Darcy Flow and Heat Transfer Through Porous Media Inside a Horizontal Fixed Packed Bed

Alhassen A. Ahmed[1], Ramadan Gennish[1 (*)], Amhimmid Bilrrazig[2], Shaban A. Jolgam[1]

[1]*Dept. of Mechanical Engineering, University of Zawia, Zawia, Libya*
[1]*Dept. of Mechanical Engineering, Libyan Academy, Tripoli, Libya*

Abstract

The present work is focused on the simulation of forced convection airflow through a horizontal fixed packed bed. The flow was considered at low Reynolds numbers (0.01 to 5), where the problem was governed by the Darcy model and the solution performed by COMSOL Multiphysics 05. The analysis was carried out under the assumptions of steady,

---

(∗) Email: r.gennish@zu.edu.ly

incompressible, Newtonian, constant fluid properties. For the thermal conditions, a uniform wall heat flux at the wall boundary is taken to be constant as q = 150 W/m^2 while the porosity of the bed is set to be as ⍰ = 0.39. The results showed that the temperature is greatly affected by the Reynolds number. As the Reynolds number increases the Nusselt number and convective heat transfer coefficient increase consequently the temperature decreases through all the bed, also the pressure drop through the bed increases as the Reynolds number increases and vice versa.

Index Terms— *Convection heat transfer - Porous media - Darcy model - Packed bed.*

A. Introduction

Porous medium is a material consisting of a solid matrix with an interconnected void that allows the flow of one or more fluids through the material, in the simplest situation (single-phase flow) the void is saturated by a single fluid, in two-phase flow a liquid and a gas share the void space.

The study of transport phenomenon in porous media have primarily been initiated by the research activity in geophysical systems and chemical engineering industry. A new area of research was considered since the recognition of the engineering importance of the porous media, where it can be found in a broad range of engineering applications including agricultural applications, industrial applications, thermal conversion and storage systems, and environmental applications.

Therefore, the transport phenomena through fluid-saturated porous media and forced convection heat transfer in porous media is a rapidly growing branch of thermal science, several thermal engineering applications can benefit from a better understanding of convection through porous materials such as thermal insulations, fuel cells, microelectronic cooling system, filtering devices and products manufactured in the chemical industry, the flow of fluid in porous media plays an important role in temperature distribution and heat transfer rate, the term transpiration cooling is used to describe heat removal associated with fluid flow through porous media, the idea is to provide intimate contact between the coolant and the material to be cooled. Several studies have been already carried out in this field with the aim of investigation heat transfer phenomena in porous media for engineering processes. Many researchers have studied the laminar forced convection flow experimentally through packed beds filled with porous media and constant heat flux conditions at the wall surfaces [1-3]. The results revealed that the thermal entry length of the fluid flow through the metal foam (porous media) is much smaller than that for laminar internal flow through an empty channel. The result also showed that the local surface temperature increases along with increasing the axial flow direction for steady flow case.

Simulations of a fixed-bed flow reactor by COMSOL Multiphysics have been presented by many researchers [4-9]. Assuming a uniform velocity profile across the bed implies that Darcy’s law expressions can be used to model the pressure drop across the reactor. Carmen-Kozeny equations were used to determine the permeability of the packed bed, the solutions obtained using COMSOL agreed with validation calculations of Darcy’s Law.

Their results of average local surface temperature distributions, local Nusselt numbers and temperature contours were illustrated, a good agreement between experimental and numerical technique has been achieved.

This work aims to study heat transfer of air flow through porous media at low Reynolds numbers. In such flows, the inertia effects are neglected and the Darcy model is valid. To understand the effect of varying Reynolds numbers on flow temperature through a horizontal packed bed filled with spherical particles, as a porous media, the simulation was done by COMSOL multiphysics 5.0. In this simulation, two physics (porous media and heat transfer) are employed to study heat transfer with Darcy model of flow through porous materials.

B. Main parameters and governing equations

The porosity ε of a porous medium packed bed is the ratio of the pore space volume V_P to the bulk volume of the bed V_t, that is :

$$\varepsilon = \frac{V_P}{V_t} \tag{1}$$

Furnas in [10] proposed an equation for the porosity in a packed column with sphere packing as a function of particle and bed diameter, as shown below:

$$\varepsilon = 0.375 + 0.34\,\frac{dp}{D} \tag{2}$$

Where : dp is the equivalent bead diameter and D is the pipe diameter.

