Thermal Analysis of Porous Fin under Natural Convection

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Abstract: Recently high rate of heat transfer with reduced size and cost have demand for a number of engineering applications such as heat exchangers, economizers, super heaters, conventional furnaces, gas turbines etc. Now days the need of small, intricate and parts fins play an important role in heat exchanger. Hence, study of thermal analysis of porous fin under natural convection is necessary. Porous fins are more efficient and compact than other fins in case of heat transfer in electronic gadgets. They transmit heat at a better rate as compared to solid fins. For the above discussed needs, the experiment is performed by using porous fins for optimum use of material in fin and for maximum heat transfer. For this reason it is proposed to conduct experimental study by using porous fin under natural convection by varying various parameters of fin. In this paper, we present our recent experimental results on natural convection in aluminum metal foams of different pore densities and for different orientations of metal foam. [i.e. 5, 10, 20, and 40 pores per in (PPI)] and porosities (0.89–0.96). The experimental results show that the enhancement in heat transfer depends on the porosity and pore size of the foam sample. The heat transfer rate increases with pore size and shows inverse effect with increase in porosity i.e. heat transfer rate increases with decrease in porosity. Also the present study provides a beneficial path to initiate the application of porous fins resulting in cost reduction with increase in heat dissipation & durability.

Keywords: Thermal Analysis, Porous fin (Metal Foam), Natural convection, Porosity.

1. INTRODUCTION

In this age of technology with need of light, intricate and small parts fins play an important role in heat exchanging. Variety of fins has been invented so that they can be made immaculate and more efficient. Now days, electronic gadgets and appliances are becoming smaller in size and hence increasing the demand for small but efficient parts. Porous fins are more efficient and compact than other fins in case of heat transfer in electronic gadgets. Similarly porous fin is more efficient than fin with rectangular cross section. Porous fin also transmit heat at a better rate as compared to solid fins. For the above discussed needs, research is going on for optimum use of material in fin for maximum heat transfer.

Recently, the use of high porosity metal foams have applications, such as aircraft wing structures for the aerospace industry, catalytic surfaces for chemical reactions, core structures for high strength panels, and containment matrices and burn rate enhancers for solid propellants. Due to the high surface-area density and strong mixing capability for the fluid, open cell metal foams are now considered as one of the most promising materials for the manufacture of efficient compact heat exchangers. Due to high prices, & lack of research in previous years this technology will be rarely used. But nowadays with decreasing in manufacturing costs, using metal foams has become more efficient. Therefore recently some scientific research will be investigated to study the phenomenon of heat transfer in fluid flow inside the metal foam. Horton C. W., and Rogers, F. T., Lapwood, E. R., [1, 2] have been introduces and studied Fundamental investigations on natural convection in saturated porous media. It started with the linearised stability theory applied to an infinite horizontal layer heated from below. Prasad, V., Kulacki, F. A. [3] introduces experimental and analytical studies which deal with buoyancy-induced convection through saturated porous media in various geometries, including rectangular cavities heated from bottom or sides, and horizontal and vertical annuli. The most of the earlier theoretical and numerical studies on buoyancy-induced convection in a porous medium are based on empirical models using the Darcy formulation. Beckerman et al. [4] Non-Darcian effects have been investigated by a number of researchers including Beckerman et al. It is reported that the non-Darcy terms contribute toward decreasing the superficial velocities and heat transfer. A numerical study of non- Darcian natural convection in a vertical enclosure filled with a porous medium is performed. The flow is modeled using the

