A Numerical Approach to Study the Steady State Heat Transfer Characteristics of an Annular Porous Heat Exchanger

Subhankar Ghosh¹, S. Senthilkumar², Dewanshu Deep² and K. J. Bharanitharan²
¹Department of Aeronautical Engineering, Vel Tech Rangarajan Dr. Sagunthala R&D Institute of Science and Technology, Chennai- 600062, Tamil Nadu, India.
²Department of Aerospace Engineering, SRM Institute of Science and Technology, Kattankulathur – 603203, Tamil Nadu, India.

E-mail: s.senthilms@gmail.com

Abstract. Heat exchangers are one of the most heavily studied devices and extensive work has been performed over the years to increase their effectiveness. The present work investigates the heat transfer characteristics of an APHE (annular porous heat exchanger) in terms of different parameters. A modified design for the APHE is proposed, which resembles a conventional double pipe heat exchanger, with the annular portion of the outer pipe filled with a specific type of porous medium in order to intensify the heat transfer process. Commercial CFD package ANSYS Fluent has been utilized to investigate the performance of the proposed design numerically. Introduction of porous medium induces an increase in pressure loss which is undesirable; hence, a trade-off is present between hydrodynamic and thermodynamic performance. In the present work different inlet parameters have been modified such as different values of porosity (70% to 90%), different inlet velocities of hot fluid (1 m/s to 9 m/s), different inlet velocities of cold fluid (5 mm/s to 25 mm/s), and different inlet temperature of hot fluid (400 K to 480K), and their effects on the outlet parameters have been studied. The change in heat transfer has been presented quantitatively along with other significant parameters such as mass flow rate, pressure drop and hot gas outlet temperature. These results have been compared with the values for conventional heat exchangers in order to establish the effectiveness of APHE.

1. Introduction
Heat exchangers are at the core of almost all modern machinery at the disposal of humankind and constant research and development keeps happening to enhance their effectiveness and efficiency. The major concern is increasing the efficiency of the heat transfer process while reducing the energy loss, reducing complexity of design and manufacture, and reducing the overall manufacture and operation costs. Numerous papers relating to various heat exchangers and their performances have been published. The NASA report [1] on annular flows gives a good overview of the properties of such heat exchangers.

Lochan et al. [2] have investigated the effect of porosity on the heat transfer occurring inside a cylindrical heat exchanger with 5 tubes carrying hot and cold fluids. They present a review of the various types of heat exchangers and the effect of porous media in enhancing the heat transfer process. Alkam and Ak-Nimr [3] have carried out simulations for efficiency enhancement of conventional concentric tube heat exchangers through use of porous substrates added to the inner tube wall on both
inner and outer side. The method improved the heat transfer between the fluid and the wall for both parallel and counter flow. A critical value of the thickness of the substrate was identified beyond which there was no significant increase in the effectiveness of heat transfer. Mohamad [4] carried out a numerical analysis to test the effectiveness of fully and partially filled porous media in a channel. Heat transfer and fluid pressure drop investigations were performed with various porous layer thicknesses in forced laminar flow. Partially filled arrangement with 0.6 porous thickness or radius ratio was found to be optimum for enhanced heat transfer with minimal pressure drop. Zheng et al. [5] also found that partially filled porous medium gives better heat transfer in vertical thermal heat receivers. Senthilkumar and Palanisamy [6] have also tested various porous media attached to the outer wall of the inner tube in a tube-in-tube heat exchanger.

Jiang et al. [7] have studied the upward fluid flow in a porous vertical annulus. Different Reynolds numbers were tested to determine the effect on the flow inertia on the local heat transfer and flow field. The porous media helped in increasing the coefficient of heat transfer with an increase in friction resistance. Increase in the particle size was seen to give better heat transfer coefficient with reduced pressure drop. Whereas, Wang and Du [8] have conducted experiments for the convective heat transfer inside a vertical annulus with water flowing upwards. The porous media present in the annulus caused disturbance to the flow causing thermal dispersion. Khaleed et al. [9] have studied the effect of aspect ratio of porous medium of a vertical annular heat exchanger.

Chikh and Allouache [10] have performed numerical analyses to study the entropy generation rate caused by heat transfer and fluid friction and use it to determine the performance of an annular heat exchanger. Different parameters of the porous substrate attached on the inner pipe were studied and the optimal thickness for total entropy generation reduction was identified. Xu et al. [11] have also tested an annular heat exchanger filled with porous medium where they tested various models for finding out the best model for applications with asymmetrical heating.

