ISSN: 2321-8169
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CFD analysis of Metallic Foam-Filled Triple Tube Concentric Heat Exchanger

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Abstract

Aim: To enhance the heat transfer rate using metal foams.

The performance of Triple tube coaxial heat exchanger is evaluated using CFD simulation technique for different mass-flow rates, where the flow pattern is kept counter-current. A metal foam is placed in the inner annulus of the middle pipe. Water is used as a working fluid in all the tubes but their temperatures were kept different for heat transfer to take place. Hot water flowing through the middle pipe transfers the heat to the fluids flowing through the other pipes due to the temperature difference but in this case the amount of heat transferred is more compared to that in plain tube due to the addition of aluminum foam. For middle pipe in which foam is placed, the temperature and pressure drops are plotted for the hot water against the mass flow rates both for with and without foam conditions. Results shows that the temperature drop decreases with the increase in mass flow rate whereas the pressure drop increases with the increase in mass-flow rate. The noticeable content of the report is that, the temperature and pressure drop in tube with foam was more compared to that in tube without foam.

Keywords: *Triple tube; Metal foam; Simulation of aluminum foam using CFD.*

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The Triple tube heat exchanger mentioned in the topic consists of three concentric tubes of different diameters & lengths. The third pipe improves the heat transfer through an additional flow passage and a larger heat transfer area per unit exchanger length. The key element of this heat exchanger is the aluminum foam which is placed inside the inner annulus of the middle pipe of the heat exchanger as shown in fig no.2. The metal (aluminum) foam increases the surface area and therefore it has the capability of enhancing the heat transfer. The main objective of this project is to find an alternative method for heat dissipation. Since the advancement in technology demands for compactness in devices and equipment, therefore, it becomes necessary to device a system which would for the same heat transfer acquires smaller space. The concept arises from the much higher area to volume ratio, which is almost five times higher than finned-tube bundles. This means that the same weight of metal foam should be five times more compact than the fins and consequently also requires much less area for setup. The need for compactness led the researchers to focus on materials and their arrangements for enhancing the heat transfer/dissipation at comparatively higher rate. Moreover, the use of fins also does not reduce the area to greater extent as would be expected for compactness. Metal foams could thus be used to replace even finned tubes. The foams are rigid, and lightweight, non-poisonous structure which have high surface area and recyclable which improve energy absorption and heat transfer in thermal applications, such as heat exchangers. Foam ligaments in the flow direction results in boundary layer disruption and mixing. The advantages of metal-foams lie on their low-density, large surface area in a limited volume and high strength structure. Metal foams are very costly but due to recent developments in the metal sintering method for foam manufacture, there costs have been reduced. **Calmidi and Mahajan (1999) [1]** investigated the effective thermal conductivity of high-porosity fibrous metal foams experimentally. An empirical correlation was developed and a theoretical model was derived. The model predictions agreed closely with the experimental data and were used for the evaluation of metal foams as possible candidates for heat sinks in electronics cooling applications. **K. Boomsma, D. Poulikakos, F.Zwick (2003) [2]** observed that open-cell metal foams with an average cell diameter of 2.3 mm were manufactured from 6101-T6 aluminum alloy and were compressed into compact heat exchangers