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ARTICLE

A Study on the Effects of Internal Heat Generation on the Thermal Performance of Solid and Porous Fins using Differential Transformation Method

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ABSTRACT

In this study, the impacts of internal heat generation on heat transfer enhancement of porous fin is theoretical investigated using differential transform method. The parametric studies reveal that porosity enhances the fin heat dissipating capacity but the internal heat generation decreases the heat enhancement capacity of extended surface. Also, it is established that when the internal heat parameter increases to some certain values, some negative effects are recorded where the fin stores heat rather than dissipating it. This scenario defeats the prime purpose of the cooling fin. Additionally, it is established in the present study that the limiting value of porosity parameter for thermal stability for the passive device increases as internal heat parameter increases. This shows that although the internal heat parameter can help assist higher range and value of thermal stability of the fin, it produces negative effect which greatly defeats the ultimate purpose of the fin. The results in the work will help in fin design for industrial applications where internal heat generation is involved.

1. Introduction

In many thermal systems, heat is excessive generated that might lead to thermal damage of the systems. Over the years, different active and passive methods have been adopted to dissipate the excessive heat from the thermal systems. Although fins have been used as extended surfaces heat transfer augmentation in most devices, the presence of pores in the fins further increases the heat enhancement capacity of the extended surfaces. In fact, the application of porous fin with certain number of pores may give same performance as convectional fin and save 100ϕ of the fin material [1]. Consequently, in some earlier works on extended surfaces, various studies have been put forward on the porous fins [1-9]. In recent times, different authors have adopted different techniques to study the heat transfer in porous fin [10-27]. However, a study on the effects of variable internal heat generation on the thermal performance of the solid and porous fins have not been addressed. Therefore, in this work, heat transfer analysis of porous fin with linear and non-linear variable internal heat generation using differential transform method is presented.

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2. Problem Formulation

Consider the flow of heat through a longitudinal rectangular porous fin that as shown in Figure1. Following the model assumptions in our previous studies [27], the thermal energy balance could be expressed

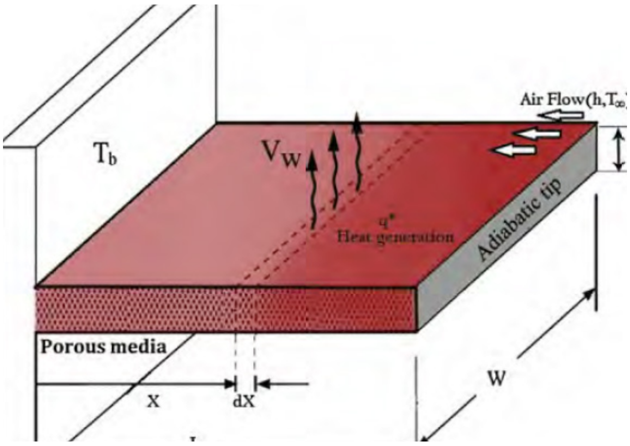

Figure 1. Schematic of a longitudinal rectangular porous fin with internal heat generation [18]

$$\frac{d^2T}{dx^2}-\frac{h(T-T_a)}{k_{eff,a}t}-\frac{\rho c_p\, g K\beta'(T-T_a)^2}{k_{eff,a}t\nu_f}+\frac{q(T)}{k_{eff,a}}=0 \tag{1}$$

where the boundary conditions of the fin are given as

$$\begin{aligned} &when \quad x=0, \quad T=T_b \\ &when \quad x=L, \quad \frac{dT}{dx}=0 \end{aligned} \tag{2}$$

The internal heat generation are temperature-dependent. Therefore, the linear and non-linear temperature-dependent internal heat generations are given by

$$q_{int}(T)=q_a[1+\psi(T-T_a)] \tag{3}$$

$$q_{int}(T)=q_a[1+\psi_1(T-T_a)+\psi_2(T-T_a)^2] \tag{4}$$

where T, T_b, T_a, h_b g, k_{eff} , q, t, v , c_p ρ, L and w temperature of the fin, base temperature, ambient temperature, heat transfer coefficient at the base of the fin, gravity constant, effective thermal conductivity of the fin, internal heat generation, thickness of the fin, kinematic viscosity of fluid passing through porous fin, density of the fluid, length of the fin and width of the fin. respectively.

