equation. Under the "thermal energy" option, it activates the enthalpy/temperature equation, but does not include compressibility effects. It is used for low speed thermal models like combustion, heat exchangers,

Table 1

The thermal and physical properties of some gas coolants at 60 bar and 500 °C.

Property	He	CO ₂	N ₂
Density (kg/m ³)	3.70	40.85	25.53
Specific Heat (J/kg-K)	5188	1183	1126
Thermal conductivity W/m-K	0.3030	0.05583	0.0548
Viscosity (10 ⁻⁶ Pa-s)	37.30	34.46	35.39
Absorption cross section (barn)	0.0	0.003	2.4

reactors etc.

The “total energy” option activates the full enthalpy equation, including compressibility effects. It is used for high speed flows or anywhere else where compressibility is important. However, it adds complexity and might affect robustness due to additional coupling. Here, the option used is “thermal energy”.

It should be mentioned that radiation heat transfer is not accounted for in the BCC packed bed because Sobesa et al. [33] showed that, in a helium gas cooled high temperature reactor, the coolant is almost transparent to thermal radiation and the temperature difference between the neighboring pebbles is small.

2.2. Governing equations for the whole core

For the whole core, an implicit or porous media model in which the presence and the effect of the pebbles / fuel spheres have been considered, was used.

Continuity equation

$$\frac{\partial(\epsilon\rho)}{\partial t} + \nabla \cdot (\epsilon\rho\mathbf{V}) = 0 \quad (5)$$

Momentum equation

$$\frac{\partial(\epsilon\rho\mathbf{V})}{\partial t} + \nabla \cdot (\epsilon\rho\mathbf{V}\mathbf{V}) = -\epsilon\nabla P + \nabla \cdot (\epsilon\boldsymbol{\tau}) + \epsilon\rho\mathbf{g} - \nabla P_{\text{porous}} \quad (6)$$

where $-\nabla P_{\text{porous}}$ is the extra pressure drop due to the presence of fuel pebbles inside the core, which is accounted for by the modified Ergun correlation as follows ([6,8,16,24]):

$$\nabla P_{\text{porous}} = -180 \frac{(1-\epsilon)^2}{\epsilon^3} \frac{\mu \mathbf{V}_s}{d^2} - 1.8 \frac{1-\epsilon}{\epsilon^3} \rho \frac{|\mathbf{V}_s| \mathbf{V}_s}{d} \quad (7)$$

where $\mathbf{V}_s$ is the superficial velocity.

It should be mentioned that the CFD code used for the simulation of the full core only makes provision for the Ergun correlation. However, Hicks [32] showed that the Ergun correlation is not valid for packed beds consisting of uniformly-sized spheres for $Re/(1-\epsilon) > 500$ with $Re = \rho V_s d / \mu$. At $Re/(1-\epsilon) = 5000$ the Ergun correlation differs by +35.7% from the KTA pressure drop correlation [28], at $Re/(1-\epsilon) = 10,000$ by +45.8% and at $Re/(1-\epsilon) = 30,000$ by +63.2%. Thus, it is more appropriate to employ the KTA pressure drop correlation [28]. However, in the simulations discussed in the paper the fact that the pressure drop is not predicted entirely accurately is not crucial because (i) fixed mass flow rates have been considered, and (ii) considering the high operating system pressure of 9 MPa the difference in the local pressure at any point will have a negligible effect on the phenomena that are being focused on.

2.3. Energy equation

Fluid phase

$$\left[(\rho c_p)_f \right] \epsilon \left(\frac{\partial T_f}{\partial t} + \nabla \cdot (\mathbf{V} T_f) \right) = \nabla \cdot (K_{\text{eff},f} \nabla T_f) + h_{sf} a_{sf} (T_s - T_f) \quad (8)$$

Solid phase

$$\left[(\rho c_p)_s (1-\epsilon) \right] \left(\frac{\partial T_s}{\partial t} \right) = (1-\epsilon) \nabla \cdot (k_s \nabla T_s) - h_{sf} a_{sf} (T_s - T_f) + S_h \quad (9)$$

where k_s is the effective thermal conductivity for the solid, which accounts for both the conduction and radiation heat transfer between fuel pebbles. The effective thermal conductivity is calculated using the modified Zehner–Schlünder [12] correlation as follows:

$$k_s = 4\sigma T^3 d_{\text{peb}} \left\{ \left[1 - p^{0.5} \right] (1-p) + \frac{p^{0.5}}{\left(\frac{2}{\epsilon} - 1 \right)} \left(\frac{B_z + 1}{B_z} \right) \left[1 + \frac{1}{\left(\frac{2}{\epsilon} - 1 \right) k_{\text{peb}}} \right]^{-1} \right\} \quad (10)$$

Where

$$B_z = 1.25 \left(\frac{p}{1-p} \right)^{\frac{10}{9}}$$

The last term in Eq. (9), S_h^3 (W/m) is the heat source generated by the nuclear chain reactions.

2.4. $k-\epsilon$ Turbulence equation

The standard $k-\epsilon$ turbulence model is applied in the present work for both models: segment and whole core. The turbulent kinetic energy, k , and energy dissipation rate, ϵ_e are obtained by using the following transport equations [2,21].

$$\frac{\partial(\rho k)}{\partial t} + \nabla \cdot (\rho \mathbf{V} k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \nabla k \right] + G_k - \rho \epsilon_e \quad (11)$$

$$\frac{\partial(\rho \epsilon_e)}{\partial t} + \nabla \cdot (\rho \mathbf{V} \epsilon_e) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_e} \right) \nabla \epsilon_e \right] + \frac{\epsilon_e}{k} (C_{\epsilon 1} G_k - C_{\epsilon 2} \rho \epsilon_e) \quad (12)$$

where μ_t turbulent viscosity is modeled by

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon_e} \quad (13)$$

and G_k represents the generation of turbulent kinetic energy, given by:

$$G_k = (\mu + \mu_t) \nabla \mathbf{V} : [\nabla \mathbf{V} + (\nabla \mathbf{V})^T] \quad (14)$$

$C_\mu = 0.09$; $C_{\epsilon 1} = 1.44$; $C_{\epsilon 2} = 1.92$; $\sigma_k = 1$; $\sigma_e = 1.3$ are empirical constants for the turbulence model.

2.5. Power variation after shutdown

The fission power produced by delayed neutrons decreases rapidly after shutdown and then the decay heat determines the reactor power. The decay heat depends on the reactor power, the operating time, and the time since shutdown. The decay heat is calculated empirically [38] using the following equation:

$$Q_{DH}(t_0, t_s) = Q_T A (t_s^{-a} - (t_0 + t_s)^{-a}) \quad (15)$$

where Q_T is the reactor power before the shutdown, t_s is the time elapsed since reactor shutdown, t_0 is the time in operation before shutdown, which in this study was considered to be 35,424,000 s taken from the DIN document that served as a reference for this study [5]. A and a are the constants and their values for various time intervals are given in Table 2. During steady-state operations, the heat source term in Eq. (4), S_E , is Q_T per unit fuel volume. After shutdown, during the unsteady phase, the heat source term is Q_{DH} per unit fuel volume. It should be mentioned that for the segment of the pebbles and the whole core, Q_T , the reactor power before shutdown, is assumed constant and distributed according to a semi-sine function of the axial distance from the bottom

Table 2
Constants A and a values.

Time Intervals (s)	A	a
$0.1 < t_s < 10$	0.0603	0.0639
$10 < t_s < 150$	0.0766	0.181
$150 < t_s < 4e+6$	0.130	0.283
$4e+6 < t_s < 2e+8$	0.266	0.335

of the core respectively. Since the power density is the highest around the middle core, it will be reasonable to assume that the power profile varies approximately as a semi-sine function of axial position [20].

3. CFD simulation

3.1. Geometry and mesh models

Fig. 1 shows the schematic of the geometry of the simulation domain and mesh models of the BCC arrangement of the segment of fuel pebbles. Fig. 1(a) shows a three-dimensional view of the BCC fuel pebbles, which consists of nine layers of pebbles with four full pebbles, twelve quarter pebbles and eight eighth pebbles. The value of the overall porosity in the segment is 0.32 and the width of the bed is 0.069 m, and the diameter of the pebbles is 0.06 m. As can be seen from Fig. 1(b), in order to get more accurate results, the mesh is unstructured and an inflation layer is applied between the gas and pebbles. This arrangement can be extended to a whole pebble bed reactor core by applying symmetry boundaries on the four side surfaces. The computational domain of the full reactor core is given in Fig. 2, where the coolant enters from the top of the core. The main parameters of the core are given in Table 3.

It can be seen in Fig. 2 that the computational domain consists of an inner or center graphite reflector, an annular packed pebble bed, namely the fueled zone, and an outer graphite reflector.

3.2. Physical properties

The dependence of the physical properties of both helium and nitrogen on temperature and pressure is accounted for employing the NIST REFPROP database [26] implemented in FLUENT and CFX.

3.3. Numerical method and boundary conditions for a segment of pebbles

The heat transfer process within the segment of pebbles has been simulated using ANSYS CFX 19.1 in which an upwind discretization

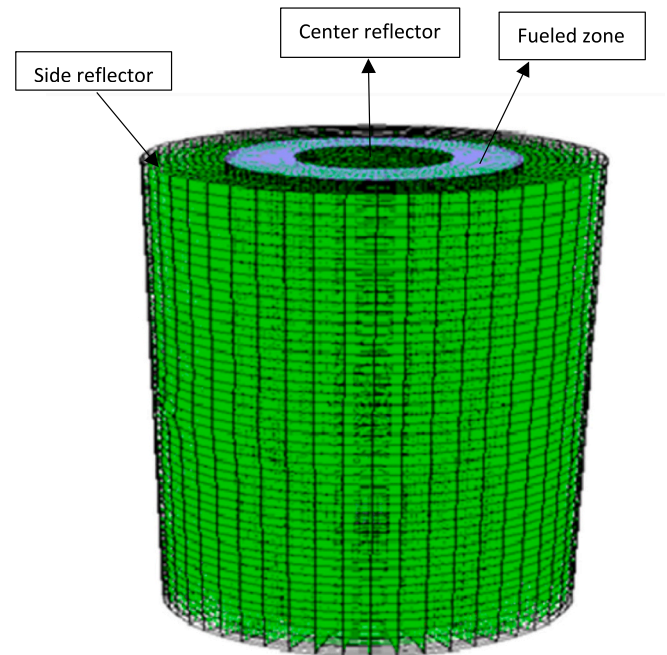


Fig. 2. Computational domain of the reactor core.

scheme, second-order backward Euler, RMS residuals, convergence criterion of 10^{-6} , are all employed to ensure sufficiently small convergence errors. It should be noted that CFX considers the contacts between the spheres automatically to calculate the contact heat transfer.

At the top of the model geometry located at $y = 0.276$ m, the inlet mass flow rate of the coolant is prescribed with a temperature of 780 K, turbulence intensity of 5%, and the mass flow rate for the helium has been assumed to be 0.0086 kg/s. Based on the assumption that the

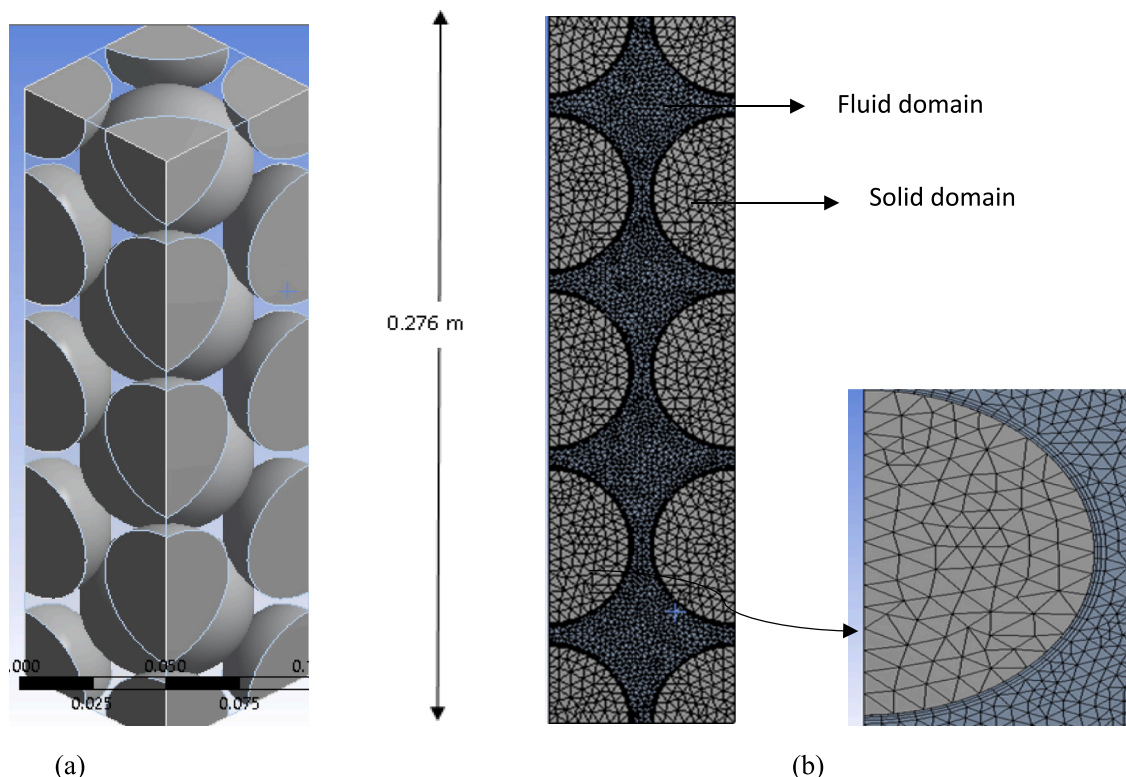


Fig. 1. Schematic of (a) isometric view of the geometry and (b) side view of the mesh for BCC arrangement.

