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Numerical study of the effect of porous media on heat transfer in a horizontal annular tube

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ABSTRACT

In the current study, to enhance the characteristics and forced convection performance in the horizontal annular in the case of the presence of porous material and without porous material, energy analyses were performed. Many types of porous material, porosities, and diameters were used. Computational fluid dynamics was used to simulate an annuli tube in case of the presence of porous material and without porous material by utilization of ANSYS FLUENT software 17.2. The working fluid utilized was water with Reynolds number from 100-500 and constant wall heat flux at 150 kW/m2. Two types of porous media glass and steel balls, two different porosities (0.6 and 0.7), and two different porous material diameters (12 and 24mm) were utilized. Investigations occurred under the study state for studying heat transfer properties and flow of fluid in the annuli tube. The energy analysis outcomes showed that there is a relationship between Nu and Reynolds number. The highest enhancement of Nu number happened at 12mm diameter and 0.6 porosity for bolls of glass and 0.7 for bolls of steel. The pressure drop rising occurs with the rising of Re for all cases and the diameter of 12mm gives the maximum pressure drop for both steel and glass pellets and the uppermost pressure drop occurs at a porosity of 0.6. As compared with those in the annulus in the absence of a glass sphere as porous material at the same ball volumes.

1. Introduction

The porous channels which fluid flow and heat transfer occur have significant requests in many engineering arenas as geological studies [1,2], petroleum industries, solar collectors, water resources, filtration, heat exchangers and purification processes [3]. Over time a considerable interest has haggard for studying thermal and characteristics of flow confidential channels full of porous medium [4,5]. Vineet & Pawan [6] used computational fluid dynamics to investigate the magnetic field influence on the hydraulic flow performance, the investigation was between two axial tubes fraught with a porous medium. The work appeared that when the magnetic field and permeability were equal to zero, the normal results were higher than results. Reason that the permeability and the magnetic field have salient influence on the flow. Habibollaa & Hossein [7] the performance of heat-transfer in circular tube partly full of a porous medium was studied using computational fluid dynamics. Results appeared that increasing or decreasing in the Darcy number and decreased the pressure were by increasing of the porosity. The increasing of Darcy number or the porous material thermal conductivity enhanced heat transfer. Poulikakos & Renken [8] examine the heat transfer numerically inside a channel full of a porous medium. The results appeared an increase of 22% in the Nusselt number value in the developed area of the circular channel compared with the expected value when using the Darcy method. Isbeyeh et al. [9] experimentally studied enhancement of thermal heat exchangers performance in case of presence porous media.

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Nomenclature:

Ai	outer surface area of internal tube, (m2)
Ao	inner surface area of external tube, (m2)
As	surface area of heat transfer, (m2)
d	diameter of glass and steel pellet, (m)
Dh	hydraulic diameter of annuli tube, (m)
Di	external diameter of internal tube, (m)
Do	internal diameter of outside tube, (m)
h	forced heat convection coefficient, (W/m2.K)
K	permeability
Ks	thermal conductivity of glass and steel pellets, (W/m.K)
Keff	effective of thermal conductivity, (W/m.K)
Kf	thermal conductivity of working fluid, (W/m.K)
L	length of annuli, (m)

Greek symbols

ṁ	mass flow rate , (kg/s)
n	glass and steel pellets number
Nu	Nusselt number
r	radius of glass and steel pellet, (m)
Re	Reynolds number
Ti	average wall temperatures of internal tubes for annuli, (oC)
Tm	mean temperature, (K)
Vd	bulk volume, (m3)
Vp	glass and steel pellets volume, (m3)
To	average wall temperatures of external tubes for annuli, (oC)

Enhancement of the thermal performance in the cylinders caused by increase in porosity. Saad [10] studied experimentally free convective heat transfer, the studied was of a concentric horizontal annular tube considering the effect of porous medium. Results show that increasing radius of the annular tube, diameter of porous pellets caused enhancement of the rate of Nu, and Ra decreased with increasing of Nusselt number. Mehmet [11] numerically investigated the impact of utilizing a porous medium on a pipe thermal performance. The results show that the Nusselt number was found in the longitudinal direction and studied the flow rate. This research purpose is analyses energy for improving the properties and forced convection performance into horizontal annular in case of presence porous media and without porous media using ANSYS Fluent software version 17.2. Different types of porous media and different diameters and porosities were used. Glass and steel balls porous media are used.

2. Numerical study

2.1 Physical Perfect of Annuli Tube

Two computational domains of annuli tube occupied with porous media. The solid domain is major, which comprises of the internal copper cylinder and porous medium (glass and steel spheres); another domain exemplifies the water (working fluid) inside the annuli tube. Annuli tube contains of double exterior and interior cylinder having multi-axes during the flow of fluid as appear in Fig. [1]. An annulus of double pipes involves of double pipe length (L=300mm), inside diameter of tube heated by the thermal flux (Di=20mm), outside diameter of tube (Do=120mm), pipes thickness (10mm) and the glass and steel spheres is diameters (d=12 and 24 mm) on behalf of the porous medium. Internal tube diameter wall is heated under heat flux. The water utilized (working fluid) is at a variable speed at input uniform temperature 300 K. The heat transfer take place between porous medium and the surface of the interior tube heated with working fluid in directions x, y and z.

2. 2 Annuli Tube Computational Model

The simulation is used ANSYS fluent software version (17.2). In this work used Darcy's flow. To provide thermal hydraulic analysis, SOLID WORK version (18) software is utilization for generating horizontal annular tube 3D model occupied by porous material (steel & glass pellets). The utilization of Solid Works software is done to generate a horizontal annuli tube 3D model to provide thermal hydraulic analysis in this work. Two heat transfer regions shown in figure [1]. The copper tube is the major region, where the heat transfer by conduction is main. The porous media is representing another region, where two heat transfer instruments are main: convection by working fluid and conduction by porous material section.