When Eqs. (3) and (4) are substituted, Eq. (1) becomes

For the linear temperature-dependent internal heat generation

$$\frac{d^2T}{dx^2}-\frac{h(T-T_a)}{k_{eff,a}t}-\frac{\rho c_p\, g K\beta'(T-T_a)^2}{k_{eff,a}t\nu_f}+\frac{q_a}{k_{eff,a}}[1+(T-T_a)]=0 \tag{5a}$$

For the nonlinear temperature-dependent internal heat generation

$$\frac{d^2T}{dx^2}-\frac{h(T-T_a)}{k_{eff,a}t}-\frac{\rho c_p\, g K\beta'(T-T_a)^2}{k_{eff,a}t\nu_f}+\frac{q_a}{k_{eff,a}}[1+\psi_1(T-T_a)+\psi_2(T-T_a)^2]=0 \tag{5b}$$

Using the following dimensionless parameters in Eq. (5a) and (5b);

$$X=\frac{x}{L},\quad \theta=\frac{T-T_a}{T_b-T_a},\quad Ra=Gr.\Pr=\left(\frac{\beta' g T_b t^3}{\nu_f^2}\right)\left(\frac{\rho c_p \nu_f}{k_{eff,a}}\right),\quad Da=\frac{K}{t^2},\quad Q=\frac{q_a A_c}{h_b P(T_b-T_a)},\quad M^2=\frac{hL^2}{k_{eff,a}t}$$
$$S_h=\left(\frac{\beta' g(T_b-T_a)t^3}{\nu_f^2}\right)\left(\frac{\rho c_p \nu_f K}{k_{eff,a}t^2}\right)\frac{(L/t)^2}{k_{eff,a}}=\frac{RaDa(L/t)^2}{k_{eff,a}},\quad \gamma=\psi(T_b-T_a),\quad \gamma_1=\psi_1(T_b-T_a),\quad \gamma_2=\psi_2(T_b-T_a) \tag{6}$$

Da, K, M, Q, Ra, S_h, γ and θ are Darcy number, permeability of the porous fin, dimensionless thermo-geometric parameter, dimensionless heat transfer rate per unit area, Rayleigh number, porosity parameter, dimensionless internal heat parameter and temperature, respectively.

The dimensionless forms of the Eqs. (5a) and (5b) are

For the linear temperature-dependent internal heat generation

$$\frac{d^2\theta}{dX^2}-M^2\theta-S_H\theta^2+M^2Q\gamma\theta+M^2Q=0 \tag{7a}$$

For the nonlinear temperature-dependent internal heat generation

$$\frac{d^2\theta}{dX^2}-M^2\theta-S_H\theta^2+M^2Q\gamma_1\theta+M^2Q\gamma_2\theta^2+M^2Q=0 \tag{7b}$$

The dimensionless boundary conditions are

$$\begin{aligned} &when \quad X=0, \quad \theta=1 \\ &when \quad X=1, \quad \frac{d\theta}{dX}=0 \end{aligned} \tag{8}$$

3. Method of Solution: Differential Transform Method

The nonlinearities in Eqs. (7a) and (7b) call for the use of an approximate analytical method or a numerical method. In this study, we use differential transformation method. The definition and the operational properties of the method can be found in our previous study [28]. The differential transformation of the Eq. (7a) are given as

For the linear temperature-dependent internal heat gen-

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eration is given as

$$\left(p+1\right)\left(p+2\right)\theta(p+2)-M^2\theta(p)-S_h\sum_{r=0}^{p}\theta\left(r\right)\theta\left(p-r\right)+M^2Q\gamma\theta(p)+M^2Q\delta\left(p\right)=0 \tag{13}$$

where

$$\theta(p+2)=\frac{M^2\theta(p)+S_h\sum_{r=0}^{p}\theta\left(r\right)\theta\left(p-r\right)-M^2Q\gamma\theta(p)-M^2Q\delta\left(p\right)}{\left(p+1\right)\left(p+2\right)} \tag{14}$$

