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An analytical prediction for performance and optimum design analysis of porous fins

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ABSTRACT

Enhancement of heat transfer rate through porous fins is one of the common choices nowadays. As the energy equation is highly nonlinear, researchers never concentrated on analyzing porous fins analytically. In the present study, an effort has been devoted to develop an analytical model for determination of the performance and optimum dimensions of porous fins with consideration of different models of predictions. Every result has been presented in a comparative way so that the merit of the models adopting in the present work can easily be understood. The optimum design analysis of porous fins has also been carried out. The influences of all the dependent parameters on the performances and optimization conditions have been studied for the selection of a design criterion of porous fins in such applications where the requirement of heat dissipation is essentially high.

Prévision, analytique de la performance et la conception optimale d'ailettes poreuses

Mots clés : Échangeur de chaleur ; Ailette ; Milieu poreux ; Calcul ; Amélioration ; Performance

1. Introduction

The heat conduction through solids, walls or boundaries is required to dissipate continuously to the surrounding environment to maintain the system in a steady state condition. In many devices such as electronic components, compressors, transformers, refrigerators, boiler super-heater tubes, condenser coils, air cooled engines, etc. the capacity of a surface to loose heat to the surroundings is not enough to maintain the surface at an optimum operating temperature. It is well known fact that the heat transfer by convection between a surface and the fluid surroundings can be increased by the attachment of fins. Different kinds of shapes and sizes of fins can be employed to the surface depending upon the

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Nomenclature

A_i, B_{ij}, C_{ij}, D_{ij}, E_{ij} Adomian polynomials for $i = 0,1,2\ldots$, and $j = 2,3,4\ldots$
Bi Biot Number, ht/k_s
c_p specific heat ($\mathrm{J\,kg^{-1}\,K^{-1}}$)
D dimensionless temperature gradient at the base, see Eq. (13)
F function defined in Eq. (20)
g gravity constant ($\mathrm{m\,s^{-2}}$)
G function defined in Eq. (21)
h heat transfer coefficient over the fin surface ($\mathrm{W\,m^{-2}\,K^{-1}}$)
J Jacobian matrix, see Eq. (23)
k thermal conductivity ($\mathrm{W\,m^{-1}\,K^{-1}}$)
K permeability of the porous fin
K_R thermal conductivity ratio, k_f/k_s
L fin length (m)
L_X second order operator
L_X^{-1} inverse operator of L_X
q actual heat transfer rate through the fin ($\mathrm{W\,m^{-1}}$)
Q dimensionless actual heat transfer rate
q_i ideal heat transfer rate ($\mathrm{W\,m^{-1}}$)
Q_i dimensionless ideal heat transfer rate
q_w heat transfer through the same base area with the consideration of no fin situation ($\mathrm{W\,m^{-1}}$)
Q_w dimensionless heat transfer rate
R_1 dimensionless parameter defined in Eq. (4)
R_2 dimensionless radiation-conduction parameter, $4\sigma T_a^3/(3\beta_R k_s)$
R_3 dimensionless surface ambient radiation parameter, $4\sigma\bar{\varepsilon}T_a^3/h$
t fin thickness (m)
T local fin temperature (°C)
T_a ambient temperature (°C)
T_b fin base temperature (°C)
U dimensionless fin volume per unit width
W fin width taken unity (m)
x coordinate taken from the tip of the fin shown in Fig. 1 (m)
X dimension coordinate, x/L
Y dimensionless variable, see Eq. (4)
Z_0 dimensionless fin parameter defined in Eq. (4)
Z_1, Z_2 dimensionless notations, see Eq. (4)

Greek symbols

β coefficient of thermal expansion ($\mathrm{K^{-1}}$)
β_R Rosseland extinction coefficient ($\mathrm{L^2\,kg^{-1}}$)
$\bar{\beta}$ Variable defined in Eq. (4)
ε fin effectiveness
$\bar{\varepsilon}$ emissivity
η fin efficiency
λ dimensionless notation, $\theta_b - 1$
μ_1, μ_2 parameters, see Eq. (4)
ϕ porosity
ψ thickness to length ratio, t/L
θ dimensionless temperature, $(T - T_a)/(T_b - T_a)$
θ_0 dimensionless tip temperature
θ_b surface temperature parameter, T_b/T_a
γ kinematic viscosity ($\mathrm{m^2\,s^{-1}}$)
σ Stefen Boltzman constant ($\mathrm{W\,m^{-2}\,K^{-4}}$)
ρ density of the fluid ($\mathrm{kg\,m^{-3}}$)
Ω $1 - \phi + \phi K_R$
$\omega_1, \omega_2, \ldots, \omega_4$ notations see Eq. (4)
τ_1, τ_2, τ_3 see Eq. (4)
ξ_1, ξ_2, ξ_3 see Eq. (4)

Subscripts

eff effective properties
f fluid
s solid

application and nature of the design. Not only that now-a-days the main objective of the fin industry is to reduce the size and cost of the fin and it can be achieved by improving heat transfer carried out by the fin. This improvement can be attained through the following common techniques: increasing the surface area to volume ratio, increasing the thermal conductivity of the fin and increasing the convective heat transfer coefficient between the surface of the solid and surrounding fluid.

To fulfill industrial importance several experimental and analytical studies have been performed to find out the optimum shape of conventional fins in order to increase the heat transfer rate per unit fin volume. This approach is mainly based on splitting a certain dimension of the fins in an optimal way providing that the total volume of the fin material is minimized for a constant heat transfer duty. A variational calculus technique has been used first by Duffin (1959) to find out the optimum fin shape. Hung and App (1967) presented the performance of a straight fin with temperature dependent thermal conductivity and internal heat generation, while Jany and Bejan (1988) investigated the optimum shape for straight fins with temperature dependent thermal conductivity. An overview of the fin optimum shape issue has been described by Razelos (1995). Karlekar and Chao (1963) have shown an optimization procedure for achieving maximum dissipation from a longitudinal fin system of trapezoidal profile with mutual irradiation. Razelos and Imre (1980) considered the variation of the convective heat transfer coefficient from the base of a fin to its tip. Kundu and Das (1997, 2005) determined the optimum fin shape of convective fins with and without volumetric heat generation. Under dehumidification of air on the fin surface, Kundu (2008a, 2010) determined the optimum fin shape for longitudinal, spine and annular fins by using calculus of variation. With consideration of manufacturing aspect, different fin shapes existing in the literature (Kundu, 2007, 2008b) were established based on the improvement of heat transfer rate per unit volume.

A considerable amount of research has been conducted by various authors on constructal fin for the betterment of heat transfer rate through base surface. Bejan and Almogbel (2000) optimized the performance of a T-shaped fin by constructal theory using thermal conductance as an evaluation parameter. An analysis for Y-shaped fins for determining fin efficiency by a new approach has been demonstrated by