Democratic and Popular Republic of Algeria
Ministry of Higher Education and Scientific Research
University of BECHAR

Printed from
Journal of Scientific Research

http://www.univ-bechar.dz/jrs/

Porous Media Applied to Pebble Bed Modular Reactor Thermal-hydraulics

Kh. Oukil[1], K. Sidi-Ali[1], A. Alem[2], T. Hassani[3], Y. Amri[3]

[1] *Commissariat à l'Energie Atomique, Centre de Recherche Nucléaire de Draria, Division Sureté Nucléaire et Radioprotection / BP, 43 sebala, Draria, Alger, Algeria.*
[2] *Département de mécanique USDB, faculté des sciences de l'ingénieur, Blida, Algeria.*
[3] *Département thermo-énergétique USTHB, FGM&GP/ BP, 32 El Alia, Bab Ezzouar, Alger, Algeria.*

Published on 20 December 2013

Journal of Scientific Research
ISSN 2170-1237

Journal of
Scientific Research

The Editor, on behalf of the Editorial Board and Reviewers, has great pleasure in presenting this number of the Journal of Scientific Research. This journal (ISSN 2170-1237) is a periodic and multidisciplinary journal, published by the University of Bechar. This journal is located at the interface of research journals, and the vulgarization journals in the field of scientific research. It publishes quality articles in the domain of basic and applied sciences, technologies and humanities sciences, where the main objective is to coordinate and disseminate scientific and technical information relating to various disciplines.

The research articles and the development must be original and contribute innovative, helping in the development of new and advanced technologies, like the studies that have concrete ideas which are of primary interest in mastering a contemporary scientific concepts. Actually, the JRS is indexed in **Google Scholar**, **Universal Impact Factor**, **Research Bible**, **DRJI**, **Scientific Indexing Services**, **Global Impact Factor (with GIF=0,632 in 2012)** and **Index-Copernicus (with 2012 ICV : 4.87 points)**. The journal is obtainable in electronic form, which is available worldwide on the Internet and can be accessed at the journal URL:

http://www.univ-bechar.dz/jrs/.

Director of Journal
Pr. BELGHACHI Abderrahmane

Editor in Chief
Dr. HASNI Abdelhafid

Co-Editor in Chief
Pr. BASSOU Abdesselam

Editorial Member
TERFAYA Nazihe
BOUIDA Ahmed
LATFAOUI Mohieddine
MOSTADI Siham

Reviewers board of the Journal.