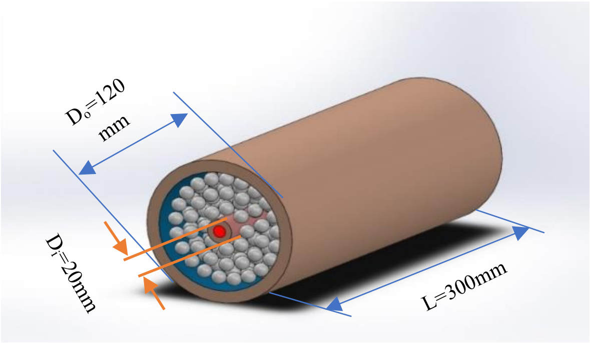


Figure 1. Schematic diagram a horizontal annuli tube filled steel spheres

2.3 Porous Medium

The porous material used in this study is glass and steel balls. In this work Darcy’s flow is used. Two different diameters (12 and 24 mm) are used to study the effect of these balls. Porous material with two different diameters which have been examined in the simulations the balls are placed between the two cylinders representing the porous medium in saturated form. The porous mean includes three important properties that are considered in this work.

2.3.1 Porosity

Porosity (ε) is a characteristic of the porous medium, which rely on the porous diameter of the glass and steel balls and the diameter of the test part containing the porous material, the annular tube [12,13].

$$\varepsilon = \frac{V_d - V_p}{V_d} \tag{1}$$

$$V_d = A \times L \tag{2}$$

$$V_p = \frac{4}{3}\pi r^3 n \tag{3}$$

Where; Vd is the volume of annular tube (test section), m3; Vp is the volume of porous medium, m3; A is the area of (test part), m2; r is the radius of glass and steel balls, mm; and n is the number of glass and steel spheres.

2.3.2 Permeability

Another important feature of the porous medium is permeability which rely on the porosity and diameter of porous media [14,15].

$$K = \left(\frac{\varepsilon^2\, d^2}{175}\right)(1-\varepsilon) \tag{4}$$

Where d is the porous medium diameter & ε is porosity of porous medium.

2.3.3 Thermal Conductivity

The effective thermal conductivity of filled fluid is found in the porous medium, depending on the porosity of the porous balls, the water and porous medium thermal conductivity [16, 17].

$$k_{eff} = \varepsilon\, k_f + (1-\varepsilon)\, k_s \tag{5}$$

Where; keff is the effective thermal conductivity, ks is the porous balls thermal conductivity, and kf is the water thermal conductivity.

The nusselt number can be calculated by.

$$Nu = \frac{h\, D_h}{k_{eff}} \tag{6}$$

The porous media thermal conductivity is found at [18], [19].

Table 1. Properties of porous medium

Types of porous media	Diameter (mm)	Porosity (ε)	Permeability (K)	Thermal conductivity (ks) w/m.k	Number of balls
Glass balls	d = 12	0.7	2.3×10^{-8}	0.81	792
	d = 24	0.7	1.2×10^{-7}		070
Steel balls	d = 12	0.7	2.3×10^{-8}	16.3	792
	d = 24	0.7	1.2×10^{-7}		070

2.4 Boundary conditions and governing equations

For the laminar forced convection heat transfer, incompressible, laminar flow, stable and single-phase in the annuli tube, must be solve the following governing equations :

- *Equation of continuity[20,21,22]*

$$\rho_f \nabla.\vec{U} = 0 \tag{7}$$

- *Equation of momentum [23,24]*

$$\frac{\rho_f}{\varepsilon^2}(\nabla.\vec{U})\vec{U} = -\nabla P + \rho_w g - \gamma\left[\frac{\mu_f}{K} + \frac{\rho_f C_{p,f}}{\sqrt{K}}\left|\vec{U}\right|\right] + \frac{\mu_f}{\varepsilon}\nabla^2\vec{U} \tag{8}$$

Where ρw and μw are the density and dynamic viscosity of water (working fluid), correspondingly; and P is the pressure of local fluid.

- *Equation of energy [25,26]*

$$\rho_f C p_f\left(\vec{U}.\nabla T\right) = k\nabla^2 \mathrm{T} \tag{9}$$

Where k and Cpf are the thermal conductivity and specific heat of water (working fluid), correspondingly; and T is a temperature of local fluid.

It is must be utilization miscellaneous of boundary conditions to complete the solutions. Boundary conditions is necessity be stated and utilize as instruction relying on physics. The simulation of actual flow conditions applying based on the choose of boundary conditions [27]. Table 2 shows boundary conditions of thermal transfer and fluid flow in the inlet and exit.

Table 2. Fluid flow and heat transfer boundary conditions of for CFD simulation

	Hydraulic simulation	**Thermal simulation**
Inlet	Velocity inlet	Uniform temperature at 300 K
Exit	Zero-pressure exit	$\frac{\partial T}{\partial z} = 0$
Outer surface	No skid wall	Constant temperature wall
Steel ball surface	No skid wall	Constant temperature wall
Internal surface	No skid wall	$k_s \frac{\partial Ts}{\partial n} = q''$

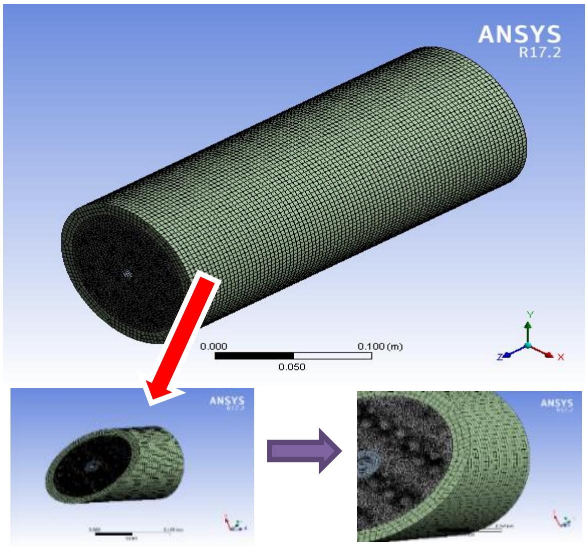
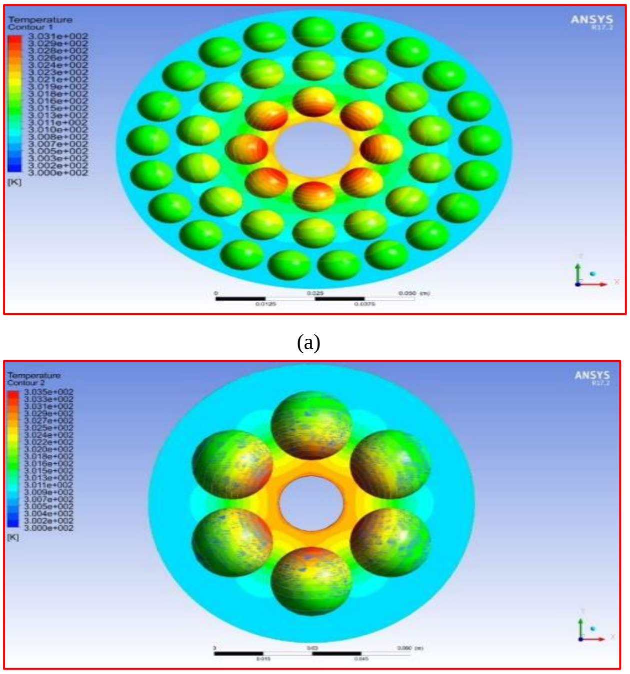