Table 3

Reactor core parameters.

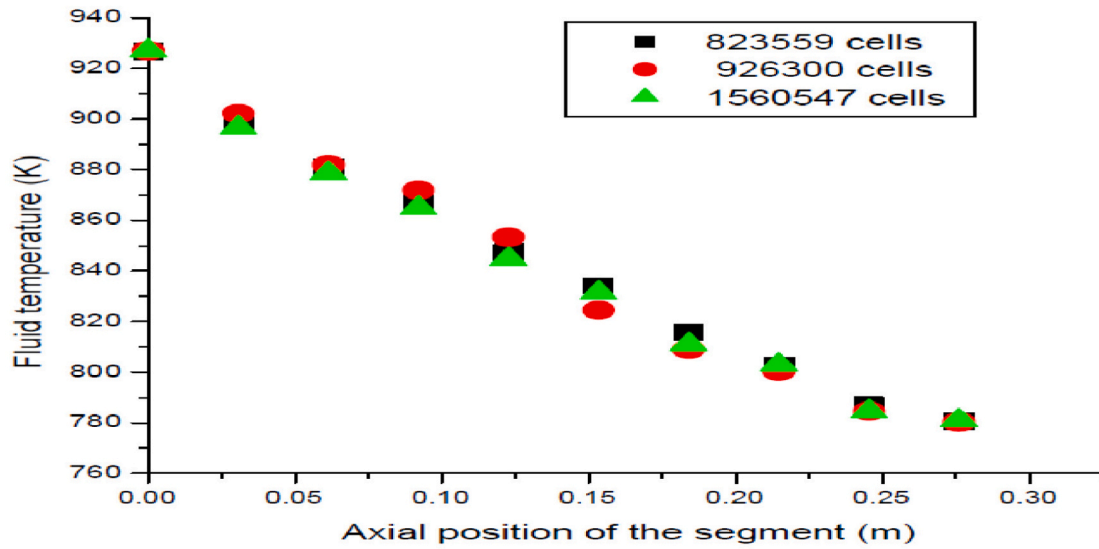
Reactor core parameters	
Core inlet temperature (K)	778
System operating pressure (MPa)	9
Coolant flow direction	Downwards
Core outer diameter (m)	3.7
Core inner diameter (m)	2
Outer diameter of the side reflector (m)	5.8
Core height (m)	11
Bulk porosity	0.39

temperature rises over the length of the segment of pebble associated with the helium and the nitrogen must be the same, $\Delta T_{He} = Q_T / (\dot{m}C_p)_{He} = \Delta T_{N_2} = Q_T / (\dot{m}C_p)_{N_2}$, the corresponding mass flow rate for the nitrogen is obtained as 0.0387 kg/s. It can be seen from the equation

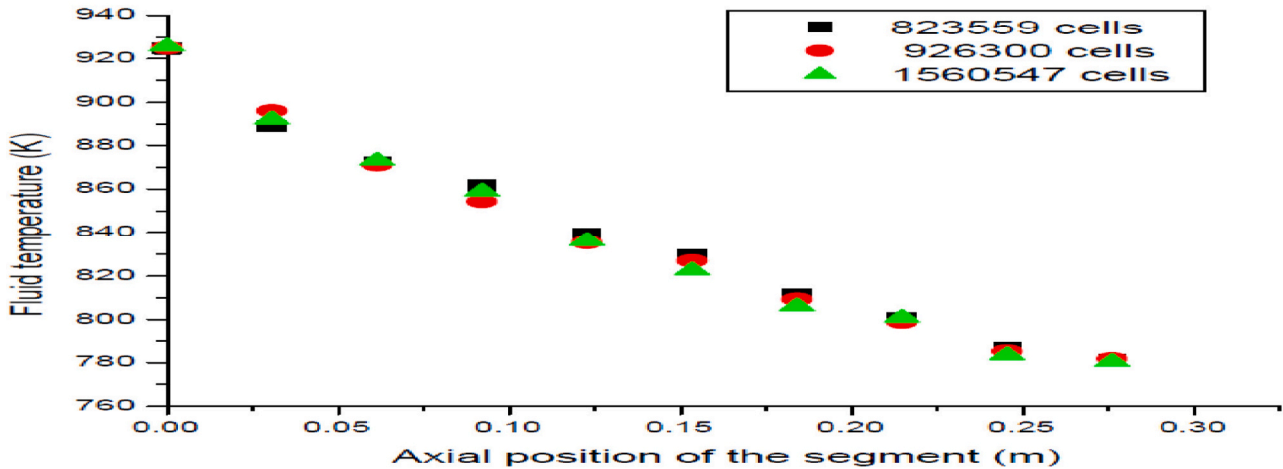
above that the ratio between the mass flow rates for the helium and the nitrogen is determined by the ratio between the C_p values for helium and nitrogen. At the outlet boundary located at $y = 0$, a zero gauge pressure is set. No-slip wall boundary conditions are assumed on the surfaces of the pebbles. The cross-sectional planes of the spheres at the inlet (top) and the outlet (bottom) of the segment as well as the four side surfaces are set as symmetry boundaries. In the fueled region, under steady-state conditions, a constant heat generation source of 7.24 MW/m³ is set as the fission source and under transient conditions; the heat source was calculated according to Eq. (15).

3.4. Mesh dependency for a segment of pebbles

In order to investigate the grid dependence of the simulation, different mesh densities have been employed, namely 823,559; 926,300; 1,560,547 cells, respectively. Fig. 3 and Fig. 4 show for helium and

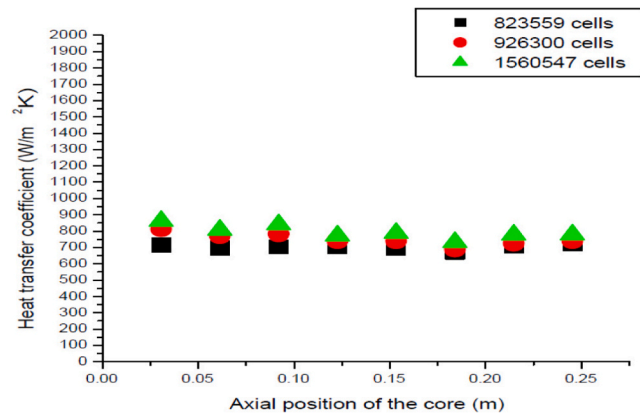


(a)

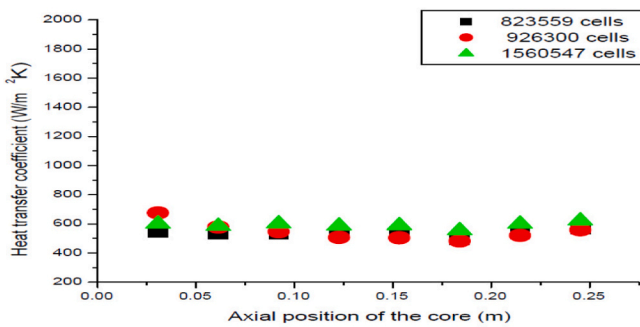


(b)

Fig. 3. Fluid temperature as a function of axial position for grid dependence test for the segment of pebbles for a) He, b) N₂.



(a)



(b)

Fig. 4. The heat transfer coefficients as a function of axial position for grid dependence test for the segment of pebbles for a) He, b) N₂.

nitrogen, the fluid temperature and the heat transfer coefficients as function of axial position along a selected line for the three cases. From Figs. 3 and 4, it is noticed that for both coolants, the fluid temperature distributions and the heat transfer coefficients along the axial direction are almost the same (maximum difference is approximately 4%) for the three grids used. This means that the three mesh systems used in the simulations have only a small effect on the numerically predicted temperatures. Hence, considering computational time and memory, a grid size of 926,300 was considered to provide a mesh independent solution and was selected for the simulations.

3.5. Numerical method and boundary conditions for the whole core

In order to simulate the whole core, ANSYS FLUENT 14.5 has been used and the reactor core filled with thousands of fuel spheres is modeled as a porous medium and the governing equations are solved using the semi-implicit method for pressure linked equations algorithm [10,31] and the equations are discretized by using the second-order upwind scheme [31].

The boundary types are shown in Table 4. At the top of the geometry, the inlet mass flow rate for the helium is assumed to be 192 kg/s. Based on the assumption that the temperature rises over the length of the core associated with the helium and the nitrogen must be the same, $\Delta T_{He} = Q_T / (\dot{m}C_p)_{He} = \Delta T_{N_2} = Q_T / (\dot{m}C_p)_{N_2}$, the corresponding mass flow rate for the nitrogen is 864 kg/s. The temperature at the inlet is assumed to be 773 K and the turbulence intensity at the inlet to be 4%, while at the outlet boundary a zero gauge pressure is set. No-slip wall boundary conditions are assumed at the solid surfaces. The outer surface of the side reflector is kept at a constant temperature of 564 K. Adiabatic

Table 4

Boundary conditions for numerical simulation of the whole core.

Computational boundary	Boundary conditions
Inlet	Mass flow-inlet
Outlet	Pressure-outlet
Bottom surfaces of reflectors	Adiabatic
Top surfaces of reflectors	Adiabatic
Outer surface of the center reflector	Wall
Inner surface of the side reflector	Wall
Outer surface of side reflector	Fixed temperature

boundary conditions have been assumed for the top and bottom surfaces of the reflectors since they are insulated. For the whole core, the heat source is not considered to be constant and, in this study, the power profile was assumed to vary approximately as a semi-sine function of axial position. As mentioned previously, the average power density of each fuel pebble is taken to be 7.24 MW/m³ giving the power of the core to be 400 MW.

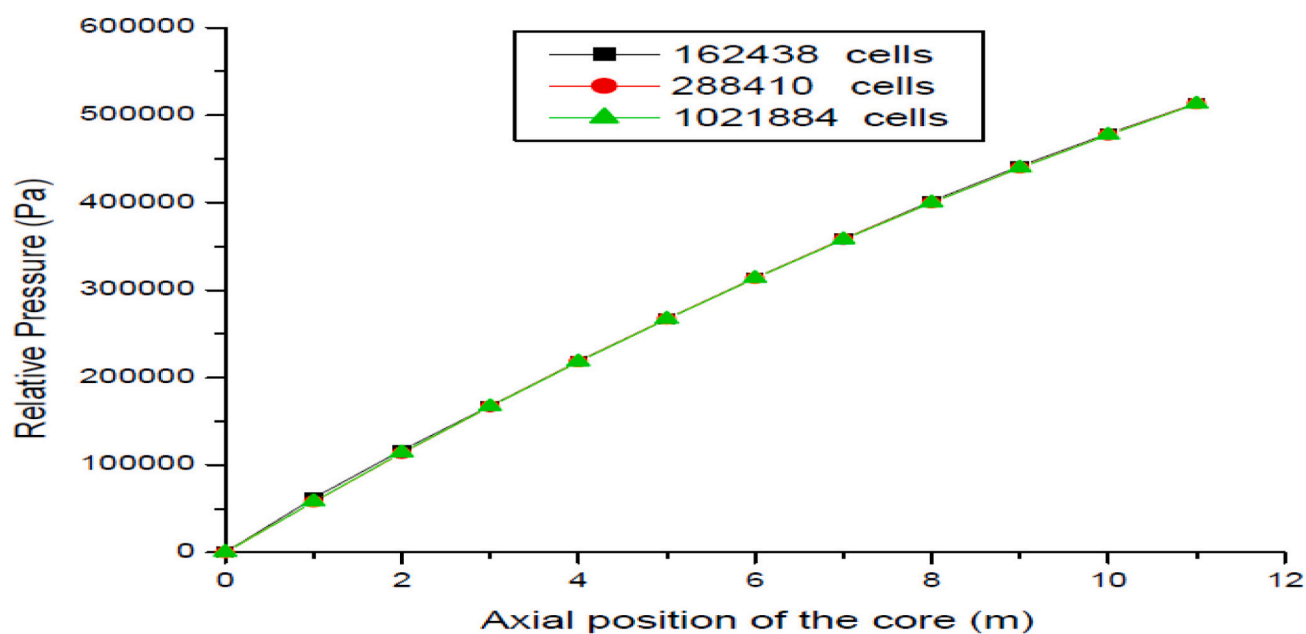
3.6. Mesh dependency for the whole core

Various grid sizes have been tested with cell numbers equal to 162,438; 288,410, and 1,021,884, respectively to investigate the grid dependence of the simulations. Fig. 5 shows for helium and nitrogen, the relative pressure distribution (relative to the operating pressure) as a function of axial position for all three cases. In Fig. 5 it can be seen that the pressures for both coolants are almost the same for all the three grids that were employed. This means that the three mesh systems used in the simulations have a negligible effect on the numerically predicted pressures. Thus, the mesh size of 288,410 was considered to provide a mesh independent solution and selected for the study.