With the boundary conditions,

$$\theta(0)=1,\quad \theta(1)=a,$$

We arrived at

$$\theta(2)=\frac{-M^2Q}{2}+\frac{S_h}{2}+\frac{M^2}{2}-\frac{M^2Q\gamma}{2}$$

$$\theta(3)=\frac{aS_h}{3}+\frac{M^2a}{6}-\frac{aM^2Q\gamma}{6}$$

$$\theta(4)=\frac{-S_hM^2Q\gamma}{8}-\frac{S_hM^2Q}{12}+\frac{S_h^2}{12}+\frac{S_hM^2}{8}-\frac{M^4Q\gamma}{12}+\frac{a^2S_h^2}{12}-\frac{M^4Q}{24}+\frac{M^4}{24}+\frac{M^4Q^2\gamma}{24}+\frac{M^4Q^2\gamma^2}{24}$$

$$\theta(5)=\frac{-S_haM^2Q}{20}-\frac{S_h^2a}{12}+\frac{S_haM^2}{12}-\frac{S_haM^2Q\gamma}{12}+\frac{aM^4}{120}-\frac{aM^4Q\gamma}{60}+\frac{M^4Q^2a\gamma^2}{120} \tag{15}$$

Therefore, from the definition

$$\theta(X)=1+aX+\left(\frac{S_h}{2}-\frac{M^2Q}{2}+\frac{M^2}{2}-\frac{M^2Q\gamma}{2}\right)X^2+\left(\frac{aS_h}{3}+\frac{M^2a}{6}-\frac{aM^2Q\gamma}{6}\right)X^2$$
$$+\left(\frac{S_hM^2}{8}-\frac{S_hM^2Q\gamma}{8}-\frac{S_hM^2Q}{12}+\frac{S_h^2}{12}-\frac{M^4Q\gamma}{12}+\frac{aS_h^2}{12}-\frac{M^4Q}{24}+\frac{M^4}{24}+\frac{M^4Q^2\gamma}{24}+\frac{M^4Q^2\gamma^2}{24}\right)X^4$$
$$+\left(\frac{S_h^2aM^2}{12}-\frac{S_haM^2Q}{20}-\frac{S_h^2a}{12}-\frac{S_haM^2Q\gamma}{12}+\frac{aM^4}{120}-\frac{aM^4Q\gamma}{60}+\frac{M^4Q^2a\gamma^2}{120}\right)X^5+.... \tag{16}$$

For the nonlinear temperature-dependent internal heat generation is given as

$$\left(p+1\right)\left(p+2\right)\theta(p+2)-M^2\theta(p)-S_h\sum_{r=0}^{p}\theta\left(r\right)\theta\left(p-r\right)+M^2Q\gamma_1\theta(p)$$
$$+M^2Q\gamma_2\sum_{r=0}^{p}\theta\left(r\right)\theta\left(p-r\right)+M^2Q\delta\left(p\right)=0 \tag{17}$$

From which

$$\theta(p+2)=\frac{M^2\theta(p)+S_h\sum_{r=0}^{p}\theta\left(r\right)\theta\left(p-r\right)-M^2Q\gamma_2\sum_{r=0}^{p}\theta\left(r\right)\theta\left(p-r\right)-M^2Q\gamma\theta(p)-M^2Q\delta\left(p\right)}{\left(p+1\right)\left(p+2\right)} \tag{18}$$

with the boundary conditions,

$$\theta(0)=1,\quad \theta(1)=a$$

we arrived at

$$\theta(2)=\frac{-M^2Q}{2}+\frac{S_h}{2}-\frac{M^2Q\gamma_2}{2}+\frac{M^2}{2}-\frac{M^2Q\gamma}{2}$$

$$\theta(3)=\frac{aS_h}{3}-\frac{aM^2Q\gamma_2}{3}+\frac{M^2a}{6}-\frac{aM^2Q\gamma}{6}$$

$$\theta(4)=\frac{-S_hM^2Q\gamma}{8}-\frac{S_hM^2Q}{12}+\frac{S_h^2}{12}+\frac{S_hM^2}{8}$$
$$+\frac{M^4Q^2\gamma_1\gamma_2}{8}+\frac{M^4Q^2\gamma_2}{12}+\frac{M^4Q^2\gamma_2^2}{12}-\frac{M^4Q\gamma_2}{8}$$
$$-\frac{M^4Q\gamma}{12}+\frac{aM^4Q^2\gamma_2^2}{12}-\frac{M^4Q}{24}+\frac{M^4}{24}+\frac{M^4Q^2\gamma}{24}+\frac{M^4Q^2\gamma^2}{24}$$

$$\theta(5)=\frac{S_h^2aM^2}{12}-\frac{S_haM^2Q}{20}-\frac{S_h^2a}{12}-\frac{S_haM^2Q\gamma}{12}+\frac{aM^4Q^2\gamma_2}{20}-\frac{M^4Q^2\gamma_2^2a}{12}$$
$$+\frac{M^4Q^2\gamma_2^2aM^2}{12}+\frac{aM^4Q^2\gamma_1\gamma_2}{12}+\frac{aM^4}{120}-\frac{aM^4Q\gamma}{60}+\frac{M^4Q^2a\gamma^2}{120} \tag{19}$$