Carmen-Kozeny equation was used to determine the permeability of the packed bed,

$$K = \frac{d_p^2\,\varepsilon^3}{175(1-\varepsilon)^2} \tag{3}$$

where K is the permeability in [m²]. The mathematical governing equations are given by the Darcy equation for the flow through the porous material and the averaged energy equation, Darcy´s law is given by the following relation

$$\Delta P = -\frac{\mu}{K}\,u \tag{4}$$

where ΔP is the pressure drop through a fixed bed, μ is the viscosity.

For steady flow through the porous media without any heat sources; the energy equation is given by

$$(\rho c)_f u \cdot \nabla T = k_m \nabla^2 T \tag{5}$$

where ρ is the density, *c* is the specific heat, *u* is the velocity, *T* is the temperature and k_m is the effective thermal conductivity which is defined by

$$k_m = (1-\varepsilon)k_s + \varepsilon k_f \tag{6}$$

where k_s and k_f are the permeability's of the solid and fluid, respectively. The Reynolds number Re_{dp}, friction factor f, heat transfer coefficient h and Nusselt number Nu_D can be defined as follows:

$$Re_{\mathrm{dp}} = \frac{U\,\rho\,d_p}{\mu\,(1-\varepsilon)} \tag{7}$$

$$\mathrm{f} = \frac{\Delta P}{L}\frac{d_p}{\rho U^2}\frac{\varepsilon^3}{(1-\varepsilon)} \tag{8}$$

$$h = \frac{q''}{T_w(x)-T_b(x)} \tag{9}$$

where *q*" is the heat flux and $T_w(x)$ and $T_b(x)$ are the temperature of the wall and the bulk at position *x* [m], respectively.

$$Nu_D = \frac{q''}{T_w(x)-T_b(x)}\frac{D}{k_m} \tag{10}$$

C. Numerical Solution

Using the COMSOL Multiphysics software, we solved heat transfer of air flow through a porous media with low Reynolds numbers where the Darcy flow is dominating the flow. The computational domain was a two-dimensional (2D) rectangle as shown in Figure 1.

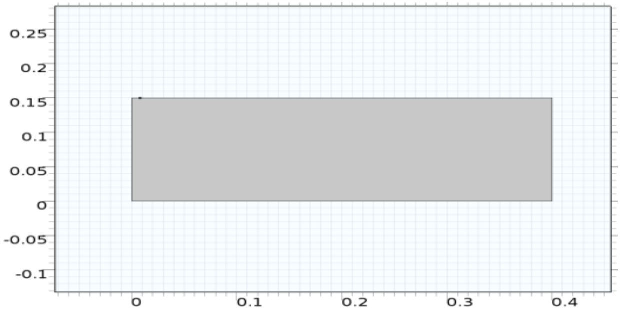

Figure 1. The computational domain, dimensions are in [m].

Figure 2 shows a hybrid unstructured grid used for the calculations of flow simulations in the packed bed of a porous media where ultra-fine triangular mesh cells have been used near solid walls to provide better resolution and spread along with the computational domain.

The boundary conditions are specified for each boundary as follows:

- Uniform inlet velocity and temperature at the inlet section.
- No-slip condition and uniform heat flux at the upper and lower walls.
- Pressure outlet at the outlet section.

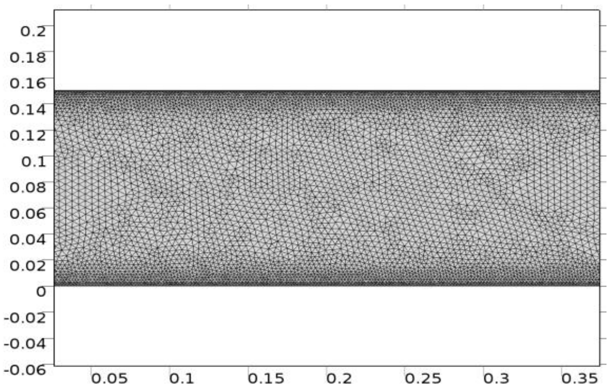

Figure 2. Mesh of the geometry, dimensions are in [m].

The discretized algebraic finite volume equations have been solved iteratively and the residuals have been reduced to value 10^{-6}. The number of iterations is set up to 5000 and the calculation is started and the iteration is continued till the convergence is reached.