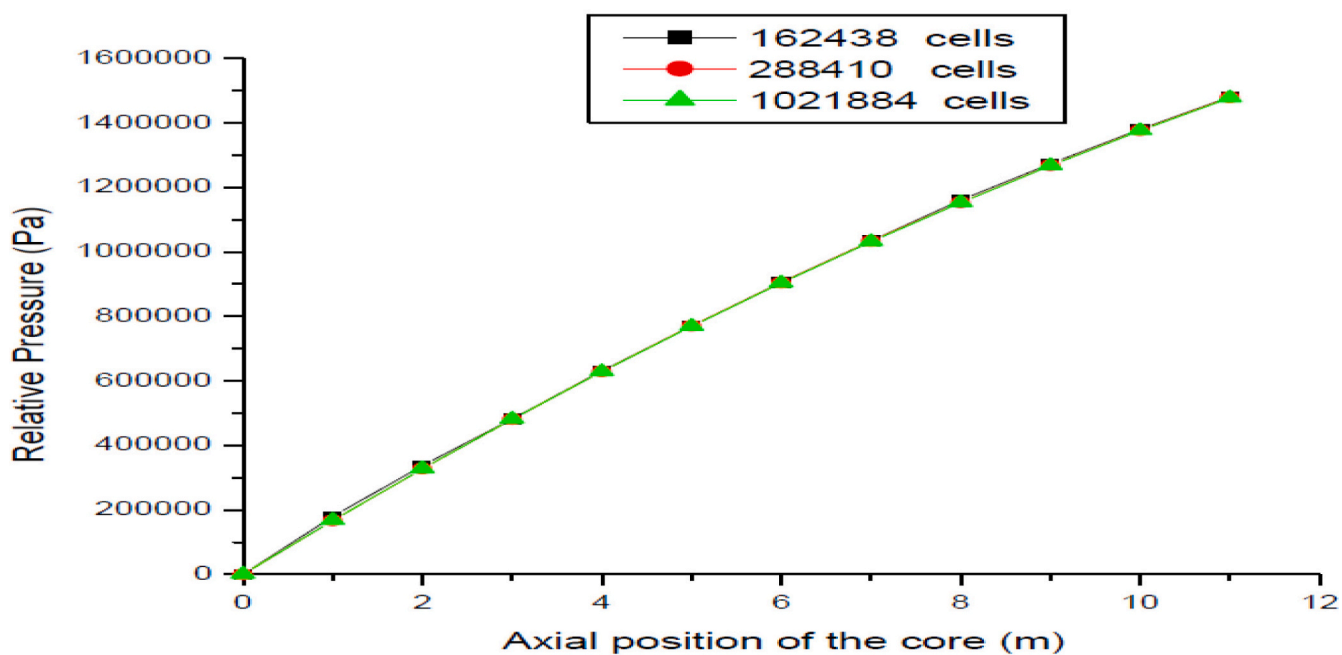
3.7. Model validation

In order to validate the numerical model, CFD simulation results of the whole core for helium and all boundary conditions, assumptions, etc. being the same as for main simulation, were compared with the calculated decay heat source obtained by the DIN 25485 standard [5]. Fig. 6 shows the comparison between the CFD results for the reactor power after shutdown obtained in this study for the whole core and the corresponding the DIN 25485 standard decay heat source. A good agreement can be observed between them. It should be mentioned that for the segment of pebbles, the well-known KTA heat transfer correlation and the Ergun pressure drop correlation are adopted as design criteria to compare the results from the CFD simulations with the values predicted by them and it will be discussed in the following section. It should be noticed that although the BCC segment is a structured packed bed and the KTA correlation was derived for an unstructured packed bed, the full core was assumed to be an unstructured packing and therefore the KTA correlation would be applicable to that.

While most studies consider reduction in inlet coolant mass flow rate after shutdown, in the current study there is no reduction in inlet coolant mass flow from the nominal value. The motivation for this choice is based on the fact that in the case of the segment of pebbles there is no lateral transport of heat due to the symmetry boundary conditions. Should a Pressurized Loss Of Forced Cooling (PLOFC) or a Depressurized Loss Of Forced Cooling (DLOFC) be modeled, this will only lead to an accumulation of heat. It was, therefore, decided to model a reactor scram without loss of forced coolant for both the segment of pebbles and the full core to understand the performance of the packed beds for the two coolants. The temperatures obtained in the current study are of the same order of magnitude as the temperatures obtained by Mkhabela [25]. Mkhabela [25] performed CFD simulations of the transient response of the PBMR-400 as a result of a PLOFC and a DLOFC. In the simulations there was a reduction in the reactor inlet coolant mass flow rate from the nominal 192.7 kg/s to 0.2 kg/s over 13 s.



(a)



(b)

Fig. 5. Relative pressure as function of axial position for grid dependence, test for the whole core for a) He, b) N₂.

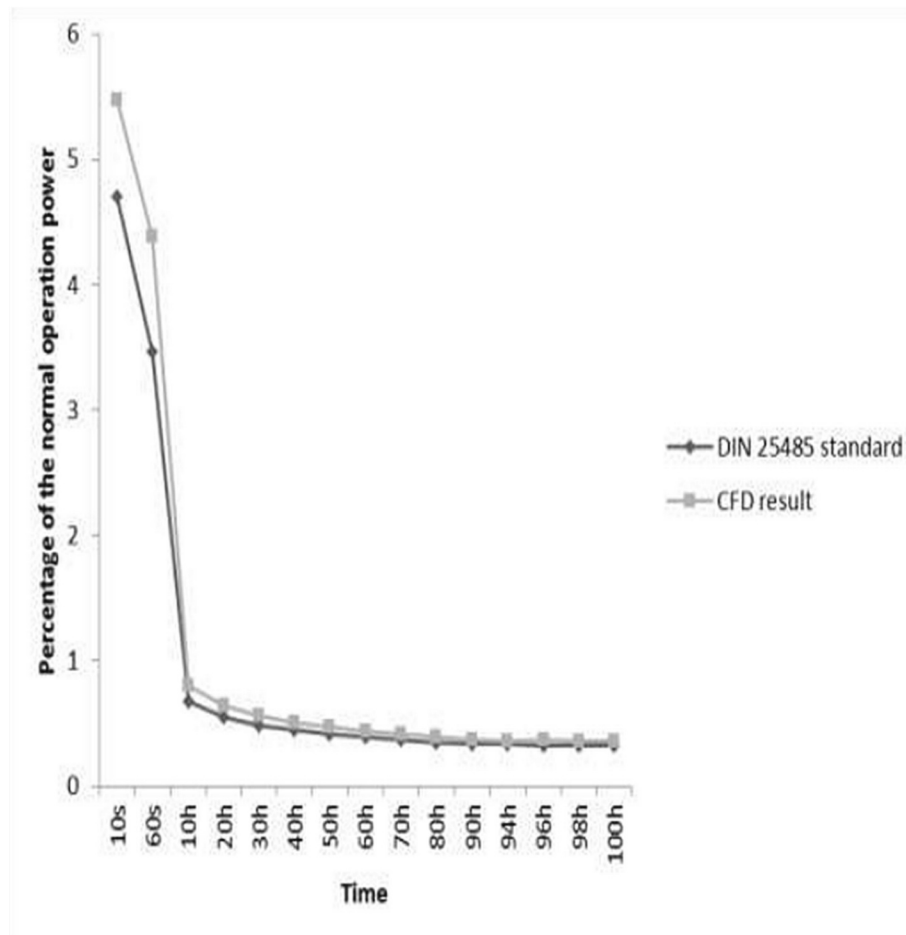


Fig. 6. Comparison between the DIN 25485 standard calculation and CFD results.

4. Results and discussion

First, in order to plot the temperature of the solid and fluid as function of the axial direction of the segment, a line with start point $(x_0, y_0, z_0) = (0.0345, 0, 0.0345)$ and endpoint $(x, y, z) = (0.0345, 0.276, 0.0345)$ for solid and a line with start point $(x_0, y_0, z_0) = (0.03875, 0, 0)$ and endpoint $(x, y, z) = (0.03875, 0.276, 0)$, shown in Fig. 7, were drawn and the temperatures shown in Fig. 8 were extracted along these

specific lines.

Figs. 8(a) and 8(b) show the temperature distributions of the fluid and solid along the axial direction of the segment of pebbles under steady-state conditions for the two coolants (helium and nitrogen) for the assumption of $\Delta T_{He} = \Delta T_{N_2}$. The fluid flows through the pebble bed and collects heat from the pebbles and so its temperature increases in the flow direction and reaches its maximum value at the outlet, as shown in Fig. 8(a). However, compared to the fluid temperature that increases

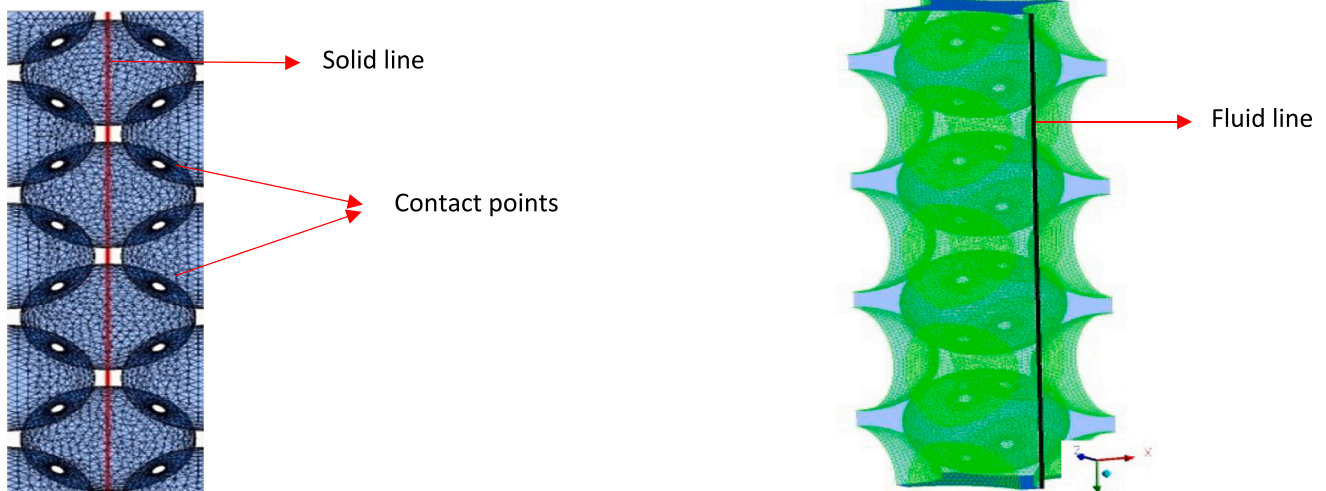
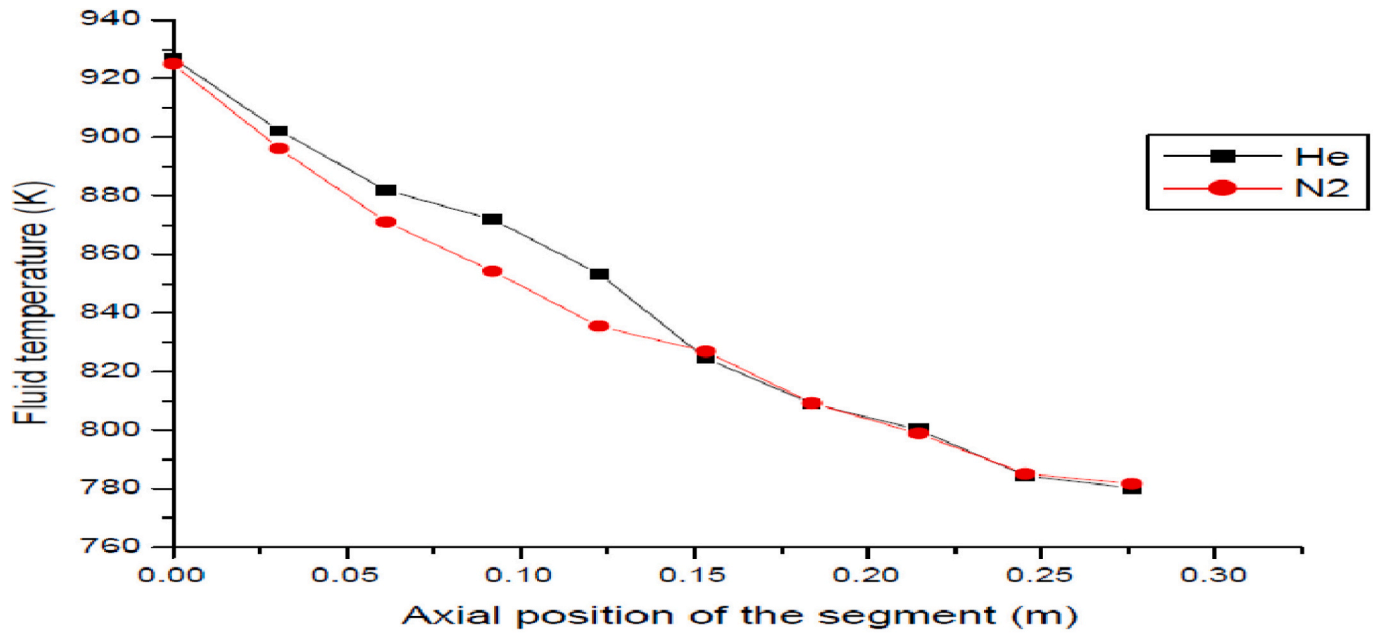
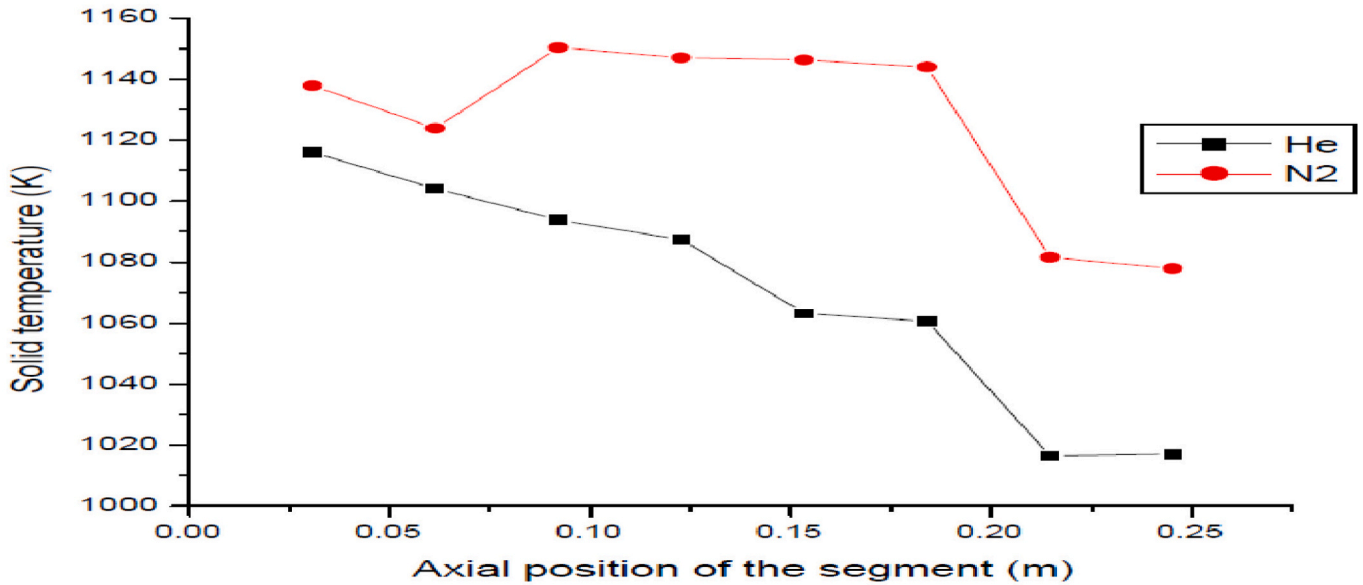


Fig. 7. Schematic of solid and fluid lines



(a)



(b)

Fig. 8. The (a) fluid and (b) solid's temperature distributions along the axial direction of the segment of pebbles for steady-state conditions.

from 780 K to 926 K for both coolants as shown in Fig. 8(b), the temperature of the solid increases only from 1016.9 K to 1115.9 K and 1077.8 K to 1137.8 for He and N2 respectively along the segment. It can also be noted that the temperatures of the solid in the case of the nitrogen are higher than the corresponding temperatures in the case of the helium.

