Numerical Analysis of Heat Exchanger Effectiveness with Porous Medium

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***Abstract*-- In the present study the effect of porous structure in heat exchanger annulus of a tube-in- tube heat exchanger was analyzed. Numerical analysis has been done in CFD software- Fluent. Experiment has been conducted in tube-in-tube heat exchanger and numerical analysis was validated with. The numerical analysis was further extended to porous medium to study the effect of porous medium on the effectiveness of the heat exchanger. Effectiveness of the heat exchanger is found to increase from 0.12 to 0.2 with the presence of wire inserts. The pressure drop was found to be not so significant.**

***Keywords*-Effectiveness, wire inserts, NTU, porous medium.**

I. INTRODUCTION

Heat exchangers are the equipments that facilitate heat exchange between two fluids without intermixing. The main aim of a heat exchanger design is to maximize heat transfer and to minimize size and pumping power. Higher heat transfer coefficient shows higher performance. In this work, the effect of porous media for heat transfer is studied in a tube-in-tube heat exchanger. Porous medium is a material containing pores or voids. Recent studies concentrate on the heat transfer characteristics of porous materials. It has found its wide application in electronic cooling, solid matrix heat exchangers, heat pipes etc due to its efficient heat transfer ability. In the case of porous medium, large heat exchange area between solid and fluid aids heat transfer between hot and cold fluids. Initially, the performance of a heat exchanger under parallel flow is studied and is compared with that of a simulated model.

Pavel and Mohammed [1] studied the effect of metallic porous material inserted in a pipe. In this work the effect of porosity, porous material diameter, thermal conductivity, Reynolds number on heat transfer rate and pressure drop are investigated. Higher heat transfer rate can be achieved using porous inserts at the expense of pressure drop in the flow path. Author concludes, accurate simulation is only possible if effective thermal conductivity is found and given for simulation.

Moraga et al. [2] studied the effect of porous media in a double pipe heat exchanger. The author reports a notable increase of heat exchange with porous medium and the increase of heat transfer is directly related to Reynolds number.

Garc et al. [3] in 2005 conducted an experiment on heat transfer enhancement using helical wire inserts in a concentric tube heat exchanger. The results show that the wire mesh do not enhance the heat transfer in the laminar regime. In the conditions where Reynolds number ranges from 500 to 2300, the flow turns to be turbulent augmenting heat flow. The ratio of wire diameter to pipe diameter has no effect on any parameters considered.

Akpinar[4] in 2005 experimentally investigated the heat transfer, dimensionless exergy loss and friction factor of a heat exchanger equipped with a helical coil of wire in the inner tube of a double tube heat exchanger. The helical wire acts as turbulator's in the inner pipe aiding heat exchange. The experiment showed that the heat transfer increased with the introduction of helical wires in the pipe for both parallel flow and counter flow. The NTU and effectiveness both showed appreciable increase in case of helical wire inserts for both parallel and counter flow. However the exergy loss also increased with the increase of NTU.

Naphon[5] in 2006 studied the heat transfer characteristics of a concentric pipe heat exchanger with coil inserts. For various types of coils the heat transfer and related parameters were compared with a normal heat exchanger. The experiment proved that introduction of a wire mesh in the heat exchanger enhanced the heat transfer and the heat transfer co-efficient. The heat transfer depends on mass flux and the enhancement is only for low Reynolds numbers. The difference is clearly pronounced only for laminar regions.

Xu et al.[6] in 2007 studied the thermal performance of wire screen meshes as heat exchanger material. The pressure drop and heat transfer coefficient of wire screen meshes were analyzed experimentally and numerically. Friction factor is almost independent of coolant velocity when the Reynolds number is less than

2000. It was found that transfer of heat across the wire screen meshes depend on solid conduction and forced convection. Porosity and surface area density was found to be the major parameter influencing heat transfer. Optimal porosity was found to be 0.8. Influence of material properties on overall heat transfer performance is found to be insignificant. A higher solid fluid conductivity ratio results in higher heat dissipation to the cold fluid.

