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ARTICLE

A Study on Thermal Performance of Palladium as Material for Passive Heat Transfer Enhancement Devices in Thermal and Electronics Systems

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ABSTRACT

In this work, the thermal behavior of fin made of palladium material under the influences of thermal radiation and internal heat generation is investigated. The thermal model for the extended surface made of palladium as the fin material is first developed and solved numerically using finite difference method. The influences of the thermal model parameters on the heat transfer behaviour of the extended surface are investigated. The results show that the rate of heat transfer through the fin and the thermal efficiency of the fin increase as the thermal conductivity of the fin material increases. This shows that fin is more efficient and effective for a larger value of thermal conductivity. However, the thermal conductivity of the fin with palladium material is low and constant at the value of approximately 75 W/mK in a wider temperature range of -100℃ and 227℃. Also, it is shown that the thermal efficiencies of potential materials (except for stainless steel and brass) for fins decrease as the fin temperatures increase. This is because the thermal conductivities of most of the materials used for fins decreases as temperature increases. However, keeping other fin properties and the external conditions constant, the thermal efficiency of the palladium is constant as the temperature of the fin increases within the temperature range of -100℃ and 227℃. And outside the given range of temperature, the thermal conductivity of the material increases which increases the efficiency of the fin. The study will assist in the selection of proper material for the fin and in the design of passive heat enhancement devices under different applications and conditions.

1. Introduction

Palladium is a lustrous silvery-white metal that belong to platinum group metals (PGMs). Palladium is used in electronics, multilayer ceramic capacitors, watch making, aircraft spark plugs, metallizing ceramics, solar energy, catalytic converter, fuel cells, electrical contacts, surgical instruments, production of ethanol fuel, oil refining, hydrogen purification, production of purified terephthalic acid, platinotype process, groundwater treatment, medicine, blood sugar test strips, industrial products, chemical applications, dentistry (dental alloys), medicine, and jewelry and it is a key component in pollution-control devices for cars and trucks.

Over the years, the demands for fins applications for passive cooling in thermal systems have grown exponentially. Fins, as passive devices for cooling and thermal control of thermal and electronics equipment. Further augmentation of the heat transfer has been achieved through the use of porous fins. The importance of such fins in various thermal

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and electronic equipment aroused various studies [1-23]. Various key parameters in the porous fin thermal models have been used for the improved heat transfer enhancement [2-6]. Some of the past works have focused on the utilizations of the fin geometry as well as the thermo-electro-magnetic properties of fin to achieve the optimized heat transfer augmentation of the porous fin [7-14]. In some of the studies, the properties of the surrounding fluid around the passive device have been used to increase the heat dissipating capacity of the fin [15-17]. Additionally, some authors displayed the efficacy of some new analytical and numerical methods in the thermal analysis of the porous fin [18-23]. Further studies on porous fin are presented in [24-47].

In the applications of fin for the heat transfer enhancement, it is established that the thermal conductivities of the materials for fins are temperature-dependent as shown in Figure 1. Therefore, the effects of the temperature-dependent thermal properties on the fin performance have been taken into consideration in previous studies. However, as depicted in Tables 1, 2 and 3, the thermal conductivities of the palladium at different temperatures. Even though the Tables present different values of thermal conductivity for palladium at different temperature, the stability of thermal conductivity palladium with temperature can be well established. Also, Figure 2 shows that the thermal conductivity of palladium is constant at a relatively low temperature. The relatively low temperature is the temperature region where the fin operates. Therefore, it is very important to analyze the thermal performance of this metal with temperature-invariant thermal conductivity. In this work, the thermal analysis of porous fin using palladium is analyzed. Parametric studies are carried out and the results are discussed.

