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# Radiative heat transfer for irregular geometries with the collapsed dimension method

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**Abstract**

A blocked-off region procedure is implemented with the collapsed dimension method (CDM) to deal with radiative transport problems in irregular geometries. Different test problems are validated for radiative and non-radiative equilibrium situations in participating or non-participating media. Results are found to be satisfactory for all straight edged, inclined and curved boundaries. The blocked-off region procedure based on Cartesian coordinate is found to be very convenient for a ray-tracing method like the CDM. The same ray tracing algorithm for a rectangular enclosure could be effectively used for any kind of 2-D geometries. This significantly reduces the effort of developing different ray-tracing algorithm for different geometries. In addition, it is an alternative than to write an algorithm in curvilinear coordinate for irregular geometries which found to be complicated for a ray-tracing method like the CDM.


*Keywords:* Collapsed dimension method; Blocked-off region; Radiation; Participating media; Irregular geometry

## 1. Introduction

The popularity and usefulness of a method basically lies in its implementation to real geometries. Almost all the real geometries are irregular and complex in nature and is the reason for ever increasing trend of research in radiative heat transfer for complicated geometries. It has also become a challenge for a particular method as far as its applicability and accuracy with the irregular structures are concerned.

Most of the papers dealing with the irregular geometries for radiative transport are found in the 90's. Sanchez and Smith [1] used the discrete ordinates method for surface radiative exchange between the faces of geometries with straight edged protrusions and obstructions. Chai et al. [2,3] simulated radiative transfer in irregular geometries using the discrete ordinates method [2] and the finite volume method [3]. They used a similar blocked-off region procedure to simulate the irregularities based on Cartesian coordinate. They found satisfactory results and discussed the advantages and disadvantages found with this procedure. Koo et al. [4] studied the effect of three different discrete ordinates methods applied to 2-D curved geometries. In another paper, Koo et al. [5] discussed the first order and second order interpolation schemes in context with the irregular geometries. Monte Carlo method has been applied by Parthasarathy et al. [6] for irregular geometries. They considered a rhombus, a quadrilateral and an enclosure with curved and straight edged boundaries. They considered absorbing, emitting and anisotropically scattering medium. Sakami and Charette [7] discussed a modified discrete ordinates method based on triangular grids with a new differencing scheme applicable to different complex geometries. Some works for 2-D irregular geometries has been done by Meng et al. [8] using the discrete transfer method with a finite element formulation. Some of the papers are also devoted to 3-D irregular geometries. Malalasekera and James [9] implemented the discrete transfer method to a 3-D L-shaped enclosure and a cylindrical enclosure based on a non-orthogonal, body-fitted coordinate system.

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**Nomenclature**

| | | |
|---|---|---|
| $I$ | intensity | $W\cdot m^{-2}\cdot sr^{-1}$ |
| $M$ | total number of intensities/rays | |
| $p$ | phase function | |
| $q$ | heat flux | $W\cdot m^{-2}$ |
| $S$ | source function | $W\cdot m^{-2}$ |
| $T$ | temperature | K |
| $T_g$ | temperature of the isothermal medium | K |
| $T_h$ | temperature of the hot boundary | K |

*Greek symbols*

| | | |
|---|---|---|
| $\alpha$ | planar angle | rad |
| $\Delta\alpha$ | angular thickness of the discrete planar angle | rad |
| $\beta$ | extinction coefficient | $m^{-1}$ |
| $\eta$ | collapsing coefficient | |
| $\varepsilon$ | emissivity | |
| $\sigma$ | Stefan–Boltzmann constant | $W\cdot m^{-2}\cdot K^{-4}$ |
| $\tau$ | optical thickness/depth | |
| $\omega$ | scattering albedo | |

*Subscripts*

| | |
|---|---|
| ref | reference |
| w | boundary/wall |

Malalasekera and Lockwood [10] also used the discrete transfer method in conjunction with a cell-blocking procedure based on Cartesian coordinate to model combustion and radiative heat transfer in complex three-dimensional tunnel geometry.

The CDM is one of the new methods emerging out in radiative transfer problems with participating and non-participating medium. The method is tested for different situations [11,12] and found to be satisfactory. It is accurate and also economical for a 2-D problem [12]. The method is also implemented for complex geometries [13] for limited cases of non-radiative equilibrium situation. A separate ray-tracing algorithm was developed for cylindrical, L-shaped and quadrilateral geometries. Due to the complexities associated with the radiative equilibrium situation for these type of geometries, it was not implemented for those situations. Even for non-radiative equilibrium, its ray tracing was quite tedious depending on the shape of the geometries. The biggest disadvantage suffered by this method was the non-availability of a single algorithm which can handle any kind of geometries. The present blocked-off region approach extends the applicability of the CDM and makes it more general in radiative transport problems in participating medium.

The concept of blocked-off region for radiation was first implemented by Chai and his co-workers for the finite volume method [3] and the discrete ordinates method [2]. They validated the results for different test problems and discussed the advantages and disadvantages of this approach.

The implementation of the blocked-off region approach to the CDM is very straightforward. Although conceptually it is similar to the work of Chai et al. [2], as far as its implementation is concerned, it has a different approach which is quite simple. A whole rectangular domain which can be called as a nominal or simulated domain is simulated, out of which one portion is considered to be inactive or blocked-off and the remaining portion is the actual domain where solutions are sought. As soon as an intensity travels through these inactive regions, its value becomes zero. The tedious part of ray tracing is only once developed for a 2-D rectangular geometry and can be successfully implemented to different irregular geometries by dividing the domain into inactive and active sub domains. Five different test problems are considered to check its accuracy and applicability. The CDM fully enjoys this new concept and presents satisfactory results.

## 2. Analysis

Radiative transfer in irregular geometries is treated with a concept used in CFD [14]. The algorithm written for a regular grid can be modified to handle an irregularly shaped calculation domain. This is done by making some of the control volumes of the regular grid inactive or blocked-off so that the remaining active control volumes represent the desired irregular domain.

Two sample geometries are shown in Fig. 1. The real domain of interest is calculated by considering the whole rectangular domain mentioned as simulated domain. The shaded portion is the inactive or blocked off region where solutions are not required. In Fig. 1(b), a curved boundary is shown which can also be handled by this concept with the step size grid. This way any type of 2-D geometry can be modelled from a rectangular domain. The main advantage achieved with this concept is that the same ray tracing algorithm can be applied to any kind of irregular structures with a little expense of computational time.

The CDM [15] is a ray tracing method. To calculate flux or incident radiation at a certain location, intensities from all directions $\alpha$ $(0 \leqslant \alpha \leqslant 2\pi)$ [11,15] have to be calculated. In the CDM, the intensities are always traced from the boundaries. If the boundary temperature is known, intensities at the boundary can be calculated from the relation,

$$I_w = \frac{\varepsilon_w \sigma T_w^4}{2} + \frac{1-\varepsilon_w}{2} \int_{\alpha=0}^{\pi} I^-(\alpha) \sin\alpha \, d\alpha \tag{1}$$

On the right-hand side, the first term in the above equation is the emitted part and the second term is the reflected part