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An approximate analytical prediction about thermal performance and optimum design of pin fins subject to condensation of saturated steam flowing under forced convection

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ABSTRACT

An approximate analytical method has been suggested for solving the governing equation for horizontal pin fins subject to condensation while saturated steam flowing over its under laminar forced convection. Adomian decomposition method is used for determination of the temperature distribution, performance and optimum dimensions of pin fins with temperature dependent thermal conductivity under the condensation of steam on the fin surface. From the results, a significant effect on the temperature distribution in the fin and its performances are noticed with the variation in fin-geometric parameters and thermo-physical properties of saturated vapor. Next, a generalized scheme for optimization has been demonstrated in such a way that either heat-transfer duty or fin volume can be taken as a constraint. Finally, the curves for the optimum design have been generated for the variation of different thermo-physical and geometric parameters, which may be helpful to a designer for selecting an appropriate design condition.

Prévision analytique approximative de la performance thermique et de la conception optimale des picots cylindriques assujettis à la condensation de vapeur d’eau saturée en écoulement en convection forcée

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Nomenclature

A_i, B_j, C_j	adomian polynomials used in Eq. (13)
c_p	specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
D	fin diameter (m)
f	function defined in Eq. (15)
F	function defined in Eq. (41)
g	gravitational acceleration ($m\,s^{-2}$)
G	function defined in Eq. (42)
h	local heat-transfer coefficient ($W\,m^{-2}\,K^{-1}$)
$\bar{h}$	circumferentially averaged heat-transfer coefficient ($W\,m^{-2}\,K^{-1}$)
h_{fg}	proper latent heat for condensation of saturated vapor (kJ/kg)
h'_{fg}	augmented latent heat, $h_{fg} + 3/8C_{p,l}(T_{sat} - T_f)$ (kJ/kg)
J	Jacobian matrix
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
k_0	thermal conductivity of the fin material at fin-base temperature ($W\,m^{-1}\,K^{-1}$)
K, K_1	thermogeometric parameters, defined in Eqs. (5) and (6), respectively
L	length of fin (m)
L_x	linear second order differential operator
q	actual heat-transfer rate through the base of the fin (W)
q_0	heat-transfer rate through the original base surface, if fin were not present (W)
q_i	ideal heat-transfer rate through the fin (W)
Re	Reynolds number $U_\infty D/\nu_l$
T	temperature (°C)
U_∞	free stream velocity of vapor ($m\,s^{-1}$)
V	volume of a pin fin (m^3)
x	coordinate, see Fig. 2 (m)
X	dimensionless coordinate, x/L

Greek symbols

α	temperature coefficient of thermal conductivity (K^{-1})
β	dimensionless variable defined in Eq. (3)
ε	fin effectiveness
η	fin efficiency
λ	Lagrange multiplier
μ	viscosity ($N\,s\,m^{-2}$)
θ	dimensionless fin surface temperature, $(T_s - T_f)/(T_s - T_b)$
ρ	density ($kg\,m^{-3}$)

Subscripts

b	base
f	fin
i	ideal
j	j-th iteration
l	liquid
m	mean fin surface
mf	mean film
s	saturation
t	tip

1. Introduction

For enhancement of heat transfer, fins or extended surfaces are extensively used in a variety of applications. Among the various applications, finned surfaces are widely found in heat exchangers in industries for condensing steam. The primary purpose of the condenser is to condense the steam for an application at constant pressure particularly in vapor absorption refrigeration system where water is the refrigerant. Surface condensers are the most common type used in many industries. Since, in most cooling coils, the coil surface temperature is below the saturation temperature of water vapor being condensed, condensation of steam takes place on the fin surface. Thus simultaneous heat and mass transfer take place and as a result the fin surface becomes wet. In this view point, it may be mentioned that extended surfaces have been traditionally employed to reduce the convective resistance in the gas side for low values of heat-transfer coefficient but in condensation applications they can prevent film condensation because of better film drainage. Among the factors affecting the thermal performance of such wet fins are the geometry, material and thermo-physical parameters. Depending upon the shape of a primary surface, different types of fins are used in heat exchange applications.

Vapor on a surface condenses if the temperature of the surface is kept below the vapor saturation temperature. Although four basic mechanisms such as homogeneous, direct contact, drop, and film take place, most condensers are designed to operate under the film condensation mode. In film condensation, the surface is blanketed by a liquid film of increasing thickness, and this liquid wall between solid surface and the vapor serves as a resistance to heat transfer. The heat of vaporization released as the vapor condenses must pass through this resistance before it can reach the solid surface and be transferred to the medium on the other side. In drop-wise condensation, however, the droplets slide down when they reach a certain size, clearing the surface and exposing it to vapor. There is no liquid film in this case to resist heat transfer. As a result, heat-transfer rate that is more than ten times larger than those associated with film condensation can be achieved with drop-wise condensation. Therefore, drop-wise condensation is the preferred mode of