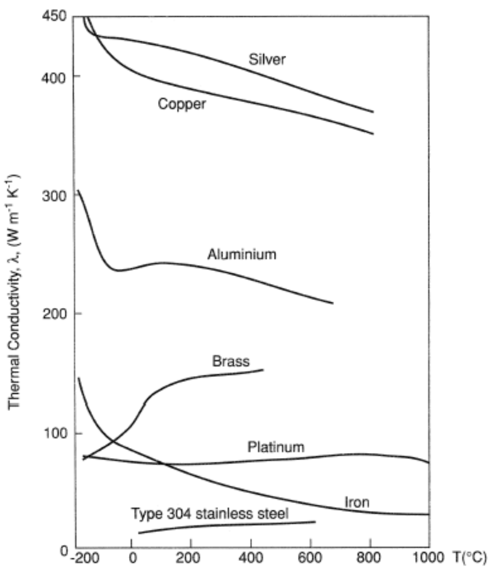

Figure 1. Variation of Thermal conductivity with temperature for difference materials

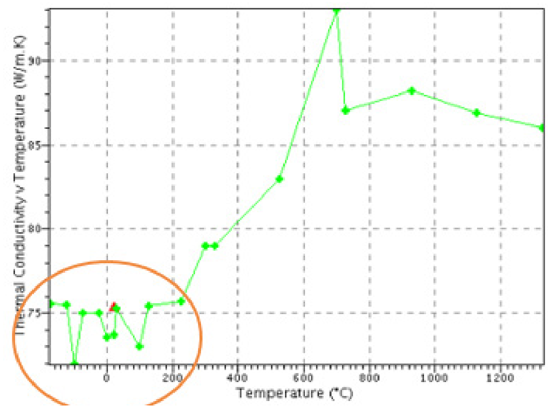

Figure 2. Variation of palladium thermal conductivity with temperature

Table 3.1 Thermal conductivity of Palladium with temperature [48]

S/N	Temperature (K)	Thermal conductivity (W/mK)
1	100.15	76.0
2	150.15	75.5
3	200.15	75.0
4	250.15	75.0
5	300.15	75.4
6	400.15	75.5
7	500.15	75.7

Table 3.2 Thermal conductivity of Palladium with temperature [50]

S/N	Temperature (K)	Thermal conductivity (W/mK)
1	100.15	75.1
2	300.15	75.4
3	400.15	75.4
4	500.15	75.7

Table 3.3 Thermal conductivity of Palladium with temperature [49]

S/N	Temperature (K)	Thermal conductivity (W/mK)
1	173.15	72.0
2	273.15	72.0
3	373.15	73.0

2. Problem Formulation

Consider a longitudinal rectangular fin with pores having convective and radiative heat transfer as shown in Figure 3. In order to derive the thermal model of the porous fin, it is assumed that the porous medium is isotropic, homogeneous and it is saturated with single-phase fluid. The physical and thermal properties of the fin and the surrounding fluid surface are constant. The temperature varies in the fin is only along the length of the fin as shown in the Figure 3. and there is a perfect contact between the fin base

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and the prime surface.

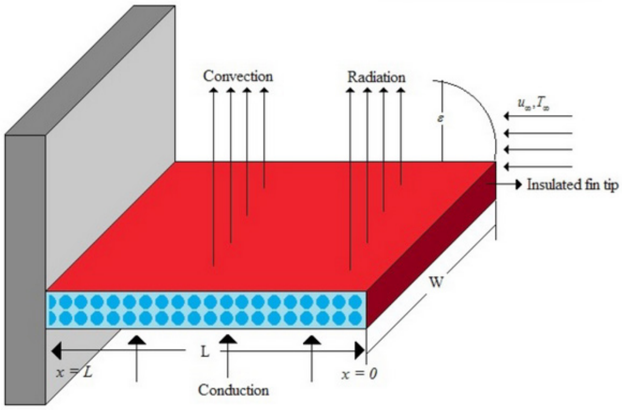

Figure 3. Schematic of the convective-radiative longitudinal porous fin with internal heat generation

From the assumptions and with the aid of Darcy's model, the energy balance is

$$q_x - \left(q_x + \frac{\delta q}{\delta x}dx\right) + q(T)dx = \dot{m}c_p(T - T_a) + hP(T - T_a)dx + \sigma\varepsilon P(T^4 - T_a^4)dx + q_{\text{int.}}(T)A_{cr}dx \quad (1)$$

The fluid flows through the pores at the rate of mass flow given as

$$\dot{m} = \rho u(x)Wdx \quad (2)$$

Also, the fluid velocity is given as

$$u(x) = \frac{gK\beta}{v}(T - T_a) \quad (3)$$

Then, Equ. (1) becomes

$$q_x - \left(q_x + \frac{\delta q}{\delta x}dx\right) = \frac{\rho c_p gK\beta}{v}(T - T_a)^2 dx + hP(T - T_a)dx + \sigma\varepsilon P(T^4 - T_a^4)dx + q_{\text{int.}}(T)A_{cr}dx \quad (4)$$