Promvonge [7], in 2008 conducted a study on thermal enhancement in heat exchangers using wire coil and snail entry. The fluid used was air and a constant heat flux was provided to the setup using an electric heater. The Nusselt number was the parameter in study which can be directly related to the heat transfer coefficient and heat flux. The implementation of wire mesh creates a higher pressure drop and a 3.4 to 3.8 times increase in Nusselt number. The increase was not seen at higher Reynolds number of the air flow.

Dyga and Placzek[8] in 2010 studied heat exchange and pressure drop during the flow of air and water within a channel with and without a wire mesh packing. The introduction of a wire mesh is expected to increase heat flux and heat transfer coefficient with a higher pressure drop. The study involved passing the fluids through a heated channel, with and without mesh packing. Using air it was seen that there is increase in the outlet temperature, heat flux density and heat transfer co efficient in the packed channel with respect to the empty channel. The effectiveness of heat transfer was also found to increase. Water when used in packed mesh had a lower exit temperature, heat flux density at lower flow rates as compared to empty channel. However packed bed channel had a higher heat transfer coefficient and higher effectiveness. Thus the application of wire mesh packing offers considerable benefits during heating of water and air and is commercially viable method to enhance heat transfer in any system. Choi et al.[9] conducted a numerical investigation with corrugated wire mesh. The wire mesh was characterized for different types of loading as per different type of flow conditions.

Yang and Hwang [10] in 2009 carried out a numerical simulation of turbulent flow through heat exchanges with porous media. Results show that field gets adjusted and thickness of boundary layer gets decreased by insertion of porous medium. The heat transfer gets intensified with the insertion of porous medium. The author concludes that optimum porous radius ratio is 0.8 and this can be used to enhance heat transfer in heat exchanges.

From the literatures mentioned above it is seen that, by the insertion of wire inserts or porous structure in heat exchanger, aids heat transfer. The effect of coiled wire inserts in heat exchanger performance is not yet studied. A comparative study of simulated model wire inserts as porous medium is also studied here. This work also aims to find the characteristics of the wire inserts used here (porosity, permeability and form drag coefficient) so as to simulate it as porous medium with the above characteristics.

II. EXPERIMENTAL SETUP

A concentric tube heat exchanger was fabricated with the inner tube made of stainless steel with an internal diameter of 19.05 mm and outer diameter of 21.05 mm. The outer tube was made of PVC and had an inner diameter of 38.1 mm. The overall length of the heat exchange section was 1500mm and the outer tube was insulated to minimize losses. Hot water was supplied from a water heater and digital thermometers (BABA digital thermometer) were used to measure the temperature readings at inlet and outlet of the heat exchanger. Experiment was also simulated in Ansys workbench 12, commercial software available for modeling and analysis. Design was created in design modeler and analysis was done on Fluent 12.0.16. Results obtained in the actual experiment and simulations were compared.

Fig.1. Experimental set up.

III. METHODOLOGY

The analysis was done for parallel flow arrangement. The governing equations of flow used for the analysis are

Continuity equation

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0$$

Momentum equation

$$u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+w\frac{\partial u}{\partial z}=-\frac{1}{\rho_0}\frac{\partial p}{\partial x}+v\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right)$$

$$u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+w\frac{\partial v}{\partial z}=-\frac{1}{\rho_0}\frac{\partial p}{\partial y}+v\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)$$

$$u\frac{\partial w}{\partial x}+v\frac{\partial w}{\partial y}+w\frac{\partial w}{\partial z}=-\frac{1}{\rho_0}\frac{\partial p}{\partial z}+v\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)$$

Energy equation

$$u\frac{\partial T}{\partial x}+v\frac{\partial T}{\partial y}+w\frac{\partial T}{\partial z}=\alpha\left(\frac{\partial^2 T}{\partial^2 x}+\frac{\partial^2 T}{\partial^2 y}+\frac{\partial^2 T}{\partial^2 z}\right)$$