Figure 2. Mesh generation of annular tube geometry

2.5 Numerical simulation

The grid creation is significant in the simulation. The mesh is geometrically minor and shelters the whole physical area. Conservation laws can be applied by drive of this mesh and regulate the distinct sizes. The principal step is the numerical solutions calculation of equations that label the mesh generation physical process. The quality of mesh is determined by the solution consequence. Refining the solution excellence can principal to the creation of another mesh, while the use of an undeveloped mesh clues to deviations in the solution. Grid cells are coordinated to the boundary surface, and additional areas of flow are recognized using flexible elements. Figure [2] exemplifies the arithmetic mesh delivery of the model.



(a)

(b)

Figure 3. Temperature delivery along the fluid part annuli tube with two diameters: (a) d=12mm, (b) 24mm

3. Result and discussion

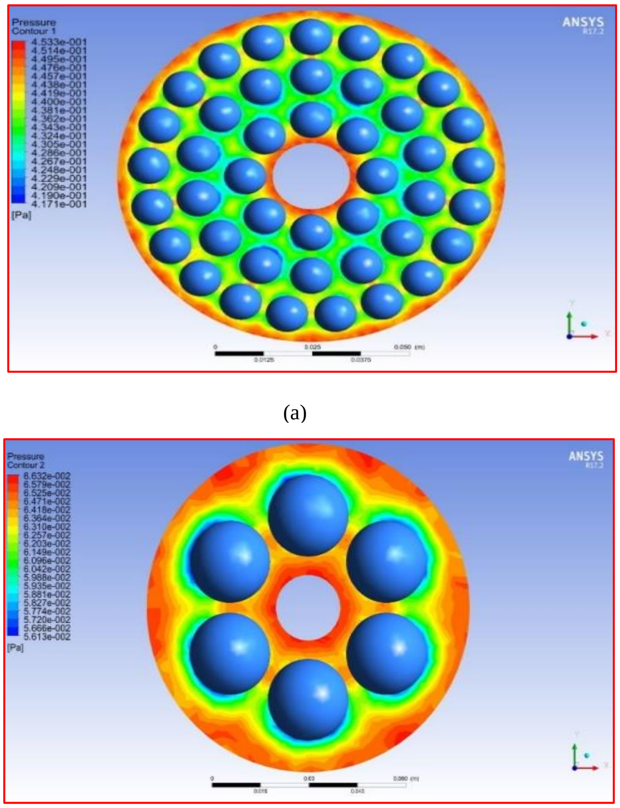
The numerical results of the annuli tube occupied with a porous media are analyzed and discussed. The ANSYS fluent programmer is used to demonstrate and analyses the results. Several variables are adopted in this section to demonstrate their influence on the performance of the annuli tube. Two different diameters (12 and 24mm) of glass balls and steel balls are used, and the porosity ε = 0.7 is stabilized by change number of ball(n). Two different standards of porosity (0.65 and 0.7) are used, with the constant value of the diameter of the glass and steel balls (24 mm). The inlet water temperature is fixed at 300 K, whereas the velocity of water input depends on the Reynolds number in the annular tube. To show effect of Reynolds number on hydrothermal performance of the annular tube occupied with a porous material, Reynolds number range between 100 and 500 is use.

3.1 Temperature delivery

A annuli tube filled with porous material which lies between the internal and external surfaces of tubes, deliver with temperature of liquid and solid domain at Ti= 300K at entry. A uniform thermal heat flux equal q = 150 kW/m2 and Reynolds number value equal 500 along the annuli tube. Figure [3] explain that the axis is z = 0 and plane (x,y) taken at center of fluid for annuli tube. For all cases, the inlet working fluid temperature is 300K. The layer contacts interior cylinder which represents the heat flow that temperature high and reduction slowly towards x-axis. Heat is decreased in the middle of annuli and gain heat from uniform heat flux with maximum heat exchange. When touching towards x and y-axis the water is lose heat, due to an influence of heat flux is big at the area of contact and at fewer as x-axis is loomed. At diameter of 12 mm glass balls, the temperature is low as compare to glass balls of 24 mm diameter. This is owing to upsurge in heat transfer area between the thermal flux and working fluid. Therefore, water spreads the maximum temperature in heat transfer process from thermal flux.

3.2 Pressure Delivery

The delivery of pressure drop over the length of annuli tube occupied by porous media, which lies between the internal and external surfaces of tubes, deliver with pressure of solid and liquid part is equal to zero in the output. The value of a uniform thermal heat flux q = 150 kW/m2 and Reynolds number value of 500 are considered. Figure [4] demonstrations the plane (x, z) is taken a center of fluid part of the annuli tube, and the axis is (z = 0). For all cases, a decrease in pressure drop is observed along the annuli tube. The pressure drop is occur due to existence of porous materials, and the low speed that causes a change in the flow field. Therefore, the pressure starts to decrease, and the porous materials cause high shear stress and result in a decrease in pressure. As for x-axis, the pressure drop is relatively small, and its value is convergent whilst moving towards x-axis. The pressure drop is maximum in porous sphere with a diameter of 12mm because of the large number of balls and their proximity with some, which cause increased shear stress, change the flow area and thus lead to lower pressure gradually descending along the pipe length compared with the porous balls with diameters 24 mm.