As dx→0, Eq. (3.5) reduces

$$-\frac{dq}{dx} = \frac{\rho c_p gK\beta}{v}(T - T_a)^2 + hP(T - T_a) + \sigma\varepsilon P(T^4 - T_a^4) + q_{\text{int.}}(T)A_{cr} \quad (5)$$

Applying Fourier's law for the heat conduction in the solid, one has

$$q = -k_{eff}A_{cr}\frac{dT}{dx} \quad (6)$$

where the effective thermal conductivity of the fin is given as

$$k_{eff} = \phi k_f + (1-\phi)k_s \quad (7)$$

According to Roseland diffusion approximation, the rate of radiation heat transfer is

$$q = -\frac{4\sigma A_{cr}}{3\beta_R}\frac{dT^4}{dx} \quad (8)$$

From Eqs. (6) and (8), the total rate of heat transfer is given by

$$q = -k_{eff}A_{cr}\frac{dT}{dx} - \frac{4\sigma A_{cr}}{3\beta_R}\frac{dT^4}{dx} \quad (9)$$

Substitution of Eq. (9) into Eq. (6) leads to

$$\frac{d}{dx}\left(k_{eff}A_{cr}\frac{dT}{dx} + \frac{4\sigma A_{cr}}{3\beta_R}\frac{dT^4}{dx}\right) = \frac{\rho c_p gK\beta}{v}(T - T_a)^2 + hP(T - T_a) + \sigma\varepsilon P(T^4 - T_a^4) + q_{\text{int.}}(T)A_{cr} \quad (10)$$

Expansion of the first term in Eq. (10), provides the governing equation for the required heat transfer

$$\frac{d^2T}{dx^2} + \frac{4\sigma}{3\beta_R k_{eff}}\frac{d}{dx}\left(\frac{dT^4}{dx}\right) - \frac{\rho c_p gK\beta}{k_{eff}tv}(T - T_a)^2 - \frac{h}{k_{eff}t}(T - T_a) - \frac{\sigma\varepsilon}{k_{eff}t}(T^4 - T_a^4)dx - q_{\text{int.}}(T) = 0 \quad (11)$$

The boundary conditions are

$$x = 0, \quad \frac{dT}{dx} = 0, \quad x = L, \quad T = T_b \quad (12b)$$

The internal heat general varies linearly with temperature as

$$q_{\text{int.}}(T) = q_a\left(1 + \lambda(T - T_a)\right) \quad (13)$$

When Eq. (13) is substituted into Eq. (11), one e arrives at

$$\frac{d^2T}{dx^2}+\frac{4\sigma}{3\beta_R k_{eff}}\frac{d}{dx}\left(\frac{dT^4}{dx}\right)-\frac{\rho c_p gK\beta}{k_{eff}tv}(T-T_a)^2-\frac{h}{k_{eff}t}(T-T_a)$$
$$-\sigma\varepsilon P(T^4-T_a^4)dx-q_{\text{int.}}(T)+\frac{q_o}{k_{eff}}\left(1+\lambda\left(T-T_a\right)\right)=0 \tag{14}$$

The term T^4 can be expressed as a linear function of temperature as

$$T^4=T_\infty^4+4T_\infty^3\left(T-T_\infty\right)+6T_\infty^2\left(T-T_\infty\right)^2+\ldots\cong 4T_\infty^3T-3T_\infty^4 \tag{15}$$

Substitution of Eq. (15) into Eq. (14), results in

$$\frac{d^2T}{dx^2}+\frac{16\sigma}{3\beta_R k_{eff}}\frac{d^2T}{dx^2}-\frac{\rho c_p gK\beta}{k_{eff}tv}(T-T_a)^2-\frac{h}{k_{eff}t}(T-T_a)$$
$$-4\sigma\varepsilon PT_a^3(T-T_a)dx+\frac{q_o}{k_{eff}}\left(1+\lambda\left(T-T_a\right)\right)=0 \tag{16}$$