Pr. KADRY SEIFEDINE (The American University in KUWAIT)
Pr. RAZZAQ GHUMMAN Abdul (Al Qassim University KSA)
Pr. PK. MD. MOTIUR RAHMAN (University of Dhaka Bangladesh)
Pr. MAHMOOD GHAZAW Yousry (Al Qassim University KSA)
Pr. RAOUS Michel (Laboratory of Mechanic and Acoustic France)
Pr. RATAN Y. Borse (M S G College Malegaon Camp India)
Pr. LEBON Frédéric (University of Aix-Marseille 1 France)
Pr. MONGI Ben Ouézdou (National Engineering School of Tunis)
Pr. BOUKELIF Aoued (University of Sidi Bel Abbes Algeria)
Pr. DJORDJEVICH Alexandar (University of Hong Kong)
Pr. BENABBASSI Abdelhakem (University of Bechar Algeria)
Pr. BOULARD Thierry (National Institute of Agronomic Research France)
Pr. LUCA Varani (University of Montpellier France)
Pr. NEBBOU Mohamed (University of Bechar Algeria)
Pr. LABBACI Boudjemaa (University of Bechar Algeria)
Pr. DJERMANE Mohammed (University of Bechar Algeria)
Pr. BASSOU Abdesselam (University of Bechar Algeria)
Pr. ABOU-BEKR Nabil (Universit of Tlemcen Algeria)
Pr. TAMALI Mohamed (University of Bechar Algeria)
Pr. ABDELAZIZ Yazid (University of Bechar Algeria)
Pr. BERGA Abdelmadjid (University of Bechar Algeria)
Pr. Rachid KHALFAOUI (University of Bechar Algeria)
Dr. FELLAH Zine El Abiddine Laboratory of Mechanic and Acoustic France)
Dr. ZHEN Gao (University of Ontario Institute of Technology Canada)
Dr. OUERDACHI Lahbassi (University of Annaba Algeria)
Dr. HADJ ABDELKADER Hicham (IBISC – University of Evry France)
Dr. KARRAY M'HAMED ALI (National Engineering School of Tunis)
Dr. ALLAL Mohammed Amine (University of Tlemcen Algeria)
Dr. FOUCHAL Fazia (GEMH - University of Limoges France)
Dr. TORRES Jeremi (University of Montpellier 2 France)
Dr. CHANDRAKANT Govindrao Dighavka (L. V. H. College of Panchavati India)
Dr. ABID Chérifa (Polytech' University of Aix-Marseille France)
Dr. HAMMADI Fodil (University of Bechar Algeria)
Dr. BENSAFI Abd-El-Hamid (University of Tlemcem)
Dr. BENBACHIR Maamar (University of Bechar Algeria)
Dr. BOUNOUA Abdennacer (University of Sidi bel abbes Algeria)
Dr. FAZALUL RAHIMAN Mohd Hafiz (University of Malaysia)
Dr. TIWARI Shashank Amity University Lucknow (India)
Pr. BALBINOT Alexandre (Federal University of Rio Grande do Sul Brazil)
Pr. TEHIRICHI Mohamed (University of Bechar Algeria)
Pr. JAIN GOTAN (Materials Research Lab., A.C.S. College, Nandgaon India)
Pr. SAIDANE Abdelkader (ENSET Oran Algeria)
Pr. DI GIAMBERARDINO Paolo (University of Rome « La Sapienza » Italy)
Pr. SENGOUGA Nouredine (University of Biskra Algeria)
Pr. CHERITI Abdelkarim (University of Bechar Algeria)
Pr. MEDALE Marc (University of Aix-Marseille France)
Pr. HELMAOUI Abderrachid (University of Bechar Algeria)
Pr. HAMOUINE Abdelmadjid (University of Bechar Algeria)
Pr. DRAOUI Belkacem (University of Bechar Algeria)
Pr. BELGHACHI Abderrahmane (University of Bechar Algeria)
Pr. SHAILENDHRA Karthikeyan (AMRITA School of Engineering India)
Pr. BURAK Barutcu (University of Istanbul Turkey)
Pr. LAOUFI Abdallah (University of Bechar Algeria)
Pr. Ahmed Farouk ELSAFTY (American University of the Middle East Kuwait)
Pr. Sohrab MIRSAEIDI (Centre of Electrical Energy Systems Malaysia)
Pr. SELLAM Mebrouk (University of Bechar Algeria)
Pr. BELBOUKHARI Nasser (University of Bechar Algeria)
Pr. BENACHAIBA Chellali (University of Bechar Algeria)
Dr. ABDUL RAHIM Ruzairi (University Technology of Malaysia)
Dr. CHIKR EL MEZOUAR Zouaoui (University of Bechar Algeria)
Dr. KAMECHE Mohamed (Centre des Techniques Spatiales, Oran Algeria)
Dr. MERAD Lotfi (Ecole Préparatoire en Sciences et Techniques Tlemcen Algeria)
Dr. SANJAY KHER Sanjay (Raja Ramanna Centre for Advanced Technology INDIA)
Dr. BOUCHAHM Nora (Centre de Recherche Scientifique et Technique sur les Régions Arides Biskra)
Dr. Fateh Mebarek-OUDINA (University of Skikda Algeria)

Journal of Scientific Research
University of Bechar
P.O.Box 417 route de Kenadsa
08000 Bechar - ALGERIA
Tel: +213 (0) 49 81 90 24
Fax: +213 (0) 49 81 52 44
Editorial mail: jrs.bechar@gmail.com
Submission mail: submission.bechar@gmail.com
Web: http://www.univ-bechar.dz/jrs/

