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Prediction of porosity and thermal diffusivity in a porous fin using differential evolution algorithm

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ABSTRACT

In this paper, simultaneous inverse prediction of two parameters such as the porosity and thermal diffusivity of the fluid in a porous fin is done for satisfying a given temperature distribution. Only three temperature measurements are assumed to be available on the surface of the fin and prediction of the parameters is accomplished by using the differential evolution (DE)-based optimization technique. It is shown that the present problem is inherently ill-posed in terms of the retrieval of the value of fluid thermal diffusivity for which many possible solutions exist, which is expected to adapt the fin under different conditions. In the present work, two numerical examples provide engineering insight into the problem of designing porous fins using good thermal conductors like aluminum and copper along with the working of DE. Finally, the efficacy of DE for the present problem is also shown by comparing its performance with few other optimization methods.

1. Introduction

The porous fins have got several advantages over conventional fins [1–9] and its investigation is one of the widely investigated topics of research in the area of heat and mass transfer. The heat transfer analysis of porous fins requires the consideration of simultaneous heat and mass transfer of both solid and fluid media [10]. The investigation of literature on porous fins indicates that most studies intend to obtain the performance parameters (temperature, efficiency, etc.) using various schemes using the *a priori* knowledge of thermo-physical quantities. Such cases fall under the purview of direct (forward) problems [11]. However, the situation becomes different and interesting when the conditions satisfying a given objective are required to be estimated using the inverse method. The procedure of estimating the feasible combination of various unknowns is known as the inverse problem [12,13]. Inverse problems are generally design-oriented, which can provide possible unknown parameters of an engineering system when subjected to some given requirement.

The situations requiring solution of inverse problems occur quite often in practical engineering problems, where it is easier to measure the temperature in a particular state of the system. Fins form a popular example of such a situation where the inverse problem such as mentioned above is encountered [14,15]. In this paper, the computation of the temperature for a known set of physical parameters of the fin comprises the forward problem and the focus of the paper is to solve an inverse problem for a porous fin. The problem is solved to compute the unknown physical parameters such as the thermal diffusivity of the fluid medium and the porosity of the fin of the porous fin.

In heat transfer and fluid mechanics, similar to other inverse problems in engineering [16,17], the inverse problem is difficult to solve due to the ill-posedness and non-linearity of the mathematical model. Although the investigation of inverse problems in porous fins is limited, but inverse problems involving non-porous fins have been studied by many researchers [18–23]. For inverse problems, it is found that the evolutionary-based optimization methods fare better than conventional gradient-based techniques [24,25] by performing global searching in the solution space. The differential evolution (DE) [26] is used in the present study for being one of the recently-used evolutionary methods which is receiving considerable attention for inverse problems [27,28]. The reason of its popularity is due to good convergence properties, simplicity and capability of optimizing objective functions involving difficulties associated with evaluating gradients due to the presence of nonlinear terms (for example due to the involvement of the radiative effects) [29].

In view of the above points, the present work intends to introduce the usage of DE for inverse problems in porous fins. It has been observed from the available literature that DE has not yet been used for studying inverse problem of porous fins involving

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Nomenclature

Symbol	Description
†	vector transpose operator
α	thermal diffusivity ($m^2\,s^{-1}$)
β	coefficient of volumetric thermal expansion (K^{-1})
ε	emissivity
ϕ	porosity of the fin
ν	kinematic viscosity ($m^2\,s^{-1}$)
θ	non-dimensional temperature (used in the forward model and forward solver)
$\tilde{\theta}$	measured non-dimensional temperature used as input data in the inverse problem
ρ	density of the fluid ($kg\,m^{-3}$)
σ	Stefan–Boltzmann constant ($5.67\times10^{-8}\,Wm^{-2}\,K^{-4}$)
c_p	specific heat at constant pressure ($J\,kg^{-1}\,{}^\circ K^{-1}$)
A	transverse cross-section area of the fin (m^2)
C_T	dimensionless
F	objective function used in the optimization scheme
g	acceleration due to gravity ($9.81\,m\,s^{-2}$)
G	radiative parameter
K	permeability of the fin (m^2)
k_{eff}	effective thermal conductivity ($W\,m^{-1}\,K^{-1}$)
k_f	thermal conductivity of the fluid ($W\,m^{-1}\,K^{-1}$)
k_s	thermal conductivity of the solid ($W\,m^{-1}\,K^{-1}$)
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
q	heat transfer rate (W)
q_c	heat transfer rate due to conduction (W)
q_r	heat transfer rate due to radiation (W)
L	length of the fin (m)
N	number of grid points used in the forward solver
P	perimeter of the transverse cross-section (m)
S_H	porous parameter
$\bar{s}$	optimization variable, a vector given as $\begin{bmatrix}\alpha & \varphi\end{bmatrix}^{\dagger}$ (different units along different dimensions)
t	thickness of the fin (m)
T	dimensional temperature (°C)
T_b	temperature at the base of the fin (°C)
T_∞	ambient temperature (°C)
v_w	fluid velocity ($m\,s^{-1}$)
W	width of the fin (m)
δx	elementary small portion of fin length (m)
x	distance of a point along the length of the fin from the west edge of the fin (m)
x^*	dimensionless distance of a point along the length of the fin from the west edge of the fin