Applying the following adimensional parameters in Eq. (17) to Eq. (16),

$$X=\frac{x}{L},\ \theta=\frac{T-T_a}{T_b-T_a}\ S_h=\frac{gk\beta\left(T_b-T_\infty\right)b}{\alpha\nu k_r}\ M^2=\frac{pbh}{A_b k_{eff}}$$
$$Rd=\frac{4\sigma_{st}T_\infty^3}{3\beta_R k_{eff}}\ Nr=\frac{4\sigma_{st}bT_\infty^3}{k_{eff}}. \tag{17}$$

$$Q=\frac{qb}{k_{eff}(T_b-T_\infty)}\quad \gamma=\lambda(T_b-T_a)$$

One arrives at the adimensional form of the governing Eq. (16) as presented in Eq. (18),

$$\left(1+4Rd\right)\frac{d^2\theta}{dX^2}-S_h\theta^2-M^2\theta-Nr\theta+Q\left(1+\gamma\theta\right)=0 \tag{18}$$

and the adimensional boundary conditions

$$X=0,\quad \frac{d\theta}{dX}=0 \tag{19a}$$

$$X=1,\quad \theta=1 \tag{19b}$$

3. Numerical Solution of the Thermal Model using Finite Difference Method

The numerical analysis of the nonlinear thermal model using finite difference method is presented in this section. The governing Eq. (18) and also, the boundary conditions in Eq. (19) are discretized as shown in Figure 4, Eqs. (20) and (22).

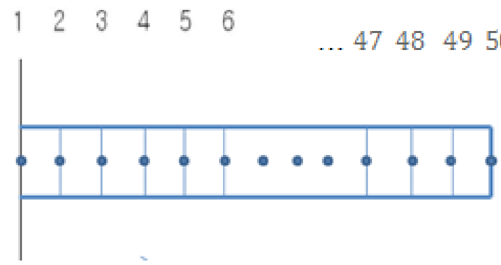

Figure 4. Nodal representation for finite difference method

$$\left(1+4Rd\right)\left(\frac{\theta_{i+1}-2\theta_i+\theta_{i-1}}{\Delta^2X}\right)-S_h\theta_i^2-M^2\theta_i-Nr\theta_i+Q(1+\gamma\theta_i)=0 \tag{20}$$

From Eq. (20), the final algebraic form of the finite difference equation becomes

$$\theta_{i+1}-2\theta_i+\theta_{i-1}-\frac{S_h(\Delta^2X)}{\left(1+4Rd\right)}\theta_i^2-\frac{M^2(\Delta^2X)}{\left(1+4Rd\right)}\theta_i$$
$$-\frac{Nr(\Delta^2X)}{\left(1+4Rd\right)}\theta_i+\frac{Q(\Delta^2X)}{\left(1+4Rd\right)}+\frac{\gamma Q(\Delta^2X)}{\left(1+4Rd\right)}\theta_i=0 \tag{21}$$

The finite difference discretization of the boundary conditions is

$$i=1,\quad \frac{\theta_2-\theta_0}{2\Delta X}=0\ \Rightarrow\theta_2=\theta_0 \tag{22a}$$

$$i=N,\quad \theta_N=1 \tag{22b}$$

From the above finite difference scheme in Eqs. (21) and (22), a set of 50 non-linear algebraic equations are developed. These systems of the non-linear equations are solved simultaneously with the aid of MATLAB using fsolve.

In order to investigate the impact of the constant thermal conductivity (temperature-invariant thermal conductivity), a variable thermal conductivity is introduced as

$$k=k_a\left(1+\psi\left(T-T_a\right)\right) \tag{23}$$

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The dimensionless thermal model becomes

$$\left(1+4Rd\right)\left(\frac{d^2\theta}{dX^2}+\beta\theta\frac{d^2\theta}{dX^2}+\beta\left(\frac{d\theta}{dX}\right)^2\right)-S_h\theta^2$$
$$-M^2\theta-Nr\theta+Q\left(1+\gamma\theta\right)=0=0 \tag{24}$$

where

$$\beta=\psi(T_b-T_a) \tag{25}$$

The finite difference discretization of Eq. (24) is

$$\left(1+4Rd\right)\left(\frac{\theta_{i+1}-2\theta_i+\theta_{i-1}}{\Delta^2 X}+\beta\theta_i\left(\frac{\theta_{i+1}-2\theta_i+\theta_{i-1}}{\Delta^2 X}\right)+\beta\left(\frac{\theta_{i+1}-\theta_{i-1}}{2\Delta X}\right)^2\right)$$
$$-S_h\theta_i^2-M^2\theta_i-Nr\theta_i+Q(1+\gamma\theta_i)=0 \tag{26}$$

