THE APPLICATION OF DISCRETE TRANSFER METHOD IN THE SIMULATION OF RADIATION HEATING OR COOLING

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(Received 29 May 2002; Accepted 18 October 2002)

ABSTRACT

This paper presents a brief introduction of discrete transfer method (DTM) and the results compared with other methods in the calculation of radiation heat transfer. It is concluded that DTM is very simple, reliable and valid in the calculation of radiation heat transfer. It was also shown that DTM should be advocated and applied in such fields as CFD, assessment of thermal comfort, design of radiant heating or cooling etc.

1. INTRODUCTION

Radiation is a complicate phenomenon, particularly in an absorbing, emitting and scattering medium. The equations of radiant heat transfer are highly nonlinear. In practice engineers adopt various methods such as Monte-Carlo method (MCM), zonal method (ZM), flux method (FM), spherical harmonics method, discrete ordinate method to handle the radiation integral equations.

MCM can be applied in the fields with complex boundary and handle various wavelength radiation conveniently. Its result fluctuates around the true solution. By increasing the number of rays traced, it will get the actuate result eventually. But it will consume a lot of computation time and may encounter strong challenges of converging difficulties. ZM is not suitable to solve the cases with complex boundary conditions. It also cannot deal with nongray body and the cases in which the radiant property is the function of temperature. FM is very simple, but with poor precision, sometimes cannot accord with the physical phenomena and cannot deal with scattering, anisotropism medium.

Those methods mentioned above consume a lot of computer time and need high memory. Discrete transfer method (DTM) has the characteristic of all above methods. Its main idea is to consider the boundary surface as the radiant source and absorption. It divides energy emitted into the hemisphere into finite number of rays and assumes that the radiation leaving the surface element in a certain range of solid angles can be approximated by the single ray. Those rays are absorbed or reflected by the inner grid before they reach the boundary grids. The energy balances at each boundary surface [1-3]. The first description of DTM was presented by Lockwood and Shah [1], and Doherty and Fairweather [2].

Over the last several years scientists and technicians develop the method and have made rapid progress [3]. Coelho and Carvalho [4] find that the DTM being used to calculate radiative heat transfer in combustion chambers is not conservative and put forward the conservative formulation of the method by local correction of energy per unit time of the irradiation rays leaving the boundary.

In order to consider the strong ray effects which usually leads to a large error, Liu et al. [5] presented an improved DTM in which a total of nine discrete directions over a control angle instead of a single discrete direction as used in the traditional DTM was selected and the incident radiative intensity over this control angle is then replaced by a weighted-averaged intensity from these nine discrete directions.

Talukdar and Mishra [6] investigated the effect of variable thermal conductivity on transient conduction and radiation heat transfer in a planar medium. Versteeg et al. [7] discussed the truncation error due to the spatial discretisation of the enclosure surface and medium conditions. Liu and Chen [8] investigated the accuracy and efficiency of the MDTM compared with the solutions from the exact approach, the DTM, and discrete ordinates method (DOM) with three benchmark problems covering different geometric and boundary conditions. Malalasekera [9] used a generalized weighted-sum-of-gases-discrete transfer deal with a complex geometry of a pent-roof spark-ignition engine and got the instantaneous radiative heat flux.

Furthermore they integrated the WDT into the computational fluid dynamics code KIVA-II. Versteeg et al. [10] examine approximation errors in the heat flux integral of the discrete transfer method. Novo et al. [11] use the ray domain
decomposition and the spatial domain decomposition in the application of DTM and achieve good accurate result. Docherty and Fairweather in their paper [2] get the prediction of radiative transfer from non-homogeneous combustion products using the DTM.

In this study, we use the discrete transfer method to solve the radiation heat transfer in the design and assessment of radiation heating especially the net heat gain of the targets (such as persons) which is very important for the engineers but is still far from solution.

2. THE PHYSICAL IDEA OF DISCRETE TRANSFER METHOD

A detailed description of the discrete transfer method can be found in Lockwood and Shah [1]. We will only consider aspects of the algorithm of relevance to the issue addressed in the present article. The grids used for both DTM method and flow field simulation are identical. We call the boundary element surface that emits energy as radiating surface, surface that receives energy is termed as receiving surface (See Fig. 1). In Fig. 1, P_i and P_j are the boundary grids whose center points are P_i and P_j. At the boundary grid P_i, we can draw N = N_θ × N_φ rays which divide the hemisphere of P_i into many differential solid angles. The direction of each differential solid angle (dΩ_r) is Ω_r. The rays are called characteristics line. The N rays will intersect other boundary faces at N points. At each radiating surface, rays are fired at discrete values of the zenith and azimuth angles (θ = 0 ~ 90, φ = 0 ~ 2π), covering the radiating hemisphere). Each ray is then traced to determine the control volumes it intercepts as well as its length within each control volume. The transfer equation for thermal radiation along a ray, neglecting scattering can be written as the following formulation.

\[
\frac{dI}{ds} = -aI + \frac{a\sigma T^4}{\pi}
\]  

(1)

The intensity entering and leaving the control volume (or grid) is then computed by integrating the radiation transfer equation (1) along a series of rays emanating from the boundary faces in each discrete control volume as:

\[
I_{n+1} = \frac{\sigma T^4_n}{\pi} (1 - e^{-as}) + I_n e^{-as}
\]

(2)

where T is the temperature of the medium in the control volume (K); a is absorption coefficient; s is the ray’s length within the grid (or control volume), m; \( \sigma \) is Stefan Boltzmann constant (5.672E-8 Wm^{-2}K^{-4}); I_n and I_{n+1} are the intensity of the ray on entry and exit at the nth control volume.