The thermal power of the segment of pebbles can be calculated as follows:

$$Q_T = V_{fuel} \times S_E = \dot{m} C_p \Delta T \quad (16)$$

where $\dot{m}$ is the mass flow rate of the coolant, ΔT is the inlet-outlet temperature rise and V_{fuel} is the volume of the pebbles. From the CFD results, during normal operation the thermal power or rate at which heat is released by the reactor and transferred to the coolant, not accounting for losses, can be calculated as follows:

$$Q_T = (\dot{m}h)_{outlet} - (\dot{m}h)_{inlet} \quad (17)$$

where h is the enthalpy.

The outlet temperature for both coolants can be calculated using Eq. (16) and (17). According to the value for the constant heat generation source given, the total power generated in the segment of pebbles is:

$$Q = V_{fuel} \times S_E = 8 \times \frac{\pi \times 0.06^3}{6} \times 7.24 \times 10^6 = 6551 \text{ W} \quad (18)$$

Then the expected value of the outlet temperature for helium according to the power generated in the segment of pebbles is:

$$T_{out} = T_{in} + \frac{Q}{\dot{m}c_p} = 780 + \frac{6550.598}{0.0086 \times 5188} = 926.8 \text{ K} \quad (19)$$

Based on the fact that the C_p value for helium is 4.5 times that of nitrogen and the mass flow rate for nitrogen is 4.5 times that for helium, that outlet temperature for the nitrogen will be the same as that for helium. As can be seen from Fig. 8(a) for the given ΔT the value of the outlet temperature for nitrogen is 925.0 K which confirms the good accuracy of CFD results.

Fig. 9(a) and 9(b) show the temperature distributions of the fluid and solid respectively along the axial direction of the full core under steady-state conditions for the two coolants (helium and nitrogen) at a radius of 1.425 m from the centerline. The fluid temperatures increase in the flow direction due to collecting heat from the fuel pebbles as the coolants flow through the core from the top to the bottom and the maximum value of the temperature of both coolants occurs at the outlet, as shown in Fig. 9(a).

As mentioned before, when considering the whole core, the power

profile is assumed to vary approximately as a semi-sine function in the axial direction and that the maximum value of the heat generation per unit volume occurs in the middle of the core height. When, comparing Figs. 8(b) and 9(b), it can be seen that unlike the whole core filled with thousands of pebbles where the temperature of the solids rise by >400 K, in the segment of the pebbles in which there are just a small number of fuel pebbles, the value of the temperature of the solids along the axial direction of the segment rise by <100 K. This is in accordance with the temperature rises of the coolants associated with the respective powers released by the full core and the segment of pebbles.

The power P_p required to circulate fluid through reactor is given by Eq. (21) [35].

$$\begin{aligned} P_p &= \rho g Q h_p \\ &= \rho g \frac{\dot{m}}{\rho} \times \frac{\left(\frac{\partial p}{\partial z} \times H_c \right)}{\rho g} \\ &= \frac{\dot{m}}{\rho} \times \left(\frac{\partial p}{\partial z} \times H_c \right) \end{aligned} \quad (21)$$

Where h_p is differential head over the core and H_c the length of the core. As can be seen in Eq. (21), the pumping power increases with increase in mass flow rate and pressure gradient and decrease with density. Therefore, for the assumption, even though the mass flow rate of nitrogen is about 4.5 times the helium mass flow rate, its density is also about 7 times the helium density and its pressure drop over the core is about 3 times the helium pressure drop, as can be seen in Fig. 10. Therefore, the power required to circulate nitrogen through the reactor

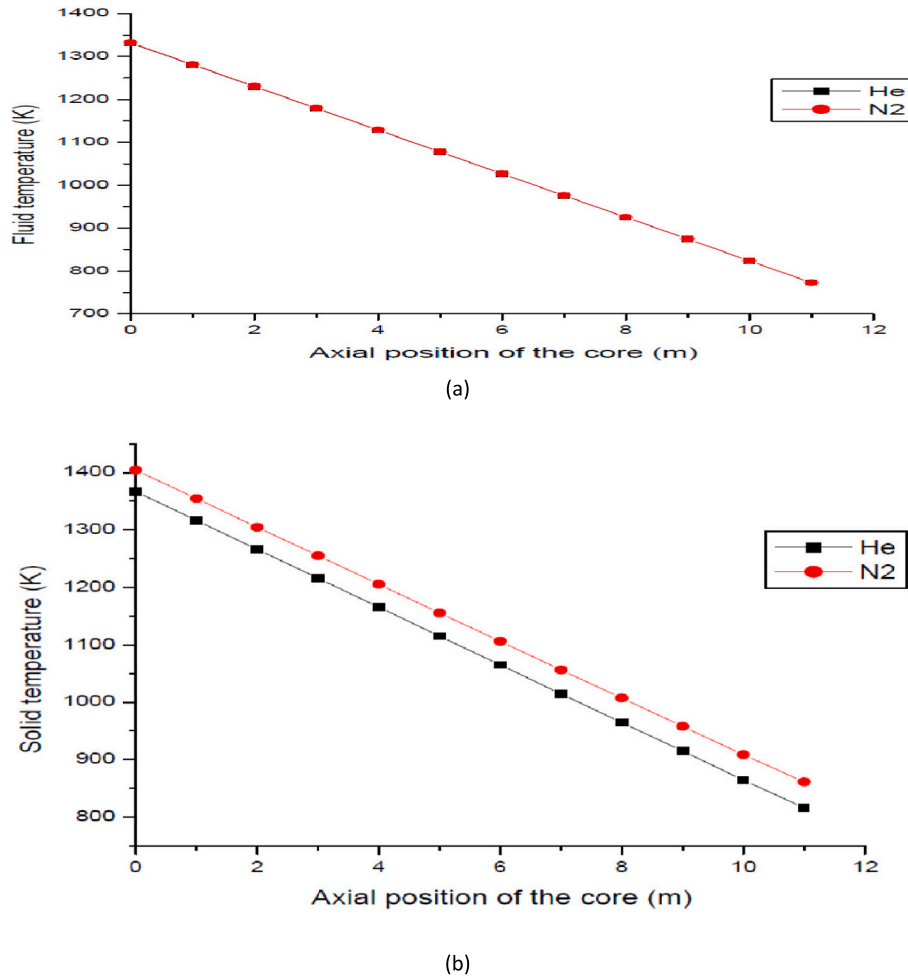


Fig. 9. Temperature distributions for (a) fluid, (b) solid along the axial direction of the core for steady-state conditions.

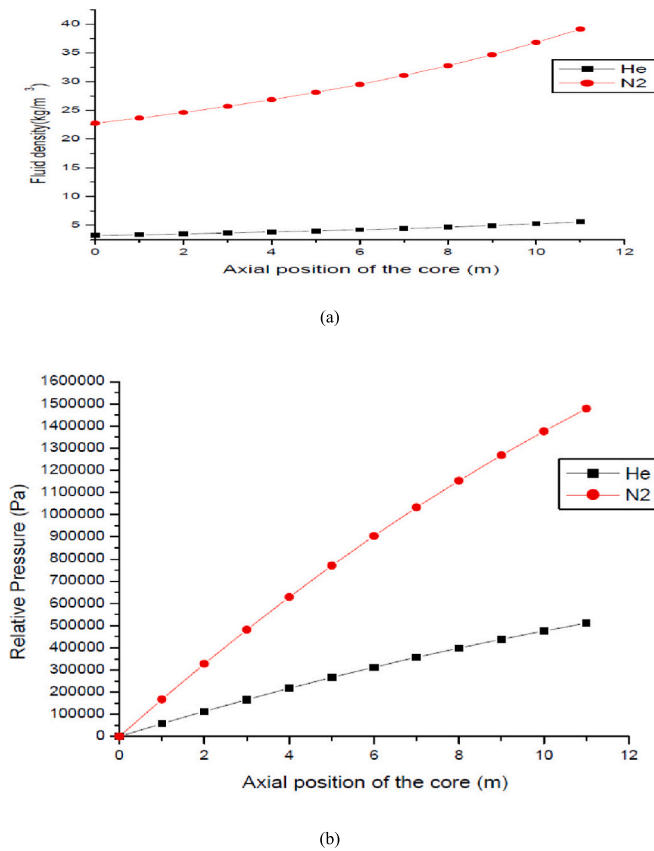


Fig. 10. The a) Fluid density, b) Relative pressure along the height of the core.

is about 1.9 times the power required for the circulation of helium. Hence, the increase in mass flow rate required by the nitrogen-cooled pebble bed reactor to obtain the same cooling performance or heat removal as the helium-cooled pebble bed reactor comes at the cost of increased pumping power consumption.

As mentioned previously, in the current study, the effect of the two different coolants on the thermal-hydraulic phenomena in the pebble bed reactor core has been examined considering the temperature rise over the reactor core for the two coolants to be the same, $\Delta T_{He} = \Delta T_{N2} \cong 559$ K. Thus, according to Eqs. (16) and (21), by changing the value of $\Delta T_{He} = \Delta T_{N2}$, besides the value of the outlet temperatures for the fluid and solid, the value of mass flow rate, pumping power, pressure drop and velocity will change too for the given normal reactor power of 400 MW. For instance, by decreasing the value of temperature rise over the reactor from about 559 K to about 459 K, the value of mass flow rate for helium and nitrogen will be increased from 192 kg/s to 234 kg/s and 864 kg/s to 1052 kg/s respectively and as a result the values of velocity and relative pressure for both coolants will increase, as can be seen in Figs. 11 and 12, and thus the pumping power will increase. Likewise, by increasing the value of temperature rise over the reactor from about 559 K to about 659 K, the values of mass flow rate for helium and nitrogen will be decreased to about 163 kg/s and 733 kg/s respectively and as a result the value of velocity and pressure drop for both coolants will decrease as can be seen in Figs. 11 and 12, and thus the pumping power will also decrease. From Figs. 11 and 12, it can be observed that by decreasing or increasing the value of the temperature rise over the reactor core, the values of velocity and pressure drop change in the same pattern for both coolants i.e. these parameters decrease or increase in ratio for both coolants. For instance, for both coolants at the outlet of the core, the ratio of the value of the velocity of $\Delta T = 559$ K to the value of the velocity of $\Delta T = 659$ K for both coolants is about 1.09. As a result, according to Eq. (21) the pumping power for both coolants will change

according to the same pattern when changing the value of the temperature rise. It should be noted that it is evident that for a given heat source, by increasing the value of the temperature rise, the mass flow rate and pressure drop and pumping power will decrease and these results seem positive. However, on the other hand, there could be some problems related to overheating and the lifetime of the vanes of the turbines being subjected to higher temperatures, etc.

The heat transfer coefficients are calculated from the thermal solution obtained by the CFD simulation using the following equation:

$$\dot{q}'' = h(T_w - T_{nw}) \quad (22)$$

where $\dot{q}''$ is the local heat flux (W/m^2) obtained from CFD calculations, T_{nw} is the temperature of the coolant in the vicinity of the pebble (K), and T_w is the surface temperature of a pebble (K). It should be mentioned that the values of T_w were taken at the closest line to the fluid line and these values are different from the values of solid temperature shown in Fig. 8(b) that was taken at the line passed through the middle of the segment (four points (temperatures) of eight points were taken at the center of the pebbles).

Fig. 13 depicts the distribution of the local heat transfer coefficient along the axial direction of the segment for nitrogen and helium. To draw this figure, two lines, one line for T_w and the other for T_{nw} , with starting points $(x_0, y_0, z_0)_1 = (0.034, 0, 0.034)$ and $(x_0, y_0, z_0)_2 = (0.03505, 0, 0)$ and endpoints $(x, y, z)_1 = (0.034, 0.276, 0.034)$ and $(x, y, z)_2 = (0.03505, 0.276, 0)$ respectively were drawn and the distribution of the local heat transfer was calculated by ANSYS CFX 19.1 using the temperatures along these specific lines. As shown in Fig. 13, the local heat transfer coefficient for helium is larger than the local heat coefficient transfer for nitrogen. This outcome is because the heat flux, $\dot{q}''$ obtained from CFD calculations is the same for both coolants and $(T_w - T_{nw})$, calculated from the CFD simulations for helium is smaller than the corresponding values obtained for nitrogen.