After simplification, we have

$$\theta_{i+1}-2\theta_i+\theta_{i-1}+\beta\theta_i\left(\theta_{i+1}-2\theta_i+\theta_{i-1}\right)+\beta\left(\frac{\theta_{i+1}-\theta_{i-1}}{2}\right)^2-\frac{S_h(\Delta^2 X)}{\left(1+4Rd\right)}\theta_i^2$$
$$-\frac{M^2(\Delta^2 X)}{\left(1+4Rd\right)}\theta_i-\frac{Nr(\Delta^2 X)}{\left(1+4Rd\right)}\theta_i+\frac{Q(\Delta^2 X)}{\left(1+4Rd\right)}+\frac{\gamma Q(\Delta^2 X)}{\left(1+4Rd\right)}\theta_i=0 \tag{27}$$

The finite difference discretization of the boundary conditions is

$$i=1,\quad \frac{\theta_2-\theta_0}{2\Delta X}=0\ \Rightarrow\theta_2=\theta_0 \tag{28a}$$

$$i=N,\quad \theta_N=1 \tag{28b}$$

Also, a set of 50 non-linear algebraic equations are developed from Eq. (27) and (28). As before, these systems of the non-linear equations are solved simultaneously with the aid of MATLAB using fsolve.

It should be noted that when $\beta=0$ in Eq. (27), Eq. (21) is recovered as well the results of the temperature-invariant thermal conductivity,

4. Heat Flux and Efficiency Models of the Fin

The fin base heat flux is given by

$$q_{bn}=A_c k(T)\frac{dT}{dx} \tag{29}$$

Using the dimensionless parameters in Eq. (17), at the base of the fin, the dimensionless heat transfer rate is developed as

$$q_b=\frac{q_{bn}L}{k_a A_c(T_b-T_\infty)}=\frac{d\theta}{dX} \tag{30}$$

The finite difference discretization is given by

$$q_b=\left(\frac{\theta_{i+1}-\theta_i}{\Delta X}\right) \tag{31}$$

The total heat flux of the fin is given by

$$q_T=\frac{q_b}{A_c h(T-T_b)} \tag{32}$$

After substitution of Eq. (29) and using the dimensionless parameters in Eq. (17), one arrives at

$$q_T=\frac{1}{Bi}\frac{k}{h}\frac{d\theta}{dX}=\frac{1}{Bi}\frac{d\theta}{dX} \tag{33}$$

The finite difference discretization is given by

$$q_T=\frac{1}{Bi}\left(\frac{\theta_{i+1}-\theta_i}{\Delta X}\right) \tag{34}$$

The fin efficiency is the ratio of the rate of heat transfer rate by the fin to the rate of heat transfer that would be if the entire fin were at the base temperature and is given by

$$\eta=\frac{Q_f}{Q_{\max}}=\frac{\int_0^L Ph(T-T_\infty)dx}{Ph_b L(T_b-T_\infty)} \tag{35}$$

Applying the dimensionless parameters in Eq. (17) to Eq. (35), the fin efficiency in dimensionless variables is given by

$$\eta=\int_0^1\theta\,dX \tag{36}$$

After finite difference discretization, we have is

$$\eta=\sum_{i=1}^N\theta_i \tag{37}$$

5. Results and Discussion

The numerical solutions are coded in MATLAB and the parametric and sensitivity analyses are carried out using the codes.