possessing a surface area to volume ratio of the order of 10,000 m^2/m^3. They were placed into a forced convection arrangement using water as the coolant. These experiments performed with water were scaled to estimate the heat exchangers performance when used with a 50% water–ethylene glycol solution, and were then compared to the performance of commercially available heat exchangers which were designed for the same heat transfer application. The heat exchangers were compared on the basis of required pumping power versus thermal resistance. The compressed open-cell aluminum foam heat exchangers generated thermal resistances that were two to three times lower than the best commercially available heat exchanger tested, while requiring the same pumping power. **W. Lua, C.Y. Zhao, S.A.Tassou (2005) [3]** presents an analytical study of the forced convection heat transfer characteristics in high porosity open-cell metal-foam filled pipes. Based on the analytical solutions, the velocity and temperature distributions in metal-foam filled pipes were obtained. The effects of the microstructure of metal foams on overall heat transfer were examined. The results show that the pore size and porosity of metal-foams play important roles on overall heat transfer performance. The use of metal-foam can dramatically enhance the heat transfer but at the expense of higher pressure drop. **ShadiMahjoob, KambizVafai (2007) [4]** states that Metal foam heat exchangers have considerable advantages in thermal management and heat recovery over several commercially available heat exchangers. In this work, the effects of micro structural metal foam properties, such as porosity, pore and fiber diameters, tortuosity, pore density, and relative density, on the heat exchanger performance are discussed. Three main categories are synthesized. In the first category, the correlations for pressure drop and heat transfer coefficient based on the microstructural properties of the metal foam are given. In the second category, the correlations are specialized for metal foam tube heat exchangers. In the third category, correlations are specialized for metal foam channel heat exchangers. To investigate the performance of the foam filled heat exchangers in comparison with the plain ones, the required pumping power to overcome the pressure drop and heat transfer rate of foam filled and plain heat exchangers are studied and compared. A performance factor is introduced which includes the effects of both heat transfer rate and pressure drop after inclusion of the metal foam. The results indicate that the performance will be improved substantially when a metal foam is inserted in the tube/channel.**M. A. Delavar and M. Azimi (2013) [5]** states that the heat transfer duty of heat exchangers can be improved by passive heat transfer enhancement techniques. On the basis of a theoretical and experimental analysis the conclusion derived was that the best heat transfer enhancement can be reached by the use of porous material as an inexpensive technique to extend the heat transfer area, improve effective thermal conductivity, and mix fluid flow. **G.A.Quadir, IrfanAnjumBadruddin, N.J. Salman Ahmed et al (2013) [6]** experimented the performance of a triple concentric pipe heat exchanger and carried out numerically using finite element method (FEM) under steady state conditions for different flow arrangements and for insulated as well as non-insulated conditions of the heat exchanger. The three fluids being considered are hot water, cold water and the normal tap water. The results are presented in the form of the dimensionless temperature variations of the three fluids along the length of the heat exchanger for their different flow rates. It is found that the numerical predictions of the temperature variations of the three fluids by using FEM follow closely to those obtained from experiments both in magnitude and trend provided correct overall heat transfer coefficients are used. Triple concentric-tube heat exchangers provide better heat transfer efficiencies compared to the double concentric-tube heat exchangers.

