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Direct and inverse approaches for analysis and optimization of fins under sensible and latent heat load

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ABSTRACT

An inverse methodology is introduced by differential evolution (DE) search algorithm to determine optimal dimensions of a wet fin for a given volume for to maximize heat transfer rate. The DE optimization method is first employed to explore multiple combinations of geometrical fin parameters satisfying a constraint volume. The pertinent rates of heat transfer are computed using a forward analysis based on the differential transform method. In this study for a fixed fin volume, a same value of heat transfer rate in wet fins can be acquired for multiple values of surface areas, and also, even a given surface area can yield multiple values of heat transfer rates. Hence, the local temperature distribution acts as an important factor in selecting a unique set of fin dimensions towards maximizing the rate of heat transfer. The evaluation of sensitivity coefficients reveals that among various geometric parameters, the fin thickness plays an influential role significantly to govern the heat transfer rate.

1. Introduction

The application and the importance of fins for heat transfer enhancement are well-known [1]. From the view point of heat and mass transport phenomena, fins are classified as either dry or wet. Generally, dry fins do not involve the transport of mass and the heat dissipation occurs due to convection and radiation [2]. However, wet fins involve simultaneous transport of heat and mass [3,4]. The fin surface turns wet when the local temperature prevailing at the fin surface falls below the dew point temperature of the surrounding cold air. Wet fins find many applications in refrigeration, air-conditioning, and chemical industries where heat transfer involves simultaneous cooling and dehumidification of the humid air at the ambient condition [5,6]. In wet fins, heat is absorbed from the air by the fin surface which is subsequently conducted in the fin material. When the fin surface temperature becomes lesser than the dew point temperature of the air at ambient condition, simultaneous transport of heat and mass occurs on the fin surface due to the condensation of moisture. The heat transfer phenomenon in wet fins is again divided into two parts, such as sensible heat transfer and latent heat transfer [4,7]. The sensible heat transfer process is governed by the prevailing temperature gradient between the ambient air and the surface of the fin, whereas, the latent heat transfer process is governed by the humidity potential between the air and the fin surface. In wet fins, with an increase in the relative humidity (RH), the driving potential for mass transfer increases that consequently enhances the ideal heat transfer, whereas, corresponding actual heat transfer does not increase in the same proportion. Therefore, unlike dry fins, the fin efficiency decreases under wet surface conditions. For latent heat transfer, interestingly, the humidity ratio again depends on the dry-bulb temperatures of the air and the fin surface for which diverse relationships were reported in the literatures [8–11]. As mentioned earlier that as compared with dry fins, the disadvantage of wet fins is the reduction of fin efficiency [12].

In the past, many studies considered the analysis of wet fins. For instance, Kundu [13] obtained analytical expressions for the temperature distribution and presented an optimization analysis of a fully wet tapered fin to optimize the aspect ratio involving the fin semi-thickness and the length. Sharqawy and Zubair [14] provided analytical solution for calculating the local temperature distribution in annular disc fins, and for a given base radius, they optimized the thickness to maximize the rate of heat transfer. They along with other researchers further reported closed form solutions of temperature distribution for rectangular, triangular, hyperbolic, and parabolic fin profiles, and optimized the fin thickness under a given set of operating conditions [15,16]. The heat transfer and friction characteristics of fin-and-tube heat exchangers under

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Nomenclature

A_x	area of cross section, m^2
A_s	surface area of fin, m^2
a, b, c	random numbers outside population in DE algorithm
c_p	specific heat at constant pressure, J/(kg K)
D	dimension of vector of unknown parameters in DE algorithm
F	objective function for volume, m^6
F_1	objective function for heat transfer rate, W^{-1}
f	function in Runge-Kutta method
h	surface heat transfer coefficient, W/(m^2 K)
h_D	mass transfer coefficient, kg/(m^2 s)
i_{fg}	latent heat of vaporization, J/kg
k	thermal conductivity, W/(m K)
L	fin length, m
Le	Lewis number
M	mutant vector in DE algorithm
m_o	dimensionless dry fin parameter
n	fin geometry coefficient
N_p	population size in DE and NSGA-II algorithms
p	constant, defined in Eq. (13b)
P	fin perimeter, m
Q	heat transfer rate, W
S	sensitivity coefficient, W/m
t	local fin thickness, m
T_a	surrounding air temperature, °C
T_b	base temperature, °C
T_s	local fin surface temperature, °C
U	velocity of air, m/s
V	fin volume, m^3
W	fin width, m
x	arbitrary location along fin length, m
y	arbitrary location along fin width, m
Z	parent solution vector in DE algorithm
z	child solution vector in DE algorithm