Journal of Scientific Research
ISSN 2170-1237

Journal of Science Research N 6, p. 19-23

Porous Media Applied to Pebble Bed Modular Reactor Thermal-hydraulics

Kh. Oukil[1], K. Sidi-Ali[1], A. Alem[2], T. Hassani[3], Y. Amri[3]
[1] *Commissariat à l'Energie Atomique, Centre de Recherche Nucléaire de Draria, Division Sureté Nucléaire et Radioprotection / BP, 43 sebala, Draria, Alger, Algeria.*
[2] *Département de mécanique USDB, faculté des sciences de l'ingénieur, Blida, Algeria.*
[3] *Département thermo-énergétique USTHB, FGM&GP/ BP, 32 El Alia, Bab Ezzouar, Alger, Algeria.*

Abstract – *Among the SMRs (Small and Medium sized Reactors) for electricity generation currently under development we find the PBMRs (Pebble Bed Modular Reactors). These nuclear reactors work at very high temperature and are cooled generally by helium flowing through spherical fuel pebbles. In this work we focus on the thermal hydraulic differences when using air or helium as a cooling fluid. The porous media model can be used for PBMR thermal-hydraulic studies. A mathematical model is developed thanks to the conservation equation of mass, momentum and energy. The model is made for a two-dimensional permanent flow regime in an annular cylindrical geometry filled with a porous media saturated by a single fluid phase. The convective heat transfer is evaluated for different ratios of internal and external radius and for different Biot numbers, for both air and helium. The results show that helium still the best cooling fluid. Air can ensure the transfer of less than 40% of the heat generated in the nuclear reactor core. In some particular situations: as cooling accidents or when removing the residual heat, air can then play a significant role.*

Keywords: *porous media, core thermal-hydraulics, nuclear reactor, PBMR, behavior, cooling.*

I. Introduction

Pebble Bed Modular Reactors (PBMRs), are high temperature thermal reactors of 6.2 m diameter and 27 m height as described by Nam Zin Cho (2008) [1]. These reactors use uranium spheres as fuel and helium as coolant. The spheres are covered with carbon layers ensuring the thermal moderation of neutrons. In the PBMR concept, the core having a cylindrical similarity is filled with a random pebble bed of spheres. The helium used as primary coolant is flowing downwardly at high pressure to remove the heat generated in the PBMR's core. The coupled thermal hydraulic phenomena occurring in steady state bed nuclear reactor core, were analyzed by developing mathematical models, one can cite Kaviany (1995)[2], Becker and Laurien (2003)[3], Stroh et al. (1979-a) [4], Stroh et al. (1979-b) [5]. And then later, results obtained by mathematical models developed to analyze the coupled thermal hydraulic problems were compared to experimental values measured on full scale loop as done by Stroh et al. (1979-b) [5]. It has been shown limitations and ability to thus mathematical models to adequately calculate flow distribution. This study deals with the cooling of PBMR's core when using helium or air as cooling fluid. Therefore it is important to identify the thermal hydraulic transfer phenomena in the PBMR's core. It shows a wide spread dispersion on heat flux data in natural convection, between experimental data and data obtained by analytical solutions as reported by Vadasz (2010)[6]. Thus the stability of mixed convection in a vertical porous medium is shown to be greatly, in the cases of gases, destabilized by inertia and drag forces, Kumar et al. (2010)[7]. The thermal non-equilibrium model has been used also to perform numerical investigation of effects of several parameters on enhancement or retardation of heat transfer rate in vertical cylinder filled with saturated porous medium by Salman et al. (2011) [8].The PBMR's core is a vertical annular cylinder as shown in figure (1), having inner and outer radius denoted r_i and r_e, and a height H. This cylinder is filled with a porous medium saturated with a single fluid phase and the solid phase consist of fuel spheres of 6 cm diameter. The arrangement of spheres in the annular part of the nuclear reactor core can make the theory of porous media possible and then the thermal hydraulic calculations. As the porous media theory is considered, Darcy's law will be used. Some CFD results show that air can be used as a cooling fluid among some other gases as shown by Sidi Ali and Meftah (2010)[9]. Also recently it has been seen a growing interest to write equations representing flow misdistribution in pebble bed as done by Becker and Laurien (2003) [3] and also by Stroh et al. (1979-a) [4]. In fact the geometric characteristics have a great influence on coupled thermal hydraulic issues. The performed simulation results show a significant impact on the temperature distribution and the maximum temperature when an eccentric misplaced package takes place in the reactor core as mentioned by Kadak and Bazant (2004) [10]. One is interested, in this work, to the evaluation of the capacity of cooling of air and of helium.