D. Results and Discussion

The study is carried out by COMSOL software for single-phase flow with heat transfer through porous media according to the Darcy model. The geometry is a rectangle with length and width equal to forty and fifteen centimeters, respectively. The air is considered as a working fluid inside a pipe filled with porous media (it is spherical particles of stone). The properties of the fluid and porous media are taken at the inlet temperature. The study is carried out for various Reynolds numbers (0.01 to 5), while the heat flux, bed porosity and the porous media thermal conductivity are kept constant at 150W/m², 0.39 and 1.26 W/m K, respectively.

Samples of temperature contours for Reynolds numbers 1.0 and 5.0 are presented in Figures 3 and 4. They illustrate the temperature distribution inside the pipe, one can observe that the temperature of the fluid increases as the flow moves downstream due to the heat flux assigned to the upper and lower sides of the pipe. Moreover, one can notice that as the Reynolds number increases the temperature of the fluid decreases.

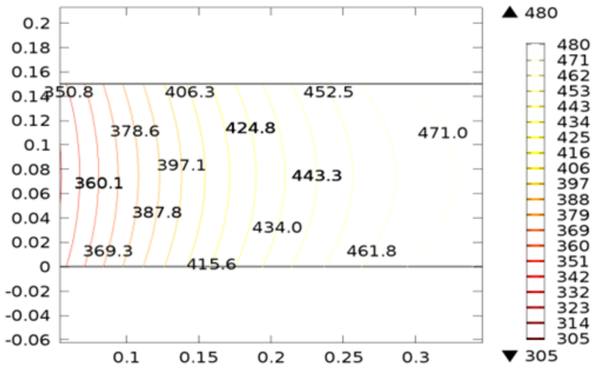

Figure 3. Contour temperature [K] for Re=1

Figure 5 shows the centerline temperature distribution along the porous bed length for different Reynolds numbers. The results showed that the temperature decreases faster as the Reynolds number increase indicating higher heat transfer rates.

Figure 6 shows the heat transfer coefficient lines which are initially decrease dramatically and then continue straight to the end of the pipe, this is because the temperature difference between the surface temperature and bulk temperature decreases, also shows the heat transfer coefficient increases when Reynolds number increases. Figures 7 and 8 show that the relations of the local and average Nusselt numbers where the overall result indicates that the Nusselt increases with an increase in Reynolds number, thus the heat transfer is enhanced.

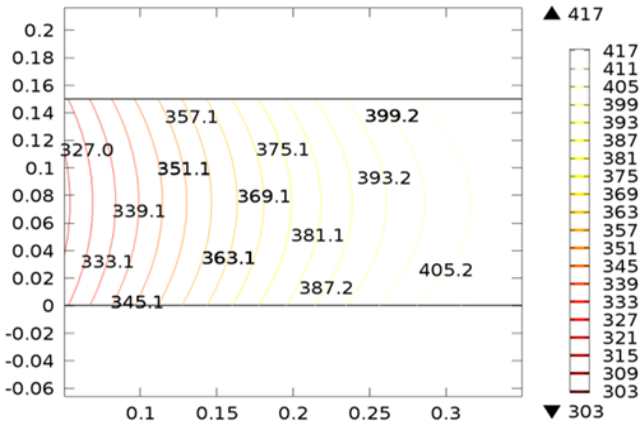

Figure 4. Contour temperature [K] for Re = 5, dimensions are in [m]