From the definition of DTM, we have,

$$\theta(X)=1+aX+\left(\frac{S_h}{2}-\frac{M^2Q}{2}-\frac{M^2Q\gamma_2}{2}+\frac{M^2}{2}-\frac{M^2Q\gamma}{2}\right)X^2+\left(\frac{aS_h}{3}-\frac{aM^2Q\gamma_2}{3}+\frac{M^2a}{6}-\frac{aM^2Q\gamma}{6}\right)X^3$$
$$+\left(\begin{array}{l}\frac{-S_hM^2Q\gamma}{8}-\frac{S_hM^2Q}{12}+\frac{S_h^2}{12}+\frac{S_hM^2}{8}+\frac{M^4Q^2\gamma_1\gamma_2}{8}+\frac{M^4Q^2\gamma_2}{12}+\frac{M^4Q^2\gamma_2^2}{12}\\ -\frac{M^4Q\gamma_2}{8}-\frac{M^4Q\gamma}{12}+\frac{aM^4Q^2\gamma_2^2}{12}-\frac{M^4Q}{24}+\frac{M^4}{24}+\frac{M^4Q^2\gamma}{24}+\frac{M^4Q^2\gamma^2}{24}\end{array}\right)X^4$$
$$+\left(\begin{array}{l}\frac{S_h^2aM^2}{12}-\frac{S_haM^2Q}{20}-\frac{S_h^2a}{12}-\frac{S_haM^2Q\gamma}{12}+\frac{aM^4Q^2\gamma_2}{20}-\frac{M^4Q^2\gamma_2^2a}{12}\\ +\frac{M^4Q^2\gamma_2^2aM^2}{12}+\frac{aM^4Q^2\gamma_1\gamma_2}{12}+\frac{aM^4}{120}-\frac{aM^4Q\gamma}{60}+\frac{M^4Q^2a\gamma^2}{120}\end{array}\right)X^5+.... \tag{20}$$

For the solid fin

For the linear temperature-dependent internal heat generation is given as

$$\frac{d^2\theta}{dX^2}-M^2\theta+M^2Q\gamma\theta+M^2Q=0 \tag{21}$$

The recursive relation of the governing equation is given as

$$\left(p+1\right)\left(p+2\right)\theta(p+2)-M^2\theta(p)+M^2Q\gamma\theta(p)+M^2Q\delta\left(p\right)=0 \tag{22}$$

then

$$\theta(p+2)=\frac{M^2\theta(p)-M^2Q\gamma\theta(p)-M^2Q\delta\left(p\right)}{\left(p+1\right)\left(p+2\right)}$$

With the boundary conditions, we arrived at

$$\theta(0)=1, \quad \theta(1)=a,$$

$$\theta(2)=\frac{-M^2Q}{2}+\frac{M^2}{2}-\frac{M^2Q\gamma}{2}$$

$$\theta(3)=\frac{M^2a}{6}-\frac{aM^2Q\gamma}{6} \tag{23}$$

$$\theta(4)=-\frac{M^4Q\gamma}{12}-\frac{M^4Q}{24}+\frac{M^4}{24}+\frac{M^4Q^2\gamma}{24}+\frac{M^4Q^2\gamma^2}{24}$$

$$\theta(5)=\frac{aM^4}{120}-\frac{aM^4Q\gamma}{60}+\frac{M^4Q^2a\gamma^2}{120}$$

Therefore,

$$\theta(X)=1+aX+\left(\frac{M^2}{2}-\frac{M^2Q}{2}-\frac{M^2Q\gamma}{2}\right)X^2+\left(\frac{M^2a}{6}-\frac{aM^2Q\gamma}{6}\right)X^2 \\ +\left(\frac{M^4}{24}-\frac{M^4Q\gamma}{12}-\frac{M^4Q}{24}+\frac{M^4Q^2\gamma}{24}+\frac{M^4Q^2\gamma^2}{24}\right)X^4 \\ +\left(\frac{aM^4}{120}-\frac{aM^4Q\gamma}{60}+\frac{M^4Q^2a\gamma^2}{120}\right)X^5+.... \tag{24}$$

