The effects of natural convection and radiation heat transfer in metal-foam- fin (Aluminum)

S. Abdolahi, S. Zeinali Heris, A. Dashti*, M. R. Khosravi
Department of Chemical Engineering, Faculty of Engineering, Ferdowsi University of Mashhad, Iran
dashti@um.ac.ir

Abstract
The effect of radiation losses on the natural convection heat transfer from metal-foam of convex parabolic profile is studied analytically and numerically. Two models, with and without effect of radiation, are introduced based on using energy balance and Darcy's model to formulate the heat transfer equation. Air and Aluminum are employed as the cold fluid and porous medium, respectively, and the effects of radiation, pore density (PPI), Rayleigh number (Ra) and porosity on the heat transfer rate are studied in detail. The results show by increasing PPI and decreasing Ra the heat transfer rate decreases as permeability decreases.Furthermore, the effect of porosity on heat transfer without radiation is negligible, but the effects of radiation is considerable in rising heat transfer rate.

Keywords: Porous fin, Metal foam, Radiation, Pore density, Heat transfer.

Introduction
One of the effective ways to enhance heat transfer rate is using porous media, because of considerably increasing the contact surface area with fluid inside [1-5]. Although the effective thermal conductivity of the porous fin decreases, enhancement of effective surface area may overcome this reduction. Kiwan and Al-Nimr [1] introduced the concept of using porous fins to enhance the heat transfer from a given porous surface. Kundu and Bhanja [2] presented an analytical prediction for performance of porous fins. Gorla and Bakier [3] investigated the effect of radiation on the performance of porous fins in a natural convection environment. Yang et al. [4] used the CFD simulation of forced convective heat transfer in three-dimensional porous fin channels. Recently, Hatami et al. [5] simulated the heat transfer rate for a rectangular porous fin with temperature-dependent internal heat generation in steady-state condition. To transfer large amount of heat over a small volume, the high porosity open celled metals foams are the most promising materials [6, 7]. However, it is necessary to carry out more accurate evaluation about transport properties such as effective thermal conductivity, permeability and etc. In the present work, the effect of radiation losses on the natural convection heat transfer is simulated and investigated for metal foam-fin (Aluminum) of convex parabolic profile.

Mathematical modelling

Figure 1 represents a straight porous fin of convex parabolic profile attached to a vertical constant temperature wall. The porous fin allows fluid to penetrate through it, which enhances the convective heat transfer. the main assumptions for simplification are considered:

I. Porous medium is homogeneous, one-dimensional, isotropic and saturated with a single-phase fluid. Both the fluid and the solid matrix have constant physical properties except the density in the buoyancy term where Boussinesq approximation (buoyancy) is used.
II. The solid matrix and fluid are assumed to be at local thermal equilibrium with each other.
III. Darcy formulation is used to simulate the interaction between the porous medium and fluid.
IV. It is supposed the radiation heat flux inside the porous medium behaves as an optically thick gas.

All the symbols and nomenclatures used here are listed in table 1.

Table 1. The applied symbols and nomenclatures in the modeling.

Nomenclature		Nomenclature	
Bi	Biot Number	x	Axial coordinate
c_p	Specific heat, ht/k_s	X	Dimensionless axial coordinate, x/L
Da	Darcy number, K/δ^2	PPI	Pore density
$f_2(x)$	Profile function	Greek symbols	
g	Gravity constant(ms^{-2})	β	Coefficient of volumetric thermal expansion (K^{-1})
Gr	Grashof number, $\frac{g\beta\theta_b\delta^3}{\nu^2}$	ε	Emissivity
h	Heat transfer coefficient ($Wm^{-2}K^{-1}$)	η	Fin efficiency
k	Thermal conductivity ($Wm^{-1}K^{-1}$)	λ	Dimensionless parameter, L/δ
K	Permeability of the porous fin	φ	porosity
L	Length of porous fin	θ	Dimensionless temperature, $\frac{T-T_\infty}{T_b-T_\infty}$
Pr	Prandtl number, ν/α	ω	Dimensionless notation, $\frac{T_\infty}{T_b-T_\infty}$
q	Heat transfer rate	σ	Stefen-Boltzaman constant ($Wm^{-2}K^{-4}$)
q_w	Heat transfer rate through The base of fin	ρ	Density of fluid (kgm^{-3})
Ra	Rayleigh number, Gr×Pr	ν	Kinematic viscosity
Rd	Radiation-conduction parameter, $\frac{2\sigma\epsilon\delta\theta_b^3}{k_{eff}}$	Subscript	
T	Local fin temperature	s	Solid properties
T_b	Fin base temperature	f	Fluid properties
v_w	Velocity of fluid passing Through the fin at any point (ms^{-1})	eff	Porous properties