The model was meshed using ANSYS Meshing 12.01. The mesh was then refined for optimum aspect ratio and skewness. Numerical analysis was done using CFD software fluent by considering that the fluid is Newtonian, incompressible and the flow is in steady state. The flow is assumed to be turbulent and k-ε model was chosen. Radiation in this model is simulated using discrete ordinate method. Water is used as the working fluid in the heat exchanger. A quarter of the model was meshed for simulation. Velocity inlet boundary conditions were chosen for hot and cold fluid inlets. Effectiveness was compared for different porosity by maintaining the mass flow rate constant. The constant mass flow rate chosen are:

Mass flow rate at hot side = 112.6 * 10^{-3}kg/s

Mass flow rate at cold side = 124.6 * 10^{-3}kg/s

No-slip boundary conditions are chosen in all the surfaces of each model. Solver uses SIMPLE algorithms for pressure-velocity coupling in Cartesian coordinate. Discretization was done using second order upwind scheme for convection terms and governing equations. Convergence criteria chosen here are 10^{-4} for continuity, x y z-velocities, k, epsilon, do-intensity and 10^{-8} for energy.

IV. MESH CHARACTERIZATION STUDY

Permeability is the measure of the resistance offered to a fluid flow by a porous medium. A porous structure with high permeability gives very less resistance to flow through it. The permeability is obtained by measuring the pressure drop along the length of the heat exchanger. The heat exchanger was provided with two pressure tappings, one at the start of the section and other at the end. The static pressure at each point was found using a peizometers. The figure given below shows the variation in pressure head obtained from the test.

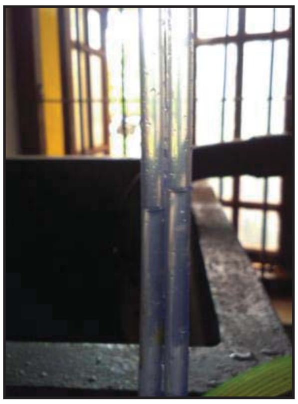

Fig. 2: Figure showing piezometric pressure difference at two pressure tapping's.

flow rates and the graph was plotted refer Fig 3.

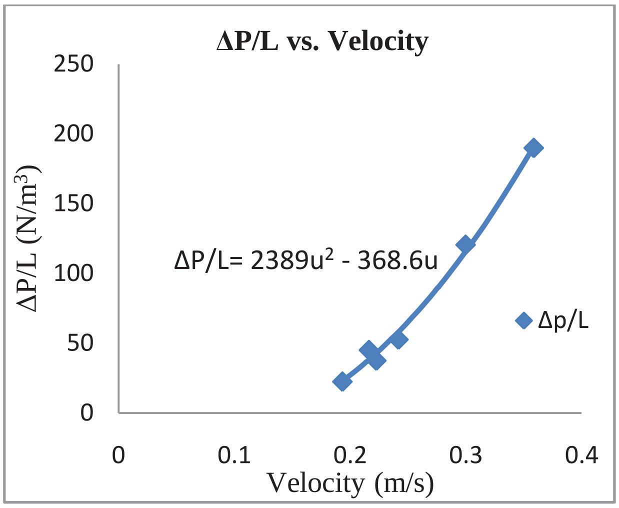

Fig. 3:.Variation of ΔP/L vs. velocity

The pressure drop per unit length is related to the velocity by the equation,

$$\frac{\Delta P}{L}=-\frac{\mu}{k}u+\rho C u^2 \quad (1)$$

Where, ΔP is the pressure drop across the length, L is the length of the heat exchanger, u is the velocity of flow, k is the permeability, C is the form drag co efficient, μ is the viscosity of the fluid.