Louw and Meyer [12] preformed an experimental study to compare a traditional tube-in-tube heat exchanger having concentric tubes, with a helical wound tube-in-tube exchanger. The helical arrangement results in annular contact inside the heat exchanger which is absent in the traditional arrangement. The modified helical arrangement gave an overall 20% increase in the heat transfer coefficient and was found to be a better option. Kral et al. [13] have also worked on a modification of the traditional annular heat exchanger by using helical baffles also called helixchangers. The helixchanger design can be optimized based on the application and was found to give good efficiency for conversion of pressure drop to heat transfer. Sanaye and Hajabdollahi [14] and Costa and Queiroz [15] performed numerical studies to optimize the design of shell and tube heat exchangers using different algorithms. Different parameters were optimized to get the best effectiveness and total cost.

Pavel and Mohamad [16] have carried out experimental and numerical investigations to study how the heat transfer rates are affected by metallic porous media used inside a pipe subjected to a uniform heat flux. Noh et al. [17] have carried out an experimental study with aluminium foam used as the porous medium inside an annulus. The method gave good enhancement in heat transfer and can be used for design of compact annular heat exchangers. Zhao et al. [18] used a tube filled with metal foam in heat exchanger and found the effectiveness of the heat exchanger to significantly improve over the conventional heat exchanger with fins.

Targui and Kahalerras 2008 [19] have carried out a numerical analysis for a double pipe heat exchanger with a porous structure. The heat transfer and fluid flow phenomena inside it were studied with two configurations of the porous structure. They conducted another study [20] with pulsating flows for different configurations of porous material in a double pipe heat exchanger. It was found that the combined use of a pulsating flow and porous baffles gave the best improvement of the heat exchanger performance.

The present work attempts at addressing the issues concerning traditional heat exchangers as seen throughout the literature. Pressure loss across the heat exchanger and the effectiveness of heat transfer are the major concerns present in order to improve heat exchangers. A heat exchanger with porous medium is proposed in the present work and different porosities have been tested for the medium to obtain the ideal balance between effective heat transfer and pressure loss.
2. Model Description
Figure 1 shows the isometric view of the heat exchanger where the length of the heat exchanger has been kept at 30 cm. The inner and outer diameters of the annulus are 2 cm and 10.5 cm respectively. The inner wall is considered to be made of a metal with high heat transfer coefficient and specific heat capacity. The wall is assumed smooth with negligible thickness to avoid wall friction and fluid mixing. The outer wall of the annulus is given a thickness of 2.5 mm with low thermal conductivity to avoid heat loss. Hot fluid passes through the annulus and cold fluid through the inner pipe. Ball-packed type porous medium is present in the annulus.

3. Computational Modelling
2-dimensional heat transfer simulations have been carried out using finite volume method via commercial CFD software ANSYS Fluent. Pressure based solver has been invoked with viscous-laminar mathematical model using SIMPLE algorithm for pressure-velocity coupling. For the convective flux, a second-order upwind scheme is used with convergence threshold for residuals at $1 \times 10^{-4}$. A rectangular domain with appropriate boundary conditions has been employed as shown in Figure 2 which is the cross section of the 3-D model shown in Figure 1. The domain dimensions are, length $X_L = 30$ cm and height $Y_L = 10$ cm. The thickness of the porous medium is $Y_{Po} = 4$ cm each in the upper and lower part. The hydraulic diameter for the middle pipe is $Y_{Pi} = 2$ cm with thin pipe wall. A structured non-uniform quad mesh has been generated with high density close to the inner pipe in order to effectively capture the heat transfer phenomenon as shown in Figure 3.

Ergun’s equation has been used to calculate the viscous and inertial losses in the porous medium [21]:

$$R_f = \frac{3.5 \times (1 - e)}{\phi \times D \times e^3} \quad (1)$$

$$R_v = \frac{150 \times (1 - e)^2}{\phi^2 \times D^2 \times e^3} \quad (2)$$

Where $\phi$ is the sphericity and $D$ is the diameter of solid particles, $e$ is the porosity value, and $R_f$ and $R_v$ stand for inertial and viscous resistance respectively.
4. Results and Discussion

For the present study, analyses have been performed with variations in the inlet parameters and consequently comparing the annular porous heat exchanger (APHE) with the traditional double pipe heat exchanger (DPHE) of similar configuration. The porous medium used for the APHE is a ball-packed type medium where copper balls with 5mm diameter have been assumed. The density of packing determines the porosity of the medium. Increasing the density of porous medium reduces its porosity and increases the viscous and inertial resistance offered by the medium. Table 1 shows the change in permeability and resistance on varying the porosity of the medium.

