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Establishment of non-Fourier heat conduction model for an accurate transient thermal response in wet fins

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ABSTRACT

In this work, transient heat transfer response of wet fins is carried out using both Fourier and non-Fourier heat conduction models. The separation of variables is used to establish a classical analytical model defining the actual transient thermal response. The present analysis has been focused and generalized for both longitudinal and pin fins under isothermal and convective base conditions. During the analysis, the instantaneous efficiency has been introduced with both Fourier and non-Fourier heat conduction models in fins operating under dehumidifying conditions. The analysis shows for a significant deviation in temperature response with the non-Fourier heat conduction as compared with that of the Fourier model. The effect of different design variables and fin surface conditions is reported. From the present analysis it becomes apparent that the instantaneous fin efficiency for wet fin surface is always less than the dry one and the condensation of vapor on the fin surface amplifies the non-Fourier heat conduction. Hence, the present analysis of non-Fourier heat transfer for determining the performance parameters of wet fins would help to have actual design information under transient behavior conditions.

1. Introduction

For any heat transfer application in general, a transient response always exist during the initial operation of the system. In connection with finned heat transfer, it is therefore important to study the performance of heat sinks used in applications, such as, electronic cooling, nuclear reactors, and high speed aircrafts, with a transient temperature response. The same analysis is also essential for the investigation of evaporative coils in case of refrigeration and air conditioning applications when the moisture in air condenses on the fin surface. In these applications, fin surface temperature is maintained below the dewpoint of temperature of surrounding humid air to be cooled, and when humid air strikes this fin surface, moisture in the air condenses. The condensation may take place filmwise, dropwise, or any mode, depending upon the surface condition of the fin [1,2].

In the past, many researchers attempted the transient heat transfer analysis on various problems of fins. For example, a transient heat transfer analysis of dry straight fins with isothermal and constant heat flux boundary conditions was proposed by Suryanarayana [3]. The solution was obtained using Laplace transforms. Sobhan et al. [4] reported an experimental study of an array of horizontal fins subjected to unsteady heat convection. Using the variable separable method and the superposition principle, a transient heat transfer study on two-dimensional pin fin in cylindrical coordinate system was done by Su and Hwang [5]. Chu and Chang [6] numerically analyzed a cylindrical pin fin subjected to variable surface heat transfer coefficient and different boundary conditions. A time-dependent thermoelastic study of an annular fin was carried out by Lee et al. [7]. A hybrid methodology based on the Laplace transformation and finite difference scheme was used in their study. Yang et al. [8] used a numerical scheme involving the Laplace transformation with finite differencing for a two-dimensional heat transfer analysis of pin fins operating under variable heat flux at the fin base. Huang and Tsai [9] used the steepest descent method to estimate the heat transfer coefficient in a plate fin through a three-dimensional transient inverse heat transfer analysis. Mosayebidorcheh et al. [10] made the transient thermal analysis of longitudinal fins of different profiles with variable cross section area and internal heat generation by the differential transform and the finite difference method. Ma et al. [11] used the spectral collocation method to analyze a moving plate fin involving simultaneous

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Nomenclature

A dimensionless humidity parameter, $(\omega_b T_\infty - \omega_\infty T_b)/(T_\infty - T_b)$
A_1, A_2, A_3 dimensionless variables defined in Eq. (12)
A_c cross-sectional area (m^2)
B moisture content parameter, $(\omega_\infty - \omega_b)/(T_\infty - T_b)$ (K^{-1})
Bi Biot number, ht_f/k
Bi_o Biot number based on the base condition, $h_L Lk$
Bi_t Biot number based on the tip condition, $h_t L/k$
C_0 dimensionless notation defined in Eq. (4)
c_p specific heat ($J\,kg^{-1}\,K^{-1}$)
D_0, D_1, D_2 notations used, see Eqs. (18a) and (18b)
E_0 variable, see Eq. (18c)
h convection heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_{fg} latent heat of condensation of moisture ($J\,kg^{-1}$)
h_L convection heat transfer coefficient at the base surface ($W\,m^{-2}\,K^{-1}$)
h_m mass transfer coefficient ($kg\,m^{-2}\,s^{-1}$)
h_t convection heat transfer coefficient at the tip surface ($W\,m^{-2}\,K^{-1}$)
I_n, J_n dimensionless design variables defined in Eqs. (18d) and (18e), respectively
k thermal conductivity ($W\,m^{-1}\,K^{-1}$)
L fin length (m)
Le Lewis number
m, n parameters, see Eqs. (2) and (4)
P fin perimeter (m)
q actual heat transfer rate (W)
Q actual dimensionless heat transfer rate, $q/2kL(T_\infty - T_r)$
t time (s)
t_f semi-thickness of a fin (m)
t^* dimensionless geometry, t_f/W
T local fin surface temperature (°C)
T_∞ ambient temperature (°C)
T_b fin base temperature (°C)
T_L fluid temperature at base for convected condition (°C)
T_m mean fin surface temperature as a function of Fourier number (°C)
T_r reference temperature, base temperature for constant base temperature condition/fluid temperature for convected base condition
T_t fin tip temperature (°C)
Ve Vernotte number, $\sqrt{\tau_0 \alpha / L^2}$
W width of longitudinal fin (m)
x coordinate starting from fin base (m)
X dimensionless coordinate, x/L
Z_0 fin parameter, see Eq. (6)