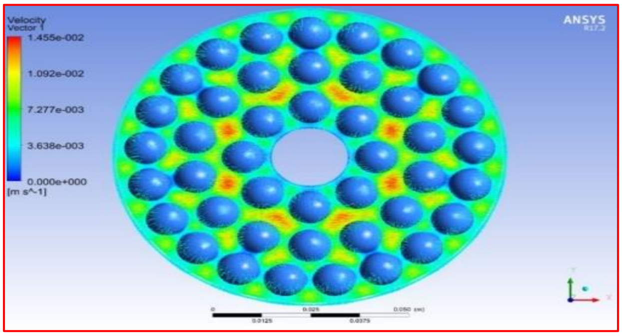
(a)

(b)

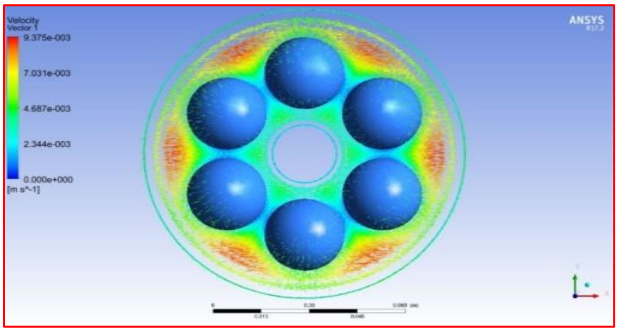
Figure 4. Pressure delivery along the fluid part annuli tube with two diameters: (a) d=12mm, (b) 24mm

3.3 Velocity Delivery

Figure [5] show the delivery of velocity over the length of annuli tube occupied by porous media amid of the inside and outside tubes surfaces of the solid and liquid at the burden of the entrance speed is 0.0035 m /s, at Reynolds number of 500 and value of uniform thermal flux is 150 kW/m2. Figure [5] displays that plane (x , y) is taken a center annuli tube, and the axis is z = 0 .The speed instigates for increasing along tube length and differs from one region to another. The speed is tall from the area close to the surface of the interior tube and amongst the spaces of the pellets for all cases. The velocity value is few in the sphere crash region due to the deterioration of working fluid velocity. The velocity in x-axis, is tall at the area of contact with the interior surface of tube and then slow down at sphere collision whilst touching to x-axis. Lastly, the working fluid velocity reductions at it contact the porous material then climb at the void among pellets along the annuli tube.



(a)



(b)

Figure 5. Vvelocity delivery along the fluid part annuli tube with two diameters: (a) d=12mm, (b) 24mm

3.4 Influence of diameter (glass ball)

The influence of annuli tube filled by spheres of glass on the hydraulic and thermal performances is investigate by two diameters of 12 & 24mm. The diameter is variable whereas porosity ($\varepsilon = 0.7$) is the uniform value. Figures [6]–[8] display the influence of Re on performance factor, Nu and pressure drop in the annuli tube occupied by glass pellets. The thermal heat flux value is established at150 kW/m2. Figure [6] displays disparity in Nu with Re for annuli tube complete by pellets of glass for two diameters. It can be notice for the two cases that Nu is climb with Re. The Nu value in the turbulent region in presence of porous media of annuli tube is higher as compare of with case of absence of porous media. Nu rising can be returns to high glass pellets conductivity. The presence of glass pellets enhanced the Nu, where it is led increase heat transfer because of the tall conductivity of the porous media. High Nu value originate with diameters of 12 mm for the pellets of glass. Figure [7] demonstrations variance between pressure drop and Re in case of presence glass pellets and without porous material. It can be notice that the increasing of pressure drop occur with augmented Re in the presence or absence of glass balls. Glass pellets with diameters of 12 mm have compared with diameters of 24 mm. The upsurges of pressure drop occur with plummeting the diameter and pellets porosity. The minimum pellets diameter led to space between spheres is fewer, thus cumulative the pressure drop and plummeting flow of water. Figure [8] displays the performance factor variance of annuli tube complete by porous medium. Reduction of pellets diameter from 24 mm to 12 mm causing performance factor upsurges. The pellets with a diameter of 24 mm is attained finest performance factor. Diameter reduction of the porous media causing the performance factor reduction. The increasing pellets diameter led to rising in convection heat transfer due to the increasing of glass pellets porosity and heat conductivity, where that led to increasing the performance factor. The highest performance factor was obtained at diameter of 24 mm, highest heat-transfer at 12 mm diameter and the greatest water diameter is 24 mm.

3.5 Porosity influence (glass ball)

The performance of heat transfer was investigated by utilization two porosity (0.6 and 0.7) to find out its influence on the performance. The values of two porosities are mutable part, but the glass pellets diameter is constant at 24 mm. Figures [9]–[11] show effect of Re on the performance factor, Nu and pressure drop in the annuli tube occupied with glass balls. Figures [9]–[11] show the Re effect on the performance factor pressure drop and Nu, in the annuli tube occupied with glass balls. The thermal heat flux value is 150 kW/m2 and two values of porosity are utilization. Figure [9] displays the variance of Nu with Re in the annuli tube occupied by glass pellets. There are rising in Nu with cumulative Re with and without glass spheres. The annuli tube without glass pellets has slight Nu value, whereas the annuli tube filled with glass pellets have upsurge Nu value. The little porosity of the glass pellets give rises in Nu. The porosity of 0.6 is give the maximum value of Nu due to high glass pellets thermal conductivity and that led to higher heat transfer as compare to the annuli tube without glass pellets. Figure [10] demonstrations the variance of pressure drop with Re for annuli tube occupied by glass pellets. Increasing of Re led to rising the pressure drop with and without porous media. A decrease of the porosity of the glass pellets is causing the influence on pressure drop. The porosity of 0.6 gives the maximum pressure drop. The annuli tube without glass balls has little pressure drop. Figure [11] displays the performance factor variance with Re in the annuli tube occupied with a glass pellet with diameter of 24 mm. The improvement of performance factor is occurred by rising of Re and the glass pellets porosity. The maximum performance factor is attained at porosity of 0.6. The reduction of porosity of the glass pellets is causing convection heat transfer rising.