Nomenclature

NF	Normal fluid at 30°C
HF	Hot fluid at 70°C
T_{c1}	Inlet temperature of innermost fluid
T_{c2}	Outlet temperature of innermost fluid
T_{h1}	Inlet temperature of middle fluid
T_{h2}	Outlet temperature of middle fluid
T_{c3}	Inlet temperature of outermost fluid
T_{c4}	Outlet temperature of outermost fluid
K	Thermal conductivity
C_f	Inertial coefficient
D_p	Pore diameter
D_f	Fiber diameter
PPI	Pores per inch
α	Permeability
h	Convective heat transfer coefficient

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The experimental model as shown in fig 1 is made on solid works as per the dimensions mentioned above and the same is imported in Ansys 14.5 where simulation is done. The boundary conditions for the simulation are described below. All inlets are provided with the same mass flow rate as the input. All the outlets are kept as pressure outlets. The outer wall pipe is maintained Adiabatic. The metal foam is given a porous condition and it is been applied with necessary foam properties like porosity, inertial resistance & viscous resistance allowed by Ansys. Porosity kept for simulation is 0.65.

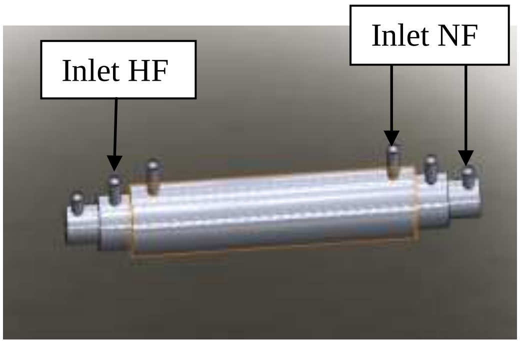

Fig 1 Model in Solid works

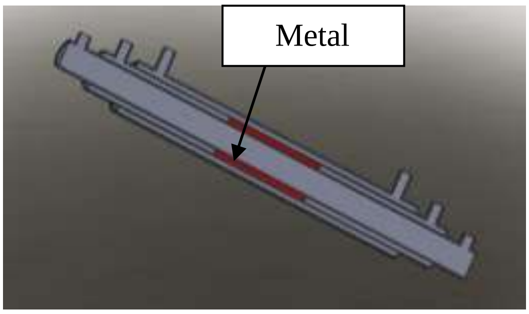

Fig 2 Sectional view indicating Location of metal foam

The solution methods adopted are Pressure-velocity coupling scheme SIMPLE, Spatial Discretization Gradient Green-Gauss Node Based, Pressure Standard, Momentum Second Order Upwind, Energy Second Order Upwind. The under-relaxation factors for: pressure =0.3, Density=1, Body forces=1, Momentum=0.7 & energy=0.7.The total no of iterations (500) are kept uniform for all the simulations. Mesh was tetrahedral with prism layers on boundary. Simulation was done for two cases, one was for plain triple tube i.e. without foam & another was by putting the metal foam inside the inner annular space of the middle pipe. After simulation the results obtained are shown in table no.1 & 2 below.

Appearance

Fig 3 Truncated-octahedron foam

Fig 4 Large porosity of metal foam

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Porosity or void fraction:

It is a measure of the void (i.e. "empty") spaces in a material, and is a fraction of the volume of voids over the total volume, between 0 and 1, or as a percentage between 0 and 100%. There are many ways to test porosity in a substance or part, such as industrial CT scanning. The term porosity is used in multiple fields including pharmaceutics, ceramics, metallurgy, materials, manufacturing, earth sciences, soil mechanics and engineering. Based on whether they have larger void spaces they are called as large porosity foams or small porosity foams. As shown in fig. 5 above, it is large porosity metal foam and in fig 6 below is small porosity metal foam.

Fig 5 Small porosity of metal foam

Placing the metal foam in the heat exchanger

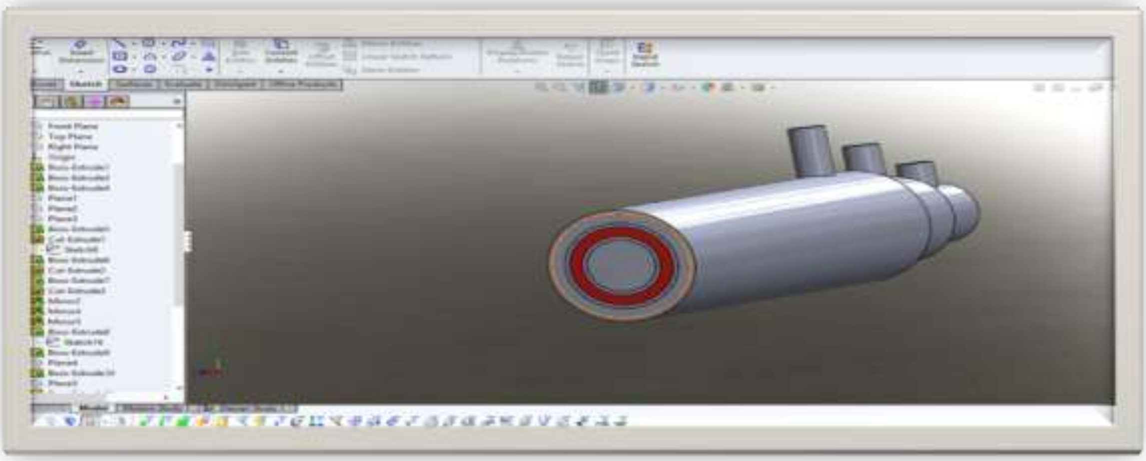

Fig 6 Metal foam placed inside the heat exchanger (Solid works)

The authors also found that good thermal contact between the foam and the tube was critical to the heat transfer and noted that more research is required to develop a cost effective and efficient attachment process to fix the metal foams to the tube cores. In this regard, de Jaeger et al (2012) have identified four possible methods of connecting the foam to the tube:

a. Brazing
b. Co-casting
c. Thermal glue bonding and
d. Mechanical press-fitting.

