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Performance evaluation of hybrid differential evolution approach for estimation of the strength of a heat source in a radiatively participating medium

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ABSTRACT

In this work, a hybrid method is developed for estimation of the strength of a transient heat source in a 2D gray participating medium where radiation and conduction occur simultaneously. The medium is considered to be absorbing, emitting and non-scattering. All the boundaries of the 2D enclosure are considered to be black with known temperature. A numerical model is developed for solving this inverse radiation-conduction problem through the minimization of a performance function, which is expressed by the sum of square residuals between calculated and observed temperature. A hybrid differential evolution approach with a local optimization algorithm is proposed for minimization of the performance function. The conjugate gradient method with an adjoint equation is used as a local optimization algorithm to speed up the convergence speed. The finite volume method is used to solve the radiative transfer equation and the energy equation. In comparison to differential evolution approach, the proposed hybrid differential evolution approach is more accurate and computationally economical.

1. Introduction

When the direct measurements for a problem become difficult, inverse techniques are applied to estimate the boundary or inlet conditions, thermal properties or source term distributions in a medium. The determination of the unknown source term in conduction problems has been investigated by several authors due to numerous applications in engineering and science. The time wise variation of the strength of a plane surface heat source was estimated by Huang and Ozisik [1] utilizing the conjugate gradient method [CGM] with an adjoint equation which is also called Alifanov's iterative regularization method. They applied a modified CGM approach for estimation of the source strength at final time. Neto and Ozisik estimated the time wise variation of a line heat source [2], the space and time dependent strength of a volumetric heat source [3] and transient strengths of two simultaneous heat sources [4] based on the CGM. Yang [5] applied the linear least square error model to estimate the strength of a heat source. Lin and Yang [6] estimated the strength of transient heat source in Fourier and non-Fourier heat conduction problems using modified Newton–Raphson method. Johansson and Lesnic [7] estimated the spacewise dependent heat source using an iterative algorithm based on a sequence of direct problems.

Inverse radiation problems that deal with prediction of the strength of heat source have also been reported by many researchers. Park and Lee [8] and Park and Yoo [9] estimated the strength of a transient heat source using modified CGM in a furnace where radiation and conduction occur simultaneously. Li [10] employed the CGM to estimate the unknown source term in a radiative 2D rectangular medium with transparent boundaries. Liu and Tan [11] estimated the three-dimensional source term distribution in complicated geometric systems in a radiative medium using CGM.

Besides than the determination of strength of source, inverse radiation problems have also been conducted to estimate radiative properties or heat flux. Matthews et al. [12] estimated the extinction coefficient, back scattering fraction, and thermal conductivity using the temperature and transmittance measurements in a one-dimensional planer layer. They have used a nonlinear parameter estimation technique. Li [13] estimated single scattering albedo, optical thickness, conduction-to-radiation parameter, and scattering phase function with the exit radiation intensities in a one-dimensional plane-parallel medium using CGM. Park and Lee [14] estimated the spatially varying heat transfer coefficient and the absorption coefficient in a radiant cooler by improved adjoint variable method. Park and Yoon [15] estimated radiative parameters such as absorption coefficient, scattering coefficient and the linear anisotropic coefficient using the CGM in a 3D participating medium. Kim and Baek [16] estimated total heat flux distribution on a heater surface utilizing Levenberg–Marquardt (LM) method

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Nomenclature

c_p	specific heat capacity of fluid (J/kg K)
D	number of time steps
$d(t)$	direction of descent
RMS	RMS error
F_1, F_2	mutation scale factors
G	current iteration
I	intensity (W/m^2 sr)
I_b	blackbody intensity (W/m^2 sr)
J	objective function, defined by Eq. (6)
k	thermal conductivity (W/m K)
M	number of measured data
P, Q	Lagrange multipliers
q_R	radiative heat flux (W/m^2)
$\vec{r}$	position vector
s	distance (m)
$\hat{s}$	unit vector in given direction
$So(t)$	heat source function (W/m)
t	time (s)
t_f	final time (s)
T	temperature (K)
T_c	temperature obtained with estimated flux (K)
T_m	measured temperature by sensors (K)
T_w	wall temperature (K)
$\vec{u}_{i,G}$	crossover vector
$\vec{v}$	mutation vector
x, y	coordinate directions
x^*, y^*	location of heat source

Greek Symbols:

β	extinction coefficient (m^{-1})
β^n	search step size
δ_n	dirac delta function
ε	convergence criteria
γ	conjugation coefficient, defined by Eq. (15)
κ	absorption coefficient (m^{-1})
ω	random variable (K)
ϕ	azimuthal angle (rad)
ρ	density of fluid (kg/m^3)
σ	standard deviation
σ_b	Stefan–Boltzmann constant (W/m^2 K^4)
θ	polar angle (rad)

Superscripts

n	iteration number

in a two-dimensional concentric cylindrical absorbing, emitting and scattering medium.