radiation heat transfer. The work is aimed at implementing DE to a porous fin involving natural convection along with surface radiation for solving an inverse optimization problem. The involvement of radiation mode of heat transfer makes the present problem nonlinear for which the evaluation of gradients does not remain so simple, thereby justifying the usage of an evolutionary method of optimization, such as DE. The performance of DE is also compared with the deterministic Levenberg–Marquardt (LM) algorithm [30] and the meta-heuristic simulated annealing (SA) algorithm [23,31] along with the genetic algorithm (GA) [15,15]. It is shown that for the present problem, DE performs better than LM and SA algorithms with enhanced probability of converging to the actual solution and requiring less number of function evaluations. Below the problem and the solution procedure are discussed.

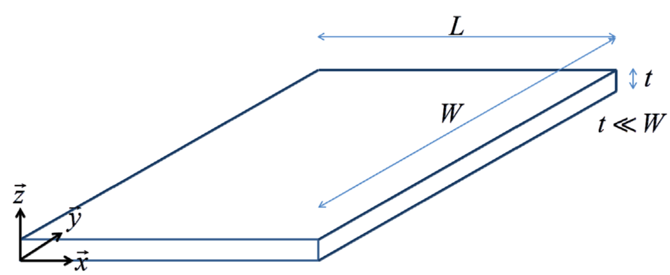

Fig. 1. Description of geometry of the porous fin.

2. Forward problem

2.1. Problem set-up

Let us consider the porous fin geometry as shown in Figs. 1 and 2. It is assumed that the thickness of the fin, t, is small in comparison to the width, i.e., $(t/W)\ll 1$, thus, the temperature changes along the longitudinal direction only. Furthermore, the only source of heat is at the west boundary where a base temperature T_b is maintained.

The heat conduction problem through a porous fin is completely described by the fin's solid thermal conductivity k_s, emissivity ε, permeability K, porosity ϕ, the fluid's thermal conductivity k_f, viscosity ν, coefficient of volumetric thermal expansion β, thermal diffusivity α, and the temperatures T_b and T_∞. The fluid–solid interaction is governed by the Darcy law. For any location, x, along the fin length, the steady-state energy equation can be expressed as [4,7]

$$q(x)-q(x+\delta x)=\dot{m}c_p(T-T_\infty) \tag{1}$$

where q is the heat transfer rate, δx is an infinitesimally small incremental length, c_p is the specific heat of the fluid at constant pressure and T is the temperature. The fluid's mass flow rate

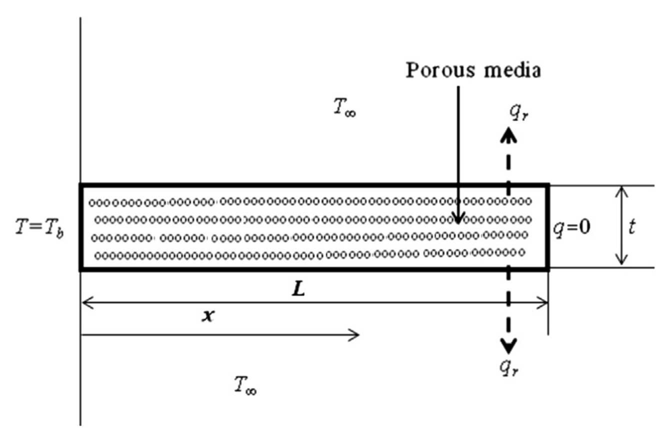

Fig. 2. Longitudinal section of the porous fin.

through the fin $\dot{m}$ can be calculated as [4]

$$\dot{m}=\rho v_w\,\delta x\,W. \tag{2}$$

In the above expression, ρ is the fluid density and the fluid velocity, v_w, is calculated using Darcy's expression as mentioned