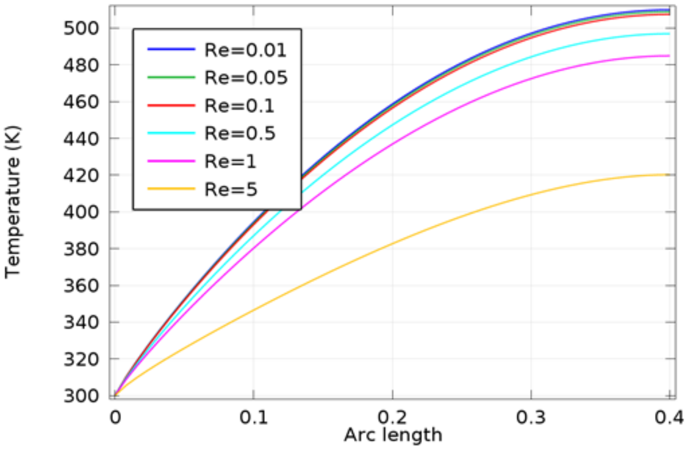

Figure 5. Line temperature [K] at different Reynolds numbers

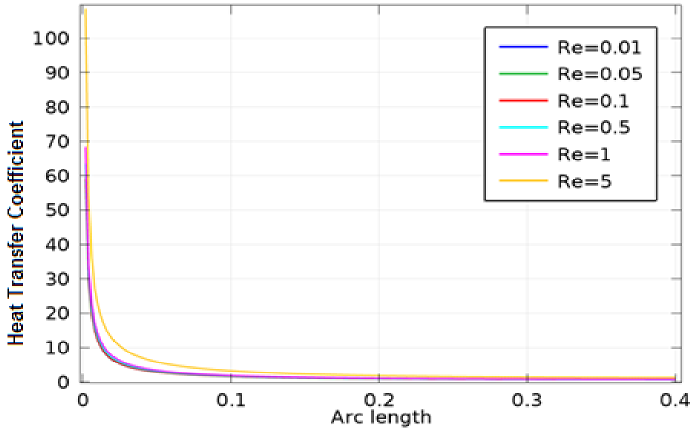

Figure 6. Local heat transfer coefficient at different Reynolds numbers, arc length in [m].

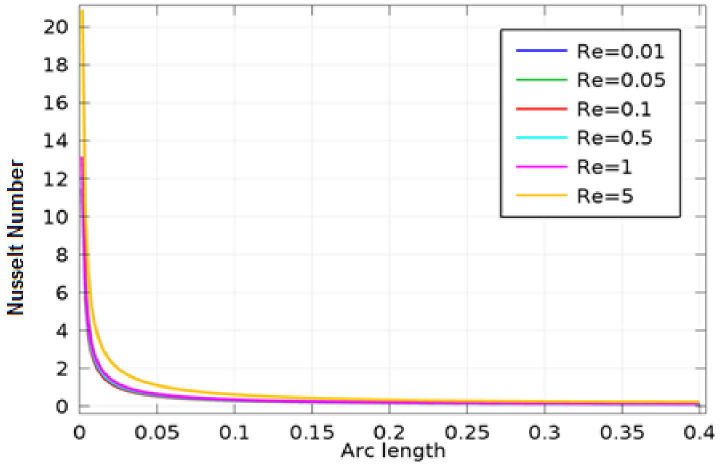

Figure 7. Local Nusselt number at different Reynolds numbers, arc length in [m].

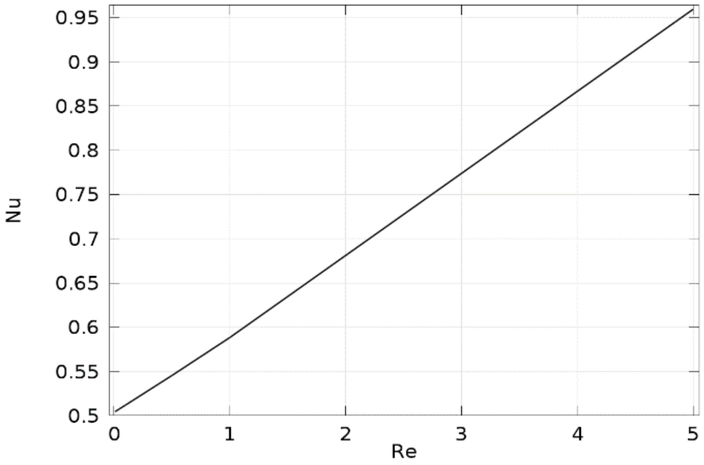

Figure 8. The average Nusselt number vs Reynolds number

Figure 9 shows the relationship between pressure and Reynolds number where the relation is approximately linear below Re = 1.0 then the non-Darcian effects appear over Re = 1.0. The friction factor graph presented in figure 10 based on pressure drop calculations.

