Applied Thermal Engineering 31 (2011) 3262–3274

Contents lists available at ScienceDirect

Applied Thermal Engineering

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

Effects of locations of a 3-D design object in a 3-D radiant furnace for prescribed uniform thermal conditions

Ramchandra P. Chopade [a], Subhash C. Mishra [a,*], P. Mahanta [a], S. Maruyama [b]

[a] Department of Mechanical Engineering, Indian Institute of Technology Guwahati, Guwahati 781039, India
[b] Institute of Fluid Science, Tohoku University, Aoba-ku, Katahira 2-1-1, Sendai 980-8577, Japan

ARTICLE INFO

Article history:
Received 27 January 2011
Accepted 31 May 2011
Available online 13 June 2011

Keywords:
Uniform thermal conditions
Location
Radiation heat transfer
Genetic algorithm

ABSTRACT

This article deals with the study of effects of locations for prescribed uniform thermal conditions on a 3-D design object (DO) placed on the bottom of a 3-D radiant furnace. For the desired uniform thermal conditions, importance of locations of the DO is exemplified. For a given power range of the panel heaters, for each of the three sizes of the DO, study is made for different possible locations. In each case, the heat flux distribution on the surfaces of DO is estimated. For a particular DO, the suitability of any location is judged by comparing the estimated heat flux distribution on the DO, with that of the desired one. For any DO, at any location, for uniform thermal conditions, all panel heaters may not be operating at the same power. This aspect also has been demonstrated for three sample locations of DO, and the results have been analyzed. For each of the locations, powers of the heaters vary a lot, and to yield the prescribed uniform thermal conditions, not all but very few heaters are needed. The estimated uniformity of the thermal conditions is greatly influenced by location of the DO inside the furnace. In this analysis, radiative information has been calculated using the radiation element method by ray emission model and the objective function has been minimized using the micro-genetic algorithm.

1. Introduction

Many industrial applications require uniform thermal condition(s) over a specific region, called the design surface. In precision thermal processing, the desired post-processing results require the fine control of thermal conditions on a design object (DO). These situations are found in heating of products for precision hot working processes/heat treatments, metallurgical laboratory experiments, curing of paints, design of the precise casting, etc [1]. Among various heating devices, radiant furnace is preferred for maintaining the precise control of thermal conditions [2]. The desired thermal conditions for any particular engineering application depend on appropriate selection of furnace geometry, properties of the furnace materials and the participating medium. Locations and powers of the panel heaters are other factors that need to be considered. The DO is placed at the bottom surface of the furnace, and it is obvious that in a 3-D radiant furnace, for uniform thermal conditions, it cannot be placed anywhere. Thus, with other parameters fixed, for the desired uniform thermal conditions, it is equally important to know the possible locations where a DO can be placed.

For the desired conditions over the specific region (design surface), estimation of thermal boundary conditions in a radiant furnace falls under the purview of inverse boundary design problems [3–7]. Unlike the direct problems, in which for the known initial conditions, the boundary conditions and the medium properties, the objective remains the determination of unknown temperature and/or heat flux distributions in the medium. The solution of an inverse problem determine the unknown initial and/or boundary conditions and/or the medium properties that has/have yielded the known temperature or heat flux distributions. In one hand, if the direct problems are well behaved and their solutions are straightforward, because of the ill-posed nature of the inverse problems, their solutions are relatively difficult [3]. For the solution of an inverse problem, along with the method(s) used in the direct problem, an efficient regularization/optimization method becomes essential [5–18].

Due to the increased relevance, and demand as well, of the precision thermal processing in various fields, a good number of studies related to inverse optimization problems involving estimation of medium material properties [8–10], and boundary design problems dealing with radiation heat transfer [1,5,6,13,14] have been reported. To handle the ill-posed nature of the inverse problems, several regularization and optimization techniques have been proposed [5–18]. Quasi-Newton minimization [3], simulated

* Corresponding author. Tel.: +91 361 2582660; fax: +91 361 2690762.
E-mail address: scm_iitg@yahoo.com (S.C. Mishra).

1359-4311/$ – see front matter
doi:10.1016/j.applthermaleng.2011.05.047

Nomenclature

A_i	area of surface element "i" (m^2)
dA_i	differential surface element on A_i
$F_{i,j}$	view factor from surface element "i" to "j"
$F_{i,j}^A$	absorption view factor
$F_{i,j}^D$	diffuse reflection view factor
F	view factor matrix
G_i	irradiance (W m^{-2})
J_{Di}	diffuse radiosity (W m^{-2})
N	total number of surface elements
N_P	number of population in the micro-genetic algorithm
Q_G	heat transfer rate of irradiation (W m^{-2} s^{-1})
Q_J	heat transfer rate of diffuse radiosity (W m^{-2} s^{-1})
Q_T	heat transfer rate of thermal emission (W m^{-2} s^{-1})
Q_x	net heat loss (W m^{-2})
Q	heat transfer vector
q_i	heat flux at element A_i (W m^{-2})
T_i	temperature of surface element "i" (K)

