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Research Article

Transient analysis of convective-radiative heat transfer through porous fins with temperature-dependent thermal conductivity and internal heat generation

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ABSTRACT

In this research study, the transient study of heat transfer through a convective-radiative porous fin is carried out considering temperature-dependent thermal conductivity and internal heat generation. The unsteady Galerkin weighted residuals technique is employed to obtain the transient temperatures of the porous fin. The results indicate that increasing of the fin base temperature, internal heat generation and, thermal conductivity lead to increase heat transfer along the fin and consequently the higher temperature of the entire of the fin achieved. However, increasing of the porous and radiative parameters result in more heat dissipation from the fin and cause to lowering the fin temperature which leads to increase heat flux entering the fin through the base. Furthermore, the transient thermal analysis of the porous fin illustrates that by increasing the porous and the radiation parameters, the fin cools down faster, so in the applications that the time of cooling is more important, these parameters can be more noticeable.

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INTRODUCTION

Fin's manufacturing industries always seek to reduce the size and price of these extended surfaces which can be gained through enhancing heat transfer of the fins [1]. Porous mediums which are constructed with high thermal conductivity materials like metal foams can increase the fluid-solid contact which results in enhancing the heat transfer [2-4]. In recent years, Using of porous fins to enhance the performance of thermal systems like photovoltaic-thermal (PVT)

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systems, high power semiconductor devices, electronic cooling systems, heat exchangers, enhancing of the heat transfer of fluids in enclosures, pipes and channels, thermal insulators etc, [5-12] has been an attractive subject for many researchers. Kiwan and Al-Namir [1] employed finite element method to analyze the enhancing performance of porous fins compared to solid fins and demonstrated that in the large Darcy numbers, the effect of the Rayleigh number is more significant. Kiwan used the Runge-Kutta [13] and the finite difference methods [14] to investigate the effect of the porosity, convective, conductive and radiative heat transfer parameters on the fin performance and resulted that increasing the porosity parameter, increases the heat transfer of the fin. Gorla and Bakier [15] numerically analyzed convection and radiation heat transfer parameters in a rectangular porous fin and showed that the fin base temperature has the minor effect on heat transfer through the porous fins. Kundu et al. [16] analytically studied the thermal performance of four different porous fin profiles and resulted that exponential profile has the maximum heat transfer. They also observed that heat transfer of all profiles is significantly increased compared to the solid fins. Hatami et al. [17] analytically investigated the temperature distribution in porous fins with two different materials (Al and Si3N4) and compared their results with numerical results. Hatami and Ganji [18] analytically analyzed four various porous fin profiles (exponential, rectangular, triangular and convex) and three different materials (Al, Si_3N_4 and Sic) and resulted that Si_3N_4 with exponential profile has the most heat transfer among these fins. In another work. Hatami and Ganji [19] studied effect of Darcy number, Lewis number, Rayleigh number and porosity of porous fins in wet conditions and demonstrated that rectangular fins have more efficiency than triangular and convex fins. Darvishi et al. [20] numerically investigated unsteady performance of three types of porous fins considering natural convection and radiation and demonstrated that increasing porous parameter increases the heat transfer of fin while increasing the radiation parameter for small Biot numbers can increase the heat transfer of the fin. Ganji and Dogonchi [21] analytically and numerically investigated heat transfer in longitudinal porous fin with variable heat generation and thermal conductivity and resulted that increasing the heat generation causes to increase of the fin tip temperature. Das[22] solved heat transfer equation in porous fin considering conduction, radiation and convection and investigated effect of various parameters like porosity, permeability and emissivity on the fin performance. Moreover, he applied an inverse analysis to estimate unknown parameters and showed that permeability is more considerable than other parameters. Hatami et al. [23] used Least square method with Runge-Kutta to analyze refrigeration efficiency of fully wet semi spherical porous fins considering variable heat and mass coefficient and demonstrated that high refrigeration efficiencies can be achieved for Lewis numbers more than unit. Turkyilmazoglu [24] analytically investigated heat and mass transfer mechanisms in exponential fully wet porous fins and resulted that these type of fins are much better than straight porous wet fins. Das and Prasad [25] applied inverse analysis to obtain porosity and thermal diffusivity of the fluid for a specified temperature distribution using Differential evolution optimization technique and compared their results with other optimization methods. Vahabzadeh et al. [26] analytically solved the heat equation in porous fins in fully wet conditions with different geometries and compared results of various thermo-physical parameters. They concluded that the higher relative humidity cause to higher temperature distribution. Dogonchi and Ganji [27] analytically investigated moving longitudinal porous fin convection radiation heat transfer and studied effect of Peclet number and heat transfer parameters on fin performance. Sobamovo employed Chebychev Spectral Collocation Method [28], Galerkin weighted residuals method [29, 30] and Homotopy perturbation method [31] to study the steady heat transfer through porous fins with variable properties and resulted that improving of fin efficiency can be achieved by increasing the porosity, the Darcy, Rayleigh and Nusselt numbers and the thickness length ration of the porous fin. Shateri and Salahshour [32] analytically studied temperature distribution in three different longitudinal porous fin profiles with variable internal heat generation, using least square method and compared the effects of convection, radiation and conduction in fin performance. Logesh et al. [33] used finite volume method to investigate the effect of porous fins in enhancement of concentric tube heat exchanger performance. They concluded that the fin spacing and thermal conductivity have great influence on the performance of the heat exchanger. Panchal and Sathyamurthi [34] experimentally studied the application of porous fins in single basin solar still and showed that performance of solar still is enhanced due to increment in surface area. Moreover, they found that porous holes of these fins can cause to store excess heat of water. Selimefendigil et al. [35] experimentally investigated use of metal foam porous fins in a photovoltaic module and reported enhancement of higher efficiency and output power. Oguntala et al. [36] used finite volume method to study the effect of magnetic field, conduction, convection, radiation and porosity on the transient thermal behavior of a porous fin and showed that thermal performance of the fin increases with increase in magnetic field, convective and radiative heat transfer parameters. They also presented the optimized values of the Darcy and Nusselt numbers, thickness to length ratio and the porosity of the porous fin. Ndvolu et al. [37] utilized differential transform method to solve the unsteady heat transfer equation in moving porous fins and resulted that increasing the Peclet number leads to faster dissociating heat to the surrounding. They also demonstrated that the rectangular fin is more efficient that the hyperbolic one.

Hoseinzadeh et al. [38] employed three methods namely, the collocation method, the homotopy analysis technique and the homotopy perturbation technique to investigate the heat transfer in a rectangular porous fin and compared the results with themselves. They demonstrated that by increasing the porosity, the convection and the radiation parameters leads to more heat transfer from the fin.

The literature survey, indicates that, the most of the studies concern the steady state analysis of the fins. However a lot of applications encountered in engineering systems need limited period of times for heat transfer and the transient investigation is essential for precise thermal analysis through fins. Considering variable thermo-physical properties makes the energy equation non-linear and difficult to solve. Due to this complication, closed-form solutions for the nonlinear transient heat equation in the porous fins should be found. In the current study, the Galerkin weighted residuals method is used to obtain a semi-analytical solution for the non-linear heat equation in a porous fin with temperature-dependent thermal conductivity and internal heat generation considering the influence of the convection and radiation. The effect of the porosity and heat transfer parameters on the temperature distribution is studied.

PHYSICAL MODEL

Geometry

Fig. 1 schematically represents convective-radiative heat transfer through porous fin. This configuration includes a rectangular straight porous fin with length, width and thickness of L, W and t, respectively. Also, constant cross section area is considered in the present study. The both faces of the fin are exposed to convective-radiative environment at temperature T_∞.

The following assumptions are considered to simplify the problem.

- The porous fin tip is assumed to be insulated.
- Fluid flow can penetrate through the fin due to porosity of it.
- Porous medium is homogeneous, isotropic and completely saturated with a single-phase fluid.

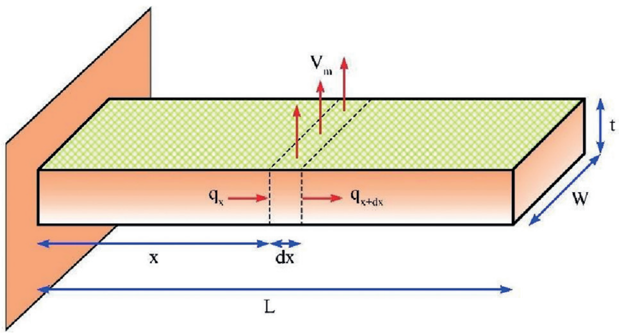

Figure 1. Schematic of the studied problem.

- The surface of the fin, transfers radiative energy to the environment.
- The fin is considered one-dimensional and temperature varies only along the length of it.
- The Darcy's model is used to simulate the interactions between the solid and fluid mediums.
- The fluid and porous medium are assumed to be locally in thermal equilibrium.
- Thermal conductivity of porous media is temperature dependent.

Mathematical Formulation

Energy balance for the small control volume of length Δx is written as:

$$q(x) - q(x+\Delta x) + q'\, A\Delta x - mC_p[T(x) - T_\infty] - q^r - hP\Delta x[T(x) - T_\infty] = \rho A\Delta x C_p \frac{\partial \Gamma}{\partial t^*} \tag{1}$$

Where the left hand side terms of the Eq. (1) represents the conduction heat transfer, the internal heat generation, the energy storage in the porous fin, the radiation heat transfer and the convective heat transfer respectively, and the right hand side is the variation of the thermal energy.

The following mass flow rate is passed through this section of porous fin:

$$\dot{m} = \rho V_W \Delta x W \tag{2}$$

According to the Darcy model the velocity of flow can obtain as:

$$V_W(x) = \frac{\rho g K \beta^*}{u}[T(x) - T_\infty] \tag{3}$$

Furthermore, the Fourier heat conduction model as follows:

$$q(x) = -kA\frac{dT}{dx} \tag{4}$$

$$q(x+\Delta x) = kA\frac{dT}{dx} - kA\frac{d^2T}{dx^2}\Delta x \tag{5}$$

$$q^r = 2\sigma o W\Delta x(T^4 - T_\infty^4) \tag{6}$$

Substitutions of Eqs. (4) to (6) into Eq. (1) yields:

$$kA\frac{d^2T}{dx^2}\Delta x + q''.A.\Delta x - \rho_w A.\frac{\rho g K\beta^- C_p}{\mu}[T(x) - T_\infty]^2\Delta x - 2\sigma o W\Delta x(T(x)^4 - T_\infty^4) = \rho A\Delta x C_p\frac{\partial T}{\partial t} \tag{7}$$

Temperature dependent effective thermal conductivity of the porous fin is written as:

$$k_{eff}(T) = \varphi k_f + (1-\varphi)k_s = k_{eff,a}[1+\lambda(T-T_\infty)] \quad (8)$$

Where k_s and k_f are the solid and the fluid thermal conductivity and φ is the porosity variable.

The initial and boundary conditions are:

$$T(0,t) = T_b, \frac{\partial T}{\partial x}(L,t) = 0, T(x,0) = T_b. \quad (9)$$

To make the Eq. (7) dimensionless the following non dimensional parameters are introduced:

$$\begin{gathered} X = \frac{x}{L}, \theta = \frac{T-T_\infty}{T_b - T_\infty}, Ra = Gr \cdot \Pr = \left(\frac{\beta^* g T_b t^3}{\upsilon_f^2}\right) \\ \left(\frac{\rho C_p \upsilon_f}{k_{eff,a}}\right) Sh = \frac{(RaDa(L/t)^2)}{k_{(eff,a)}} \\ M^2 = \frac{hPL^2}{kA}, Q = \frac{q''_\infty}{hP(T_b - T_\infty)}, \varepsilon_G = \varepsilon(T_b - T_\infty), \\ \beta = \lambda(T_b - T_\infty), \\ C_T = \frac{T_\infty}{T_b - T_\infty}, G = \frac{2\sigma\varepsilon}{kt} L^2 (T_b - T_\infty), \tau = \frac{\alpha t^*}{L^2}, \end{gathered} \quad (10)$$

In the Eq. (10), *Ra*, *Da* and k_{eff} are the Rayleigh number, the Darcy number and the thermal conductivity ratio, respectively. *Sh* is the porous parameter which represents the effect of the permeability of the porous medium. *M* is the convection parameter which represents the convection heat transfer from the fin surface. *Q* is the internal heat generation parameter. C_T is the dimensionless parameter of the ambient temperature. In addition, ε and β are the temperature dependence and internal heat generation and thermal conductivity, respectively.

Applying above parameters, the dimensionless form of Eq. (7) can be derived as follows:

$$\begin{gathered} \frac{\partial\theta}{\partial\tau} = \frac{d^2\theta}{dX^2} + \beta\theta\frac{d^2\theta}{dX^2} + \beta\left(\frac{d\theta}{dX}\right) - M^2\theta + \\ M^2 Q(1+\varepsilon_G\theta) - Sh\theta^2 - G[(\theta + C_T)^4 - C_T^4] \end{gathered} \quad (11)$$

As the same way dimensionless boundary and initial conditions may be deduced as follows:

$$\theta(0,\tau) = 1, \frac{\partial\theta}{\partial X}(1,\tau) = 0, \theta(X,0) = 1 \quad (12)$$

The heat transfer rate at the fin base is:

$$q_b = -k_{eff} A \left(\frac{dT}{dX}\right)_{X=0} \quad (13)$$

Therefore, the dimensionless heat transfer rate at the fin base is can be derived as:

$$Q_b = \frac{qL}{kA(T_b - T_\infty)} = \left[1 + \beta\theta\frac{d\theta}{dX}\right]_{X=0} \quad (14)$$

Solution Procedure

Governing closed-form solution for Eq. (11) is very difficult due to complex nonlinearity arisen in this equation. Thus in the present work, the Galerkin weighted residuals technique is used to obtain transient response of heat equation in porous fins. Firstly, the temperature profile for porous fin is considered as:

$$\theta(x,t) = 1 + \sum_{i=1}^{n} C_i(t)\,\varphi_i(x) \quad (15)$$

$$\varphi_i(x) = \left(x - \frac{x^{i+1}}{i+1}\right) \quad (16)$$

Where $C_i(t)$, $i = 1(1)n$ are the unknown parameters and $\varphi_i(x)$ are the basis functions that satisfy the boundary conditions regardless of the values of unknown coefficients. Inserting the profile (15) into Eq. (11) an error function called residual is produced.

$$\begin{gathered} R = \frac{\partial\theta}{\partial\tau} = \frac{d^2\theta}{dX^2} + \beta\theta\frac{d^2\theta}{dX^2} + \beta\left(\frac{d\theta}{dX}\right)^- - M_2\theta + \\ M_2 Q(1+\varepsilon_G\theta) - Sh\theta_2 - G[(\theta + C_T)^4 - C_{T4}] \end{gathered} \quad (17)$$

The unknown coefficients subsequently can be determined by equating the weighted integral of this residual to zero.

$$\int_0^L R W_i(x)dx = 0, i = 1(1)n \quad (18)$$

In the Galerkin method, the weighting functions and the basis functions are the same.

$$W_i(x) = \left(x - \frac{x^{i+1}}{i+1}\right) \quad (19)$$

Various weighting functions *Wi*, *i* = 1(1) can be used which yield different weighted residuals methods. In the Galerkin weighted residuals technique used in the present work, the weighting functions are the same as the basis functions, substituting Eq. (19) in Eq. (18) and simplifying the results, result a system of first-order ordinary differential equation for the unknown coefficients $C_i(t)$, $i = 1(1)n$ with time as the independent variable. To solve the system of n first-order ODE's for the unknown coefficients, n initial conditions namely $C_i(t = 0)$, $i = 1(1)n$ are required. The initial conditions $C_i(0)$, $i = 1(1)n$ are obtained by applying the Galerkin weighted residuals technique to the following residual of the initial conditions (12):

$$R_0 = \theta_b - \tilde{\theta}(x,0) = \theta_b - \left(1 + \sum_{i=1}^{n} C_i(0)\left(x - \frac{x^{i+1}}{i=1}\right)\right) \tag{20}$$

Which yields

$$\int_0^L R_0 W_i(x)dx = \int_0^L (\theta_b - \tilde{\theta}(x,0)dx = \int_0^L (\theta_b W_i(x)dx - \int_0^L 1 + \sum_{i=1}^{n} C_i(t)\left(x - \frac{x^{i+1}}{i=1}\right)W_i(x)dx \tag{21}$$

The results obtained from Eq.(21) for n = 3 are:

$$C_i(0) = 0, i = 1(1)3 \tag{22}$$

Due to the initial conditions Eq. (12) the $Ci(0)$ coefficients are obtained zero. In the current study, the fourth-order Runge-Kutta technique was used to solve the system of ordinary differential equations obtained from the Eq. (18) for ($n = 3$) with the initial conditions Eq. (22). Also, to solve the governing equations, MAPLE software was used.

Verification

The validity of the introduced scheme was assessed by comparing the simulation results with the analytical solution in Fig. 2. To verify the solution, the steady state temperature distribution for the porous fin obtained utilizing the proposed method is compared with the analytical solution for the same case presented by Hatami et al. [17] using the DTM approach. As is cleared, there is a good agreement between Galerkin weighted residuals and numerical results. According to Fig. 2, the present solution exhibited negligible difference with the literature. It can be inferred form Fig. 2, the presented Galerkin weighted residuals technique is an accurate method to obtain the solution of the nonlinear heat transfer equations through the porous fins.

RESULTS AND DISCUSSION

In this section, the effect of various parameters such as convective, radiative and porosity parameters, Darcy and

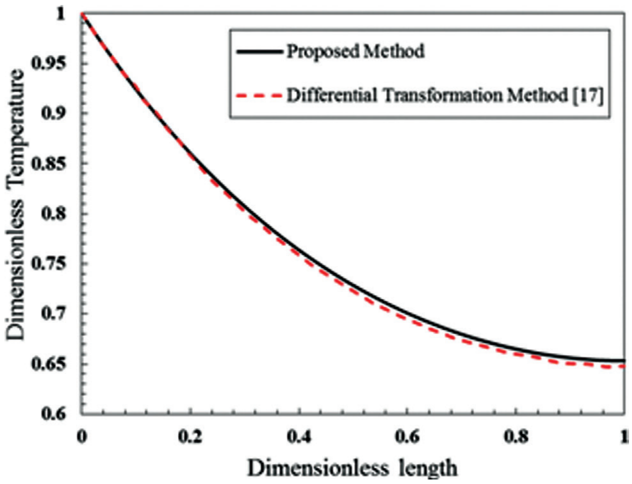

Figure 2. Comparison between the presented method and the analytical solution of Hatami et al. [17], $Sh = 1$, $G = 0.4$, $M = 1$, $J = 1$, $L/t = 10$.

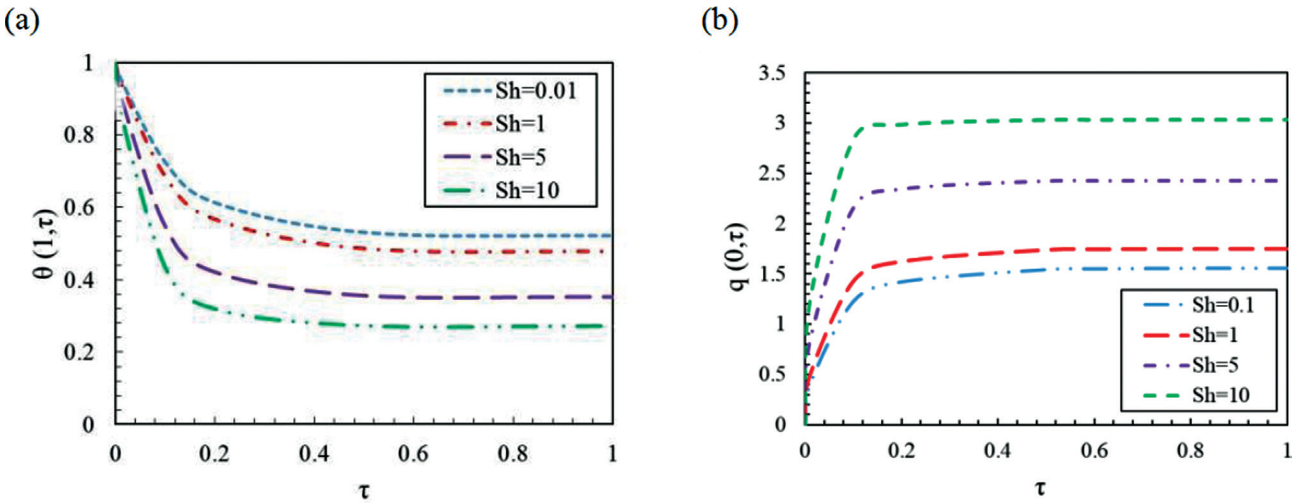

Figure 3. a) Dimensionless temperature at the fin tip b) Dimensionless heat flux at the fin base, with respect to dimensionless time for different porosity parameters.

Rayleigh numbers, thermal conductivity and internal heat generation on transient response of fin base temperature and heat flux is presented.

The Effect of Porous Parameter

The effect of the porous parameter (*Sh*) on the temperature at the fin tip and heat transfer profiles in the fin base is shown in Figs. 3 and 4. It is noticeable that in Fig. 3(a and b), increasing the values of the porosity parameter decrease the temperature and consequently increase the rate of the heat transfer through the fin. By improving the permeability of the porous fin, the working fluid can better penetrate through the pores of the fin, enhancing the convective heat transfer of the porous fin. Also, Fig. 3 illustrate that as the porosity parameter increases, the time of reaching steady state decreases. It is noticed that in higher values of the *Sh* parameter, the fin cools down faster, so in the applications that the time of cooling is more important, the *Sh*, can be more considerable.

The Effect of Radiation Parameter

Figs. 5 and 6. demonstrate the effect of the radiation parameter on the temperature and heat transfer profiles of the fin at different dimensionless times. According to Fig. 5

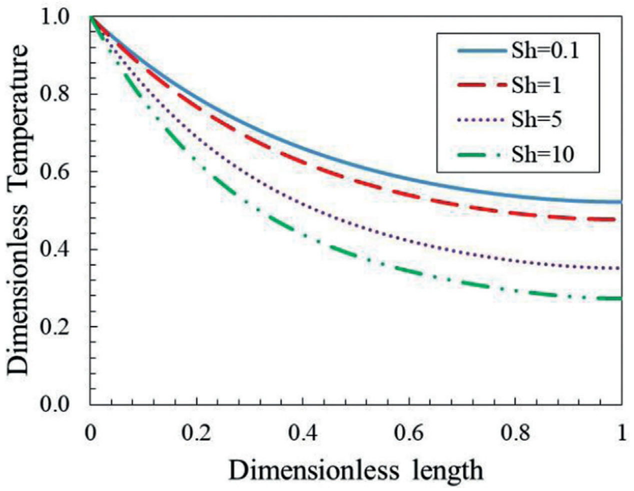

Figure 4. Temperature Distribution through the porous fin with respect to dimensionless length for different porosity parameters.

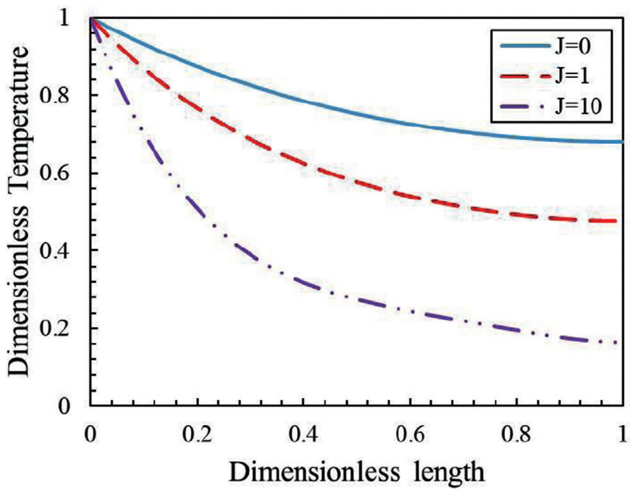

Figure 6. Temperature Distribution through the porous fin with respect to dimensionless length for different radiation parameters.

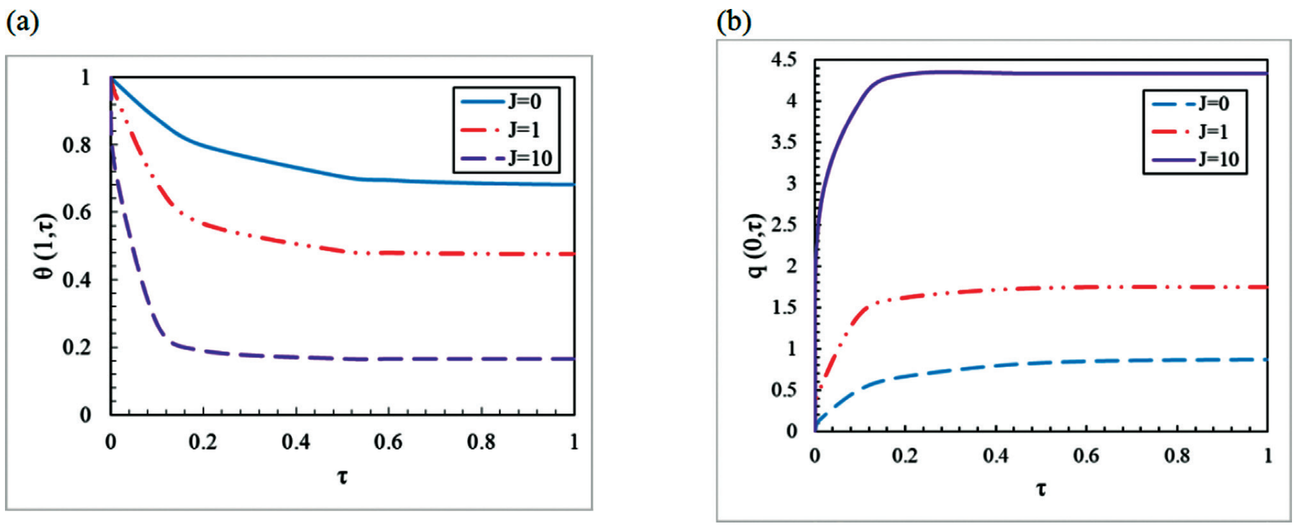

Figure 5. a) Dimensionless temperature at the fin tip b) Dimensionless heat flux at the fin base with respect to dimensionless time for different radiation parameters.

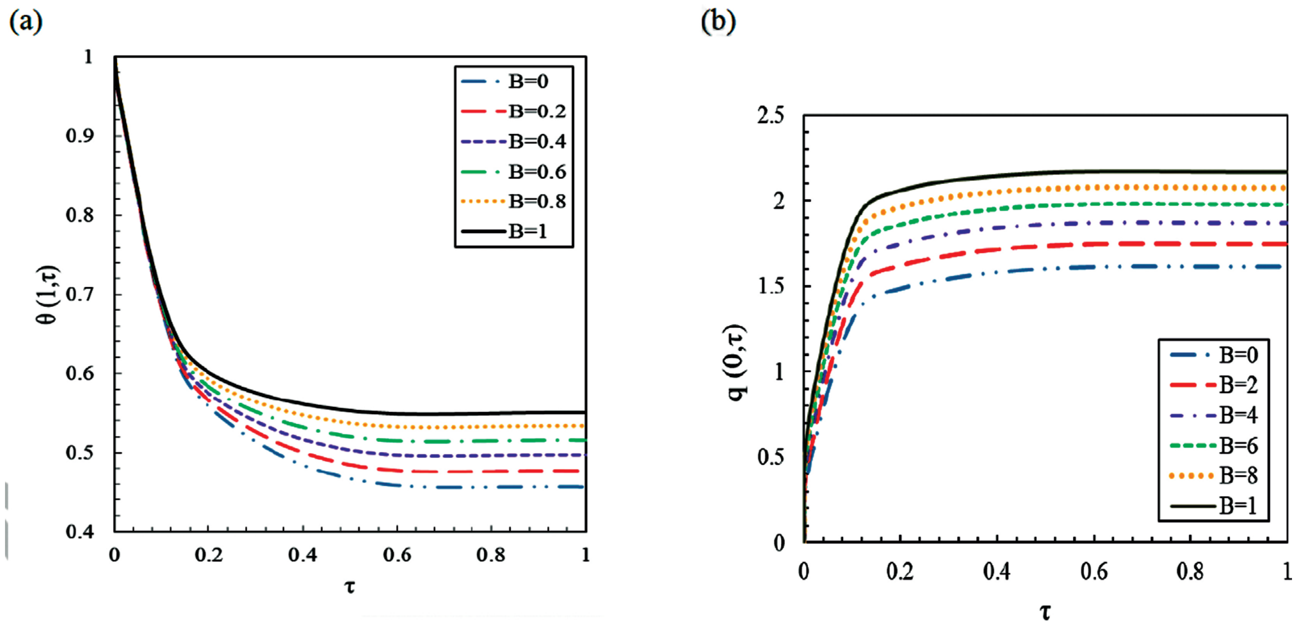

Figure 7. a) Dimensionless temperature at the fin tip b) Dimensionless heat flux at the fin base with respect to dimensionless time for different variable thermal conductivity parameters.

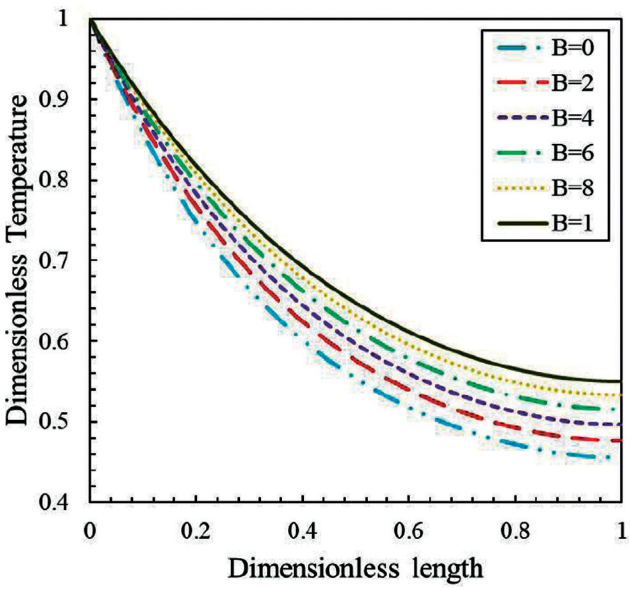

Figure 8. Temperature Distribution through the porous fin with respect to dimensionless length for different variable thermal conductivity parameters.

(a and b), as the radiation parameter increases, there would be higher amounts of the radiation heat transfer, resulting in lower temperatures along the fin. As it can be seen in Fig. 5, the fin reaches steady state condition at the dimensionless time $t = 0.52$, 0.47 and 0.4 for $J = 0$, $J = 1$ and $J = 10$ respectively, which means that considering the radiation can has a significant effect on the cooling speed of the porous fin.

The Effect of Thermal Conductivity Parameter

The effect of the variable thermal conductivity parameter on the dimensionless temperature profiles at different dimensionless times and consequently on the rate of the heat transfer are depicted in Figs. 7 and 8. According to Fig. 7, by increasing the thermal conductivity, the dimensionless temperatures in the fin increases. In fact, increasing the coefficient B leads to the larger thermal conductivities results in more conductive heat transfer to the fin and higher temperatures in the fin can be achieved.

The Effect of The Fin Base Temperature

Fig. 9 and 10 depict the effect of the base temperature of the porous fin on the heat and temperature profile at different dimensionless times. The larger values of the C_T parameter indicates the smaller fin base temperatures. The term Q_b in Eq. (14) which indicates the dimensionless rate of heat transfer through fin is derived dividing the rate of heat transfer by $(T_b - T_\infty)$ and $(T_b - T_\infty)$ is different for each C_T parameter. In order to compare the rate of heat transfer rate through the fin, the parameter $Q_b (T_b - T_\infty)$ is calculated for each C_T parameter. It is clear that, increasing the base temperature, leads to increase the rate of the heat transfer through the fin and consequently, the temperatures along the fin increases.

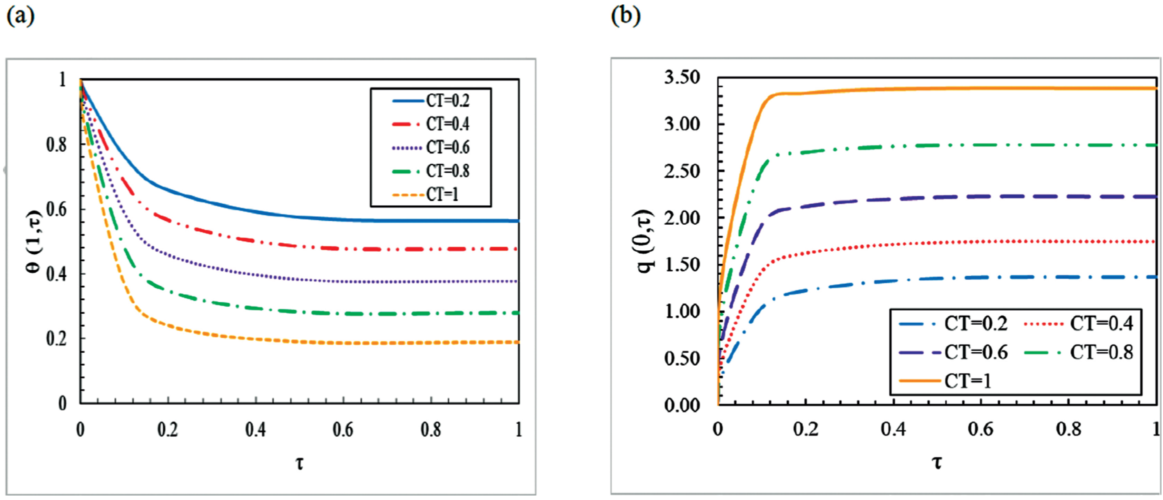

Figure 9. a) Dimensionless temperature at the fin tip b) Dimensionless heat flux at the fin base with respect to dimensionless time for different fin base temperature parameters.

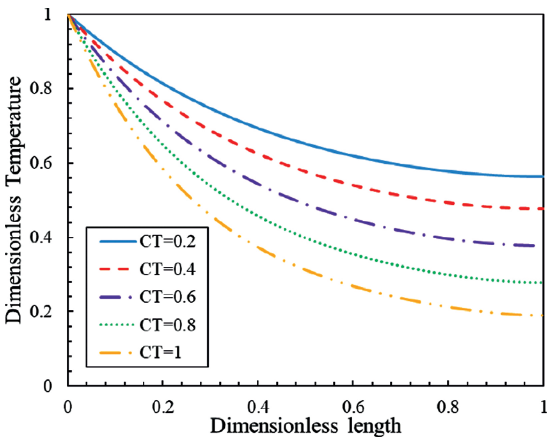

Figure 10. Temperature Distribution through the porous fin with respect to dimensionless length for different fin base temperature parameters.

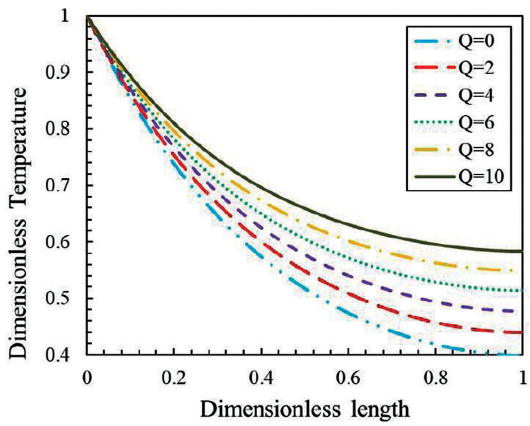

Figure 12. Temperature Distribution through the porous fin with respect to dimensionless length for different internal heat generation parameters.

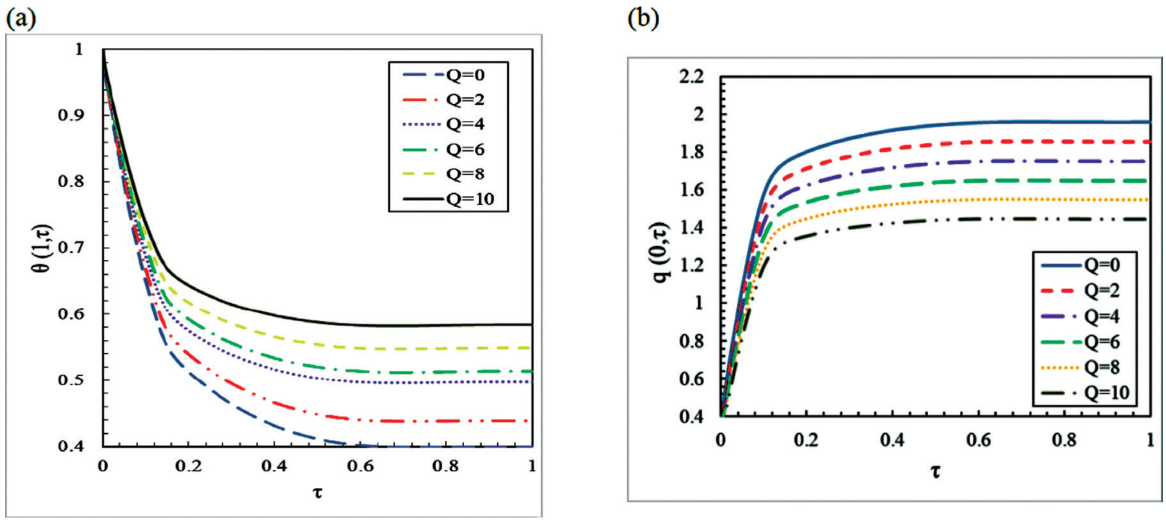

Figure 11. a) Dimensionless temperature at the fin tip b) Dimensionless heat flux at the fin base with respect to dimensionless time for different internal heat generation parameters.

The Effect of Internal Heat Generation Parameter

The temperature and heat profiles for different values of the temperature-dependent internal heat generation have been shown in the Figs. 11 and 12. It is obvious that the higher values of the internal heat generation result in the higher temperatures in the porous fin and more conduction heat transfer through the fin.

CONCLUSION

In this work, the transient convective-radiative heat transfer in a rectangular porous fin with temperature-dependent thermal conductivity and internal heat generation is investigated. Semi-analytical solutions for the non- linear heat transfer equations are obtained using the Galerkin weighted residuals technique. The results indicate that increasing the porosity by increasing either the Rayleigh or the Darcy numbers or decreasing the effective conduction heat coefficient leads to decreasing trend in the temperature distribution through the porous fin that cause to rise the heat transfer from the fin. Furthermore, it was concluded that considering the radiative heat transfer in the porous fins plays an important role in the temperature distribution through the fin. Increasing the radiative parameter result in more heat dissipation from the fin which leads to decrease the fin temperature. Also, increasing the variable internal heat generation cause to increase the temperature of the fin which prevents more heat flux entering the fin. However, increasing the temperature-dependent thermal conductivity coefficient result in more heat transfer to the fin and higher temperatures in the fin in comparison with the corresponding results for the constant thermal conductivity.

NOMENCLATURE

A	Area, m^2
β	Thermal conductivity parameter
β^*	Volumetric thermal expansion coefficient (1/K)
C_T	Base temperature of the porous fin
g	Gravity Acceleration (m/s^2)
h	Heat transfer coefficient (W/m^2 K)
J	Radiation parameter
k_s	solid thermal conductivity (W/mK)
k_f	fluid thermal conductivity (W/mK)
k_{eff}	Thermal Conductivity ratio
L	Length (m)
M	Convection Parameter
$\dot{m}$	Mass flow rate (kg/s)
Q	Internal Heat Generation Parameter
q''	Heat flux (W/m^2)
C_p	Specific Heat (J/kg K)
V	Velocity (m/s)
Greek symbols	
α	Thermal Diffusivity (m^2/s)
β	Temperature dependence thermal conductivity
ε	Internal heat generation parameter
θ	Dimensionless temperature
μ	Dynamic Viscosity (kg/m s)
r	Dimensionless time
Abbreviations	
ADM	Adomian decomposition method
DTM	Differential transformation method
PVT	Photovoltaic-thermal
Da	Darcy Number
Ra	Rayleigh number
Sh	Porous Parameter
Pr	Prandtl Number
Gr	Grashof Number
Sh	Porous parameter
Nu	Nusselt Number

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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