For solid fin with nonlinear temperature-dependent internal heat generation is given as

$$\frac{d^2\theta}{dX^2}-M^2\theta+M^2Q\gamma_1\theta+M^2Q\gamma_2\theta^2+M^2Q=0 \tag{25}$$

And the recursive relation of the governing equation is given as

$$(p+1)(p+2)\theta(p+2)-M^2\theta(p)+M^2Q\gamma_2\sum_{r=0}^{p}\theta(r)\theta(p-r)+M^2Q\gamma\theta(p)+M^2Q\delta(p)=0 \tag{26}$$

From which we arrived at

$$\theta(p+2)=\frac{M^2\theta(p)-M^2Q\gamma_2\sum_{r=0}^{p}\theta(r)\theta(p-r)-M^2Q\gamma\theta(p)-M^2Q\delta(p)}{(p+1)(p+2)} \tag{27}$$

With the boundary conditions, we arrived at

$$\theta(0)=1, \quad \theta(1)=a, \quad \theta(2)=\frac{-M^2Q}{2}-\frac{M^2Q\gamma_2}{2}+\frac{M^2}{2}-\frac{M^2Q\gamma_1}{2}$$

$$\theta(3)=-\frac{aM^2Q\gamma_2}{3}+\frac{M^2a}{6}-\frac{aM^2Q\gamma_1}{6},$$

$$\theta(4)=\frac{M^3Q^2\gamma_1\gamma_2}{8}+\frac{\gamma_2M^4Q^2}{12}+\frac{M^4Q^2\gamma_2^2}{12}+\frac{M^4Q\gamma_2}{8}-\frac{M^4Q\gamma_1}{12} \\ +\frac{aM^4Q^2\gamma_2^2}{12}-\frac{M^4Q}{24}+\frac{M^4}{24}+\frac{M^4Q^2\gamma_1}{24}+\frac{M^4Q^2\gamma^2}{24} \tag{28}$$

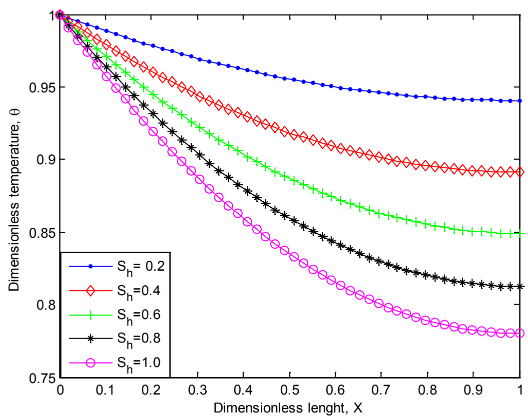
$$\theta(5)=\frac{aM^4Q^2\gamma_2}{20}-\frac{M^4Q^2\gamma_2^2a}{12}+\frac{M^4Q^2\gamma_2^2M^2}{12}+\frac{M^4Q^2\gamma_1\gamma_2}{12} \\ +\frac{aM^4}{120}-\frac{aM^4Q\gamma_1}{60}+\frac{M^4Q^2a\gamma_1^2}{120}$$

Therefore,

$$\theta(X)=1+aX+\left(\frac{-M^2Q}{2}-\frac{M^2Q\gamma_2}{2}+\frac{M^2}{2}-\frac{M^2Q\gamma_1}{2}\right)X^2+\left(-\frac{aM^2Q\gamma_2}{3}+\frac{M^2a}{6}-\frac{aM^2Q\gamma_1}{6}\right)X^3 \\ +\left(\begin{array}{l}\frac{M^3Q^2\gamma_1\gamma_2}{8}+\frac{\gamma_2M^4Q^2}{12}+\frac{M^4Q^2\gamma_2^2}{12}+\frac{M^4Q\gamma_2}{8}-\frac{M^4Q\gamma_1}{12} \\ +\frac{aM^4Q^2\gamma_2^2}{12}-\frac{M^4Q}{24}+\frac{M^4}{24}+\frac{M^4Q^2\gamma_1}{24}+\frac{M^4Q^2\gamma^2}{24}\end{array}\right)X^4 \\ +\left(\begin{array}{l}\frac{aM^4Q^2\gamma_2}{20}-\frac{M^4Q^2\gamma_2^2a}{12}+\frac{M^4Q^2\gamma_2^2M^2}{12}+\frac{M^4Q^2\gamma_1\gamma_2}{12} \\ +\frac{aM^4}{120}-\frac{aM^4Q\gamma_1}{60}+\frac{M^4Q^2a\gamma_1^2}{120}\end{array}\right)X^5+.... \tag{29}$$

4. Results and Discussion

Using the developed models, the graphical representations of the results are presented in this section. Figures 2a-d present the impacts of porosity on thermal behaviour of the porous fin. As expected, the figures illustrate heat transfer enhancement by the porous parameter.