A wide serie of flow visualization experiments were conducted at the Massachusetts Institute of Technology to explore major issues of flow in pebble bed reactors, Kadak and Bazant (2004) [10]. The main data obtained globally agree with the PBMR Safety Analysis Report when the flow is laminar, but appear disagree otherwise.

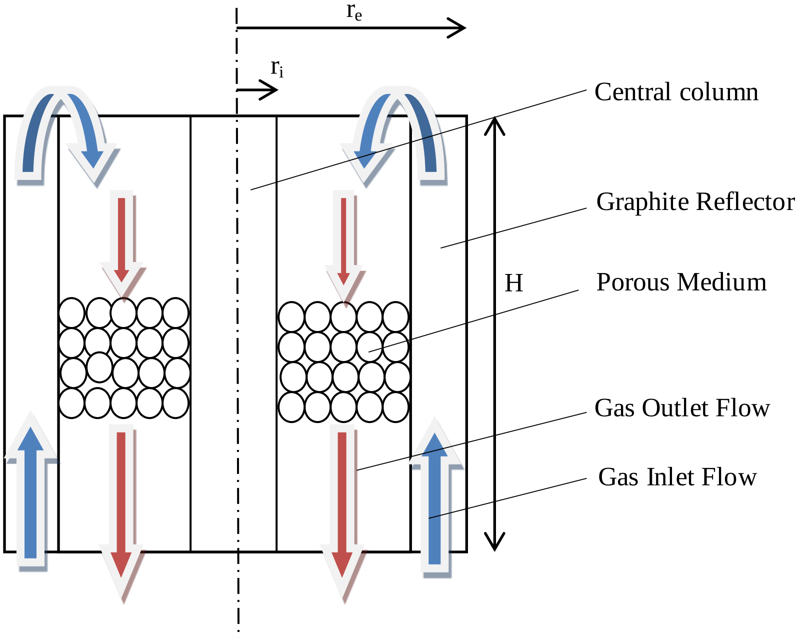

Figure 1 Thermal hydraulic configuration studied

II. Governing Equations

In this work, heat transfer by convection is evaluated for a two dimensional laminar flow in a reactive porous medium. The Darcy model is applied to a homogeneous and isotropic porous medium through which a gas flows at low velocity. The simplifying assumptions to establish the mathematical model are:

- fluid is incompressible and the flow is laminar and stationary.
- thermal equilibrium between the two phases (fluid/solid).
- viscous dissipation negligible.
- thermal conductivity of spheres is constant

Equations governing the flow are the conservation equation of mass, of momentum and of energy, as presented here after in Cartesian coordinates.

$$\nabla . V = 0 \tag{1}$$

$$V = \frac{-K}{\mu}(\nabla p + \rho g) \tag{2}$$

$$V . \nabla T = \alpha \nabla^2 T \tag{3}$$

Where : V is the fluid velocity, *K* the porosity of the medium, μ the viscosity, *p* the pressure, ρ the density, g the gravity, α the thermal diffusivity and T the temperature.

In cylindrical coordinates, the equations of continuity, momentum and energy are written as follows:

- for continuity:

$$\frac{1}{r}\frac{\partial(\mathrm{u}\, r)}{\partial r} + \frac{\partial w}{\partial z} = 0 \tag{4}$$

- for momentum:

$$\mathrm{u} = -\frac{k}{\mu}\left(\frac{\partial p}{\partial r}\right), \mathrm{w} = -\frac{k}{\mu}\left(\frac{\partial p}{\partial z} + \rho g\right) \tag{5}$$