Now applying energy balance equation at steady state condition, there are two equations:

(1) without radiation effects $$\frac{d}{dX}\left[X^{\frac{1}{2}}\frac{d\theta}{dX}\right]=\frac{Ra\times Da}{k_r}\lambda^2\theta^2+\frac{2\times Bi}{\frac{\varphi k_f}{(1-\varphi)k_s}+1}\lambda^2\theta$$

(2) with radiation effects $$\frac{d}{dX}\left[X^{\frac{1}{2}}\frac{d\theta}{dX}\right]=\frac{Ra\times Da}{k_r}\lambda^2\theta^2+\frac{2\times Bi}{\frac{\varphi k_f}{(1-\varphi)k_s}+1}\lambda^2\theta+Rd\lambda^2((\theta+\omega)^4-\omega^4)$$

With non-dimensional parameters : $\theta=\frac{T-T_\infty}{T_b-T_\infty}, X=\frac{x}{L}$.

The permeability (K) is calculated with the correlations developed from high porosity metal foams by Bhattacharya et al. [6] and Calmidi and Mahajan [7].

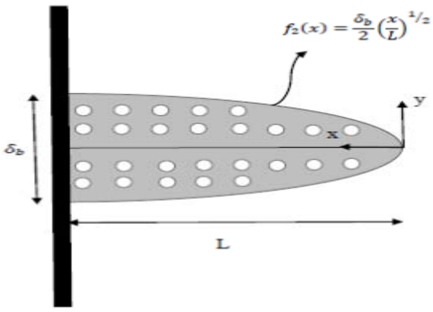

Figure 1. Schematic of a porous fin of convex parabolic close to a vertical constant temperature wall.

Results and Discussion

The equations (1) and (2) are solved analytically by using the Adomian Polynomials [8]. For validating the results obtained from analytical solution, the equations solved numerically by using Jacobian method. Figure 2 shows the variation of dimensionless temperature distribution with the dimensionless axial distance along the fin at specified conditions. The results indicate that the numerical data and analytical method are in very good agreement with each other. From the figure 2, it can be demonstrated that a greater variation of temperature occurs with radiation effect in comparison to the no radiation case.

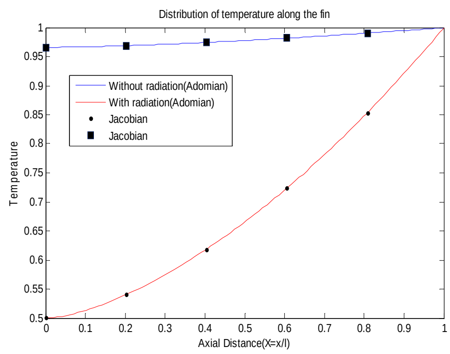

Figure 2. The distribution of axial non-dimensional temperature along the fin (ϕ=0.8,Ra=202.7, λ=12.5, Rd=1.9×10-5,Bi=0.0013,keff=47.6)

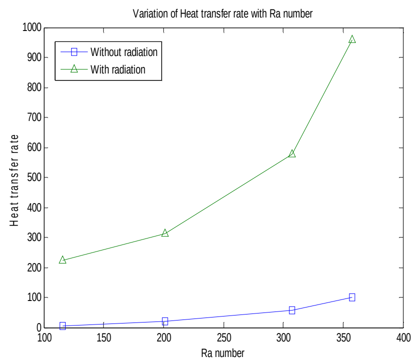

Figure 3. The variation of heat transfer rate with Ra number with and without radiation effect.

