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Research Paper

Geometric optimization of radiative heat transfer on surfaces of corrugated furnaces

Gleyzer Martins [a], Oscar Saul Hernandez Mendoza [a], Muhammad Amjad [b], Enio Pedone Bandarra Filho [a,*]

[a] School of Mechanical Engineering, Federal University of Uberlandia, Brazil
[b] Department of Mechanical, Mechatronics and Manufacturing Engineering, University of Engineering and Technology, Lahore, Pakistan

HIGHLIGHTS

- Numerical optimization of radiative heat transfer on corrugated surfaces.
- Geometric optimization of radiative heat transfer on combustion chamber.
- Assessment of different optimization methodology applied to radiative heat transfer.

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ABSTRACT

Corrugated furnace technology is used in fire tube steam generators to improve mechanical strength and heat transfer in the furnace. In this paper, geometric optimization of radiative heat transfer of corrugated furnaces using finite volume method with two optimization methods (the method of simulated annealing and the simplex method) is proposed. The methodologies were applied to two benchmark cases: one is a theoretical furnace with a constant temperature profile, gray gas and black cold walls and the other is a combustion chamber with non-gray gas of a given temperature profile and constant temperature gray furnace surfaces. For the first case study, the optimization results indicate that when the gray gas absorption coefficient increases, the corrugation amplitude also increases. However, it has no influence on the number of corrugation points. In the second case study, the problem is ill-posed, thus requiring the non-deterministic characteristic of the simulated annealing method to obtain the optimum condition. In terms of optimization methods, the simulated annealing method obtained better optimization results, especially in the furnace with combustion, at the expense of a greater number of determinations of the objective function.

1. Introduction

The heat transfer in cylindrical furnaces is consolidated knowledge in literature as shown by Kim and Baek [15], Silva [26], Maurente et al. [20] and Carvalho and Farias [6]. However studies of complex corrugated surfaces are not available in literature. Many works demonstrate the use of methodologies for complex surfaces, such as: discrete ordinates method Chai [8] and Chai and Rath [9]; finite volume method Byun et al. [5] and Kim [17]; discrete transfer method Talukdar [29]; Monte Carlo method Baek et al. [2] and zone method Coelho et al. [11]. In general these works determine the radiative heat transfer between the exchange surfaces without considering the effects of shading, only the work of Coelho et al. [11] determines the net heat flux in cavities with obstacles.

Currently the constructive design of both fire tube and water tube steam generators is very robust with projects consolidated in more than 40 years of industry [30], resulting in secure designs of high capacity and low emissions of harmful gases to the atmosphere. However the incorporation of numerical optimization methods (such as simplex and simulated annealing methods), together with the simplification of the decoupled problem of energy conservation equation, momentum equation and radiative transfer equation using a predetermined temperature profile, can obtain significant improvements in the design of these equipment.

In terms of numerical optimization, Aarts et al. [1] and Rao [23] highlighted the simulated annealing method as a versatile and robust tool for problems of continuous or discrete design variables, making it possible to obtain global optimum in nonlinear problems

* Corresponding author.
E-mail address: bandarra@ufu.br (E.P. Bandarra Filho).

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Nomenclature

Symbols

a	coefficient of the discretization
A	faces areas
$D_k^{m,n}$	directional weight
$F(X)$	objective function
h_{Amp}	half amplitude of corrugation
I	radiation Intensity
I_b	blackbody radiative intensity
$\mathbf{n}$	unitary vector area
N_p	number of points of corrugation
q	radiative heat flux
q_s	dimensionless radiative heat transfer
Q	radiative heat transfer rate
S_p	radiative source function
$\hat{\mathbf{s}}$	directional vector
$\mathbf{r}$	position vector
r	coordinate Axis
T	temperature
V	discrete volume elements
X	design variables

Greek symbols

β	extinction coefficient
ε	emissivity
κ	absorption coefficients
σ_s	scattering coefficient
ϕ	azimuthal angle
θ	polar angle
Φ	scattering phase function
ω	scattering albedo
Ω	solid angle
$\mu\eta\xi$	cosine directors of the radiation intensity

Subscripts

b	blackbody
e,w, n, s, t, b	control volume faces
p	present control volume
w	wall

Superscripts

m, n	radius direction
$\pm 1/2$	control angle faces

that are ill-posed with local minimums. However it requires the evaluation of a large number of objective functions, i.e., for each geometric configuration proposed by the method, the objective function has to be evaluated many times. In well-conditioned problems, the simplex method seems to be outstanding because of the ease and versatility of implementation and application, requiring a smaller number of evaluations of objective functions.