The heat transfer coefficients, between the pebbles and coolant, are also calculated using the KTA [28] and Heil [11] correlations. The Heil correlation is given as:

$$h = 0.68 \rho \nu C_p Re^{-0.3} Pr^{-0.66} \quad (23)$$

The KTA correlation for the heat transfer coefficient within a pebble bed reactor core is defined by the following equations.

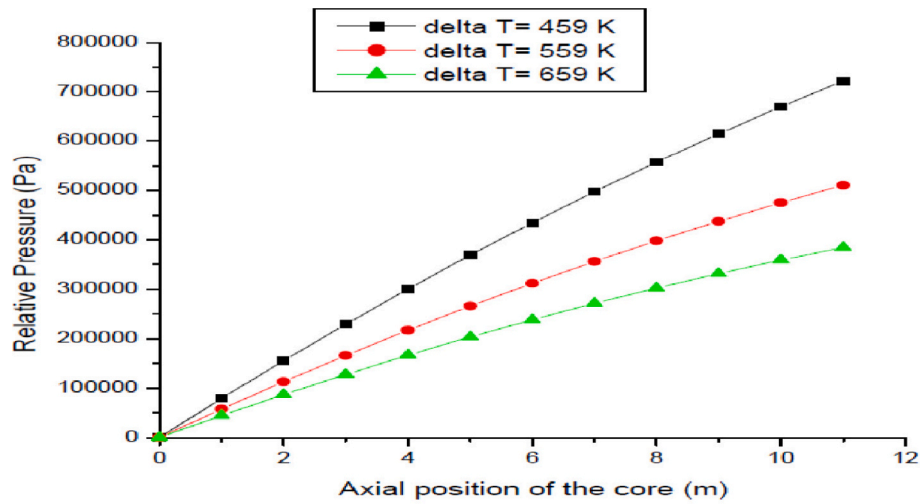
$$h = \frac{Nu \lambda}{d} \quad (24)$$

$$Nu = 1.27 \frac{Pr^{1/3}}{\varepsilon^{1.18}} Re^{0.36} + 0.033 \frac{Pr^{1/2}}{\varepsilon^{1.07}} Re^{0.86} \quad (25)$$

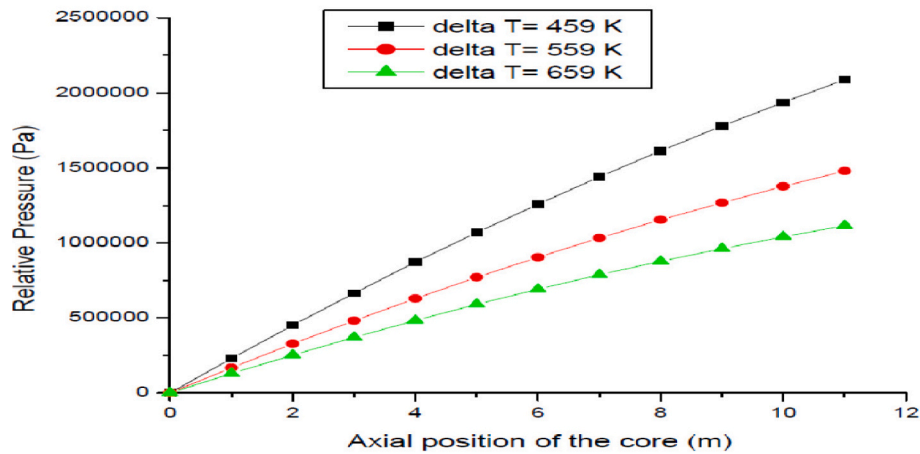
The scope of the data from which the correlation was derived is given as $100 < Re < 10^5$ for the Reynolds number and $0.36 < \varepsilon < 0.42$ for the porosity.

In Fig. 14 the heat transfer coefficients for helium obtained from the CFD simulation are compared with the corresponding heat transfer coefficients calculated using the KTA and Heil correlations. As shown in Fig. 14, the local heat transfer coefficient for helium obtained from the CFD simulation is approximately 12% smaller than the corresponding values obtained by the KTA correlation, due to among others the porosity of $\varepsilon = 0.32$ of the segment of pebbles being slightly outside the range for which KTA correlation, Eq. (25), was derived, and it is in reasonable agreement with corresponding values obtained using the Heil correlation. It should be mentioned that with regards to the BCC segment it is found that although the KTA correlation was not specifically derived for a BCC packing, there could be good agreement between the results obtained for the BCC segment and the values predicted by the KTA correlation. From Fig. 14 it can be seen that the values of the local heat transfer coefficients obtained from the CFD simulation fluctuate around the corresponding values of the heat transfer coefficients predicted by the Heil correlation.

As can be seen from Fig. 8, for nitrogen, the temperature difference



(a)



(b)

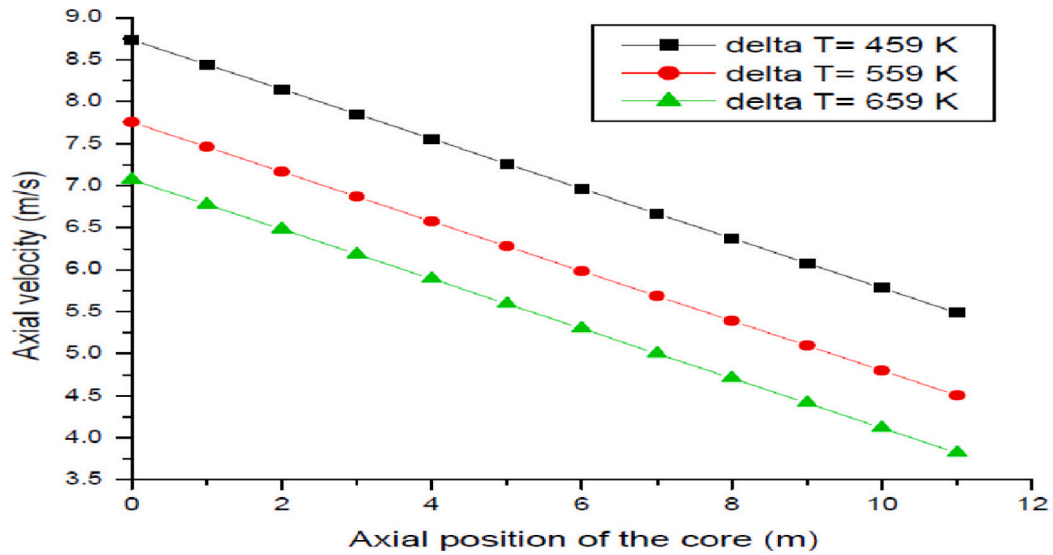
Fig. 11. Relative Pressure across the height of the core for different temperature rise over the reactor core for a) helium, b) nitrogen.

between pebble and coolant is more significant than that for helium. As mentioned before q'' obtained from CFD calculations is the same for both coolants and as can be seen from Fig. 13 the local heat transfer coefficient for helium is larger than that of nitrogen. Thus, according to Eq. (22), for a given heat flux, when decreasing the heat transfer coefficient, the temperature difference between pebble and coolant increases. Also for a given heat flux, since the heat transfer coefficient for helium is much higher than the heat transfer coefficient for nitrogen, the values of $(T_w - T_{nw})$ for nitrogen are expected to be higher than the corresponding values for helium. Thus, as mentioned before for the assumption ($\Delta T_{He} = \Delta T_{N_2}$), the values of the fluid temperature for nitrogen are almost the same as the values of the fluid temperature for helium and as a result the values of solid surface temperature (T_w) for nitrogen will be higher than the corresponding values of T_w for helium. Thus, the values of the solid temperature at the centers of the pebbles for nitrogen are expected to be higher than the value of solid temperature at the center of pebbles for helium as shown in Fig. 8(b).

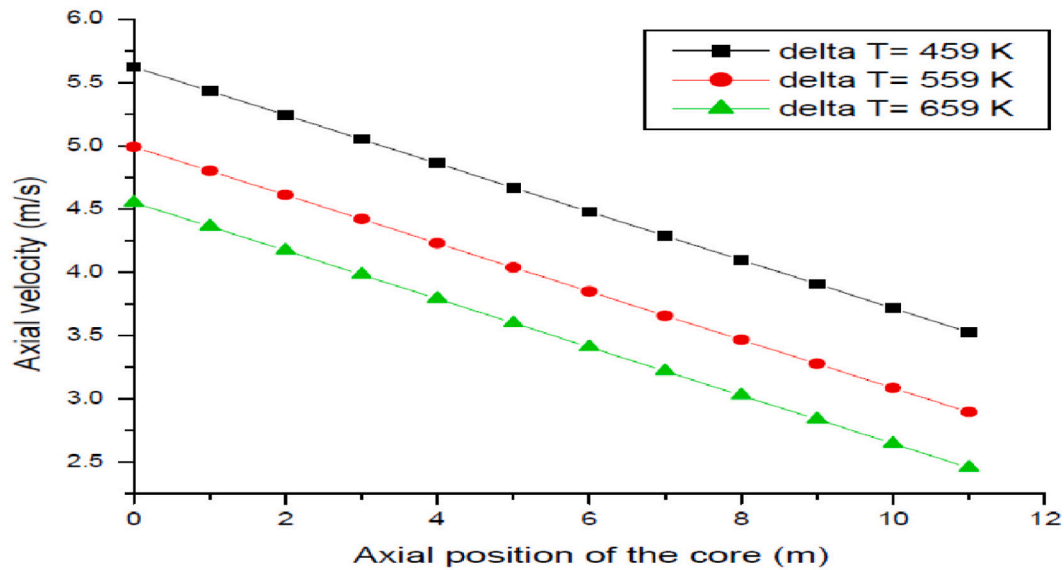
The local distributions of the Nusselt number were investigated by

selecting one of the pebbles in the segment of pebbles as shown in Fig. 15 and extracting contour plots of the value of the Nu number on the surface of the pebble. Fig. 16 shows the distribution of the Nu number on the surface of the selected pebble for the two coolants (nitrogen and helium). The color index depicts the magnitude of the Nu number. As can be seen in Fig. 16 a higher value is predicted for the Nu number on the front of the pebble due to the flow impingement and a lower value for the Nu number is found on the back of the pebble due to the flow detachment. It can also be seen in Fig. 16 that the Nu number is predicted to be higher on the pebble surface facing the pore region and to be lower on the surface around the contact areas. Despite the values of local heat transfer coefficient for helium being much larger than the corresponding values of the heat transfer coefficient for nitrogen, the thermal conductivity of nitrogen is much smaller than that of helium, thus according to Eq. (24), it is found that the Nu numbers for the nitrogen are much higher than the Nu numbers for the helium, as can be seen in Fig. 16.

The effectiveness of the decay heat removal, when the steady-state



(a)



(b)

Fig. 12. Fluid velocity for different temperature rise over the reactor core for a) helium, b) nitrogen.

temperature rise ΔT for the two coolants is the same, has been investigated considering the same boundary conditions assumed for the steady state conditions.

Fig. 17 shows the transient coolant temperature (K) as a function of the axial position of the segment of pebbles for helium and nitrogen, at 150 s after the shutdown. Compared to the steady state temperatures shown in Fig. 8(a), it can be observed in Fig. 17 that along the axial direction of the segment the temperature gradients are for helium and nitrogen less at 150 s. It is noted that after the reactor shutdown, the outlet temperature decreases from 926.95 K and 925.028 K for helium and nitrogen, respectively, to about 811.08 K and 819.98 K at time $t = 150$ s. Thus, according to Eq. (17) and considering $(\dot{m}c_p)_{\text{He}} = (\dot{m}c_p)_{\text{N}_2}$, this means that for nitrogen, less heat has been removed by the coolant

from the segment during the time interval from 0 s to 150 s.

Fig. 18(a) shows that for helium and nitrogen, at 100 h after reactor shutdown, the instantaneous power or heat being released by the segment to and removed by the fluid using Eq. (17) decreased to 0.11218%, and 0.09087% of the normal power of the segment, respectively. It does indicate that the heat is being released at a slower rate from a nitrogen cooled segment of pebbles. After 50 weeks (Fig. 18(b)), the instantaneous power released by the segment of pebbles decreased to 0.00684% of the segment power for nitrogen and 0.00814% for helium, and after that, the instantaneous power released by the segment of pebbles decreases at the same gradient for both coolants. Finally, for helium and nitrogen after 100 weeks, the trends of the gradients of the instantaneous power released by the segment of pebbles becomes very

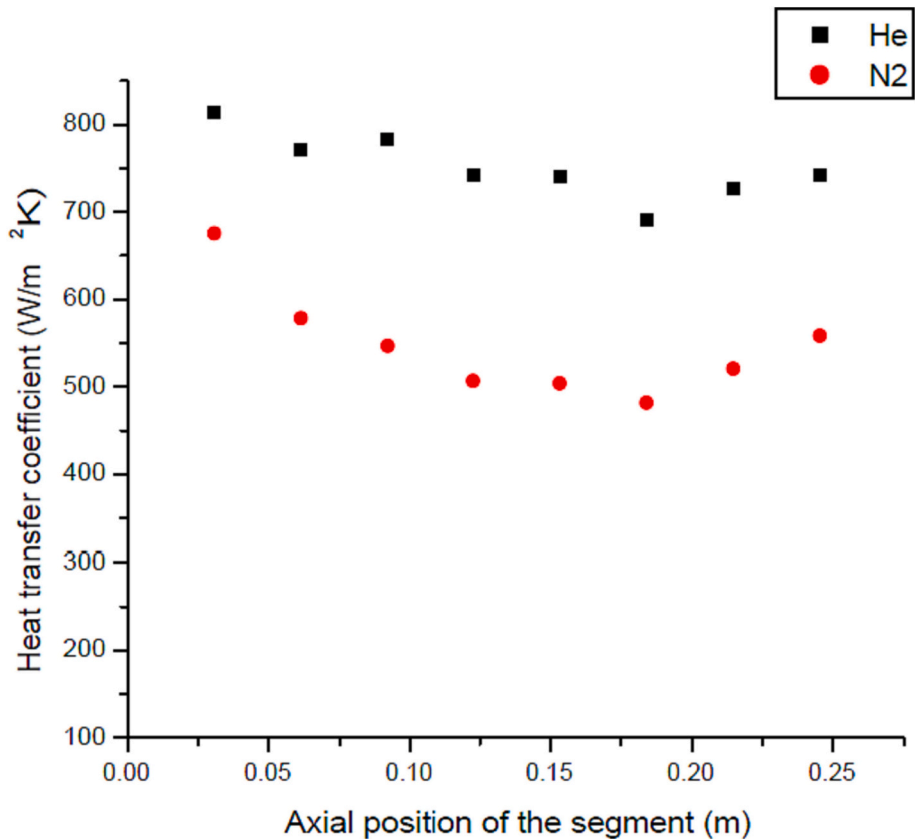


Fig. 13. The local heat transfer coefficient along the axial direction of the segment of pebbles for different coolants.