A trend line representing the polynomial equation of second degree was fit between the points so as to obtain the values of permeability and form drag coefficient. The polynomial equation obtained from the trend line is given below.

$$\frac{\Delta P}{L}=-368.6u+2389u^2 \quad (2)$$

From the above equations, knowing the values of density (995kg/m^3) and viscosity (6.57x10^{-7} Kg/ms), values of form drag coefficient and permeability were obtained as 2.401005m^{-1} and 1.7735 x$10^{-6}m^2$ respectively.

Calculation of porosity

Area of the annulus (A) = 8.4523x10^{-4} m^2

Area of the mesh (A_{mesh})= 8.835729x x10^{-6} m^2

$$\text{Porosity} = \frac{V-V_{mesh}}{V}=\frac{A-A_{mesh}}{A}=0.989 \quad (3)$$

V. RESULTS AND DISCUSSION

The effectiveness (ε) calculated from experimental data for simple concentric tube heat exchanger (0.123) is found to be in fair agreement with that obtained from numerical analysis (0.153). The effectiveness value for a porosity of 0.99 (ε = 0.206) is in good agreement with the experimentally found value of 0.2, as seen in Table 1. The effectiveness for porosities 0.98, 0.97 and 0.96 are found out using numerical simulation. The flow rates were maintained constant on both hot and cold sides same for all cases. It can be seen that the effectiveness increases with decreasing porosity, for the cases mentioned above. The improvement in effectiveness can be attributed to increase in turbulence due to the presence of twisted wire inserts. This result in increased cold side heat transfer coefficient and thereby the overall heat transfer coefficient of the heat exchanger. Insertion of wires is more effective for low Reynolds number flow. In higher Reynolds number flows there will be increased turbulence which results in better heat transfer, even with simple concentric tubes without any wire inserts.

In the case of numerical analysis with porous medium, the decrease in porosity results in increased fluid – solid contact area. This obviously results in further improvement in overall heat transfer coefficient. It is evident that the proper choice of the porous structure can enhance the turbulence, which would also help increase the heat transfer coefficient. All the above factors can favorably influence the effectiveness of the heat exchanger.

The temperature distribution along the length of heat exchanger is shown in figures 4, 5, 6, 7 and 8 for various cases analyzed in the present work. Improvement in the effectiveness was seen for heat exchanger working with porous medium. Figure 9 shows the temperature contours along the length of heat exchanger. Figure 10 shows the variation of effectiveness with different values of porosities. The rate of increase of effectiveness is found to decrease with lower value of porosity. The use of porous structure with lower porosity value (below 0.96) is not recommended as the associated pressure drop is higher, which eventually increases the pumping power.

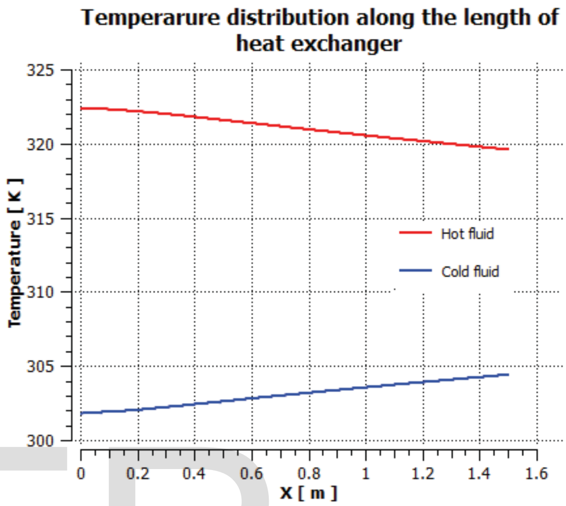

Fig. 4: Figure showing temperature contour for ordinary heat exchanger.