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extended Darcy equations**.** The governing equations are solved by using SIMPLER algorithm. An order of magnitude analysis & numerical results shows the importance of non- darcian effects. David et al. [5] shows that the variation of porosity at the walls of the enclosures was likely to induce higher velocities at the boundary layers. Their numerical result gives a significant increase in heat transfer when this porosity variation is taken into account. The problem of natural convection in differentially heated vertical cavities filled with spherical particles saturated with Newtonian fluids was investigated numerically. The Brinkman Darcy- Ergun equation was used as the momentum equation, and the wall effect on porosity variation was approximated by an exponential function. Beji and Gobin [6] numerically solved the Darcy-Brinkman-Forcheimer equations incorporating viscous, Darcy, and inertial effects including the effect of thermal dispersion. Like to forced convection, modeling of natural convection in porous media has been studied with the local thermal equilibrium [LTE] assumption. Consequently, a single energy equation describes the temperature field in the porous medium. While this assumption holds well when the thermal conductivities of the constituent phases of the porous medium were comparable, its validity could not be taken for granted, a priori, for a medium, such as metal foam, where the solid to fluid conductivity ratio was very high. Hong and Tien [7], Georgiadis and Catton [8], and Hsu and Cheng [9]. The dispersion model which is used as a factor to enhance heat transfer has been introduced by them. The work of Phanikumar and Mahajan [10] proposed only one that model buoyancy-induced convection in metal foams without invoking. There were relatively few investigations of the heat transfer with natural convection in very high porosity media $\varepsilon \sim 0.9$, such as metal foams. Buoyancy-induced convection plays a very important role in the cooling of electronic components. Despite significantly lower heat transfer coefficients compared to immersion boiling or forced convection buoyancy-induced convection in air is preferred for low end applications, such as switching devices, consumer electronics, and avionics packages, due to their reliability and simplicity. Xu et al. (2011) [11] comprised an experimental study for natural convection from horizontally-positioned copper metallic foams having different pore densities and porosities. They studied the effects of porosity and pore density on the total thermal resistance of the foam sample. It was found that porous surface enhanced natural convection and reduced thermal resistance by about 20% in comparison with a smooth surface. The effect of porosity influenced on the heat transfer performance was more remarkable when the pore density was higher. Zhao et al. (2005) [12] investigated experimentally and numerically the effect on overall heat transfer in highly porous, open-celled cellular FeCrAlY foams under natural convection. They found that natural convection is significant in metal foams due to the high porosity and inter-connected open cells, contributing more than 50% of the effective conductivity at the ambient pressure. . Zhao et al. (2004) studied the effective thermal conductivity of five FeCrAlY foam samples with different pore sizes and relative densities using a guarded-hot-plate apparatus under both vacuum and atmospheric conditions. The results showed that effective thermal conductivity increases rapidly as temperature raises, especially in the higher temperature range where the thermal radiation dominated the transport. G. Hetsroni (2008) [13] was investigated experimentally the natural convection heat transfer in metal foam strips, with internal heat generation for two porosities. It was shown that heat transfer at natural convection in the strip of metal foam was increased significantly, up to 18–20 times for metal foam of 20 ppi relative to the flat plate of the same overall dimensions. An estimation of the heat transfer from the ligaments of the metal foam was done. Ayla Dogan [14] investigates natural convection heat transfer from intermittent open-celled aluminum metallic foams in a cavity experimentally. The obtained results showed that the foam blocks with the pore density of 10 PPI showed about 86% higher average thermal performance that of the smooth surfaces. Muhammad Zaakir Angsoommuddin [15] this study was based on the standard electronic cooling devices done on natural and forced convection by comparing the between conventional fins heat sink and porous media. Porous media used were aluminium and copper porous foams. The natural convection results showed that the conventional fins heat sink has lowest thermal resistance compared to porous foam. In forced convective heat transfer, the porous media showed better heat transfer result compared to fins heat sink in terms of thermal resistance. By comparing between the porous media, copper porous shows better cooling performance in natural convection while aluminium porous had better heat transfer in forced convection. As a result of an extensive literature survey, there are few natural convection investigations of metal foams and few works have been reported for air natural convection of aluminum foam. Also the cost and thermal coefficient of aluminium foam shows significant effects than copper foam. The objective of this research is to investigate experimentally the buoyancy induced flow in aluminum metal foam blocks heated from below and surrounded by air by varying different parameters.

2. EXPERIMENTAL APPARATUS AND PROCEDURE

2.1. Experimental apparatus

The experimental setup is shown in Fig. 1. The sample is stationed inside a large MS box housing 40 cm x 40 cm x 30 cm isolated from the ambient. Holes will be drilled on the base of the samples to insert cartridge heaters. Experimental studies conducted on aluminum metal foam samples having dimension 0.5cm thick, 6 cm length and 5 cm height to evaluate their thermal performance in natural convection. The base of the sample is insulated using low conductivity insulation having dimensions 120 mm x 120 mm x 15 mm. The cartridge heaters provided by a dc power supply. The base and ambient temperatures are monitored using PT- 100 type thermocouples connected to a Digital Indicator. Experiments are conducted on foam samples of different porosities and pore densities. For each

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pore density corresponding to 5, 10, 20, and 40 PPI, two samples of different porosities are chosen. During an experimental run, the power to the heaters is varied to achieve different base plate temperatures and, hence, Rayleigh numbers. The experiments are restricted to maximum base plate temperatures of 75°C.

