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Study of coating effects on variable profile annular fins when subjected to dehumidifying operating conditions

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ABSTRACT

The coating effects on variable profile annular fins, subjected to dehumidifying operating conditions are studied. The coating has a uniform layer thickness over the entire fin free surface including tip, i.e. non-insulated tip condition is considered. The studies are conducted numerically by a non-dimensional axisymmetric finite element formulation. A piecewise linear relationship is used in the formulation to account for the non-linear psychrometric correlation between temperature and humidity ratio. It is demonstrated that the coating resistance effects are governed by a single dimensionless parameter called coating Biot number. A limiting value of the parameter is identified for which coating resistance effects become negligible. The presented non-dimensional formulation can be used to study other types of fins i.e. spines and longitudinal under partially and fully wet conditions. Similarly, more complicated cases like multiple coating layers and interface resistance at the fin base can also be studied.

Etude des effets de l'enrobage sur des ailettes à profil annulaire variable lorsqu'elles sont soumises à des conditions de fonctionnement de déshydratation.

Mots clés : Ailettes annulaires ; Profil variable ; Ailette composite ; Enrobage ; Transfert de masse ; Ailette partiellement mouillée ; Elément fini adimensionnel

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Nomenclature

B	Parameter defined in Eq. (8), °C
Bi	Biot number,
c_p	Specific heat of incoming moist air stream, $\mathrm{J\,kg^{-1}\,K^{-1}}$
H	Composite fin half thickness, m
h	Convective heat transfer coefficient, $\mathrm{W\,m^{-2}\,K^{-1}}$
h_D	Mass transfer coefficient, $\mathrm{kg\,m^{-2}\,s^{-1}}$
i_{fg}	Latent heat of evaporation for water, $\mathrm{J\,kg^{-1}}$
k	Thermal conductivity, $\mathrm{W\,m^{-1}\,K^{-1}}$
k_{cf}	Coating to fin substrate thermal conductivity ratio, $k_{cf}=\frac{k_c}{k_f}$
l	Fin substrate length, m
P_{atm}	Atmospheric pressure, Pa
Q	Heat flow rate, W
q	Heat flux, $\mathrm{W\,m^{-2}}$
$\bar{q}$	Non-dimensional heat flux,
RH	Relative humidity of air,
r	Fin substrate radius, m
R	Composite fin radius, m
r_{tb}	Fin substrate, tip to base radii ratio, $r_{tb}=\frac{r_t}{r_b}$
T	Temperature, °C
t	Thickness (for coating), and half thickness for fin substrate, m
t_{cf}	Coating layer thickness to fin substrate base half thickness ratio, $t_{cf}=\frac{t_c}{t_b}$
$\bar{r},\bar{z}$	Spatial dimensionless coordinates,
Z_0	A dimensionless parameter given by Eq. (21),

Greek symbols

θ	Dimensionless temperature,
η	Efficiency,
ω	humidity ratio of air. $\mathrm{kg_w\,kg_a^{-1}}$

Non-Dimensional Matrices and Vectors:

$\{\bar{\mathbf{f}}\}$	Element load vector,
$[\bar{\mathbf{k}}]$	Element stiffness matrix,
$[\bar{\mathbf{B}}]$	Flux-temperature matrix,
$[\bar{\mathbf{D}}]$	Material property matrix,
$[\bar{\mathbf{N}}]$	Shape function matrix,
$[\bar{\mathbf{L}}]$	Geometric dimension ratio matrix
$\{\theta\}$	Nodal temperature vector,

Subscripts and Superscripts

b	Base,
c	Coating,
f	Fin substrate,
h	Convection,
q	Conduction,
s	Surface,
t	Tip,
∞	Ambient

1. Introduction

The use of extended surfaces or fins is very common for enhancing the heat transfer between a prime surface and surrounding environment. The applications cover both scenarios where the prime surface is either at a higher or at a lower temperature than the surrounding environment. In the first case, only sensible heat transfer occurs whereas the latter is typical for refrigeration and air conditioning applications where both sensible and latent heat transfer occur. The latent heat transfer occurs only if the fin temperature is lower than the dew point of the surrounding moist air; thus, the condensation of water vapor occurs on the fin surface. The study of fins performance under combined heat and mass transfer (i.e. convection and condensation) is a well-developed research area and both numerical and analytical studies are available in the literature. Kundu and Barman (2011) presented a literature review in tabular form that summarizes the investigations about the performance of extended surfaces under dry and wet conditions. The summary includes the information about method of analysis, fin shape, individual fin or fin assembly and the fin operating condition i.e. fully wet, partially wet or dry condition. Therefore, the similar type of work can be found in the recent literature, e.g., Hatami and Ganji (2014) presented the temperature distribution equation and refrigeration efficiency for fully wet circular porous fins with variable sections, whereas Sharqawy et al. (2012) studied the efficiency for different cross-sectional area annular fins under dehumidifying conditions. Similarly, Niazmand and Dabzadeh. (2012) presented a transient two-dimensional numerical model to study the combined heat and mass transfer for a cylindrical bed with annular fins.

The main objective of using variable cross section fins is to optimize the fin performance. Sharqawy and Zubair (2007, 2009) used analytical approach for optimizing the variable thickness annular and pin fins under completely wet conditions. Moinuddin et al. (2012) used a numerical scheme to investigate the optimal dimensions of annular fins of constant and variable cross-sectional area for completely wet conditions whereas Kundu and Lee (2012a) determined the optimum pin fin profile to minimize the fin volume for a constrained heat transfer rate under dry and partially or fully wet conditions. Another approach is to determine the fin dimensions for a given fin shape and desired heat dissipation rate in order that the volume of material used would be a minimum (Kundu, 2007). Alternatively, the constructal approach has also been used for optimizing fins (Hajmohammadi et al., 2012a, 2012b, 2013).

The temperature difference between fin surface and the ambient air is the driving force for sensible heat transfer under dry condition; whereas, for the wet fin condition, the additional component of the driving force is the difference between humidity ratio of the incoming air and the saturated air existing on the fin surface. The humidity ratio of the incoming air is a function of ambient condition whereas the humidity ratio of the saturated air on the fin surface is a function of fin surface temperature. Therefore, the relationship between the temperature and humidity relationship is