(a)

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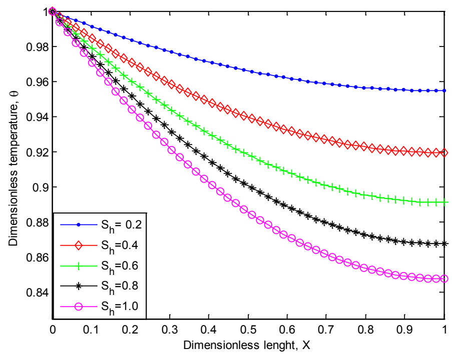

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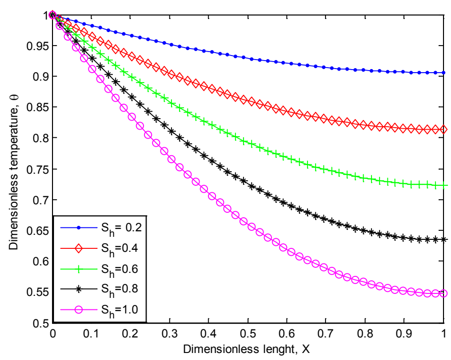

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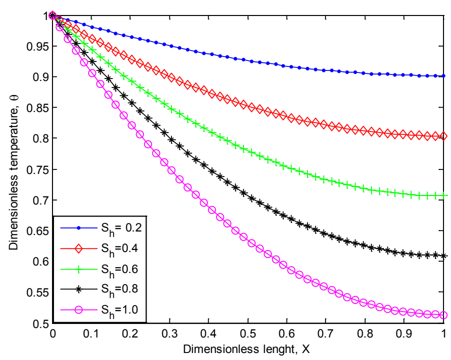
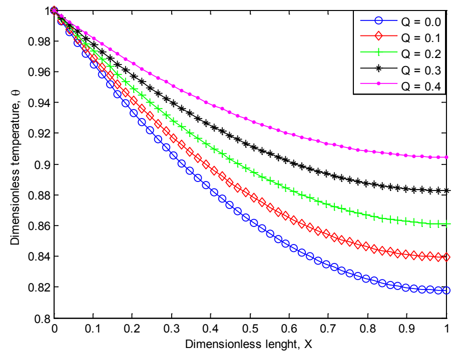


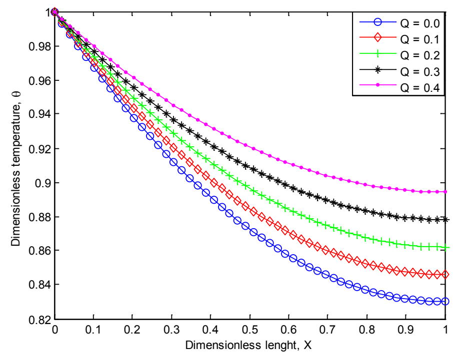
(d)

Figure 2. Impacts of porosity on the fin temperature when (a) M=0.5, Q=0.2, γ=0.4 (b) M=1.0, Q=0.2, γ=0.4 (c) M=5.0; Q=0.4, γ=0.2 (d)) M=10, Q=0.2, γ=0.4

The influences of the internal heat parameter on the thermal response of the porous fin is shown in Figure 3a-d and Figure 4a-b. It can be seen that the internal heat parameter decreases the thermal performance of the fin. Also, it is shown that when the internal heat parameter increases to some certain values, the purpose of heat dissipation by the porous was greatly defeated as the fin stores heat rather than dissipating it.