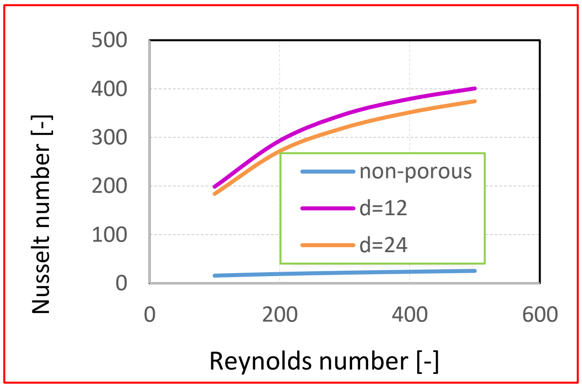


Figure 6. Variations in Nu with Re for two diameters

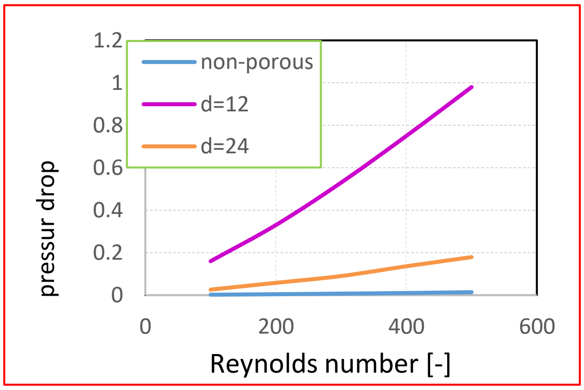


Figure 7. Variations in pressure drop with Re for two diameters

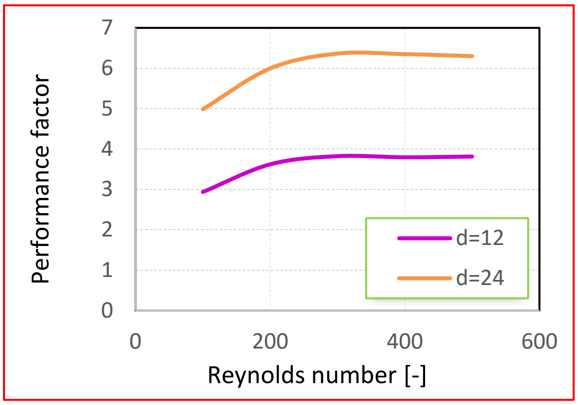


Figure 8. Performance factor variations as a purpose of Re for two diameters

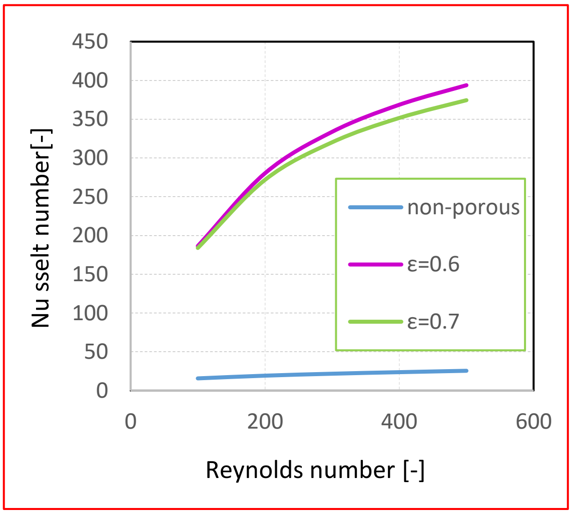


Figure 9. Variations in Nu as a function of Re below two porosities

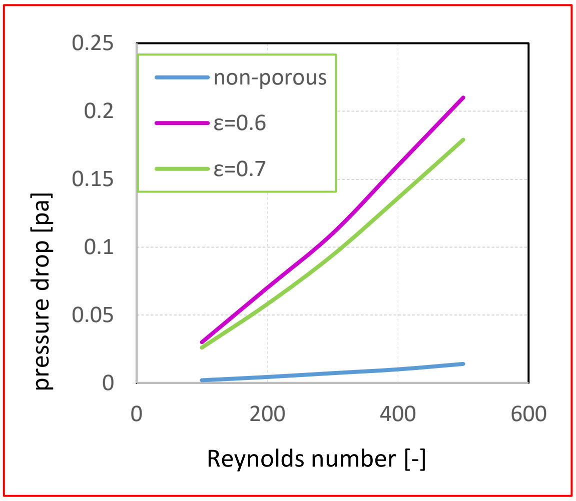


Figure 10. Variations in pressure drop with Re below two porosities

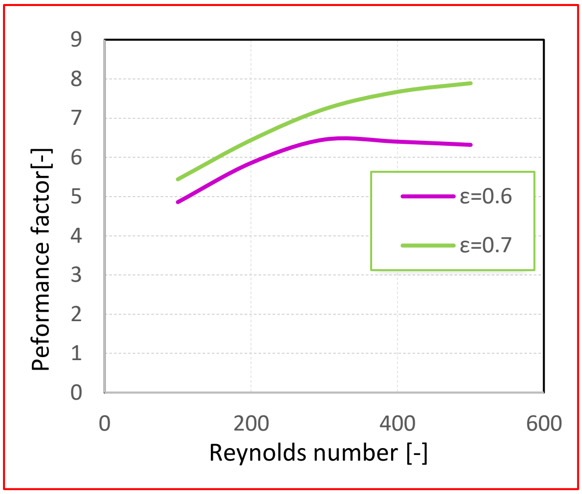


Figure 11. Performance factor variations as a function of Re below two porosities

