International Journal of Heat and Mass Transfer 88 (2015) 330–337

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Performance comparison of particle swarm optimization and genetic algorithm for inverse surface radiation problem

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ARTICLE INFO

Article history:
Received 2 February 2015
Received in revised form 23 April 2015
Accepted 23 April 2015
Available online 14 May 2015

Keywords:
Surface radiation
Inverse analysis
Particle swarm optimization algorithm
Genetic algorithm

ABSTRACT

The heat transfer mechanism of thermal radiation is directly related to either the emission and propagation of electromagnetic waves or the transport of photons. Depending on the participation of the medium in space, thermal radiation can be classified into two forms, which are surface and gas radiation, respectively. In the present study, unknown surface radiation properties are estimated by an inverse analysis for a surface radiation in an axisymmetric cylindrical enclosure. For efficiency, the repulsive particle swarm optimization (RPSO) algorithm, which showed an outstanding effectiveness in the previous inverse gas radiation problem, is adopted as an inverse solver. By comparing the convergence rates of an objective function and the estimated accuracies with the results of the hybrid genetic algorithm (HGA) and the particle swarm optimization (PSO) method, the performance of the RPSO algorithm is verified to be quite an efficient method as the inverse solver when applied to the retrieval of unknown properties of the surface radiation problem.

1. Introduction

Thermal radiation, one of the three fundamental mechanisms of heat transfer, is known to be emitted from all bodies that have a temperature greater than absolute zero by the propagation of electromagnetic waves or the transport of photons due to the thermal motion of charged particles inside the matter [1,2]. Since radiative heat transfer is emitted at a rate proportional to the fourth power of the absolute temperature, it becomes more important over conduction and convection in high temperature engineering problems such as combustion furnace, rocket propulsion, plasmas in fusion reactors, and etc. In these applications, interaction of participating media such as combustion gases as well as aerosols must be considered in thermal radiation because radiative intensity can be absorbed, emitted and scattered by these media between surfaces. Thus, a mode of radiative heat transfer involving such participating media is classified as gas radiation, which is affected by the radiation properties of the media [1,2]. On the other hand, thermal radiation can be propagated in space infinitely far away without interacting with media while both conduction and convection require the presence of some media for the transfer of thermal energy. With this phenomenon, radiation heat exchange only occurs between surfaces and radiative effects of the media can be neglected. Thus, this mode of thermal radiation with nonparticipating media is defined as surface radiation, which depends only on surface temperatures, surface radiation properties, and the geometry of the configuration. This fact that surface radiation does not need any media for thermal energy transfer makes it of great importance in vacuum and space applications such as thermal control design of satellites under not high temperature conditions [1,2].

For an inverse heat analysis field, it has been applied increasingly in recent years for various engineering problems from optimal designing to estimation of unknown thermal quantities in thermal sciences by using measurements of temperature, heat flux, radiation intensities, etc. [3,4]. Because inverse problems are classified mathematically as ill-posed which means their solutions either do not exist, or are very sensitive to random errors in the input measurements, various mathematical techniques have been adopted to obtain stable solutions by reformulating them as optimization problems [4,5]. In early studies, the solution of inverse heat transfer problems could be obtained with the classical optimization methods based on the gradient information of the objective function. But some problems have been found where unfeasible solutions can be obtained if the initial values are not guessed properly, or if the parameters are highly correlated [4,5]. As an alternative to these gradient-based methods, stochastic

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.04.075
0017-9310/

Nomenclature

c_i	acceleration coefficient
dF_{i-j}	view factor between element i and j
E_b	black emissive power
H	irradiation, W/m^2
J	radiosity, W/m^2
p_i^k	local best position of ith particle at iteration k
p_g^k	global best position of swarm at iteration k
q''	surface radiative heat flux, W/m^2
R	radius at side wall
r_i	uniform random number between 0 and 1 or radius of a finite element at side wall i
T	temperature, K
v_i^k	velocity of ith particle at iteration k
v_r	random velocity
w	inertia weight
x_i^k	position of ith particle at iteration k
z	random velocity

Greek symbols

ε	surface emissivity
ρ	reflectivity
σ	Stefan–Boltzmann constant, 5.67×10^{-8} W/(m^2 K^4)
σ_{st}	standard deviation