Greek symbols

α	absorptivity
θ	polar angle measured from normal of a surface (rad)
ϕ	circumferential angle (rad)
ρ^D	diffuse reflectivity
ρ^S	specular reflectivity
σ	Stefan–Boltzmann constant = 5.669×10^{-8} (W m^{-2} K^{-4})
ω	solid angle (rad)

Subscripts

G	values due to irradiation
J	value due to diffuse radiosity
i,j	value son surfaces A_i and A_j
R	reference
T, X	values due to thermal emission and net heat generation

Superscripts

A	absorption
D	diffuse
H	heater
S	diffuse specular
*	dimensionless quantity

annealing [3], genetic algorithms (GAs) [5,6,9,10], Levenberg-Marquart method [10], artificial neural network [10], least square minimization method [11], particle swarm optimization [12], Newton's methods [13], truncated singular value decomposition [9,15], conjugate gradient method [14,15], etc., are some of the commonly used methods. A detailed review of applications of these methods in various inverse problems for design and control of radiation sources can be found in [16–18].

Due to their superior characteristics, in the recent past, in the analysis of optimization problems, stochastic search techniques, such as the genetic algorithm (GA), the particle swarm optimization, the ant colony method, the tabu search, etc., have received great attention. These techniques do not need differentiable objective function and so the gradient of function as required in the gradient based methods are avoided. However, unlike some of the optimization methods, these techniques have very less tendency to get trapped in the local optima.

In boundary design problems, the main drawback of the regularization methods is in imposing the design constraints, which the GA handles very well. Due to its superior nature, in the recent past, GAs have emerged as an effective optimization tool for many of the engineering problems [19–22] including inverse problems [5–9,23–25]. In the present boundary design problem, we have used an improved version of the GA, called the micro-genetic algorithm (MGA) [26]. Because the MGA works well with a small population, it becomes handy in problems in which the number of unknown parameters is large. Although in other fields [27–29], MGA has been used extensively, its application to boundary design problems is very recent [5,6]. For desired thermal conditions on the design surface, Safavinejad et al. [5] used it for estimating the numbers and location of the heater surface in a 2-D enclosure. In another work [6], they used the MGA in estimating the desired thermal conditions on centrally located 2-D design surface placed in a 3-D enclosure.

Because of its importance, in the recent past, different types of boundary design problems have been studied, and in doing so, different techniques [3–7,10,15] have been used. However, most of these investigations [3,5,6,15] deal with a centrally located 2-D DO placed inside a 2-D or a 3-D radiant furnace. A 2-D DO in a 2-D or a 3-D radiant furnace does not represent a realistic situation completely. To march a step ahead, recently Chopade et al. [30,31], have studied boundary design problems involving a 3-D DO placed in a 3-D radiant furnace. In [30], for uniform thermal conditions on a centrally located 3-D DO, arrangements and power ranges of the panel heaters were estimated. Keeping the dimensions of the DO fixed, study was also made for different aspect ratios of the radiant furnace. This study concluded that for uniform thermal conditions on a 3-D DO, placement of panel heaters along the top wall does not yield the desired result, rather, heaters have to be placed along the four vertical walls also. Further, it was found that, for a particular case, not all heaters need to be considered. In the next study [31], keeping the furnace dimensions fixed, for uniform thermal conditions, the objective was to find the constraints on the size of the 3-D DO. A wide range of cases was covered by considering 29 models of the DOs. Only for some models, uniform thermal conditions were achieved.

Be it a 2-D or a 3-D radiant furnace, getting uniform thermal conditions on all locations of the bottom surface of furnace is not feasible [3]. Thus, to have the knowledge about the appropriate locations of a particular 3-D DO can have uniform thermal conditions, it is important to study the effect of locations of the DO on bottom surface of the furnace. The present work is aimed at addressing this issue.

In this work, for the uniform thermal conditions, effect of locations of the 3-D DO has been investigated. For each of the three sizes of the DOs, different possible locations on the bottom surface of the furnace that cover almost all locations, have been studied. For computation the panel heaters are considered along the five walls of the furnace, and the bottom surface not covered by the DO, is insulated. Surfaces of the panel heaters are considered diffuse and/or diffuse specular. For calculation of the radiative information, for such surfaces, in case of furnace design and other problems, the suitability of the radiation element method by ray emission model (REM^2) has been demonstrated in [5,6,30–36]. Since for uniform thermal conditions on the DO, with panel heaters along the along the five walls, the present work aims at exploring the suitability of the locations of the DO, the present problems are solved using inverse technique, and its analysis requires an efficient regularization/optimization tool. The robustness of the GA and its modified version, the MGA [26] in optimization is well established. Thus, in