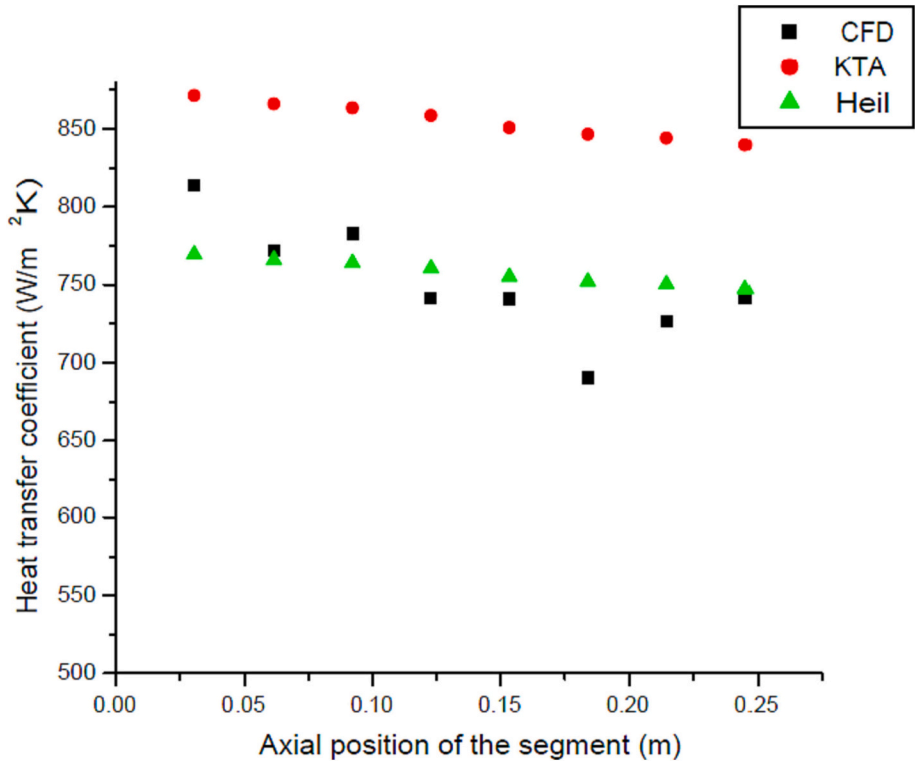


Fig. 14. Comparisons of the heat transfer coefficient for helium.

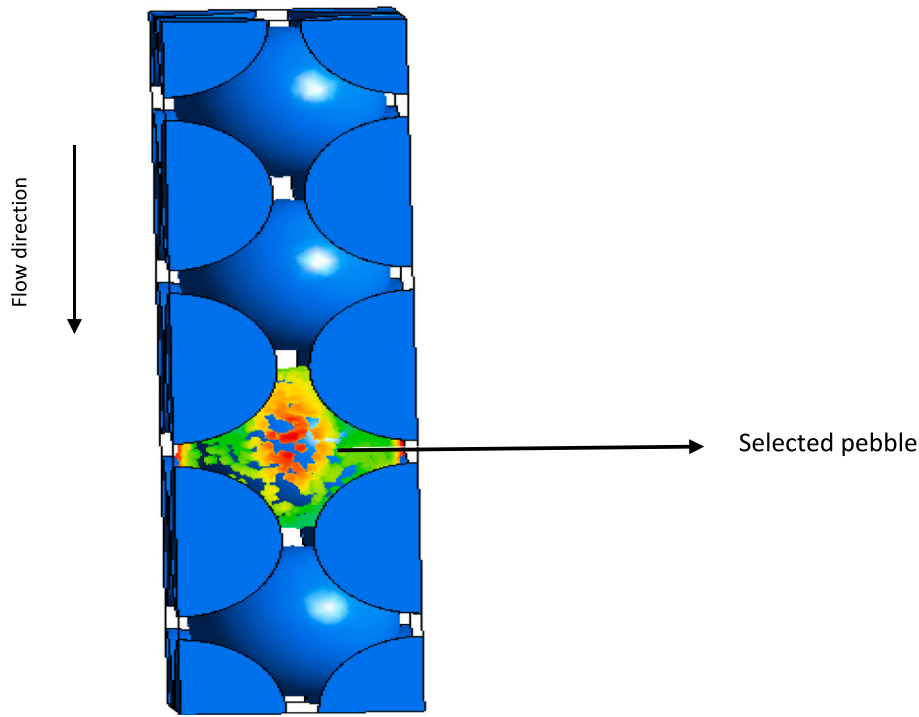


Fig. 15. The selected pebble.

similar and the segment power will continue at the same gradient until it reaches zero, as can be seen in Fig. 18(b).

Fig. 18(b) shows that for both coolants, from the 50th week to the 100th week, the instantaneous power released by the segment decreases at a sharp gradient, but after 100 weeks, the trend of the gradient becomes less steep and after 330 weeks, the instantaneous power released by the segment reaches about 0.001% of the normal operating power of the segment. From the negative growth rate calculations $((Q_{\text{after shutdown}} - Q_{\text{normal}}) / Q_{\text{normal}})$ it has been found that the nitrogen cooled pebble bed segment is being cooled at a slower rate. As can be observed from Fig. 18, for nitrogen for the first 1100 h, the heat removal rate is lower than that of helium but after 100 weeks, the heat removal rate becomes almost the same for both coolants.

In order to investigate the heat removal in further detail, the whole core has been simulated considering nitrogen and helium as coolants and Eq. (17) has been used to determine the instantaneous heat released to and removed by the fluid. Fig. 19(a) depicts that 100 h after reactor shutdown, for helium- and nitrogen-cooled pebble bed reactors, the instantaneous power released by the reactor has decreased to 0.395% for the helium, and 0.39216% for the nitrogen of the normal power of the reactor, respectively that indicates that less heat is being released from the nitrogen-cooled pebble bed reactor. A comparison between Fig. 18 (a) and Fig. 19(a) reveals that from 100th hour to 1100th hour in the segment, there is a higher difference between the values of the instantaneous power being released by the reactor for both coolants (i.e., 0.11218% for helium and 0.09087% for nitrogen of the normal power) than in the whole core.

Also, this comparison reveals that, the instantaneous heat removal rate for both coolants in the segment is about three times lower than in the whole core.

It should be remembered that the value of the porosity is different for the two cases (the value of porosity in the segment and the whole core is 0.32 and 0.39 respectively) and the porosity has a significant influence on the reactor power after shutdown and the required time for heat removal [20].

After 100 weeks, for both coolants the gradient and value of the instantaneous power released by the reactor are almost the same and the

instantaneous power released by the reactor will continue with the same gradient until it reaches zero, as can be seen in Fig. 19(b). Also, from Fig. 19(b), it can be inferred that, after 150 weeks, in the whole core, the heat removal rates for both coolants are closer to each other than in the case of the segment.

Eq. (17) can be expanded to consider the full heat balance for transient conditions to account for the heat transferred to the coolant from the solids (pebbles and reflectors) due to the decay heat generated in the pebbles and the heat stored in or released by the solids, as well as the heat losses to the surrounding environment. The heat $Q_{SH}(t)$ stored, that is accumulating, in the solids is given by:

$$Q_{SH}(t) = Q_{DH}(t) - Q_{SF}(t) \quad (26)$$

Here $Q_{SF}(t)$ is the heat transferred from the solids to the coolant. Eq. (26) can be rewritten to become:

$$Q_{SF}(t) = Q_{DH}(t) - Q_{SH}(t) \quad (27)$$

Note that when $Q_{SH}(t) > 0$ heat is stored in the solids. Eq. (17) can now be expanded to become:

$$Q_T(t) = (\dot{m}h(t))_{\text{outlet}} - (\dot{m}h)_{\text{inlet}} = Q_{SF}(t) - Q_{LS}(t) \quad (28)$$

Where $Q_{LS}(t)$ is the losses to the surrounding environment. Substituting Eq. (27) in Eq. (28) then leads to:

$$Q_T(t) = Q_{DH}(t) - Q_{SH}(t) - Q_{LS}(t) \quad (29)$$

From Eq. (29) we obtain that the heat stored in or released by the solids:

$$Q_{SH}(t) = Q_{DH}(t) - [(\dot{m}h(t))_{\text{outlet}} - (\dot{m}h)_{\text{inlet}}] - Q_{LS}(t) \quad (30)$$

Four scenarios can occur, neglecting the losses for the moment:

- $Q_{DH}(t) > Q_T(t)$ then $Q_{SH}(t) > 0$, thus heat is stored in the solids, and we get $\frac{dT}{dt} \big|_S > 0$, and the solid temperature thus increases.
- $Q_{DH}(t) = Q_T(t)$ then $Q_{SH}(t) = 0$, thus no heat stored in the solids or released from the solids, and the solid temperatures remains unchanged.

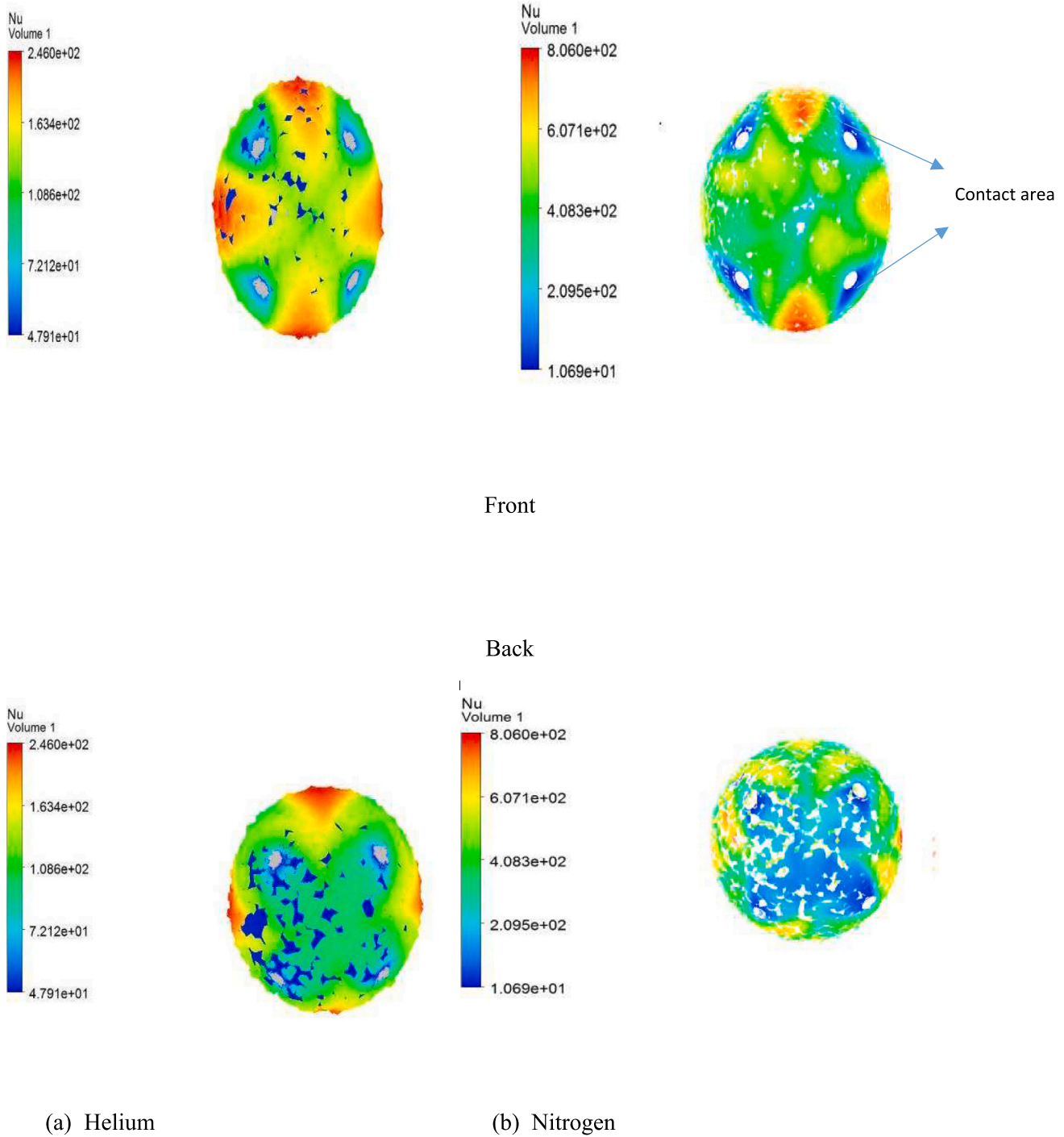


Fig. 16. The distribution of the Nu number on the surface of the selected pebble for the two coolants.