Superscript

$*$, $'$	dimensionless quantity
k	number of iteration

Subscript

i	ith particle or index of side wall
ref	reference quantity

heuristic intelligent optimization, such as generic algorithm (GA), simulated annealing (SA), ant colony optimization (ACO), and particle swarm optimization (PSO), have received increasing attention as a new inverse solver due to their superior aid in stability, solution time, and help in achieving global minimum solutions compared with the conventional gradient-based methods [5]. Among them, GA and PSO are frequently preferred for solving various inverse heat problems. From previous studies, they have been implemented in mostly inverse gas radiation analyses concerned with the determination of the unknown radiation properties of a gas medium, boundary conditions and temperature profiles from given radiation measurements [6–11]. For surface radiation problems containing transparent media, there are some works concerning the application of GA and PSO algorithms to the optimal geometry design of radiant enclosures inversely [12–16]. Hosseini Sarvari [12] applied the micro-genetic algorithm (mGA) to optimize the geometry of an enclosure which contains a transparent medium, and Safavinejad et al. [13,14] used mGA for determining the optimal number and location of heaters over boundary surfaces in irregular 2-D transparent media. Also, Chopade et al. [15] estimated heat flux distributions on a 3-D design object using mGA, while Farahmand et al. [16] studied the shape optimization of a two-dimensional radiative enclosure with diffuse-gray surfaces by the PSO algorithm and compared with mGA results from Sarvari [12] briefly.

However, to the author's best knowledge, up to now it is surveyed that GA and PSO have rarely been implemented in the inverse estimation studies of unknown surface radiative properties when no participating media is involved, except Kim and Baek [17] used hybrid GA for retrieving surface emissivity and its temperature in an axisymmetric cylinder. Moreover, no sufficient researches have yet verified and compared performances of GA and PSO with each other in detail for the inverse estimation applications in surface radiation problems, whereas their performances have been surveyed by Lee et al. [9] for searching absorption and scattering coefficients of a participating medium in the inverse gas radiation problem. Thus, the present study intends to investigate the usefulness and the efficiency of the PSO-based algorithm as an inverse method for estimating surface radiative properties inversely which are not priorly given. As the first outcomes, the performance of the PSO-based algorithm is verified by implementing it for simultaneous predictions of both the surface emissivities and the surface temperatures inversely in an axisymmetric cylindrical enclosure with nonparticipating media condition. Also, the accuracy of the estimated parameters and the computational efficiency, such as convergence rate and its speed, are compared with the results obtained by the GA-based technique.

2. Mathematical formulation of surface radiation

To investigate surface radiation problem, an axisymmetric cylindrical enclosure of Kim and Baek [17] is considered as shown in Fig. 1. Because no participating media exist inside enclosure, radiant energies are emitted and exchanged between inner surfaces only. Boundaries of the enclosure consist of gray, diffusely emitting and reflecting surfaces with their own emissivities and temperatures, respectively. Also, whole surfaces are divided into a finite number of elements for a numerical calculation and the net energy exchange method is applied to yield the radiosity from each surface element [17]. The net energy exchange on each surface can be obtained from following equations with non-dimensionalized variables given by

$$\zeta = \frac{x}{D}, \quad \eta = \frac{y}{D}, \quad l = \frac{L}{D}, \quad r'_i = \frac{r_i}{R} \quad i = 1,3 \tag{1}$$

On surface 1:

$$J_1(r'_1) = \varepsilon_1(r'_1)\sigma T_1^4(r'_1) + \rho_1(r'_1)H_1(r'_1) \tag{2a}$$

$$H_1(r'_1) = \int_{\eta=0}^{l} J_2(\eta)dF_{r'_1-d\zeta} + \int_{r'_3=0}^{1} J_3(r'_3)dF_{r'_1-r'_3} \tag{2b}$$

where J and H are radiosity and irradiation, ε is emissivity, while $\rho = 1 - \varepsilon$ is reflectivity. Here, $dF_{r'_1-d\zeta}$ and $dF_{r'_1-r'_3}$ are view factors from an element on surface 1 to an element on surface 2 and 3, respectively, and defined as follows [17].

$$dF_{r'_1-d\zeta} = \frac{8\zeta(4\zeta^2 + r_1'^2 - 1)}{\left\{(4\zeta^2 + r_1'^2 + 1)^2 - 4r_1'^2\right\}^{3/2}} d\zeta \tag{2c}$$

$$dF_{r'_1-r'_3} = \frac{1}{r'_1}\left[\frac{2R'l'^2\left(l'^2 + R'^2 + 1\right)}{\left\{\left(l'^2 + R'^2 + 1\right)^2 - 4R'^2\right\}^{3/2}}\right] dr'_3 \tag{2d}$$

where $R' = \frac{r'_3}{r'_1}$, $l' = \frac{2l}{r'_1}$