The radiation intensity approaching the point P_i is integrated to yield the incident radiation heat flux, q^+ as:

\[
q^+_p = \int I d\Omega = \sum_{r=1}^{N} I_r \sin \theta \cos \phi d\phi
\]

(3)

where \( \Omega \) is the hemispherical solid angle; and I is the intensity of the incoming ray.

The net radiation heat flux from the element P_i is then computed as a sum of the reflected portion of q^+_p and the emissive power of the element:

\[
q^-_p = (1 - \varepsilon_w)q^+_p + \varepsilon_w \sigma T^4_w
\]

(4)

where \( \varepsilon_w \) is the emissivity of wall; and T_w is the temperature off wall.

Hence, for grey walled enclosures, the element boundary condition for the radiation intensity I_op of the ray emanating from the point P_i can be calculated approximately using the following equation.

\[
I_{op} = q^-_p / \pi
\]

(5)

where I_{op} is the radiation intensity of the element boundary at the point P_i.

3. THE FLOW CHART OF DISCRETE TRANSFER METHOD

Since the initial value of the radiation intensity emanating form the boundary surface is not known exactly, the incident flux and emitted intensity make the discrete transfer method a guess and correct procedure in which an estimate of the incident flux distribution is iteratively improved. So we can draw the flowchart of DTM in Fig. 2.
For the compromise between computation time and precision, the convergence criterion is set to 0.001 in the program. Of course the smaller the criterion value, the more computation time is needed, and the more accurate the prediction of radiative heat distribution is obtained.

4. APPLICATIONS

The calculation example is shown in Fig. 3. The walls (or ceiling and floor) are labeled by the number from 0 to 5. The parameters of both the enclosures and person are written in Table 1.

The calculation results are shown in Figs. 4 to 8 and Tables 2 to 4. Because of symmetry of the calculated room, it is easy to verify the results qualitatively. Furthermore, the total heat gain is in very good agreement with the results computed by other methods. The net heat gain of the person is also approximately equal to the results using the view factor. So we can say the results are reliable and believable.
Fig. 7: Net heat contours of the surface 3

Fig. 8: Net heat contours of the surface 4 or 5

Table 1: The parameter of the walls and person

<table>
<thead>
<tr>
<th>Label or name</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Person *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td>11</td>
<td>25</td>
<td>13</td>
<td>10</td>
<td>13</td>
<td>13</td>
<td>28</td>
</tr>
<tr>
<td>Emissivity</td>
<td>0.6</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.8</td>
<td>0.97</td>
</tr>
</tbody>
</table>

* outer surface parameter of clothing

Table 2: Net radiation heat gain of the person under different temperature of radiator

<table>
<thead>
<tr>
<th>Temperature (°C)</th>
<th>25</th>
<th>30</th>
<th>35</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net radiation heat (W)</td>
<td>-94.8</td>
<td>79.1</td>
<td>86.7</td>
</tr>
</tbody>
</table>

Table 3: Convergence time and mean relative error under difference Nθ, Nφ
(compared with the results calculated using zonal method)

<table>
<thead>
<tr>
<th></th>
<th>Nθ = 50</th>
<th>Nθ = 100</th>
<th>Nθ = 150</th>
<th>Nθ = 100</th>
<th>Nθ = 100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Convergence time (s)*</td>
<td>58</td>
<td>116</td>
<td>174</td>
<td>173</td>
<td>231</td>
</tr>
<tr>
<td>Relative error (%)</td>
<td>0.88</td>
<td>0.86</td>
<td>0.77</td>
<td>0.62</td>
<td>0.58</td>
</tr>
</tbody>
</table>

* Datum obtained by the computer with CPU: PENTIUM-MMX166 MEM: 32M

Table 4: Relative error compared with the results by other methods
(Each surface was divided into 100 zones)

<table>
<thead>
<tr>
<th>Label of enclosure</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>Maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compared with</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>zonal method</td>
<td>-1.22%</td>
<td>0.06%</td>
<td>0.40%</td>
<td>-0.54%</td>
<td>-1.79%</td>
<td>-1.19%</td>
<td>-1.22%</td>
</tr>
<tr>
<td>Compared with</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Monte-Carlo method</td>
<td>1.67%</td>
<td>-0.87%</td>
<td>0.67%</td>
<td>-0.34%</td>
<td>1.34%</td>
<td>-3.2%</td>
<td>2.10%</td>
</tr>
</tbody>
</table>

For the same problem, it took about 8 minutes to converge by Monte Carlo method. Meantime view factor and both direction and total exchange area of the person can be obtained using the DTM too (omitted).

5. CONCLUSIONS

From the calculation results, we can get the distribution of radiant energy. If the radiant energy was used as the heat source and handled as the second boundary condition, it is ready for the
simulation of flow field. It can also be used in the study of thermal comfort of people. Furthermore, it is very expedient to estimate the total radiant heat and to predict the effect of the project of heating or cooling by radiator during the design stage.

REFERENCES