For heat transfer, they found brazing to be the best technique while press-fitting was the worst.

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Working:

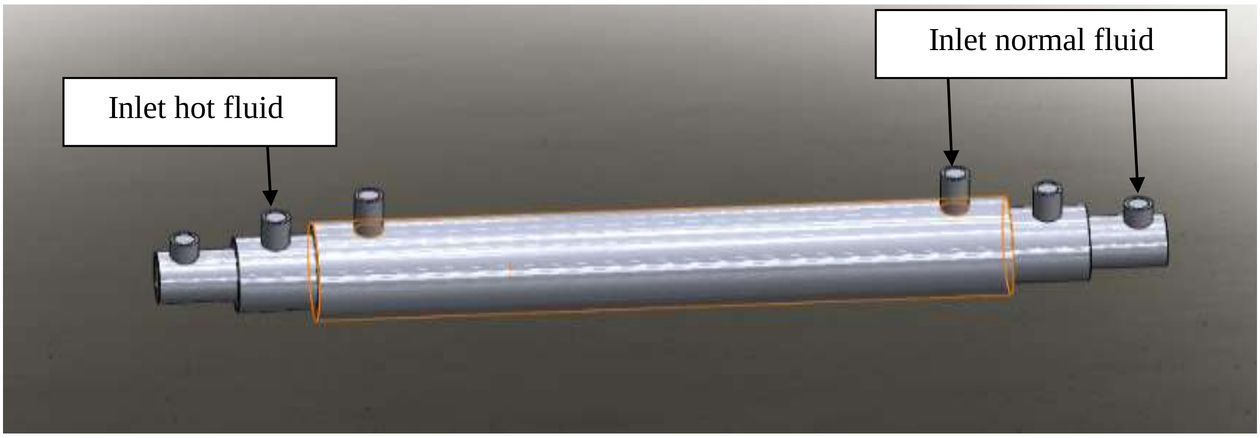

Fig 7 Model showing inlets and outlets

Hot water will be passed through the intermediate pipe as shown in fig.7 similarly cold water will be passed through the annular area and the innermost pipe. Outlets of all the pipes are exposed to the atmosphere. Heat is first transferred from hot water to pipe wall due to convection then heat is conducted through the pipe wall then finally to the cold water by convection. Here the Surface area is been increased by putting metal foams inside the heat exchanger. This results in higher heat transfer rate. But obviously at higher pressure drop. This concept is useful where pressure drop is not much important factor compared to the heat transfer.

Simulation Results:

Comparison results for different mass-flow rates for pressure drop with and without foam

Table 1 Pressure drop without foam and with foam

	Without foam	With foam
Mass flow rates	Pressure drop(pa)	Pressure drop(pa)
0.0225	3.56391	4.57219
0.0235	3.85578	6.11571
0.025	4.31572	6.62488
0.035	8.0336	10.3078
0.045	12.898	13.7486
0.05	15.762	17.7831
0.06	22.3437	24.378
0.085	43.8521	49.8955

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Table 2 Temperature drop without foam and with foam

	Without foam	With foam
Mass flow rates	Temperature drop(K)	Temperature drop(K)
0.0225	16.464	23.884
0.0235	15.919	23.2275
0.025	15.258	22.257
0.035	11.727	16.276
0.045	9.381	12.2782
0.05	8.493	10.878
0.06	7.072	8.804
0.085	4.962	5.899

Comparison of various parameters necessary for heat transfer with and without foam

Parameter comparison

Parameters	With foam	Without foam
Effectiveness (ε)	**0.596**	**0.4108**
Overall heat transfer coefficient (U)	**0.1672**	**0.0947**
Heat transfer (Q)	**2.2469**	**1.5479**

Conclusions of simulation results

From the simulation results we observe the following things:

With the increase in mass flow rate the pressure drop and temperature drop increases in both the cases but more in the case with metal foam. Heat transfer could thus be increased significantly but with an increase in pressure drop. Thus we can put only 200 mm length of metal foam for 2.2469kW of heat transfer for 0.0225kg/s of mass flow rate.

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