3.6 Influence of diameter (steel balls)

Two diameters (12 and 24 mm) of steel pellets are utilized to study its influence on the thermal and hydraulic performances of annuli tube occupied by a steel pellets. The variable part is the diameters of steel balls, whereas (ε = 0.7) is the uniform value. Figures [12]–[14] display the Re influence on pressure drop, Nu, and performance factor in the annuli tube complete by steel spheres. The heat flux value is established at 150 kW / m2. Figure [12] demonstrations the variance of Nu and Re for annuli tube occupied by steel pellets with two diameters. Nu is rises with Re increasing for two cases. An annuli tube without the steel pellets have minor disorder Nu value as compared with the annuli tube filled by steel balls. The increasing of Nu is occur due to high conductivity of steel spheres, that is enhances Nu in case of presence porous steel. The steel balls at diameter of 12 mm gives uppermost values of Nu. Figure [13] displays variation of pressure drop with Re for annuli tube filled by porous steel and in absence of porous steel. Increasing of Re led to upsurges of the pressure drop for annuli tube filled by porous steel and in absence of porous steel. The minor steel balls diameter gives better decrease in pressure drop at higher Re. At 12 mm steel balls diameter maximum pressure drop is occur as compare to 24 mm steel balls diameter.

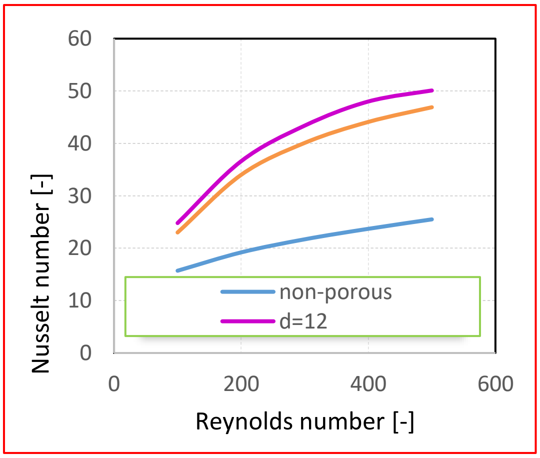


Figure 12. Variations in Nu with Re for two diameters

Dipping of porosity and diameter of the steel balls led to pressure drop upsurges. Smaller steel diameter gives fewer space between the pellets and this led to plummeting the working fluid and cumulative the pressure drop. The variance of the performance factor of the annuli tube filled by porous steel is shown in figure [14]. The rising of Re is instigates the performance factor for rising. The decreasing of steel diameters from 24 to 12 mm causing increasing in the performance factor. At 24 mm steel diameter maximum performance factor is achieved. Larger porous steel diameter is give larger convection heat transfer due to large porosity and the conductivity of the steel balls, where the performance factor is upsurge. The behavior of heat transfer is different from the working fluid behavior. The greatest diameter of heat transfer and finest diameter of working fluid are12mm and 24mm respectively. Consequently, finest performance factor is at a diameter of 24mm for the porous steel.