In this paper, the surface geometry optimization of a theoretical furnace and a combustion chamber with predetermined gas temperature profile is developed. The heat transfer by thermal radiation is modeled by the finite volume method, as in Kim [17] and Kim and Baek [15]. The method is initially used in numerical validation of the theoretical furnace and sinusoidal nozzle surfaces with different absorption coefficients and the results are compared with the works of Kim and Baek [15] and Nunes et al. [22] respectively and also a combustion chamber with predetermined gas temperature profile modeled by Silva [26]. The optimization methodologies are the classic simplex method of Nelder and Mead [21], and the simulated annealing method developed by Saramago [24].

2. Numerical methods

2.1. Finite volume method

The finite volume method is characterized by separation of geometric elements for radiative calculation. It gives excellent flexibility and ability to adapt to different geometries. The method for axial symmetric geometry was described in detail by Kim [17] for cylindrical coordinates and applied to different problems with complex geometries, Kim and Baek [16] and Kim and Baek [15]. Authors such as Tian and Chiu [31] and Ben Salah et al. [4] developed similar techniques considering cartesian and cylindrical coordinates respectively. The treatment of the azimuthal radiation intensity derivative term of the radiative transfer equation was differentiated.

The finite volume method is based on volumetric and directional integration of the radiative heat transfer equation for cylindrical coordinates, given by:

$$\int_{\Delta\Omega}\int_{\Delta V}\frac{1}{r}\cdot\frac{\partial}{\partial r}(r\cdot\mu\cdot I)dVd\Omega+\int_{\Delta\Omega}\int_{\Delta V}\frac{1}{r}\cdot\frac{\partial}{\partial\phi}(\eta\cdot I)dVd\Omega$$
$$+\int_{\Delta\Omega}\int_{\Delta V}\frac{\partial}{\partial z}(\xi\cdot I)dVd\Omega=\int_{\Delta\Omega}\int_{\Delta V}\{\kappa(\mathbf{r})I_b(\mathbf{r})-[\kappa(\mathbf{r})$$
$$+\sigma_s(\mathbf{r})]I(\mathbf{r},\hat{\mathbf{s}})+\frac{\sigma_s(\mathbf{r})}{4\pi}\int_{\Omega_i=0}^{4\pi}I(\mathbf{r},\hat{\mathbf{s}}_i)\Phi(\mathbf{r},\hat{\mathbf{s}},\hat{\mathbf{s}}_i)d\Omega_i\}dVd\Omega \quad (1)$$

where μ, η and ξ represent the cosine directors of the radiation intensity I, position r and direction $\hat{\mathbf{s}}$ respectively. I_b is the black body radiation intensity and the radiative properties of the participating media are given by the absorption κ and scattering σ_s coefficients of the medium. The volume and direction integrals are discretized in a mesh of volume elements dV and solid angle elements $d\Omega$. The radiation intensity is constant on each face of the volume element and solid angle. Similarly the volume integral values are constant and equal to a value at point p. Applying the divergence theorem, the equation becomes:

$$\sum_k I_{ki}A_{ki}(\mathbf{s}_i\cdot\mathbf{n}_k)=\beta_p\cdot(S_{pi}-I_{pi})V\cdot\Omega_i \quad (2)$$

where $(\mathbf{s}_i\cdot\mathbf{n}_k)$ is the dot product of the direction of the radiation intensity and the normal vector at the face of the volume p, β is the extinction coefficient and the term S_{pi} is radiative source function, given by:

$$S_{pi}=(1-\omega_p)I_b+\frac{\omega_p}{4\cdot\pi}\sum_{j=1}^{n}I_{pj}\overline{\Phi}_{ij} \quad (3)$$

Similarly, ω_p is the scattering albedo, where I_b is the black body irradiation and $\overline{\Phi}_{ij}$ is the average scattering phase function.

The dot product of the radiation intensity and the normal vector at volume face area are defined by the integration of the elements on the left of the radiative transfer equation Eq. (2) and discretized according to Fig. 1. The weight functions $D_k^{m,n}$ are given by the integral of each of the faces, as follows:

For the north and south sides: