International Communications in Heat and Mass Transfer 76 (2016) 69–76

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

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

Inverse boundary design solution in a combined radiating-free convecting furnace filled with participating medium containing specularly reflecting walls☆

B. Mosavati [a,*], M. Mosavati [a], F. Kowsary [b]

[a] Mechanical Engineering Department, University College of Engineering, Islamic Azad University Science and Research Branch, Tehran, Iran
[b] Mechanical Engineering Department, University College of Engineering, University of Tehran, Tehran, Iran

ARTICLE INFO

Available online 29 April 2016

Keywords:
Inverse problem
Conjugate gradients method
Natural convection-radiation
Monte Carlo method
Specularity-reflecting surfaces
Participating medium

ABSTRACT

In this paper, an inverse boundary design problem of combined natural convection-radiation considering specular reflectivity and participating media is solved. The aim of this paper is to find the strength of heaters in a step-like enclosure to produce the desired temperature and heat flux distribution on the design surface. The finite volume method for transition flow (which causes a faster convergence) is used as the direct solver of the energy and momentum equations. The SIMPLE algorithm is utilized to satisfy pressure–velocity coupling in order to solve the free convection heat transfer. Also, the backward Monte Carlo method is employed in order to be able to compute the distribution factors and carry out the radiant exchange calculations. Finally, the goal function which is defined on the basis of square root error is minimized by means of a conjugate gradients method. The effects of variation of specularity ratio for specular surfaces are investigated to compare the results for diffuse and specular surfaces in the enclosure considering radiation and free convection. The effects of variation of range of parameters such as the Rayleigh number, temperature ratio, radiation conduction parameter and the specularity ratio on the relative root mean square and heat flux are investigated and results are compared. The results demonstrate the efficiency and the accuracy of the proposed method.

1. Introduction

The inverse boundary design problem has found its way into the literature since the mid-1990s. It has many industrial applications in heat treatments, drying, backing food, and rapid processing chambers. In this type of problem, the heaters are set at optimal setting so that they provide uniform heat and temperature over the "design surface" throughout the heating process.

In inverse methods, an objective function, expressed as the sum of square residuals between estimated and desired heat fluxes over the design surface, must be minimized in order to obtain the unknown parameter [1–2]. Since the inverse radiation boundary design problem is mathematically ill-posed, which means that the solution is not unique and is highly sensitive to input fluctuations, a stable solution requires some kind of regularization techniques. These techniques have been well established and addressed comprehensively by many investigators such as Erturk et al. [3], Howell et al. [4], Emery [5], Kowsary [6], and Pourshaghaghy et al. [7].

More recently, the "inverse design problems" has been extended to cases in which radiative heat and natural convection exist simultaneously, though very little work has been carried out on the subject.

Harutunian et al. [8] developed an inverse design methodology for enclosures composed of diffuse-gray walls containing a non-participating medium, where the ill-conditioned set of equations is formed using discrete configuration factors and were solved using modified truncated singular value decomposition. This technique was later extended to treat radiant enclosures containing participating media (Morales et al., França and Goldstein [9–10]) and problems involving multimode heat transfer (França et al. [11]). The variable metric method (VMM) was utilized by Kowsary et al. [12] to investigate radiative boundary design problem in a two-dimensional furnace filled with absorbing, emitting and scattering gas. In the first test case, design surface is a step-like geometry over which a uniform dimensionless heat flux of -1 and a uniform dimensionless temperature of unity is employed whereas other enclosure surfaces are assumed to be re-radiating. In the second test case, an eccentric cylindrical surface is the design surface over which certain uniform heat flux and temperature distributions are desired. The lower surfaces are considered to be adiabatic and the remaining enclosure walls are heater surfaces. They concluded that VMM, when using a "regularized" estimator, is more accurate as compared to CGM. Salinas [13] used an inverse analysis for estimation of the temperature distribution for a gray emitting, scattering, two-

☆ Communicated by W.J. Minkowycz.

* Corresponding author at: Sciences & Research Branch, Hesarak, Tehran, Iran, P.O. Box: 1477893855.
E-mail addresses: babak_mosavati@yahoo.com (B. Mosavati), maziar_mosavati@yahoo.com (M. Mosavati), fkowsari@ut.ac.ir (F. Kowsary).

http://dx.doi.org/10.1016/j.icheatmasstransfer.2016.04.029
0735-1933/

Nomenclature

A	area
D_{ij}	distribution factor
E_{rms}	relative root mean-square error
f	objective function
g	acceleration due to gravity, (m/s^2)
J	sensitivity matrix
Ks	thermal conductivity of fluid, W/m k
L	length of the cavity (m)
ND	total no. of the elements on design surface
NH	total no. of elements on heater surface
N_r	radiation conduction interaction parameter, $N_r = \frac{\sigma T_d^4 L}{Ks \Delta T}$
Q	dimensionless heat flux
Q	total heat flux ($Q_{conv} + Q_{rad}$), W/m^2
Q_{rad}	radiative heat flux, W/m^2
Q_{conv}	free convection heat flux, W/m^2
Ra	the Rayleigh number
Rs	specularity ratio
$\vec{s}$	direction vector
T	temperature at any location in the computational domain, K
T^*	temperature ratio, $\frac{T_d}{\Delta T}$
$\Delta T = (T_h - T_d)$	
modified temperature difference, (Q_d L/ Ks), K	