Greek symbols

α	scaling factor in DE algorithm
χ	crossover probability in DE and NSGA-II algorithms
δ	Kronecker delta
ϕ	relative humidity (RH)
θ	dimensionless fin surface temperature, $(T_a - T_s)/(T_a - T_b)$
τ	differential function of T_s
ω	specific humidity (kg/kg of dry air)

Subscripts

a	ambient condition
b	fin base condition
dp	dew point condition
i	index for the member of DE algorithm
j	index for iteration/generation of DE algorithm
s	surface condition
x	arbitrary location along fin cross section

Superscripts

$\sim$	exact value

wet condition were investigated by Ma et al. [17]. Various correlations for Colburn and Fanning factors were reported in their study. Kundu [18] separately determined and optimized the length and the semi-thickness of longitudinal SRC profile for wet surface conditions. Using the finite difference method and the least squares analysis, Chen and Wang [19] estimated the heat transfer coefficients in one and two dimensional fins. Kundu [20] reported optimization analysis of partially wet annular disc and stepped fins, and individually optimized the aspect ratio and non-dimensional radius. Pirompugd and Wongwises [21] reported a study of partial wet fins of different shapes using the concept of Bessel functions. Hatami and Ganji [22] performed analysis of fully wet porous fins of rectangular, convex and triangular geometries using the least squares method, where the analysis was mainly done to study the local temperature and efficiency. Panda et al. [23] studied an inverse problem of a fully wet rectangular fin using the homotopy method and genetic algorithm. An inverse analysis of fully wet triangular fin was reported by Bhowmik et al. [24] using the homotopy analysis and the simplex search methods. Huang and Chung [25] maximized the efficiency of a partially wet annular fin, in which they optimized the fin thickness using the conjugate gradient method. Using an analytical method, Pirompugd and Wongwises [26] determined efficiencies of partially wetted spine of different profiles.

In addition to the above-mentioned studies, many work involving exponential fins are also studied in the literature. For instance, Turkyilmazoglu [27] proposed closed form solutions for exponential straight fins involving temperature-dependent thermal parameters. The study revealed that for exponential fin with positive power, the efficiency is better than that corresponding to the rectangular fin. Furthermore, analytical solutions for fully wet exponential fins are also provided where it was found that an exponential shape containing negative power perform better for cooling applications [28]. Kundu and Lee [29] used the method based on variational calculus to determine the minimum shape of porous fins. A variational method was used [30] to study the behavior of minimum envelop shape of wet fins for maximizing the heat transfer. A stepping optimization algorithm was proposed by Wang and Wang [31] for the geometric optimization of conical fins.

It is evident from the above discussion that most studies on wet fins are reported to analyze the fin behavior under an imposed set of operating conditions. The predicted fin behavior normally involved the evaluation of temperature distribution and the efficiency. Such kind of analyses is termed as the forward (direct) methods [32]. According to Hadamard [33], a well-posed problem is invariably defined by three conditions, (a) existence of the solution, (b) uniqueness of the solution, and (c) dependency of the solution on the input data. If any one or more of these conditions is unsatisfied, then the problem becomes ill-posed, and depending on the nature of the problem, an inverse problem possesses either one or more of such characteristics. Particularly, the inverse methods are those where the objective is the fulfillment of a given requirement, and predicting the set of necessary operating conditions which are required to be imposed on the system [34]. For inverse problems involving fins, some of the parameters of interest include, the fin dimensions [35], thermal properties for identifying the feasible materials [36], and surface heat transfer coefficient [37]. Evidently, compared to the forward methods, for wet fins in particular, studies on inverse problems are found to be very limited [23–25]. However, these studies predicted parameters for meeting a given temperature distribution only [23,24] and did not address