- for energy:

$$(\rho C_p)_f \left(u\,\frac{\partial T}{\partial r} + w\,\frac{\partial T}{\partial z}\right) = \frac{\lambda^*}{r}\,\frac{\partial}{\partial r}\left(r\,\frac{\partial T}{\partial r}\right) + \frac{\partial}{\partial z}\left(\lambda^*\frac{\partial T}{\partial z}\right) \tag{6}$$

where: u and w are the velocity components, *r* the radius, *z* the height, *Cp* the specific heat of fluid and λ^* the conductivity of the medium at thermal equilibrium.
By introducing the dimensionless variables as proposed by Greenberg (2001)[11]:

$$\grave{u} = \frac{u}{\alpha/r_e}, \quad \grave{w} = \frac{w}{\alpha/r_e}, \quad \grave{P} = \frac{P}{\alpha\mu/K} + \frac{\rho_e g z}{\alpha\mu/K},$$
$$\theta = \frac{T-T_e}{T_i-T_e}, \quad \grave{z} = \frac{z}{r_e}, \quad \grave{r} = \frac{r}{r_e}$$

in the equations of continuity, momentum and energy, one obtains the dimensionless forms as given in equations (7,8 and 9).

- equation of continuity:

$$\frac{\partial(\grave{u}\,\grave{r})}{\partial \grave{r}} + \grave{r}\frac{\partial \grave{w}}{\partial \grave{z}} = 0 \qquad (7)$$

- equation of motion:

$$\frac{\partial \grave{u}}{\partial \grave{z}} - \frac{\partial \grave{w}}{\partial \grave{r}} = -\,R_a \frac{\partial \theta}{\partial \grave{r}} \qquad (8)$$

Where $\grave{u}$ and $\grave{w}$ are the dimensionless forms of the flow velocity components, $\grave{r}$ and $\grave{z}$ the dimensionless form of the spatial flow coordinates, θ the dimensionless form of the medium temperature and R_a the modified Rayleigh number given by: $R_a = \frac{k r_e g \rho_e \beta \Delta T}{\alpha \mu}$, where β is the expansion coefficient

- equation of energy:

$$\left(\grave{u}\,\frac{\partial \theta}{\partial \grave{r}} + \grave{w}\,\frac{\partial \theta}{\partial \grave{z}}\right) = \left[\frac{1}{\grave{r}}\left(\frac{\partial \theta}{\partial \grave{r}}\right) + \frac{\partial^2 \theta}{\partial \grave{r}^2} + \left(\frac{\partial^2 \theta}{\partial \grave{z}^2}\right)\right] \qquad (9)$$

One defines the radius ratio by: $\eta = \frac{r_i}{r_e}$ and the ratio of the height and the external radius by: $A = \frac{H}{r_e}$, and the boundary conditions are:

At the internal wall of the core:

$$\grave{r} = \eta \quad \Rightarrow \quad \theta = 1 \qquad (10)$$

At the external wall of the core:

$$\grave{r} = 1 \quad \Rightarrow \quad \frac{\partial \theta}{\partial \grave{r}} = \text{-Bi}\,\theta \qquad (11)$$

At the core entry: $\grave{z} = A \Rightarrow \frac{\partial \theta}{\partial \grave{z}} = 0$ (12)

At the core exit: $\grave{z} = 0 \Rightarrow \frac{\partial \theta}{\partial \grave{z}} = 0$ (13)

To solve the problem, one introduces the stream function by writing :

$$\begin{cases} \grave{u} = \frac{1}{\grave{r}}\frac{\partial \psi}{\partial \grave{z}} \\ \grave{w} = -\frac{1}{\grave{r}}\frac{\partial \psi}{\partial \grave{r}} \end{cases} \qquad (14)$$

And the boundary conditions are:

$$\begin{cases} \psi(\eta, z) = 0 \\ \psi(1, z) = 0 \\ \theta(\eta, z) = 0 \\ \theta(1, z) = \frac{-1}{Bi}\frac{\partial \theta}{\partial \grave{r}} \end{cases} \qquad (15)$$