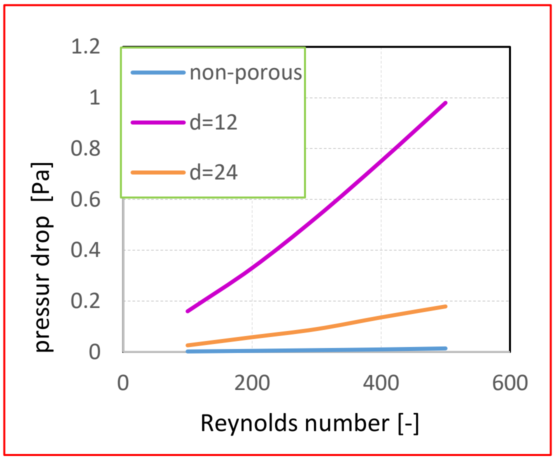


Figure 13. Variations in pressure drop with Re for two diameters

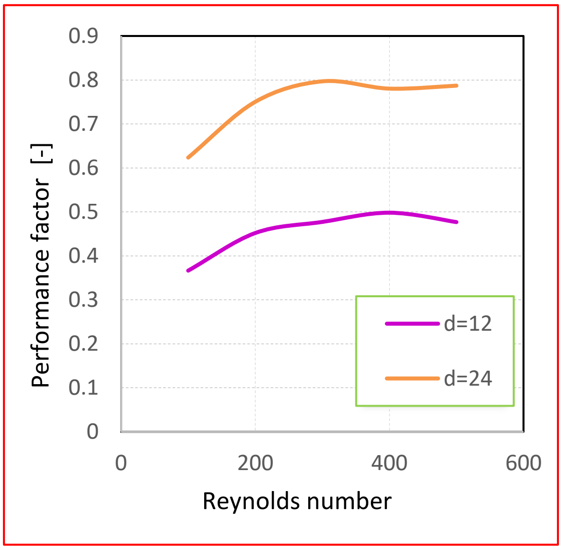


Figure 14. Performance factor variations as a purpose of Re for two diameters

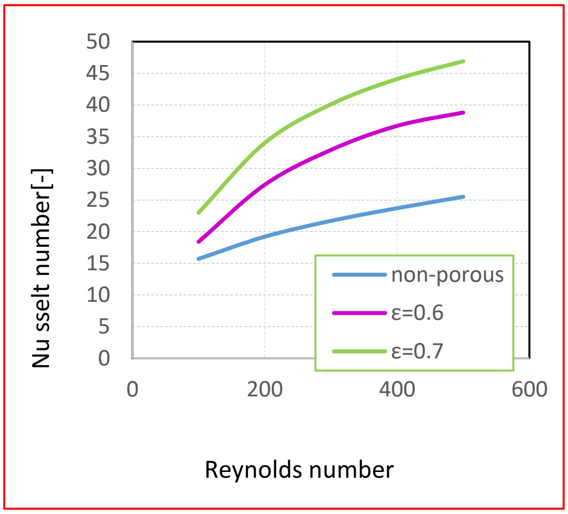


Figure 15. Variations in Nu as a function of Re at two porosities

3.7 Influence of Porosity (steel balls)

To investigate the influence of porosity on the heat transfer performance, two values of porosity (0.6 and 0.7) are utilized inside annuli tube filled by porous steel. The porosity is variable, but the steel pellets diameter is fixed at 24mm. Figure [16]-[17] exemplify the Re influence on the performance factor, Nu, pressure drop inside annuli tube filled by porous steel at diameter 24mm. Two standards porosity are utilized and thermal flux at the worth of 150 kW / m2. Figure [15] demonstrations variance in Re with Nu inside annuli tube filled by porous steel. Nu upsurges with cumulative Re in presence and without porous steel. Nu values are increased in porous steel tube, while its values slight in tube without porous steel. The Nu value is uppermost at 0.6 porosity due to high steel conductivity in the annuli tube, which led to high heat transfer. Figure [16] displays variance of pressure drop with respect to Re for annuli tube filled by porous steel. Re is augmented with upsurges of pressure drop in the absence and attendance of porous steel. The utilization of two porosities of steel balls give reduction in pressure. At porosity of 0.6 a maximum pressure drop is occur. A little pressure drop is originate inside annular tube with absence of porous steel. Additional balls of steel rise the pressure drop. Figure [17] displays variance between Re and performance factor for annular tube occupied by porous steel balls at diameter of 24mm. Two porosity values of steel balls (0.6&0.7) are rummage-sale. The improvement of performance factor is occur when porosity and Re are rise. The steel balls have porosity of 0.6 gives the greatest performance factor. The reduction of porosity of the porous steel led to increasing convection heat transfer, where it is pretentious by the heat-transfer process. The performance factor of annuli tube occupied by steel pellets is then augmented.

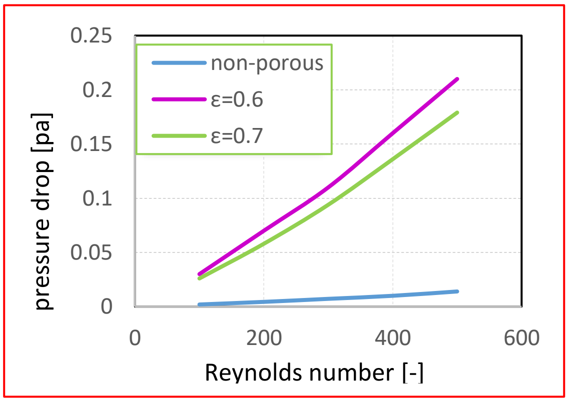


Figure 16. Variations in pressure drop with Re at two porosities

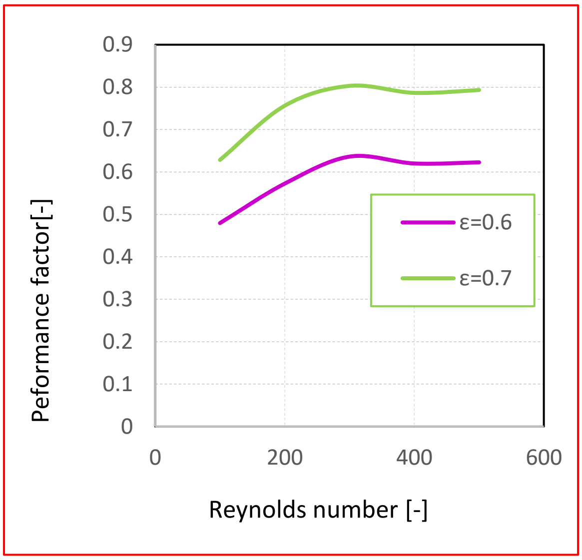


Figure 17. Performance factor variations as a meaning of Re at two porosities

4. Conclusions

The numerical results of the annuli tube occupied with a porous media. Two different diameters (12 and 24mm) of glass balls and steel balls are used, and the porosity ε = 0.7 is stabilized by change number of ball(n). Two different standards of porosity (0.65 and 0.7) are used, with the constant value of the diameter of the glass and steel balls (24 mm).

1. Nu is relative with Re for all cases and the uppermost Nu improvement happens at a diameter of 12mm and the uppermost Nu improvement happens at porosity 0.6 for glass pellets while 0.7 for steel balls. Likened than other steel pellets diameters, glass and diameters.
2. The pressure drop rising is occur with rising of Re for all cases and the diameter of 12mm gives the maximum pressure drop for both steel and glass pellets and the uppermost of pressure drop is occur at porosity of 0.6 also for both steel and glass pellets with those other cases.
3. Performance factor through horizontal porous annuli about 0.3 to 8 times greater than that annuli without porous material.
4. The porosity of 0.7 and glass ball diameter of 24mm are give best performance factor.
5. The best performance factor happens at steel pellet diameter of 24mm and porosity of0.7.

Authors' contribution

All authors contributed equally to the preparation of this article.

Declaration of competing interest

The authors declare no conflicts of interest.

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REFERENCES

[1] H.K. Dawood, Hussein A. Mohammed, Nor Azwadi Che Sidik, Kannan M. Munisamy," Forced, natural and mixed-convection heat transfer and fluid flow in annulus: A review", International Communications in Heat and Mass Transfer 62, 2015. http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.01.006

[2] Mohammad Hemmat Esfe , Mehdi Bahiraei , Hamid Hajbarati, Majid Valadkhani, "A comprehensive review on convective heat transfer of nanofluids in porous media: Energy-related and thermohydraulic characteristics ", Applied Thermal Engineering, 2020, Vol.178. https://doi.org/10.1016/j.applthermaleng.2020.115487

[3] Lingyun Zhang, Yupeng Hu, Minghai Li, "Numerical Study of Natural Convection Heat Transfer in a Porous Annulus Filled with a Cu-Nanofluid", MDPI Nanomaterial, 2021. https://doi.org/10.3390/nano11040990

[4] Ahmed F. Alfahaid, R.Y.Sakr, M.I.Ahmed, "Natural Convection Heat Transfer in Concentric Horizontal Annuli Containing a Saturated Porous Media", IIUM Engineering Journal, 2005, Vol.6, No. 1, PP. 41-54

[5] Ramadan Y. Sakr and Nabil S. Berbish, "Natural Convection Heat Transfer In A Horizontal Concentric Elliptic Annulus Containing Saturated Porous Media", Journal of Porous Media,, 2012, PP. 567–584. http://dx.doi.org/10.1615/JPorMedia.v15.i6.50