Greek Letters
α thermal diffusivity, $k/\rho c_p$ ($m^2\,sec^{-1}$)
α_n variable defined in Eq. (15b)
β_n variable defined in Eq. (16b)
$\Gamma(X)$ spatial coordinate, see Eqs. (11a) and (11b)
Γ_1, Γ_2 dimensionless notations defined in Eqs. (18f) and (18g), respectively
λ_n eigen value, see Eq. (15a)
η fin efficiency
ϕ dimensionless local temperature, $\theta + \theta_p$
ϕ_b dimensionless base temperature, $\theta_b + \theta_p$
ϕ_m dimensionless average fin surface temperature, $\theta_m + \theta_p$
ϕ_t dimensionless tip temperature, $\theta_t + \theta_p$
$\Omega(X, \tau)$ variable, see Eq. (8)
θ dimensionless local fin surface temperature, $(T_\infty - T)/(T_\infty - T_r)$
θ_b dimensionless base temperature, $(T_\infty - T_b)/(T_\infty - T_r)$
θ_m dimensionless mean surface temperature, $(T_\infty - T_m)/(T_\infty - T_r)$
θ_p dimensionless temperature parameter, see Eq. (6)
θ_t dimensionless tip temperature, $(T_\infty - T_t)/(T_\infty - T_r)$
ω specific humidity of saturated air adjacent to the fin surface (kg of water vapor per kg of dry air)
ω_∞ specific humidity of surrounding air (kg of water vapor per kg of dry air)
ζ dehumidification parameter, $h_{fg}/c_p Le^{2/3}$ (°C)
ψ dimensionless thickness, t_f/L
ρ density of fin material ($kg\,m^{-3}$)
τ Fourier number, $\alpha t/L^2$
τ_r relaxation time (s)

conduction, convection, and radiation operating under unsteady heat transfer condition. Recently, Laplace transform method-based analytical solutions for dry longitudinal fins subjected to periodic boundary conditions and volumetric internal heat generation were reported by Singh et al. [12].

The classical Fourier's law of heat conduction-based diffusion model, which is also called diffusion law, describes the thermal transport in macroscopic systems and also establishes a relationship between the heat flux and the temperature gradient. However, there is a limitation of the Fourier's law of heat conduction due to infinite speed of propagation of heat within the medium. This is because in actual cases of physical nature, the thermal waves may not travel with an infinite speed and hence such cases must be analyzed using different approaches. Contrary to the Fourier model of heat conduction, non-Fourier heat conduction model assumes a finite value for the speed of heat propagation. In the past, many researchers considered the non-Fourier heat conduction model to investigate various problems of science and engineering. Abdel-Hamid [13] modelled the non-Fourier heat conduction in a finite medium subjected to a periodic heat flux using a finite integral transform technique. For constant thermal conductivity, Ahmadikia and Rismanian [14] analytically studied the hyperbolic heat transfer model subjected to periodic boundary conditions using Laplace transform method. The results show that the relaxation time has a great influence on the temperature distribution in the fin. Based on the thermomass theory, Wang et al. [15] studied the non-Fourier heat conductions in nanomaterials. The separation of variables has been adopted by Saedodin and Torabi [16] to analytically solve the hyperbolic heat conduction equation in a cuboid involving a variable heat flux boundary condition. Das et al. [17] used a genetic algorithm, lattice Boltzmann, and finite volume method based inverse heat transfer analysis of a simultaneous non-Fourier conduction and radiation problem. Mishra and Sahai [18] used the lattice Boltzmann method to solve the non-Fourier heat conduction equation in spherical and cylindrical geometries. The effect of thermal relaxation time on the thermal performance of a convective fin under periodic thermal conditions has been reported by Lin [19]. Later, Kundu and Lee [20] investigated the non-Fourier heat conduction in dry fins involving constant volumetric heat generation. Using Laplace transform inversion, Rahbari et al. [21] investigated non-Fourier heat conduction phenomena in a finite slab with insulated boundaries. Their