| Porosity | Permeability (m²) | Viscous Resistance (1/m²) | Inertial Resistance (1/m) |
|----------|-------------------|--------------------------|--------------------------|
| 0.7      | 6.35E-07          | 1.57E+06                 | 612.245                  |
| 0.75     | 1.13E-06          | 8.89E+05                 | 414.815                  |
| 0.8      | 2.13E-06          | 4.69E+05                 | 273.438                  |
| 0.85     | 4.55E-06          | 2.20E+05                 | 170.975                  |
| 0.9      | 1.22E-05          | 8.23E+04                 | 96.022                   |

4.1. APHE vs DPHE

A comparative analysis has been performed to establish the effectiveness of the proposed APHE in comparison to a traditional DPHE of similar dimensions. The hot gas inlet temperature is kept 500K and the cold fluid (water) inlet temperature is 300K. The inlet velocities for hot and cold fluids are 7 m/s and 5 mm/s respectively. The large difference in inlet velocities is kept in order to allow sufficient
time for heat transfer between the fluids. Five different porosity values have been tested for the APHE and the outlet parameters have been given in Table 2 along with the values for DPHE. The total amount of heat transferred to the cold fluid has been calculated based on the mass flow rate and specific heat capacity. The effectiveness of APHE can be established by the increase in the heat transferred to the cold fluid in comparison to DPHE as shown in the Table 2.

Table 2. Comparison of outlet parameters for heat exchangers.

| Porosity (%) | Cold Fluid outlet temp (K) | Increase in Cold Fluid Temp over DPHE (K) | Hot Fluid outlet temp (K) | Heat Transfer to Cold Fluid (J) | Increase in Heat Transfer over DPHE (%) |
|--------------|---------------------------|------------------------------------------|--------------------------|-------------------------------|----------------------------------------|
| DPHE         |                           |                                          |                          |                               |                                        |
|              | -                         | -                                       | 494.79                   | 2112.28                       | -                                      |
| 70           | 306.93                    | 1.87                                    | 492.87                   | 2893.24                       | 36.97                                  |
| 75           | 306.89                    | 1.82                                    | 492.92                   | 2874.22                       | 36.07                                  |
| 80           | 306.81                    | 1.75                                    | 493.00                   | 2841.32                       | 34.51                                  |
| 85           | 306.70                    | 1.64                                    | 493.11                   | 2796.89                       | 32.41                                  |
| 90           | 306.68                    | 1.62                                    | 493.13                   | 2789.07                       | 32.04                                  |

4.2. Effect of porosity on pressure drop

Figure 4 shows the pressure drop in the heat exchanger for different porosity values of the medium. It is observed that with increase in the porosity of the medium, pressure drop across the heat exchanger decreases. The viscous and inertial resistance offered by the medium decreases on increasing porosity and hence the pressure drop reduces. The pressure drop in the cold fluid remains constant at a negligible 0.06 Pa. The mass flow rate inside the pipe is 0.1 kg/s and inside the porous medium remains 0.395 kg/s throughout. The inlet parameters are kept identical to the previous section with inlet temperatures 500 K and 300 K and inlet velocities 7 m/s and 5mm/s for hot and cold fluids respectively. It is important to note that in the absence of a porous medium, a DPHE gives almost negligible amount of pressure loss for the same input conditions of 4 Pa. The introduction of a porous medium adds significantly to the pumping power requirements.

Figure 4. Pressure drop across heat exchanger for different porosity values.
4.3. Effect of hot fluid velocity

The inlet velocity of hot fluid is varied from 1m/s to 9m/s and tested at 1m/s increments. The inlet temperatures are 400K and 300K for the hot and cold fluid respectively. The cold fluid inlet velocity is kept at 5mm/s. Two porosity values are tested for all the given inlet velocities and the corresponding outlet parameters are presented in Table 3. Increase in the inlet velocity leads to the increase of mass flow rate through the porous medium. Increased mass flow rate implies an increase in the net heat content passing through the porous medium and hence leads to increased heat transfer. This can be seen through the increase in the cold fluid outlet temperature. Although increase in the mass flow rate inevitably leads to increase in the pressure drop which is not desirable. The test at different velocities is carried out for two different porosity values, and it can be observed that the cold fluid outlet temperature is not much affected by the porosity of the medium. However, the pressure drop across the porous medium is greatly affected by the porosity of the medium. By increasing the porosity by 5%, a good reduction in pressure drop is observed with essentially negligible change in temperature of cold fluid. It can therefore be said that a proper choice of inlet velocity and medium porosity can lead to better heat transfer with reduced pimpling loads. The cold fluid temperature values for DPHE at all the tested inlet velocities are also presented for comparison and it can be seen that APHE gives better heat transfer in all the cases.