Porosity	$T_{hot\ in}$ (K)	$T_{cold\ in}$ (K)	$T_{hot\ out}$ (K)	$T_{cold\ out}$ (K)	Mass flow rate(Hot) (kg/s)	Mass flow rate(Cold) (kg/s)	Effectiveness
Experimental data							
Simple heat exchanger(1)	322.4	301.8	319.1	303.4	0.113	0.125	0.123
With wire mesh(.989)	322.4	301.8	317.4	304.7	0.113	0.125	0.2
Data obtained by simulation							
Simple heat exchanger (1)	322.4	301.8	319.23	304.63	0.113	0.125	0.153
0.989	322.4	301.8	318.06	305.55	0.113	0.125	0.206
0.98	322.4	301.8	317.87	305.83	0.113	0.125	0.218
0.97	322.4	301.8	317.75	305.97	0.113	0.125	0.225
0.96	322.4	301.8	317.66	306.05	0.113	0.125	0.229

Table 1: Experimental and simulation data

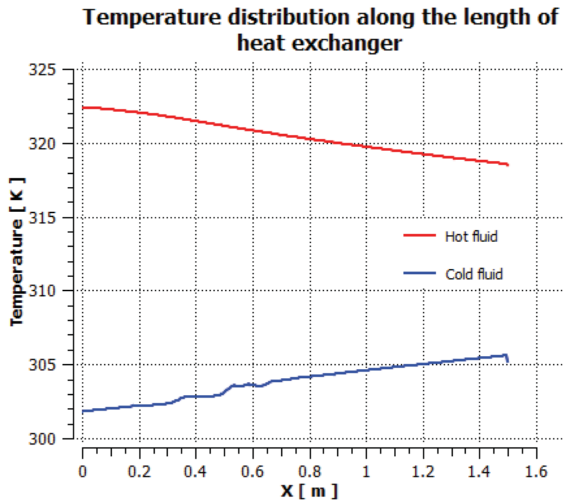

Fig. 5: Temperature distribution with porous medium in the outer anulus(with characteristics of wire inserts obtained from characterisation study).

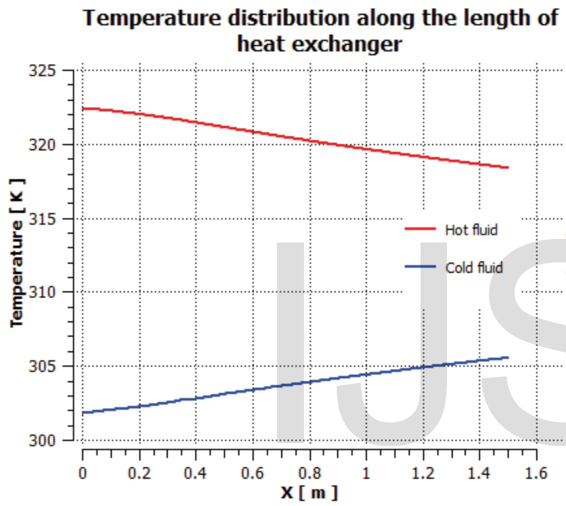

Fig. 6: Temperature contour for heat exchanger with porous medium in the outer anulus(porosity 0.98).

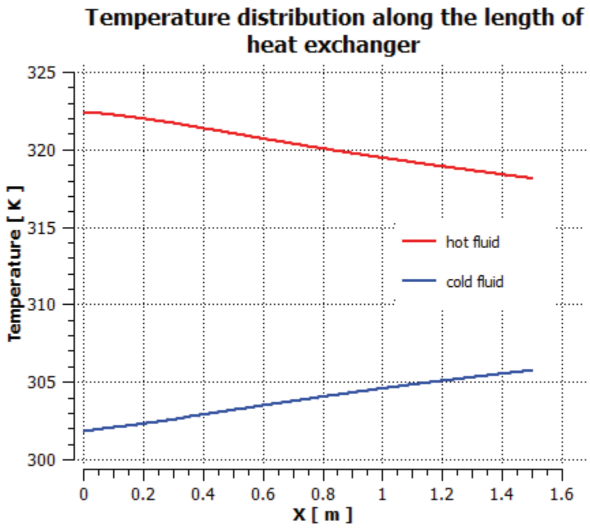

Fig. 7: Temperature contour for heat exchanger with porous medium in the outer anulus(porosity 0.97).