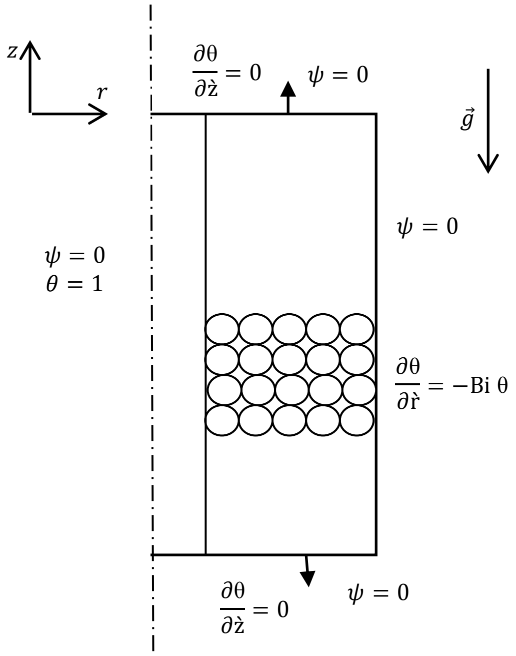

Figure 2. Boundary conditions of the problem

A solution, as proposed by Havstad and Burns (1982) [12], is given by:

$$\psi = \frac{R_{am} B_i \grave{r}^2}{2(1-B_i \ln\eta)}\left[\ln r - \frac{1}{2}\right] + C_1 \frac{r^2}{2} + D_1 \qquad (16)$$

where: $C_1 = \frac{R_a B_i}{1-B_i \ln\eta} \frac{\eta^2 \ln\eta - \frac{\eta^2}{2} + \frac{1}{2}}{\eta^2 - 1}$

and $D_1 = -\frac{R_a B_i}{2(1-B_i \ln\eta)}\left[\frac{1}{2} + \frac{\eta^2 \ln\eta - \frac{\eta^2}{2} + \frac{1}{2}}{\eta^2 - 1}\right]$

$$\theta = \frac{1}{1-Bi\ \ln\eta}\,(-Bi\ \ln\grave{r} + 1) \qquad (17)$$

and one gets:

$$\grave{w} = \frac{R_a B_i \ln\grave{r}}{1-B_i \ln\eta} - C_1 \qquad (18)$$

where $\frac{h\,r_0}{\lambda}$ is the Biot number.
The convective heat flux is calculated using:

$$\varphi_{cv} = \gamma \int_\eta^1 \grave{w}\,\theta\, 2\pi\grave{r}\,\mathrm{d}\grave{r} \qquad (19)$$

Where γ= 0.57 is a proportionality constant.
Injecting (17) and (18) in (19) and integrating, one gets the final form of convective heat flux:

$$Q_{cv} = \frac{2\gamma R_a B_i \pi}{(1-B_i \ln\eta)^2}\left[\frac{2(\eta^2 \ln\eta - \frac{\eta^2}{2} + \frac{1}{2})}{(\eta^2-1)}(1 + B_i - \eta^2 + B_i\eta^3 \ln\eta - B_i\eta^3) - B_i + \frac{1}{2} + B_i\eta^3 - \eta^3 \ln\eta + \frac{\eta^3 \ln\eta}{2} - \frac{\eta^3}{2}\right] \qquad (20)$$

III. Application, Results and Interpretation

An application is done for a PBMR; some of its characteristics are presented in table 1.

table 1 PBMR characteristics

Parameter	**Identity**
Generated power	400 MW
fluid inlet temperature	400 °C
fluid outlet temperature	800°C
Pressure of the system	9 MPa
PBMR core outside diameter	3.7 m
PBMR core inside diameter	2.0 m
Fuel spheres number	450000
Fuel sphere diameter	0.06 m
Enrobing fuel material	Carbon

The results are presented in figures (3, 4 and 5). In these figures, one presents the variations of the convective heat evacuated during cooling in normal situation when using helium as a coolant fluid and in the second case when air is used as a coolant fluid. A comparison between these two cooling cases is also presented.