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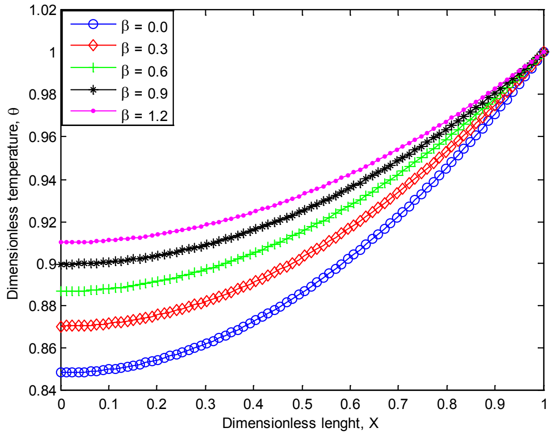

Figure 5. Dimensionless temperature distribution in the fin parameters for varying thermo-geometric parameter when S_{h},= 0.2,M=0.4

Because of the temperature-invariant of thermal conductivity of the material (palladium) under consideration, effect of thermal conductivity parameters on the dimensionless temperature distribution are first study as presented in Figures 5 and 6. It is established that as the thermal conductivity parameter (β) increases, the adimensionas temperature distribution in the fin increases which results in increase in the local temperature. A situation where $\beta = 0$ implies constant or temperature-invariant thermal conductivity as in the material (palladium) under consideration. This situation provides the lowest temperature distribution in the fin.It is shown that the temperature profile has steepest temperature gradient at the lower value of thermal conductivity especially when the thermal conductivity parameter $\beta = 0$. The higher the values of the thermal conductivity, the lower temperature difference between the base and the tip of the fin.

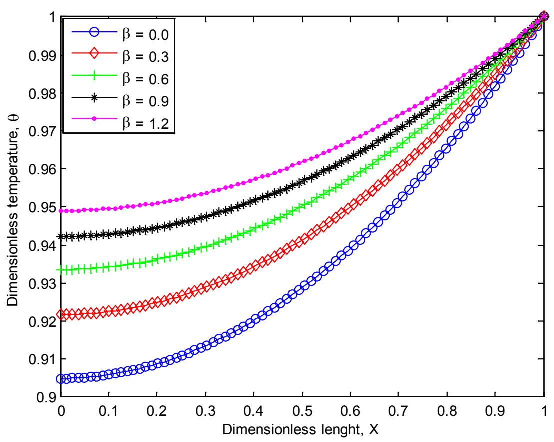

Figure 6. Dimensionless temperature distribution in the fin parameters for varying thermo-geometric parameter when S_{h},= 0.1,M=0.4

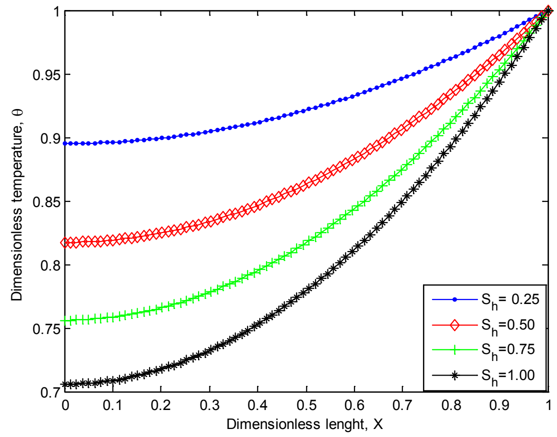

Figure 7. Dimensionless temperature distribution in the fin parameters for varying thermo-geometric parameter for constant thermal conductivity

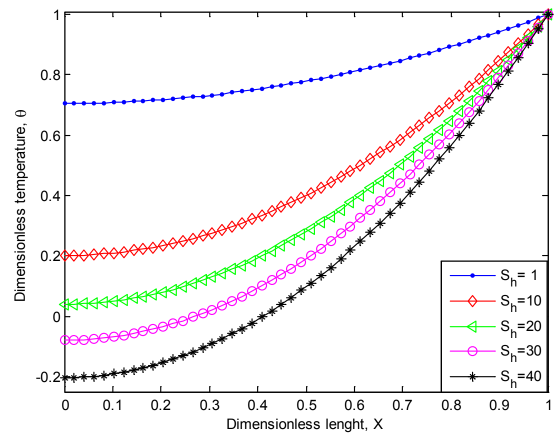

Figure 8. Effects of porous parameter on the temperature distribution in the fin parameters for constant thermal conductivity

The small value of the temperature difference between the base and the tip of the fin is attributed to lower thermal resistance offered by the material.Also, it should be noted that the temperature difference becomes more pronounced as the thermo-geometric parametric increases. From the Figure 1, except for stainless steel and brass, the thermal conductivities of most of the materials used for fins decreases as temperature increases. Therefore, the thermal efficiencies of these materials for the fins decrease as the fin temperatures increase.However, keeping other fin properties and the external conditions constant, the thermal efficiency of the palladium is constant as the temperature of the fin increases within the temperature range of -100°C and 227°C. The is due the temperature-invariant thermal conductivity of palladium.