Greek symbols

ε	emissivity
σ	Stefan Boltzmann constant (5.67×10^{-8}Wm^{-2}K^{-4})
λ	geometric path length
ρ_s	specular reflectivity
ρ_d	diffuse reflectivity
θ	dimensionless temperature ($\theta = ((T - T_d))/(\Delta T)$)

Subscripts

d	design
e	estimated
h	heater surface
k	iteration number

dimensional rectangular medium and the inverse problem is solved by using the conjugate gradients method (CGM).

Mosavati et al. [14] solved the inverse radiation boundary problem by using a "backward Monte Carlo method (MCM)" for cases where radiation is the dominant mode of heat transfer (i.e., radiative equilibrium). Payan et al. [15] proposed an inverse methodology which is employed to estimate the unknown strengths of heaters on the heater surface of a square cavity with free convection from the knowledge of the desired temperature and heat flux distributions over a given design surface.

Daun et al. [16] proposed an optimization methodology for designing radiant enclosures containing specular reflecting surfaces. They successfully implemented the methodology to design the geometry of two radiant enclosures containing specularly reflecting surfaces. The optimization was carried out using the Kiefer-Wolfowitz method [17].The Monte Carlo method was used to calculate exchange factors. They demonstrated that the optimization methodology requires far less design time, and the solution quality is usually much better than that obtained using the forward design. Hong-Liang et al. [18] proposed a hybrid ray-tracing method to solve the radiative transfer between parallel planes filled with absorbing, emitting and scattering medium composed of one specular surface and other diffuse surfaces which both of these surfaces were semitransparent or opaque. From the results, they found that the effects of anisotropic scattering is more pronounced at higher optical thicknesses, and keeping other optical parameters unchanged whereas anisotropic scattering effects on transient temperature distributions is larger at small refractive index. One of the most recent works on the subject is one by Safavinejad et al. [19], which involves optimization of the number as well as locations of the heaters in a radiant enclosure having both; diffuse and specular surfaces. Mossi et al. [20], have studied boundary radiation in a two-dimensional cavity with turbulent flow and working fluid taking part in radiation. Mosavati et al. [21] investigated the effect of surface radiation on conjugate mixed convection in inverse boundary design problem without participating media.

The approach in this paper is to employ a combination of the backward MCM and the finite volume method (FVM) for unsteady free convection flow within the participating medium containing specular insulated surfaces to compare the results of specular and diffuse reflecting surfaces. To the authors' best knowledge, none of the previous works have investigated the effects of specular reflectivity of re-radiating surfaces using these two methods (backward Monte Carol and FVM) simultaneously on inverse radiation-convection problems. In this work, we have attempted to explore the use of these methods in an inverse solution. The conjugate gradients method (CGM) is used to solve the inverse boundary design in a step-like enclosure. In this paper, the problem is solved for different parameters such as the Rayleigh number and the optimum case is obtained. Finally, evaluated temperatures of heaters lead to a uniform heat fluxes on the design surfaces which are also very close to the desired heat flux.

2. Problem description

The design problem under consideration in this paper is depicted in Fig. 1. In this two-dimensional furnace, the length and width have been chosen as a unit length. In this test case, the height of the step-like design surface is 0.5 m wide which is located at distance of 0.25 m from the enclosure side walls. The bottom wall and side walls are considered as heater surfaces and all the other walls except the step surfaces are insulated. Moreover, insulated surfaces reflect as perfectly specular ($r_s = 1$) whereas all other surfaces (heater and design surfaces) reflect completely diffuse ($r_s = 0$). One type of boundary condition (temperature or heat flux) is specified over each boundary surface, except for the heater surface for which no boundary condition is specified. The aim of the inverse problem is to find the temperature (or heat flux) distribution over the heater surfaces in such a way that the desired uniform heat flux profile is recovered over the uniform temperature-specified design surface.

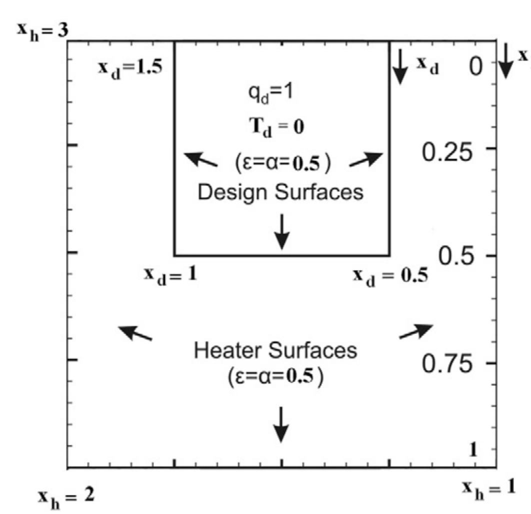

Fig. 1. Geometry and boundary condition used in inverse problem.