- $Q_{DH}(t) < Q_T(t)$ then $Q_{SH}(t) < 0$, thus stored heat is released by the solids and we get $\frac{\partial T}{\partial t}|_S < 0$, and the solid temperature thus decreases.
- $Q_{DH}(t) = Q_{SH}(t)$ then $Q_T(t) = 0$, thus no decay heat and stored heat is released by the solids, and we get $\frac{\partial T}{\partial t}|_S > 0$, the solid temperature thus increases. This will only happen when $m = 0$ and the reactor is insulated.

Finally, the performance of the segment of pebbles and the core has been investigated by comparing $(Q_{SH}/Q_T)_{helium}$ and $(Q_{SH}/Q_T)_{nitrogen}$ for the time period of the 100th hour to the 1100th hour. The results are shown in Fig. 20(a) and 20(b) for the segment and the whole core

respectively.

The results for the decay and stored heat shown in Fig. 20(a) for the segment of pebbles should be evaluated along with the results for the heat transferred to the coolant shown in Fig. 18(a). It should also be kept in mind that due to the lateral symmetry boundary conditions, no heat is lost to the surrounding environment. In Fig. 20(a) for both helium and nitrogen we find that $Q_{SH}(t) > 0$ which means that heat is stored in the pebbles. Therefore, only a part of the decay heat that is generated is transferred to the coolant, whilst the remainder of the decay heat is accumulating in the pebbles. It can be seen in Fig. 20(a) that less heat is stored in the pebbles in the case of the helium compared to the nitrogen,

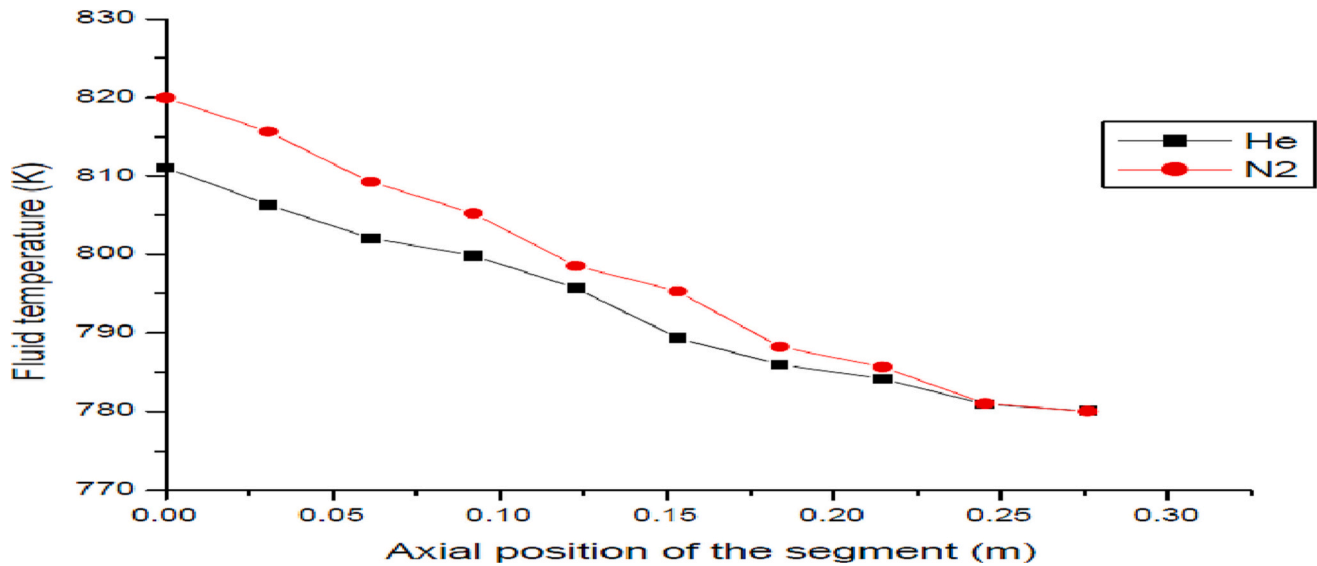


Fig. 17. The transient coolant temperature (K) as a function of the axial position of the segment for the helium and the nitrogen, at 150 s after the shutdown.

thus more heat is transferred to the coolant in the case of the helium. This is corroborated by the results shown in Fig. 18(a) which shows that more heat is being released by the helium cooled segment of pebbles.

Similarly, the results for the decay and stored heat shown in Fig. 20(b) for the core should be evaluated along with the results for the heat transferred to the coolant shown in Fig. 19(a). Note that in the case of the core the solids account for the pebbles and the reflectors. The fixed temperature boundary condition applied to the outer surface of the side reflector will, for the temperatures involved, result in a loss of heat to the surrounding environment. However, no transient data is available and will, as a first approximation, not be accounted for. Should the data for the heat losses become available, it will according to Eq. (30) only affect the values of the stored heat. In Fig. 20(b) for both helium and nitrogen we find that $Q_{SH}(t) < 0$ which means that heat is released by the solids and the temperatures of the solids will therefore decrease during the time interval considered. Thus, the decay heat that is generated and the stored heat released by the solids are transferred to the coolant. It can be seen in Fig. 20(b) that more heat is released by the solids in the case of the helium compared to the nitrogen, thus more heat is transferred to the coolant in the case of the helium. This is corroborated by the results shown in Fig. 19(a) which shows that more heat is being released by the helium cooled core.

It can be concluded that both in the case of the segment of pebbles and the core the helium cooled packed bed will cool down faster than the nitrogen cooled packed bed as reflected by the coolant outlet temperatures.

A more detailed study is required of the segment of pebbles and the core to develop a better understanding of their behavior under transient conditions. In the case of the core the study should include the losses to the surrounding environment.

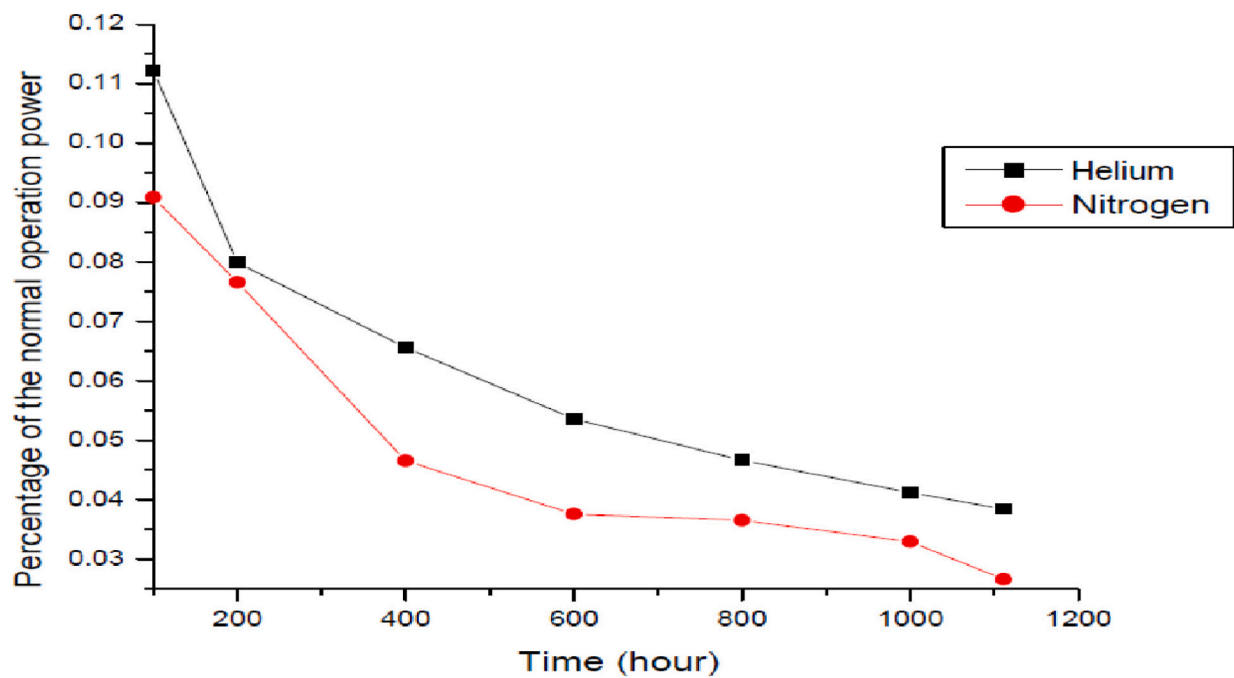
5. Conclusions

A CFD study has been performed to investigate the effects of different coolants on the thermofluid-dynamic phenomena in the pebble bed reactors considering a segment of pebbles and the whole reactor core. The following trends have been identified:

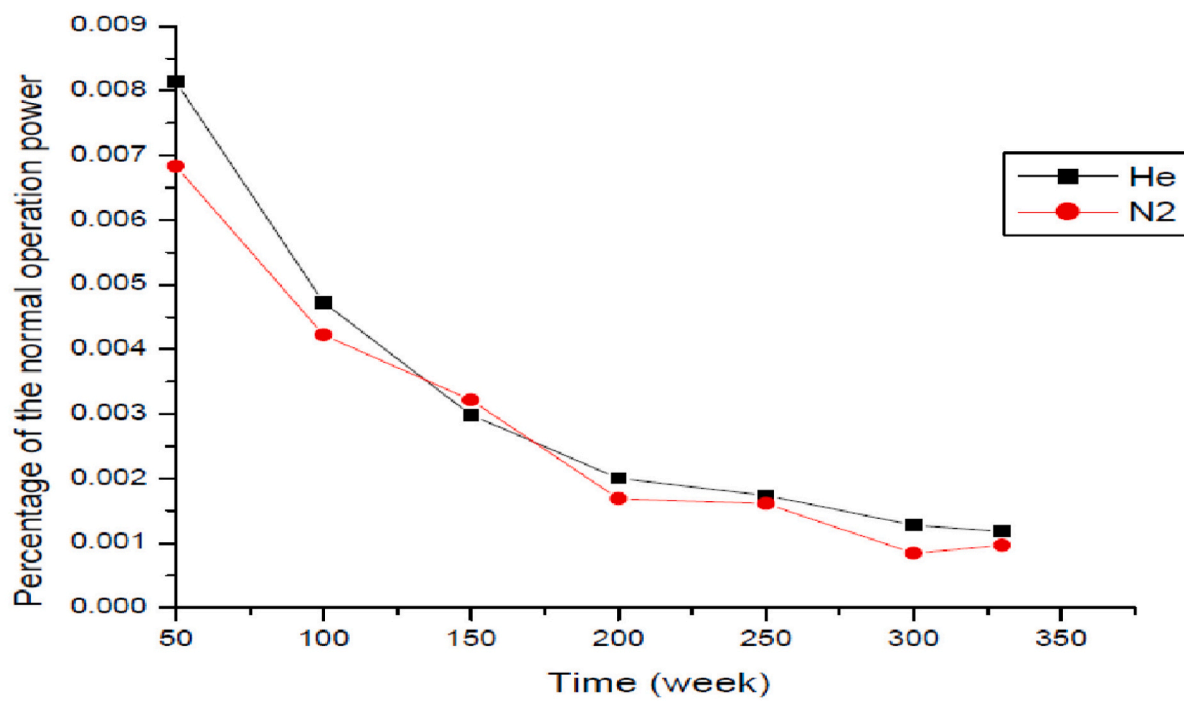
- Although it was expected to observe the same thermal fluid behavior in both the whole core and the segment of pebbles, in some cases, the thermal-hydraulic behavior of the segment of pebbles has not followed exactly the thermal-hydraulic behavior of the whole core and in some situations even there are some noticeable discrepancy. This

is due to the fact that the lateral boundary conditions are not the same. The fixed temperature at the outside surface of the side reflector and the associated unknown heat flux will have an effect that will not be present in the case of the segment of pebbles.

- In both the segment of pebbles and the whole core for both coolants, under steady-state conditions, for a given heat source and the inlet-outlet temperature difference (ΔT), the mass flow rate of nitrogen is higher than that of helium since mass flow rate depends inversely on the value of C_p and its value for helium ($5188 \text{ J kg}^{-1} \text{ K}^{-1}$) is about 4.5 times C_p of nitrogen. Thus the value of mass flow rate of nitrogen is about 4.5 times the mass flow rate of helium. It is in fact that the higher the mass flow rate, the more pumping power required. Hence, an increase in mass flow rate results in an increased cost of pumping power consumption.
- In both the segment of pebbles and the whole core, for both coolants (nitrogen and helium) the coolant temperature increases in the flow direction of the segment and the core and reaches its maximum value at the outlet. Nonetheless, in the segment unlike the whole core, compared to the fluid temperature, the temperatures of the solids vary less along the axial direction of flow for steady-state conditions.
- In both the segment and the whole core, the local heat transfer coefficient for helium is larger than the local heat transfer coefficient for nitrogen since the heat flux, q'' obtained from the steady state CFD calculations, is the same for both coolants and $(T_w - T_{nw})$, calculated from the CFD simulations, for helium is smaller than the corresponding values for nitrogen. However, despite the magnitudes of local heat transfer for helium being larger than that of nitrogen, the thermal conductivity of nitrogen is much smaller than that of helium, thus according to Eq. (24), the value of Nu number for nitrogen is larger than the value of Nu number for helium.
- In the segment, after the reactor shutdown, the outlet temperature decreases from 926.95 K to about 811.08 K and 925.028 K to 819.98 K for helium and nitrogen respectively, and this means that for helium, there is a higher heat removal during the first 150 s. For the first 1100 h, for helium, the reactor power decreases faster than that of nitrogen that indicates that more heat is being released from a helium-cooled pebble bed reactor. However, for both coolants after 100 weeks, the slope of the reactor power gradient becomes very small and the reactor power will continue with the same slope until it reaches zero. After 100 weeks, in the whole core, the heat removal rates for both coolants are closer to each other than in case of the segment.