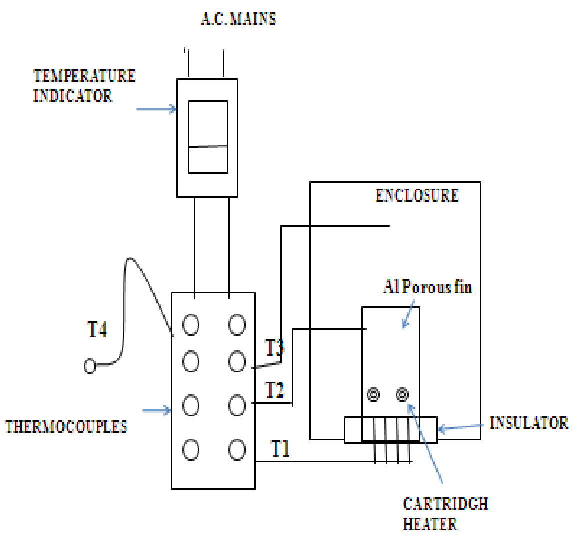

Fig.1 Schematic of the experimental setup

Voltage Inputs:

The variance controls the heating element with a voltage range of 0 – 240 V, corresponding to a heat input of 0 – 150 W. For this investigation, input voltages of 120 and 168 V will be used, generating 75 W of heat (or 4000 W/m2 heat flux intensity) and 105 W (or 8000 W/m^2). The experiment is to be carried out for different heat input i.e. for 25 W, 50 W, 75 W, and 100 W

2.2. Test samples

The specimens, made of aluminum metal foam, are used as a porous medium. The specimens of aluminum foam of four types of 5, 10, 20 & 40 pores per inch (PPI) with varying porosities are studied.
The materials used for the manufacturing of porous fins are Al, SiC, Cu and Si3N4. But the aluminum metal foam is most suitable material among all this. Aluminum Metal Foam is found to have following suitable characteristics. Hence the said metal will be selected for fabricating the fin.

- Low cost,
- High thermal conductivity& low density,
- Attractive for aircraft electronics and applications

Table 1 lists the corresponding flow properties of the porous aluminum samples.

Table: 1 Properties of aluminum metal foam

PPI	Porosity	Permeability (X 10^7), m^2	Effective Conductivity (W/mK)
5	0.93	2.40	5.33
5	0.899	2.28	7.32
10	0.9386	1.54	4.78
10	0.9085	1.62	6.71
20	0.92	1.11	5.97
20	0.9353	1.14	4.99
40	0.9091	0.51	6.67
40	0.9586	0.54	3.48

2.3. Experimentation Methodology

Experiment is to be carried out for two positions of metal foam plate i.e.

a) For Horizontal Orientation.
b) For Vertical Orientation

The first set of experiments is conducted with the metal foam samples hold in the horizontal orientation, and heated from the bottom. The next set of experiments is conducted with the metal foam samples hold in the vertical orientation and heated from the side. And follows the following steps for the calculation:

i) Determination of Nusselt Number and Rayleigh Number.
ii) Error Analysis
iii) Plotting a graph between Nusselt Number and Rayleigh number.
iv) Calculation of Heat Transfer rate

2.4. Data Reduction

The energy Q generated in the porous strip is dissipated by three mechanisms

$$Q = Q_{conv} + Q_{cond} + Q_{rad} \qquad \text{(1)}$$

Where, Q is the heat generated by Joule heating, Qconv; Qrad; Qcond are heat losses by convection, radiation and conduction, respectively.
Let, the heat input is to be calculated by

$$Q = IV \qquad \text{(2)}$$

Where ‘I’ is the DC current and ‘V’ is the voltage.
Here the losses from the conduction and radiations are negligible and hence this are neglected.

The heat losses from the foam to the environment due to natural convection are calculated as from equation (1) as,

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$Q_{conv} = Q$ ……………. (3)

On the other hand, the value of energy transferred by natural convection from the foam surface to ambient is

$Q_{conv} = h_{conv}(T_{avg} – T_a) A_s$ ………………… (4)

Where hconv is convective heat transfer coefficient, A_s is the surface area of the strip, T_{avg} is the average temperature of the strip surface, and Ta is the ambient temperature.
The heat transfer coefficient at natural convection may be easily determined now from Equations (3) and (4).