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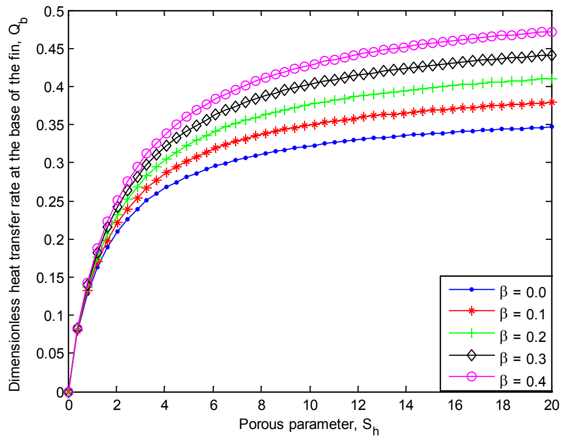

Figure 9. Effects of thermal conductivity and porosity on heat flux when M=0.5, Nr=0.2

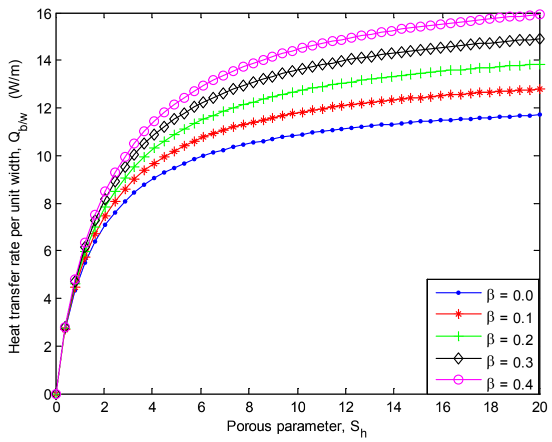

Figure 10. Effects of thermal conductivity and porosity on heat flux when M=2, Nr=0.3

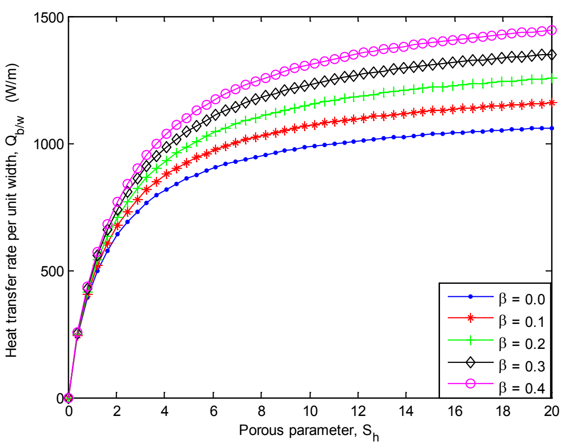

Figure 11. Effects of thermal conductivity and porosity on heat flux when M=2.5, Nr=0.4

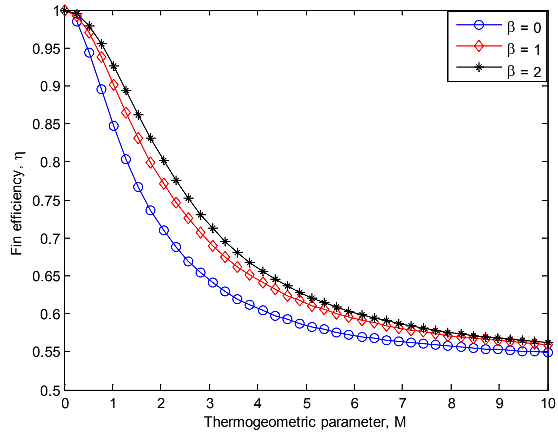

Figure 12. Effects of thermal conductivity and conductive-convective parameter on the fin efficiency when M=2, N=0.2, S=0.5

The impact of porous parameter on the adimensional temperature is presented in Figures 7 and 8. It is shown in the figures that when the porosity parameter increases, the adimensional fin temperature decreases and the heat transfer rate through the fin increases.