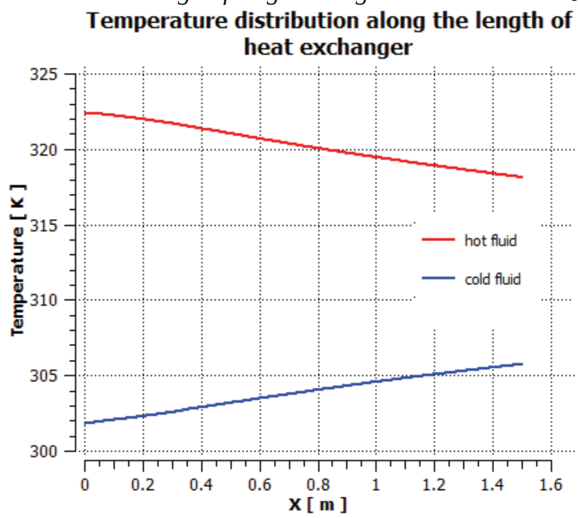

Fig. 8: Temperature contour for heat exchanger with porous medium in the outer anulus(porosity 0.96)

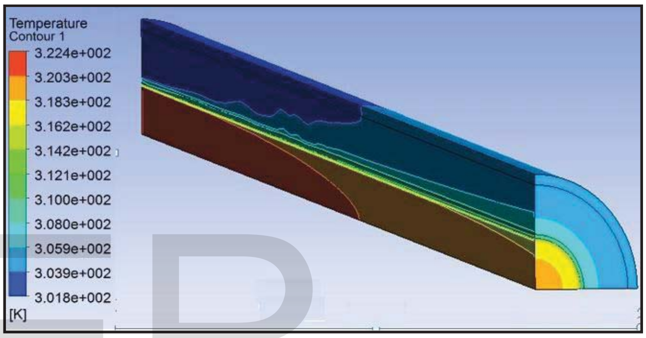

Fig. 9: Temperature contours obtained for porous structure in annulus of heat exchanger

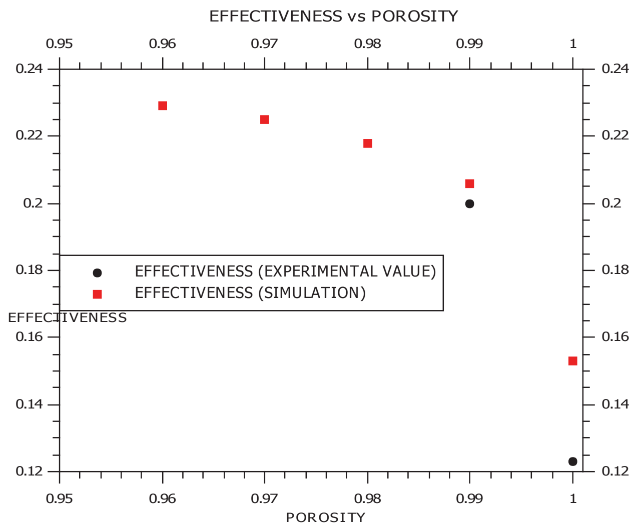

Fig.10. Graph showing variation of effectiveness with different values of porosity.

V. CONCLUSION

The working of a tube-in-tube heat exchanger was successfully simulated and the following conclusions were obtained.

1) Effectiveness found to increase from 12.3 to 20.01 with the use of wire inserts.

2) In this work the performance of wire inserts and porous structure has effectiveness 0.2 and 0.206 respectively which show that performance can be simulated as porous medium where the error in this assumption in this case is only 2.948%.

3)Isotherms are slightly disturbed with the introduction of porous inserts, which show the effect of introduction of induced turbulence and increase of heat transfer due to increase in surface area in the case of porous medium.

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