The variations in heat transfer rate per unit width from the base with Rayleigh number are presented in figure 3. Predicted results indicate that heat transfer rate with radiation is greater than heat transfer with natural convection and in two models, the heat transfer rate increases as Ra number increases. As shown in figure 4, by increasing the PPI the permeability decreases rapidly and therefore the volumetric flow rate from porous media decreases. Thus, the heat transfer rate from fin decreases as PPI increases. The ratio of heat transfer rate from porous fin and solid fin are plotted in figure 5, which is clear that heat transfer rate from porous fin is larger than solid fin as considering the radiation heat transfer. One can see, as porosity increases from 0.8 to 0.96 the heat transfer rate increases specially as the radiation effect is considered.

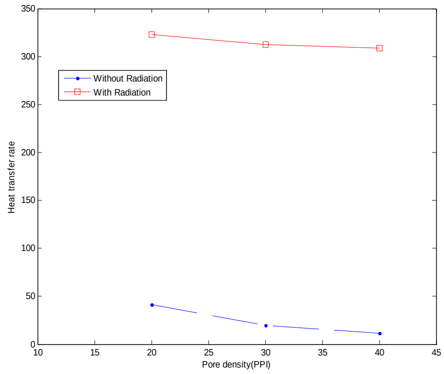

Figure 4. The effects of PPI on heat transfer rate with and without radiation effect.

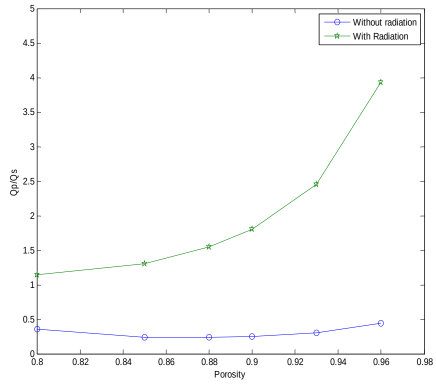

Figure 5. The plot of heat transfer ratio of porous fin to solid fin vs. porosity

Conclusions

The natural convection and radiation heat transfer in metal-foam fin are analytically and numerically studied. Air and Aluminum are employed as the cold fluid and porous medium, respectively. The effects of radiation, PPI, Ra and porosity on the heat transfer rate are carefully investigated. The main results are concluded as: The radiation effect is significant in this model. As pore density, PPI, increases, 20<PPI<40 and also Ra number decresses the heat transfer rate decreases as permeability decreases.The effects of porosity on heat transfer without radiation effect is negligible. Furthermore, with increasing the porosity of metal foam from 0.8 to 0.96, the heat transfer rate increases specially as the radiation effect is considered.

References

[1] S. Kiwan, M.A. Al-Nimr, Using porous fins for heat transfer enhancement, ASME Journal of Heat Transfer, 123 (2001) 790–795.
[2] B. Kundu, D. Bhanja, An analytical prediction for performance and optimum design analysis of porous fins, International Journal of Refrigeration, 34 (2011) 337-352.
[3] R.S. R. Gorla, A. Y.Bakier, Thermal analysis of natural convection and radiation in porous fins, International Communications in Heat and Mass Transfer, 38 (2011) 638–645.
[4] J. Yang, M. Zeng, Q. Wang, Forced Convection Heat Transfer Enhancement by Porous Pin Fins in Rectangular Channels. ASME Journal of heat transfer, 132 (2010), 051702-1 to 8.
[5] M. Hatami, A. Hasanpour, D. D. Ganji, Heat transfer study through porous fins with temperature-dependent heat generation, Energy Conversion and Management, 74 (2013) 9-16.
[6] A. Bhattacharya, V.V. Calmidi, and R.L. Mahajan. Thermophysical Properties of High Porosity Metal Foams, International journal of heat and mass transfer, 45 (2002) 1017–1031.
[7] V.V. Calmidi, and R.L Mahajan, Forced Convection in High Porosity Metal Foams, ASME Journal of heat transfer, 122 (2000) 557–565.
[8] G. Adomian, R. Rach, On composite nonlinearities and the decomposition method. Journal of Mathematical Analysis and Applications, 113 (1986), 504-509.