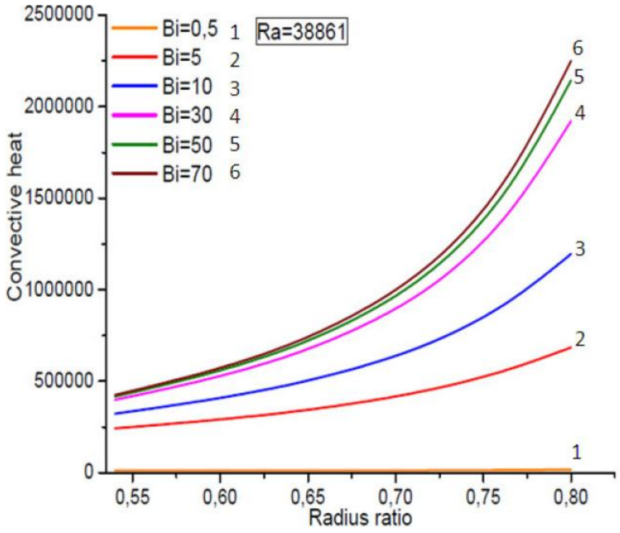

Figure 3. Variations of convective heat for different Biot numbers according to the radius ratio for a Ra (helium) =38861, Alem (2011) [13]

In figure.3, is presented the convective heat flux variations when using helium as a coolant according to the radius ratio between 0 and 0.8, and for Biot numbers between 0.5 and 70. The Rayleigh number is maintained constant and equal to 38861. One sees that for each value of the Biot number, the convective heat is almost identical for low values of the radius (below 0.3). Then the convective heat increases according to the radius ratio and reaches maximum values. For large values of Biot number, one observes that convective heat variations are the same according to Alem (2011) [13].

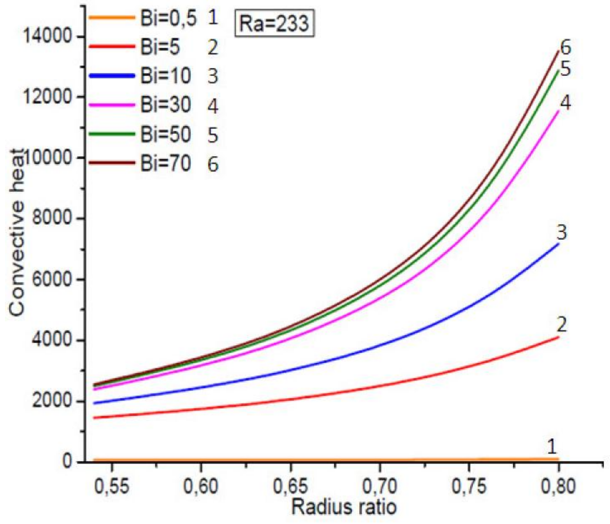

Figure 4. Variations of convective heat for different Biot numbers according to the radius ratio for a Ra (air) =233

In figure.4 is presented the convective heat flux when air is used as a coolant according to the radius ratio *r* between 0 and 0.8 and for Biot number values between 0 and 0.8 and for Biot number values between 0.5 and 70. One sees that for low variation of radius ratio, the convective heat flux is almost the same; it varies between 0 and 3000 and then increases according to *r*. For a low Biot number equal to 0.5, the convective heat flux is low and varies between 0 and 200. For large values of Biot number, the convective heat flux becomes important; we find that the convective heat variations are the same according to the radius ratio for large Biot number values.

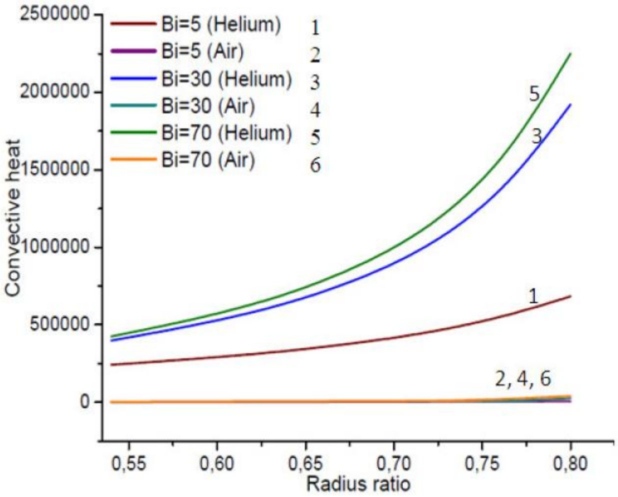

Figure 5. Comparison of the convective heat variations when using helium or air for Biot = 5, 30, 70

In figure.5, is presented a comparison between convective heat variations when using helium or when using air as a coolant according to the radius ratio for Biot numbers equal to 5, 30 and 70. We see that the heat removed when using helium as a coolant is greater than the one removed when using air for the three Biot values. It is also observed that for the three Biot numbers, the heat removed by air is very low, compared to the one removed by helium, as shown on the figure.4.