[6] Vineet Kumar Verma, Pawan Kumar Dixit, "Mhd Couette Flow in an Annular Porous Region between Two Coaxial Cylinders", International Journal of Pure and Applied Mathematics, 2017, Vol.114, No. 3, PP. 571-582. http://dx.doi.org/10.12732/ijpam.v114i3.12

[7] Habibollah Sayehvand, Hossein Shokouhmand, "Study of Forced in a Pipe Partially Filled With a Porous Medium", Heat Transfer Thermal Engineering and Environment, 2006, PP. 292-300. http://dx.doi.org/10.1615/JEnhHeatTransf.v17.i3.10

[8] Poulikakos D, Ranken K, "Forced Convection in a Channel Filled with Porous Medium, Including the Effect of Flow Inertia, Variable Porosity, and Brinkman Friction", ASME Journal of Heat Transfer, 1987, Vol.109, PP. 880-888. https://doi.org/10.1115/1.3248198

[9] Isbeyeh W.Maid, Kifah H. Hilal, Noor Samir Lafta, "Experimental Study of Heat Transfer Enhancement by Using Porous Media in Double Tube Heat Exchanger", Al-Taqani, 2017, Vol.30, No.1, PP.44-59.

[10] Saad Najeeb Shehab, "Experimental Investigation of Natural Convection into a Horizontal Annular Tube with Porous Medium Effects", Journal of Engineering, 2016, Vol.22, No.12, PP.103-117. https://doi.org/10.31026/j.eng.2016.12.07

[11] Mehmet Turgay Pamuk, "Numerical Study of Heat Transfer in a Porous Medium of Steel Balls", Piri Reis University Engineering Faculty Department of Mechanical Engineering, 2019, Vol.23, No.1, PP. 271-279.

[12] Rafel Basim Abd Alrazzik,"Effect of Cross Sectional Geometry on the Convection Heat Transfer Inside a Channel Filled with Porous Media", A thesis Submitted to the Department of Mechanical Engineering at the University of Technology in a partial fulfillment of the requirements for the Degree of Master of Science in Mechanical Engineering, 2015.

[13] Jasim Mohammed Abood, " Forced Convection Heat Transfer around a Body with Variable Cross Section Embedded in Porous Media", A Thesis Submitted to the Department of Mechanical Engineering at the University of Technology in a partial fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering, 2016.

[14] Donald A. Niled and Adrian Bejan, "Convection in Porous Media", Springer, Fifth Revised Edition, (2017).

[15] Mustafa Fouad Yousif, Saad Najeeb Shehab, Hayder Mohammed Jaffal, "Effect of Porous Media on The Performance Characteristics of a Concentric Vertical Annular Tube", Journal of Advanced Research in Fluid Mechanics and Thermal Sciences 75 (2020) 94-112. https://doi.org/10.37934/arfmts.75.2.94112

[16] Firas F.qader and Barhm Abdullah Mohamad, "Numerical study of heat transfer in circular pipe filled with porous medium", Mechanical Enginnering, 2023. http://dx.doi.org/10.1556/606.2023.00869

[17] Ayser Munner Flayh and Sajida Lafta Ghashim, "The Porosity Effect of Stainless Steel Balls on Forced Convection Pipe Flow", Al-Nahrain Journal for Engineering Sciences, 2019, PP. 102-108. http://doi.org/10.29194/NJES.22020102

[18] Rajput, R.k., **"**Heat and Mass Transfer", S. Chand and Company LTD, Fifth Revised Edition, India, (2012).

[19] Bejan A., “Convection Heat Transfer”, John Wiley and Sons, Inc., Fourth Edition, USA, (2013).

[20] Tu-Chieh Hung, Yu-Xian Huang, Wei-Mon Yan, " Thermal Performance Analysis of Porous-Microchannel Heat Sinks with Different Configuration Designs" International Journal of Heat and Mass Transfer, 2013, Vol. 66, pp (235-243).

[21] Jeremy Vu, " Modelling of Convective Heat Transfer in Porous Media" A Thesis Submitted to the Mechanical and Materials Engineering Department, College of Engineering, University of Western Ontario, in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering, 2017.

[22] Mohammed H. Alkhafaji, Basim Freegah, Mohammed Hamed Alhamdo, “Study the influence of adding fins to the plate of the solar collector on thermal performance under natural phenomena”, International Communication in Heat and Mass Transfer , 2022, 106058. https://doi.org/10.1016/j.icheatmasstransfer.2022.106058

[23] Khalil Khanafer and Abdalla Alamiri, “Numerical analysis of natural convection heat transfer in a horizontal annulus partially filled with a fluid-saturated porous substrate”, International Journal of Heat and Mass Transfer , 2008,1613-1627. http://dx.doi.org/10.1016/j.ijheatmasstransfer.2007.07.050

[24] Laith M. Jasim, Ali Alkhabbaz, Hudhaifa Hamzah, “Preferred location of the porous sleeve in a concentric annulus depending on the thermal insulation”, Journal of Mechanical Engineering Science ,2022,PP. 1989-1996. http://dx.doi.org/10.1177/09544062221133940

[25] Hyon Kook Myong, “Numerical Investigation on Heat Transfer Characteristics for Natural Convection Flows in a Doubly-Inclined Cubical-Cavity”, Transactions of the Korean Society of Mechanical Engineers, 2009, PP.435-442. http://dx.doi.org/10.3795/KSME-B.2009.33.6.435

[26] Somenath Gorai, Sarit Kumar Das, Devranjan Samanta, “Numerical investigations on the difference between aiding and opposing flows in the developing regime of laminar mixed convection in vertical tubes”, Numerical Heat Transfer Applications, 2022. http://dx.doi.org/10.1080/10407782.2022.2105600

[27] Saad M. AL-Mashaat and Manal H. AL-Hafidh,” Parametric Study Of Laminar Free Convection In Inclined Porous Annulus With Fins On The Inner Cylinder”, Journal of Engineering, 2012, Vol. 18 No. 05. https://doi.org/10.31026/j.eng.2012.05.10