(a)



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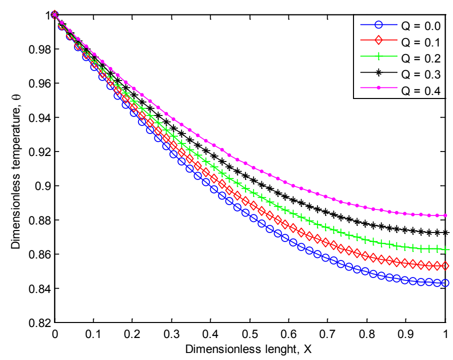

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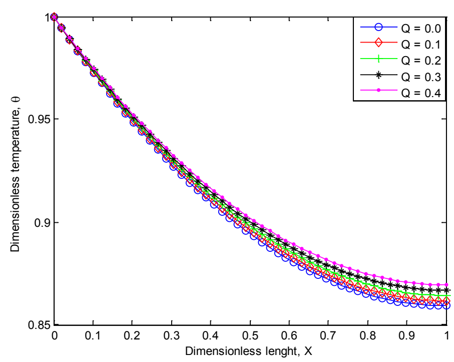


(d)

Figure 3. Influences of internal heat parameter on the fin temperature distribution when (a) M=0.1, S_h=0.5, γ=0.2 (b) M=0.5, S_h=0.5, γ=0.2, (c) M=0.75, S_h=5.0, γ=0.2 (d) M=1.0, S_h=0.5, γ=0.2

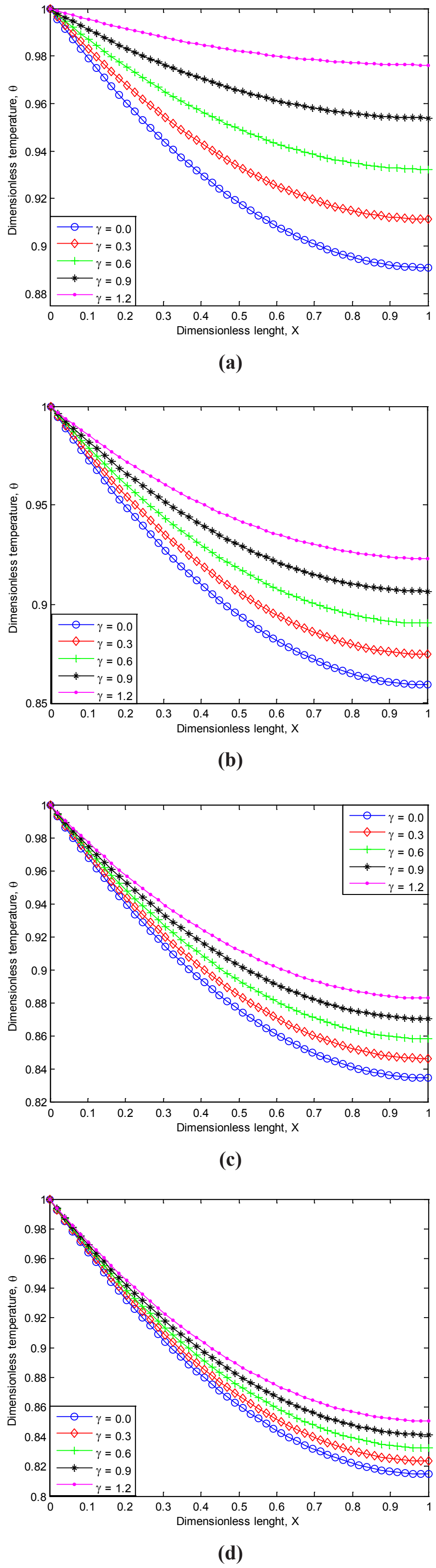
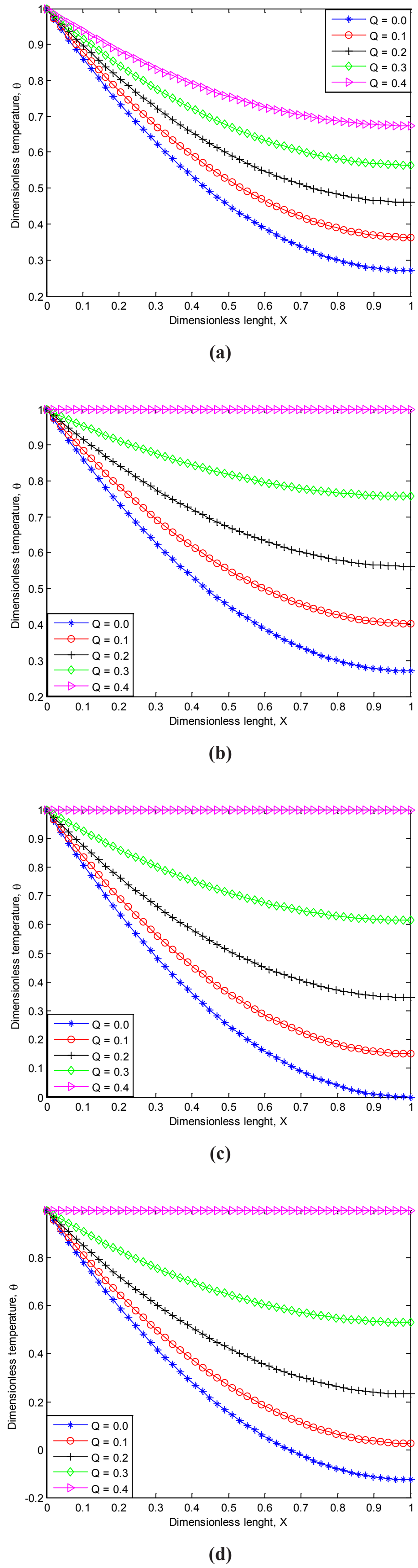