Table 3. Outlet parameters for different hot fluid inlet velocities.

| Hot fluid Inlet Velocity (m/s) | Porous Medium (kg/s) | DPHE Cold Fluid Outlet Temperature (K) | APHE Cold Fluid Outlet Temperature (K) | Pressure Drop across Porous Medium (Pa) |
|-------------------------------|---------------------|----------------------------------------|----------------------------------------|----------------------------------------|
|                               | Porosity 70% | Porosity 75% | Porosity 70% | Porosity 75% | Porosity 70% | Porosity 75% |
| 1                             | 0.04       | 301.10   | 301.48     | 301.48     | 188        | 126         |
| 2                             | 0.07       | 301.49   | 302.02     | 302.02     | 702        | 473         |
| 3                             | 0.11       | 301.77   | 302.42     | 302.42     | 1542       | 1041        |
| 4                             | 0.14       | 302.00   | 302.75     | 302.74     | 2707       | 1830        |
| 5                             | 0.18       | 302.20   | 303.04     | 303.02     | 4196       | 2838        |
| 6                             | 0.21       | 302.38   | 303.29     | 303.27     | 6010       | 4067        |
| 7                             | 0.25       | 302.53   | 303.51     | 303.49     | 8149       | 5516        |
| 8                             | 0.28       | 302.68   | 303.72     | 303.69     | 10612      | 7184        |
| 9                             | 0.32       | 302.81   | 303.91     | 303.88     | 13399      | 9073        |

4.4. Effect of cold fluid velocity

In the next stage, the cold fluid inlet velocity has been varied between 5mm/s and 25mm/s with 5mm/s intervals. Five different porosity values have been tested as before to determine the effect of cold fluid velocity on its outlet temperature and total heat transfer. The hot and cold fluid inlet temperatures are 500K and 300K respectively and the hot fluid inlet velocity is fixed at 5m/s. Figure 5 shows the amount of heat transferred from hot to cold fluid for different cold fluid inlet velocities and porosity values. It is observed that as the inlet velocity of the cold fluid increases, the heat transfer also increases and increasing the porosity decreases the heat transfer as expected. Further Figure 6 shows the cold fluid outlet temperatures for its various inlet velocities where it can be seen that although the heat transfer increased on increasing the inlet velocity, the outlet temperatures decreased due to the higher mass flow rate of cold fluid. A comparison between APHE and DPHE performance has also been showed in Figure 7 through cold fluid outlet temperatures where it can be seen that for APHE cold fluid outlet temperatures are higher than that of DPHE for all inlet velocities.
Figure 5. Heat transferred to cold fluid for different cold fluid inlet velocities.

Figure 6. Increment in cold fluid outlet temperature for different cold fluid inlet velocities.

Figure 7. Comparison between 70% porosity APHE and DPHE through increment in cold fluid outlet temperature for different cold fluid inlet velocities.

4.5. Effect of hot fluid inlet temperature

Finally, the effect of varying hot fluid inlet temperature is studied at the previously mentioned 5 different porosity values with 5 different inlet temperatures from 400K to 480K at 20K increments. The cold fluid inlet temperature is fixed at 300K. Figure 8 shows that the cold fluid outlet temperature
increases linearly on increasing the hot fluid inlet temperature. Figure 9 shows the change in pressure drop across the heat exchanger on increasing the hot gas inlet temperature. Plots for all 5 porosity values have been superimposed and a general trend can be observed of reduction in pressure drop on increasing the inlet temperature.

**Figure 8.** Increment in cold fluid outlet temperature for different hot fluid inlet temperatures.

**Figure 9.** Pressure drop across heat exchanger for different hot fluid inlet temperatures.

**Figure 10.** Comparison between 70% porosity APHE and DPHE through increment in cold fluid outlet temperature for different hot fluid inlet temperatures.
This can be attributed to the reduction in density of the hot gas on increasing temperature which allows it to pass through the porous medium with greater ease. The rate of reduction in pressure loss is seen to be highest for 70% porosity case. A comparison between 70% porosity APHE and DPHE has again been presented through comparison of the cold fluid inlet temperatures where the APHE cold fluid temperatures are again seen to be higher suggesting better heat transfer than traditional DPHE in Figure 10. For better understanding of the heat transfer phenomenon, temperature contours have been plotted for both APHE and DPHE at two different hot fluid inlet temperatures. It is observed that the primary area of heat transfer is localized to the close vicinity of the cold fluid pipe in all cases. Use of porous medium allows increase in the region of heat transfer which has been confirmed from the previous results. The heat transfer region is greatly influenced by the hot fluid inlet velocity as lower velocity allows more time for the transfer of heat from hot to cold fluid giving a larger region of influence. Another important implication of the finding is that since most of the heat transfer takes place in close vicinity of the cold fluid pipe, the size of the heat exchanger can be reduced to a great extent. Also, multiple cold fluid pipes can be utilized with a relatively thin layer of porous medium attached to them for a better transfer of heat. This will also be helpful in controlling the pressure drop across the heat exchanger as the region of porous medium will be reduced.