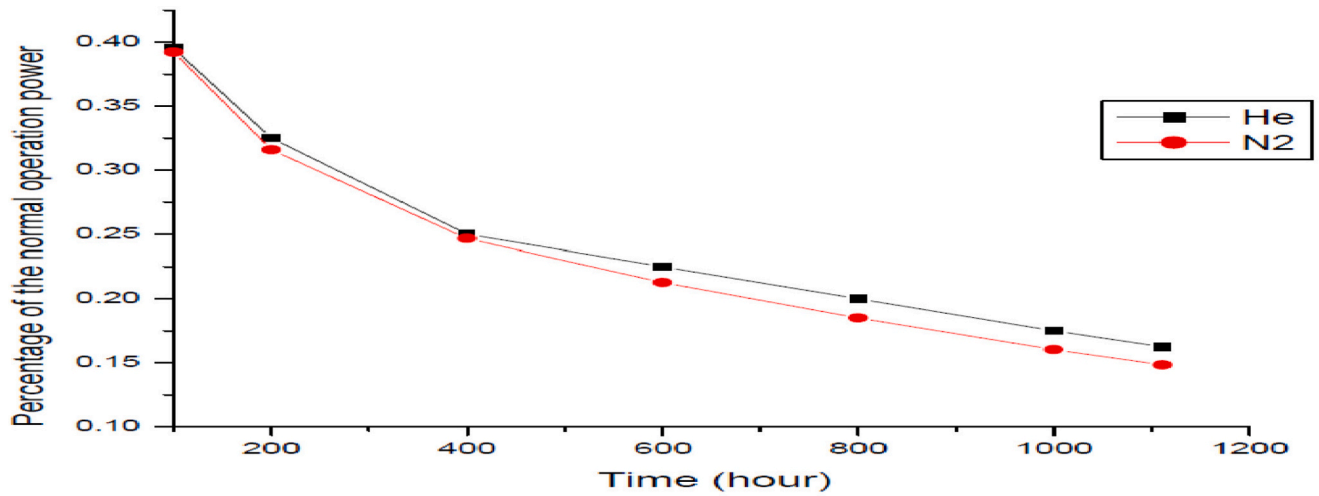


(a)

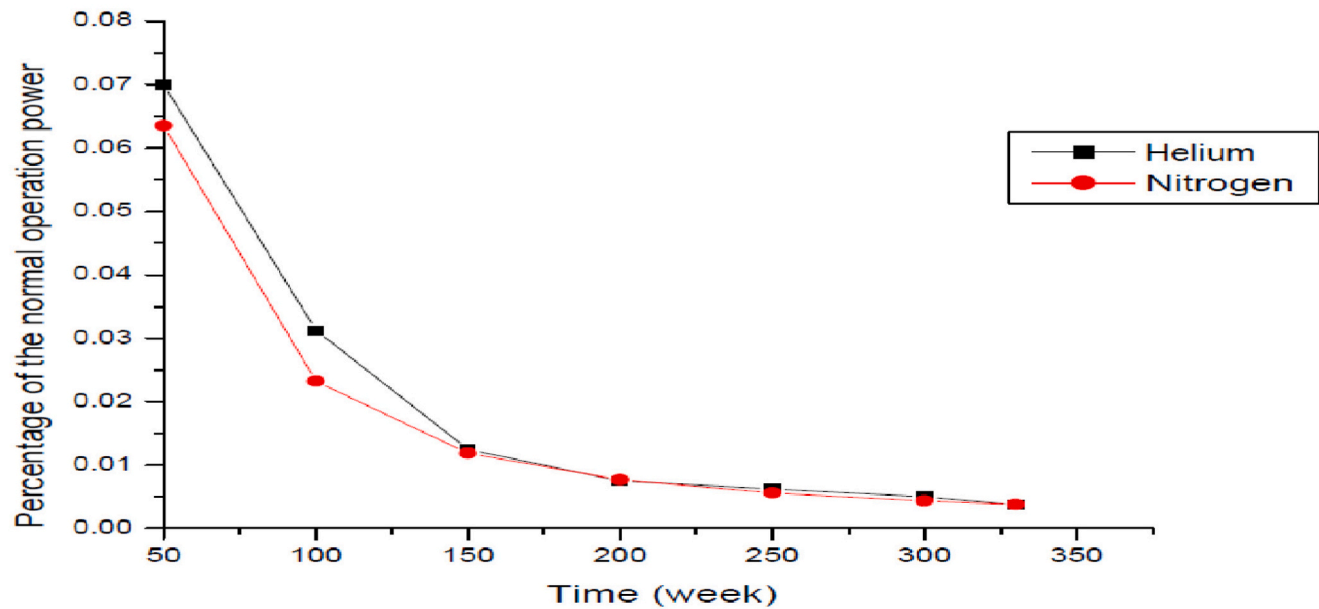


(b)

Fig. 18. The instantaneous power being released by the segment at various time instances for the segment: a) $100 \text{ h} < t < 1100 \text{ h}$; b) $50 \text{ weeks} < t < 330 \text{ weeks}$.



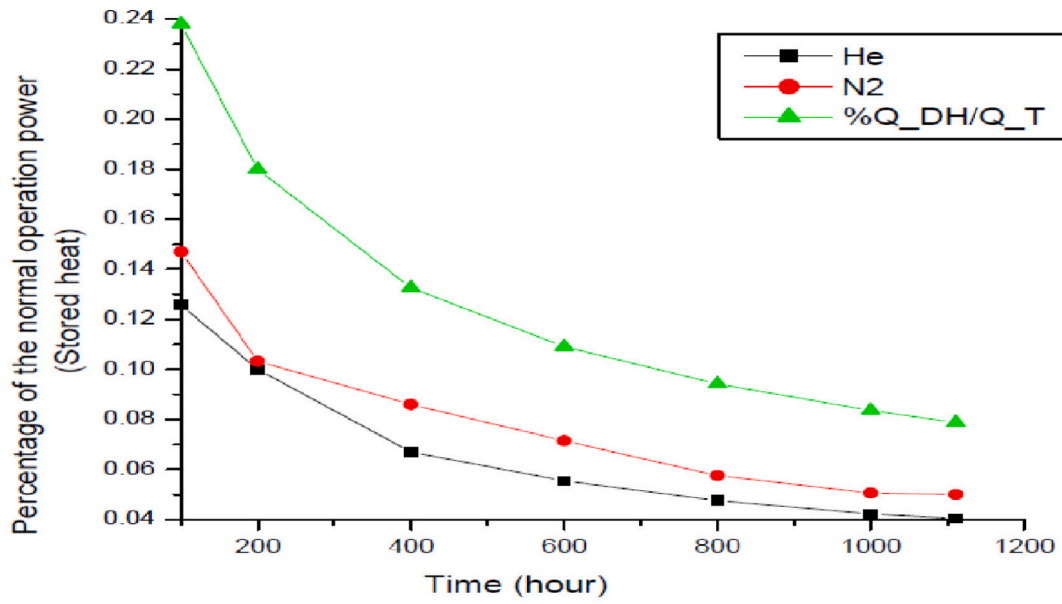
(a)



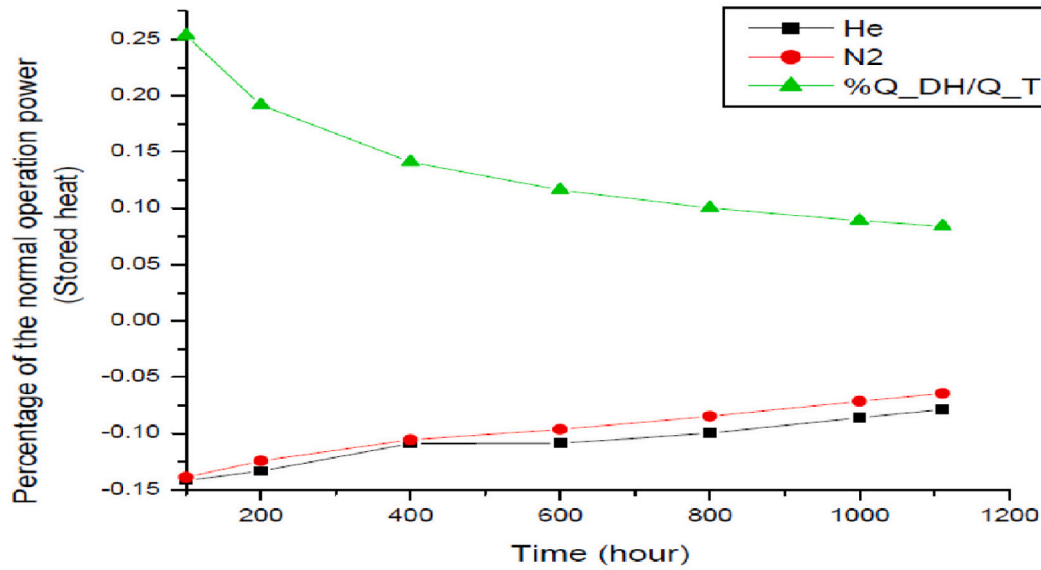
(b)

Fig. 19. The instantaneous power released by the reactor in various time period for the core: a) $100 \text{ h} < t < 1100 \text{ h}$; b) $50 \text{ weeks} < t < 330 \text{ weeks}$.

- Under steady state conditions, compared to the whole core, in the segment, the value of solid temperature in the nitrogen bed is higher than the value of solid temperature in the helium bed that means the stored heat in the pebbles in the nitrogen bed will be more than that stored in the pebbles in the helium bed. However, in the whole core, the temperatures of the pebbles in the nitrogen bed are closer to the temperatures of the pebbles in the helium bed that means there is a smaller difference between the values of (Q_{SH}/Q_T) of the two coolants.
- From the results shown in Fig. 20, it has been found that in the case of the segment of pebbles for the time interval considered, the pebbles are accumulating heat. In contrast, during the same time interval in the case of the core the solids release stored heat to the coolants.
- Nitrogen as a coolant candidate for PBR behaves in an acceptable manner and the study provides additional parameters under working conditions for this coolant that have not been reported before.
- Under reactor shutdown nitrogen behaves in a safer manner than helium does.
- The CFD code used for the simulation of the full core only makes provision for the Ergun correlation that is not valid for packed beds consisting of uniformly-sized spheres for $Re/(1-\epsilon) > 500$ with $Re = \rho V_s d / \mu$. Thus, it is more appropriate to employ the KTA pressure drop correlation. However, in the current study, the fact that the pressure drop was not predicted entirely accurately is not crucial because (i) fixed mass flow rates have been considered, and (ii) considering the high operating system pressure of 9 MPa the difference in the local



(a)



(b)

Fig. 20. The instantaneous decay heat generated and heat stored in the pebbles for time period of 100 h to 1100 h for the case of: a) the segment; b) the core.

pressure at any point will have a negligible effect on the phenomena that are being focused on.

- In order to develop a better understanding of the thermal fluid behavior of the segment of pebbles and the core under transient conditions, more detailed study is required of the segment of pebbles and the core. In the case of the core the study should include the losses to the surrounding environment.

Nomenclature

d	pebble diameter, m
e	emissivity of pebble
G_K	generation of turbulence kinetic energy, kg/(m·s ³)

h	heat transfer coefficient, W/(m ² ·K)
k	turbulence kinetic energy, m ² /s ²
C, N	porosity model coefficients
$\dot{m}$	mass flow rate, kg/s
p	pebble bed packing fraction
P	pressure, Pa
Q_T	reactor power before shutdown, W
V	superficial mean exit velocity, m/s
S_h	heat source, W/m ³
T	temperature, K
t_0	reactor operating time, s
t_s	reactor shutdown time, s
ΔT	inlet-outlet temperature difference, K

v	velocity, m/s
V	volume, m ³
TRISO	Tristructural-isotropic
c_p	specific heat of fluid, J/(kg·K)
a_{sf}	surface area per unit volume, 1/m
$C_{\mu}, C_{\epsilon 1}, C_{\epsilon 2}$	empirical constants for turbulent models
h_p	differential head (m)
g	acceleration of gravity (9.81 m/s ²)
Q	flow rate (m ³ /h)
Re	Reynolds number
PLOFC	pressurized loss of forced cooling
DLOFC	depressurized loss of forced cooling
k_s	the effective thermal conductivity for the solid

Greek letters

ε	bed porosity
ε_e	energy dissipation rate, m ² /s ³
μ	dynamic viscosity, kg/(m·s)
μ_t	turbulent viscosity, kg/(m·s)
ρ	fluid density, kg/m ³
ρ_{fuel}	power density of each fuel sphere, W/m ³
τ	shear stress, N/m ²
$\sigma_k, \sigma_\varepsilon$	empirical constants for turbulent models
σ	Stefan-Boltzmann constant = 5.670×10^{-8} W/(m ² ·K ⁴)
λ	thermal conductivity, W/(m·K)
λ_{peb}	thermal conductivity of pebble bed, W/(m·K)
δ	A functional derivative in functional calculus
ν	the kinematic viscosity

Subscripts

peb	pebble
f	fluid
s	solid
He	helium
N_2	nitrogen

CRedit authorship contribution statement

M.S. Latifi: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft. **C.G. du Toit:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – review & editing. **Gustavo Alonso:** Validation, Formal analysis, Investigation, Writing – review & editing.

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.

Data availability

No data was used for the research described in the article.

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