Figure 4. Effects of the internal heat parameter on fin temperature when (a) M=0.5, Q=0.4, S_h=0.5, (b) M=1.0, Q=0.4, S_h=0.5(c) M=1.5, Q=0.4, S_h=0.5 (d) M=2.0, Q=0.4, S_h=0.5



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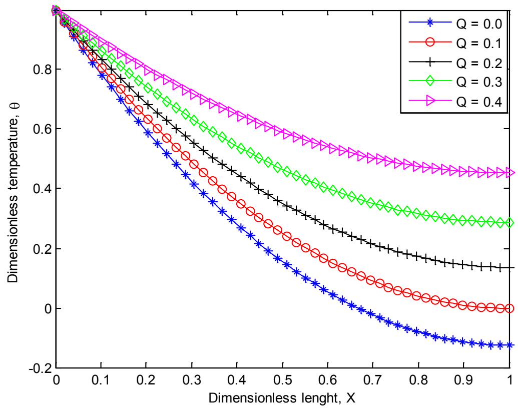

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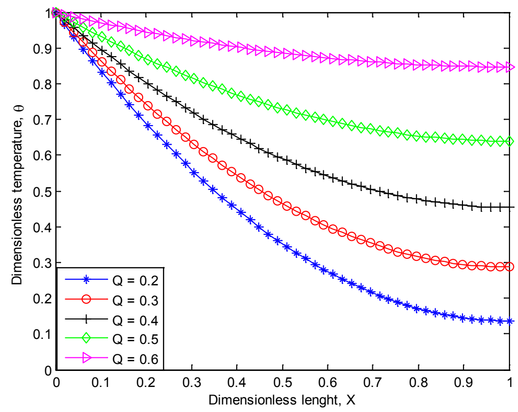

(f)

Figure 5. Impacts of internal heat values on when (a) S=0, M=2, G=0.5 (b) S=0, M=2, G=1.5 (c) S=0, M=3.35, G=1.5 (d) S=0, M=5.0, G=1.5 (e) S=0, M=5, G=0.5 (f) S=0, M=5.0, G=0.5

Also, further display of the results of the impacts of internal heat parameter on the thermal response of the fin is illustrated in Figure 5a-f. In our previous study [27], it was established that the limiting value of the porous parameter, S_h for thermal stability for fin with constant thermal properties and without internal heat parameter is approximately $4\sqrt{34}$. However, it was established in the present study that this limiting value of porosity parameter increases internal heat parameter, Q increases. This shows that although the internal heat parameter can help assist higher range and value of thermal stability of the fin, it also produces negative effect which greatly defeats the ultimate purpose of the fin where the fin stores heat rather than dissipating it.

5. Conclusion

In this work, impacts of internal heat generation on the heat transfer dissipation capacity of porous and solid fin is studied using differential transformation method. The parametric studies reveal that porosity enhances the fin heat dissipating capacity but the internal heat parameter decreases the thermal performance of the fin. Also, it was established that when the internal heat parameter increases to some certain values, some negative effects are recorded where the fin stores heat rather than dissipating it. This scenario defeats the prime purpose of the cooling fin. A further parametric study revealed that the limiting value of porosity parameter for thermal stability for the fin increases as internal heat parameter increases. This shows that although the internal heat parameter can help assist higher range and value of thermal stability of the fin, it produces negative effect which greatly defeats the ultimate purposes of the fin of heat dissipation and heat transfer enhancement. Therefore, it is highly recommended that the operational parameters of the extended surface must be properly selected for required purpose.

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