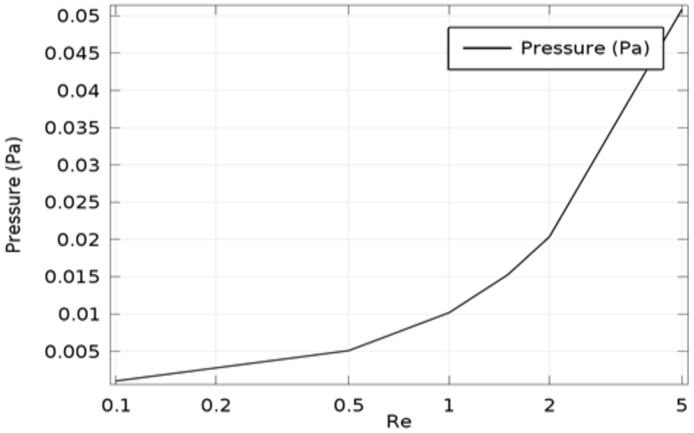

Figure 9. The relationship between pressure drop and Reynolds number

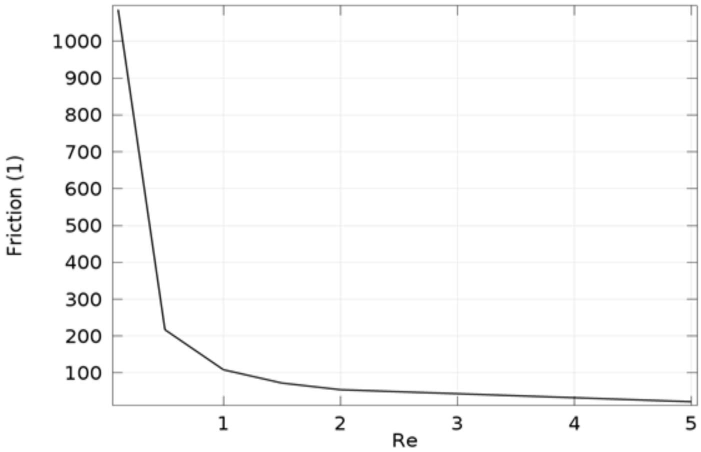

Figure 10. The relationship between friction factor and Reynolds number

E. Conclusions

A steady-state computational study of air flow and heat transfer through a fixed packed bed was simulated by COMSOL Multiphysics. The following conclusions can be deduced from the study:

1. The results showed that the maximum outlet temperature appeared with the lowest Reynolds number value indicating that the heat transfer coefficient and Nusselt number increase when the Reynolds number increases.
2. The pressure drop increases with the increase in Reynolds number, which increases the required power to overcome friction effects.
3. The results demonstrate the validity of the Darcy model when Re is less than one. At higher Reynolds numbers, non-Darcian effects such as wall and inertial effects appear.

F. References

1. *Tahseen A. T. (2007) "Experimental Study for Heat Transfer Enhancement by Laminar Forced Convection from Horizontal Tube Heated with Constant Heat Flux, Using Two Types of Porous Media". One scientific Conference Technical Authority Educating- Baghdad, 28-29 April 2007, University of Tikrit.*
2. *Souad M., El Ganaoui M., Sghaier J. and Belghith A. (2013) "Experimental Study of the Convective Heat Transfer Coefficient in a Packed Bed at Low Reynolds Numbers". Thermal Science. OnLine-First Issue 00(2). DOI: 10.2298/TSCI120715108M.*
3. *Pastore N., Cherubini C, Rapti D, and Giasi1 C. (2018) "Experimental study of forced convection heat transport in porous media". Nonlin. Processes Geophys. Vol. 25, pp. 279-290.*
4. *Elsworth A. (2008) "Modeling Flow through a Fixed Bed Packed Reactor". spring 2008, EGEE. 520*
5. *Dixon A., MacDonald B., and Olm A. (2014) "Modeling of Packed Bed Reactors: Hydrogen Production by the Steam Reforming of Methane and Glycerol". Excerpt from the Proceedings of the COMSOL Conference in Boston (2014).*
6. *Bayomy A. and Saghir M. (2014) "Numerical Investigation of Heat Transfer of Aluminum Metal Foam Subjected to Pulsating Flow". Excerpt from the Proceedings of the COMSOL Conference in Boston (2014).*
7. *Diani A., Bodla K., Rosetto L., and Garimella V., "Numerical Investigation of Pressure Drop and Heat Transfer through Reconstructed Metal Foams and Comparison Against Experiments". CTRC Research Publications, Italy. (2015).*

8. Al-*Farhany K., Abdulkadhim A. (2018) "Numerical Investigation of Conjugate Natural Convection Heat Transfer in a Square Porous Cavity Heated Partially from Left Sidewall". International Journal of Heat and Technology, Vol. 36, pp. 237-244.*
9. *Kumar A., Pramanik S. and Mishral M. (2016) "COMSOL Multiphysics Modeling in Darcian and Non-Darcian Porous Media". Excerpt from the Proceedings of the 2016 COMSOL Conference in Bangalore.*
10. *Furnas C. C. (1931) "Grading Aggregates I-Mathematical Relations for Beds of Broken Solids of Maximum Density". Industrial and Engineering Chemistry, Vol. 29, No. 9, pp. 1052-1058.*