The theoretical value of heat transfer coefficient for the conditions of natural convection [13] is defined as,

$N_u = C\ (Gr.\ Pr)^{0.25}$ ………………… (5)

C is constant depending on the plate orientation. For vertical orientation the nusselt number correlation is given by,

$N_u = 0.59\ (Gr.\ Pr)^{0.25}$ (For $10^4 < Ra < 10^9$) ……… (6)

And for horizontal orientation,

$N_u = 0.27\ (Gr.\ Pr)^{0.25}$ (For $3x10^5 < Ra < 3x10^{10}$)

……………… (7)

Where, Nu= hL_c/k is Nusselt number, Gr is Grashof number & Pr = ν/α is prandtl number. (Here h is heat transfer coefficient, k is thermal conductivity, L_c is characteristic length of sample, and ν is kinematic viscosity and α is thermal diffusivity)

The main uncertainties in this experiment are due to errors in measurements of power, physical dimensions and thermocouple readings. The maximum error in the multi-meter readings for the voltage and resistance measurements is 0.5%. Based on the preceding errors, the total error in the measurement of the effective thermal conductivity can be calculated.

3. CONCLUSIONS

Experiment will be performing on metal foams with varying porosities & pore densities in the horizontal and vertical orientations under natural convection. The results will indicate that heat transfer from a heated surface is considerably enhanced. This enhancement will depends on the porosity and pore size of the foam sample. It will observe that the heat transfer rate increases for larger pore sizes & lower porosity due to higher permeability of porous medium and due to higher entrainment of air.

REFERENCES

[1] Horton, C. W., and Rogers, F. T., 1945 “Convection Currents in Porous Me-dia,” J. Appl. Phys., 16, pp.367–370.
[2] Lapwood, E. R., 1948 “Convection of a Fluid in a Porous Medium,” Proc. Cambridge Philos. Soc., 44, pp.508–521.
[3] Prasad, V., Kulacki, F. A., and Keyhani, M., 1985, “Natural Convection in Porous Media,” J. Fluid Mech., 150, pp.89–119
[4] Beckermann, C., Viskanta, R., and Ramadhyani, S., 1986, “A Numerical Study of Non-Darcian Natural Convection in a Vertical Enclosure Filled with a Po-rous Medium,” Numer. Heat Transfer, 10, pp.557–570
[5] David, E., Lauriat, G., and Cheng, P., 1991, “A Numerical Solution of Variable Porosity Effects on Natural Convection in Packed-Sphere Cavity,” ASME J. Heat Transfer, 113, pp.391–399.
[6] Beji, H., and Gobin, D., 1992, “Influence of Thermal Dispersion on Natural Convection Heat Transfer in Porous Media,”
[7] Hong, J. T., and Tien, C. L., 1987, “Analysis of Thermal Dispersion Effects on Vertical-Plate Natural Convection in Porous Media,”
[8] Georgiadis, J. G., and Catton, I., 1988, “Dispersion in Cellular Convection in Porous Layers,” Int. J. Heat Mass Transfer, 31, pp.1081–1091.
[9] Hsu, C. T., and Cheng, P., 1990, “Thermal Dispersion in a Porous Medium,” Int. J. Heat Mass Transfer, 33, pp.1587–1597.
[10] Phanikumar, M. S., and Mahajan, R. L., 2002, “Non-Darcy Natural Convection in High Porosity Metal Foams,” Int. J. Heat Mass Transfer, 45, pp.3781–3793.
[11] Z.G. Xu, Z.G. QU, C.Y.ZHAO. (2011). Experimental study of natural convection in horizontally-positioned open-celled metal foams. IEEE pp. 923-928
[12] C.Y. Zhao, T.J.Lu, H.P.Hodson. (2005). Natural convection in metal foams with open cells, "International Journal of Heat and Mass Transfer, vol.4
[13] G. Hetsroni, M. Gurevich, R. Rozenblit, “Natural convection in metal foam strips with internal heat generation” Experimental Thermal and Fluid Science 32 (2008) 1740–1747
[14] Ayla Dogan, Oguzhan Ozbalci, Ibrahim Atmaca, “Investigation of natural convection from intermittent foam blocks in a cavity”, Department of Mechanical Engineering, Faculty of Engineering, Akdeniz University TR-07058, Antalya, Turkey.
[15] Muhammad Zaakir Angsoommuddin, Mohd Zulkifly Abdullah, Third Author, “Experimental investigation on electronic cooling performance using porous medium heat sink”. 2nd International Conference on Engineering of Tarumanagara (ICET 2015)

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