In the inverse heat transfer problems referred above, the CGM with an adjoint equation has commonly been used. The CGM is a deterministic method and in general deterministic methods are computationally faster than stochastic methods, although they can converge to a local minima or maxima, instead of the global one. In CGM with an adjoint equation, the regularization procedure is performed during the iterative processes and thus the determination of optimal regularization conditions is not needed [17,18]. The CGM derives from the perturbation principles and transforms the inverse problem to the solution of three problems, namely, the direct, sensitivity and the adjoint problem.

Search-based methods or stochastic methods like genetic algorithm (GA) and differential evolution (DE) are also applied for inverse problems for their outstanding characteristics, for instance, non-requirement of initial guess and gradient function. Li and Yang [19] used GA to solve inverse radiation problem for estimation of single scattering albedo, the optical thickness and the phase function. Verma and Balaji [20] estimated the conduction–radiation parameter, the optical thickness and the boundary emissivity by solving inverse conduction-radiation problem using GA. Liu [21] used modified GA for solving inverse heat conduction problem to estimate unknown transient heat source. Kim et al. [22] estimated the wall emissivities in irregular geometries by using hybrid genetic algorithm (HGA) which contains local optimization algorithm (LOA).

A few literatures are available which compare various inverse methods especially stochastic and deterministic methods. Tian et al. [23] estimated heat source strength in transient one dimensional heat conduction problem by quantum-behaved particle swarm optimization (QPSO) and compared the results with particle swarm optimization (PSO), GA and CGM. Orain et al. [24] compared gradient-based method with search-based method for the determination of thermal properties of thin films. The GA as well as the Gauss method was adopted as one of the search based methods together with the gradient-based method. The GA yielded a better solution when the parameters were highly correlated. Daun et al. [25] compared Tikhonov method, truncated singular value decomposition, CGM, quasi-Newton minimization and simulated annealing algorithm (SA) for estimation of transient heater settings of a furnace with radiating sources. Kim and Baek [26] estimated the boundary conditions and emissivities in axisymmetric absorbing, emitting, and scattering medium using CGM, HGA and finite-difference Newton method. Lobato et al. [27,28] used DE approach for the estimation of radiative properties in participating media. In their work [27], they considered a two-layer participating media and the results obtained with DE are compared with other approaches like SA, LM and hybrid of SA and LM. In another work [28], they considered a one-dimensional participating medium for the estimation of radiative properties using SA and DE.

The DE is a structural algorithm or a stochastic method proposed by Storn and Price [29] for optimization problems. Besides its good convergence properties and suitability for parallelization, DE's main assets are its conceptual simplicity and ease of use. This approach is an improved version of Goldberg GA for faster optimization. GA uses the values of the parameters (to be estimated) from the given range. Variables are coded in binary strings. The population is operated upon by three main operators namely reproduction, crossover and mutation to create a new population of points. Although DE uses a similar population based computing strategy, unlike GA, here a real parameter representation is used and an individual is formed by a vector array of all the variables in the problem. DE uses both crossover and mutation. Recently Lobato et al. [27,28,30,31] used DE approach for inverse radiation problems for the estimation of radiative properties. To the knowledge of the authors, DE approach has still not been used for the estimation of strength of source in a radiatively participating medium. Hence, its applicability and performance for such kind of problem needs to be tested. However, DE being a stochastic method is computationally slower than deterministic methods. Therefore, the two main objectives of the present work are (i) to see the applicability and performance of the DE algorithm for estimation of the strength of a heat source in a conduction–radiation problem in an absorbing, emitting and non scattering gray medium and (ii) to propose a hybrid method (called as hybrid DE, HDE) using the DE