![Temperature contour for DPHE at hot fluid inlet velocity (a) 1 m/s (b) 9 m/s.](image)

**Figure 11.** Temperature contour for DPHE at hot fluid inlet velocity (a) 1 m/s (b) 9 m/s.
5. Conclusion

The present work is aimed at increasing the efficiency of a traditional ‘double pipe heat exchanger’ (DPHE) by adding a porous medium in the annulus containing hot fluid converting it into an annular porous heat exchanger (APHE). Different inlet parameters have been varied individually to see the corresponding effects on the outlet parameters and the following conclusions have been drawn:

- Addition of a porous medium to the annular region of a double pipe heat exchanger enhances the heat transfer process in all cases,
- Reducing the porosity of the porous medium increases the pressure drop across the heat exchanger due to the viscous and inertial resistance offered by the medium. Although it does improve the heat transfer from hot to cold fluid.
- Increasing the hot fluid inlet temperature increases the heat transferred to the cold fluid and also reduces the pressure drop as the density of the hot fluid reduces.
- Increasing the cold fluid inlet velocity increases the heat transferred to the cold fluid but the cold fluid outlet temperatures are seen to be reduced due to the increased mass flow rate.
- Increasing the hot fluid inlet velocity leads to increased heat transfer but also results in higher pressure drop across the heat exchanger. It also reduces the time available for transfer of heat from hot fluid to cold fluid and reduces the region of heat transfer near the cold pipe.
- Based on the temperature contours of the heat exchangers tested, the region of heat transfer is localized close to the cold fluid pipe. The size of the heat exchanger can hence be reduced and the region of porous medium can be also be reduced leading to lower pressure drop.
- Use of multiple pipes containing cold fluid can greatly enhance the efficiency of such a heat exchanger as the most important parameter for better heat transfer is the surface area available for heat transfer between the fluids.

6. References

[1] Reid R S, Martin J J, Yocum D J and Stewart E T 2007. National Aeronautics and Space Administration (Marshall Space Flight Center, Alabama)
[2] Lochan R, Lochan R, Sharma H M, and Agarwal D 2016. Int. J. Innov. Res. Eng. Manag. 3 468–470
[3] Alkam M K and Al-Nimr M A 1999. Int. J. Heat Mass Transf. 42 3609–18
[4] Mohamad A A 2003 Int. J. Therm. Sci. 42 385–395
[5] Zheng Z J, Li M J and He Y L 2017 Appl. Energy 185 1152–61
[6] Senthilkumar K and Palanisamy P 2015 Int. J. Chem.Tech. Res. 8 138–147
[7] Jiang P X, Wang B X, Luo D A and Ren Z P 1996 Numer. Heat Transf. Part A Appl. 30 305–320
[8] Bu-Xuan W and Jian-Hua D 1993 Int. J. Heat Mass Transf. 36 4207–13
[9] Khaleed H M T, Pallan K M and Mulla M F 2018 AIP Conf. Proc. p 1953
[10] Chikh S and Allouache N 2016 Appl. Therm. Eng. 104 222–230
[11] Xu H, Zhao C and Vafai K 2017 Heat Mass Transf. und Stoffuebertragung 53 2663–76
[12] Louw W I and Meyer J P 2005 Heat Transf. Eng. 26 16–21
[13] Kral D, Stehlik P, Van Der Ploeg H J and Master B I 1996 Heat Transf. Eng. 17 93–101
[14] Sanaye S and Hajabdollahi H 2010 Appl. Therm. Eng. 30 1937–45
[15] Costa A L H, Queiroz E M 2008 Appl. Therm. Eng. 28 1798–1805
[16] Pavel A I and Mohamad A A 2004 Int. J. Heat Mass Transf. 47 4939–52
[17] Noh J S, Lee K B and Lee C G 2006 Int. Commun. Heat Mass Transf. 33 434–44
[18] Zhao C Y, Lu W and Tassou S A 2006 Int. J. Heat Mass Transf. 49 2762–70
[19] Targui N and Kahalerras H 2008 Energy Convers. Manag. 49 3217–29
[20] Targui N and Kahalerras H 2013 Energy Convers. Manag. 76 43–54
[21] ANSYS Fluent User’s Guide 2013, ANSYS, Inc.