IV. Conclusions

The coupled thermal hydraulic issues for pebble bed core reactor are in growing interest. Many works deal with numerical modeling and a lot of experiments have been achieved, on porous medium. Here in, the attempting is to model the pebble bed core reactor and estimate temperature and heat transfer when using helium or air as coolant. Both normal operating and shutdown cases are considered. The application of the porous media theory to study the thermal-hydraulic behavior of a Pebble Bed Modular Reactor gives good analytical results. First the effect of geometry (radius ratio) is significant regarding to the amount of heat transfer. Comparison of the convective heat transfers when using air and when using helium shows big differences mainly when the convection is forced. This is due to the thermo physical properties of the gases. One evaluates the ability of air to transfer heat by the order of 30 % to 40 % of the transfer capacity if helium is used. But in some particular situations: as cooling accidents or when removing the residual heat after shut down, air can take place instead of helium.

V. References

[1] Nam Zin Cho, Hui Yu, Jong Woon Kim, Two-temperature homogenized model for steady-state and transient thermal analyses of a pebble with distributed fuel particles, Annals of Nuclear Energy, 36, 4, 2009, pp 448-457.

[2] M. Kaviany, Principles of Heat Transfer in Porous Media, 2nd edition 1995, Springer

[3] S. Becker, E. Laurien, Three-Dimensional Numerical Simulation of Flow and Heat Transport in High-Temperature Nuclear Reactors, High Performance Computing in Science and Engineering ’02, 2003, pp 367-378

[4] K.R Stroh, R.J Jiacoletti, G.Olson, Thermal hydraulic Analysis Techniques for Axisymetric Pebble Bed Reactor Cores, Nuclear Engineering and Design, 52, 1979, pp 343-347

[5] K.R Stroh, R.J Jiacoletti, G.Olson, Comparison of Coolant Flow Prediction with those Measured on a Full-Scale Mockup of a Pebble Bed Reactor Core, Nuclear Engineering and Design, 52, 1979, pp 349-356

[6] P. Vadasz, Heat flux dispersion in natural convection in porous media, Int. J. of Heat and Mass Transfer, 53, 17–18, 2010, pp 3394-3404

[7] J. Kumar, P. Bera, A. Khalili, Influence of inertia and drag terms on the stability of mixed convection in a vertical porous-medium channel, Int. J. of Heat and Mass Transfer, 53, 23–24, 2010, pp 5261-5273

[8] N.J. Salman Ahmed, Irfan Anjum Badruddin, Jeevan Kanesan, Z.A. Zainal, K.S. Nazim Ahamed, Study of mixed convection in an annular vertical cylinder filled with saturated porous medium, using thermal non-equilibrium model, Int. J. of Heat and Mass Transfer, 54, 17–18, 2011, pp 3822-3825

[9] K. Sidi Ali, B. Meftah, Analysis of gaseous flows over a fuel pebble of a PBMR; Behavior of pressure and shear stresses, CNPA 2010, Ouargla.

[10] A.C Kadak, M.Z Bazant, Pebble Flow Experiments for Pebble Bed Reactors, 2nd International Topical Meeting on High Temperature Reactor Technology Sept 22-224, 2004, Beijing, China

[11] M. D Greenberg, Advanced Engineering Mathematics 2nd Edition 1998, Prentice Hall Ed

[12] M.A. Havstad, P.J. Burns, Convective heat transfer in vertical cylindrical annuli filled with a porous medium, International Journal of Heat and Mass Transfer, 25, 11, 1982, pp 1755-1766

[13] A. ALEM, The porous flow applied to Pebble Bed Nuclear Reactors, Master thesis, University of Blida, 2011.

Journal of Scientific Research
University of Bechar

P.O.Box 417 route de Kenadsa
08000 Bechar - ALGERIA
Tel: +213 (0) 49 81 90 24
Fax: +213 (0) 49 81 52 44
Editorial mail: jrs.bechar@gmail.com
Submission mail: submission.bechar@gmail.com
Web: http://www.univ-bechar.dz/jrs/