Figures 9, 10 and 11 show the effects of temperature-dependent thermal conductivity parameter on the adimensional heat transfer rate at the base of the fin at different radiation parameters.

Figure 12 shows that increase in the thermal conductivity parameter, the heat transfer rate through the fin and the thermal efficiency of the fin increase.Fin is more efficient and effective for larger value of thermal conductivity. This trend was also depicted in Figure 13.

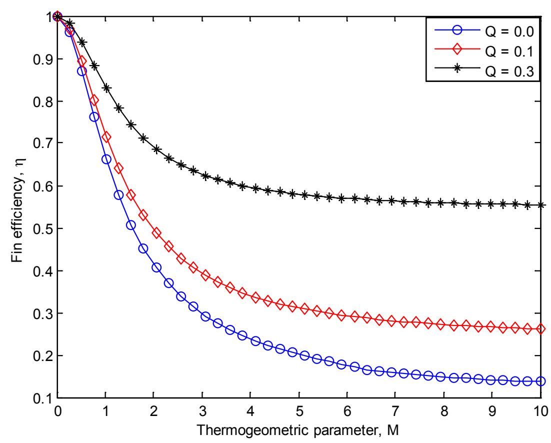

Figure 13. Effect of internal heat generation on the fin efficiency when Sh=0.5, Nr=0.2, γ=0.8

5. Conclusion

The thermal performance of fin made of palladium material under the influences of internal transfer mechanisms such as thermal radiation and temperature-dependent internal heat generation has been analyzed in this work. The developed thermal model for the extended surface made of palladium as the fin material was solved numerically with the aid of finite difference method. Effects of various parameters on the heat transfer model of the extended surface are investigated and the following are established:

(1) The results showed that the heat transfer rate through the fin and the thermal efficiency of the fin increase as the thermal conductivity of the fin material increases.

(2) This shows that fin is more efficient and effective for larger value of thermal conductivity.

(3) The thermal efficiencies of most materials (except for stainless steel and brass) for fins decrease as the fin temperatures increase.

(4) Keeping other fin properties and the external conditions constant, the thermal efficiency of the palladium is constant as the temperature of the fin increases within the temperature range of -100°C and 227°C. And outside the given range of temperature, the thermal conductivity of the material increases which increases the efficiency of the fin.

The selecting of proper material for the fin and in the design of passive heat enhancement go a long way in enhancing the heat transfer in thermal and electronic systems. Therefore, the present study will greatly help in this area of heat transfer augmentation in such systems.

Nomenclature

A Section Area of the fin

g Gravity constant

k The parameter describing the thermal conductivity variation. $\left(Wm^{-1}K^{-1}\right)$

h Convective heat transfer coefficient

L Length of the fin $\left(m\right)$

c_p Specific heat $\left(J\,kg^{-1}K^{-1}\right)$

v_w Velocity of fluid passing through the fin $\left(m\,s^{-1}\right)$

S_p Porosity parameter

N_r Radiation parameter

C_T Dimensionless ratio of ambient to difference between wall and ambient temp. $\dfrac{T_\infty}{T_b - T_\infty}$

W Width of section fin $\left(m\right)$

t Thickness of section fin $\left(m\right)$

$\dot{m}$ Mass flow rate $\left(kg\,s^{-1}\right)$

g Acceleration due to gravity $\left(9.81\,m\,s^{-2}\right)$

T Local fin temperature $\left(K\right)$

T_b Fin base temperature $\left(K\right)$

T_∞ Ambient or surrounding temperature $\left(K\right)$

x Axial coordinate $\left(m\right)$

X Dimensionless axial coordinate

Greek symbols

θ Dimensionless temperature

σ Stephen-boltzman constant $\left(5.67\times10^{-8}Wm^2s^{-1}K^{-4}\right)$

ε Emissivity of porous fin

ν Kinematic viscosity $\left(m^2s^{-1}\right)$

ρ Density $\left(kg\,m^{-3}\right)$

Subscript

b Condition at the fin base

∞ Condition of the ambient temperature

p Porous property

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