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Macro-voxel algorithm for adaptive grid generation to accelerate grid traversal in the radiative heat transfer analysis via Monte Carlo method

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ABSTRACT

In the thermal radiation analysis via Monte Carlo method, the ray tracing algorithm often consumes a significant fraction of CPU time. As such, an efficient grid traversal algorithm can considerably affect the performance of the Monte Carlo method. This paper presents a new grid traversal acceleration algorithm by merging adjacent small empty voxels in a preprocessing step due to the fact that larger empty space, named "macro-voxel", allows for traversing a ray over a large distance at a smaller cost. The proposed algorithm is validated theoretically, and the results are examined for a gray box with diffuse surfaces. Timing results of the new algorithm are compared with the USD method in a typical 3D radiation furnace with concave geometry and the speedup ratio of both the macro-voxel algorithm and the USD method with respect to direct method are calculated for an optimal grid of voxels. For the considered geometry, the macro-voxel algorithm is found to be clearly superior to the USD even if the size of the problem is large and the geometry is not convex.

1. Introduction

Radiation is the dominant mode of energy transfer in high temperature environments including combustion chambers and furnaces and in the semiconductor industry for thermal processing of wafers [1–2]. The Monte Carlo method [3–4] is one of the most versatile and widely used numerical tools in calculation of the radiative distribution factors [4] among enclosure surfaces. Practical applications of enclosures such as radiation furnaces involve complex three-dimensional geometries and surfaces with complicated surface properties. Currently due to rapid growth in computer speed, memory and availability, the Monte Carlo method has evolved from an expensive and approximate estimation tool to a more feasible accurate and cost-effective approach. As each ray bundle can independently be considered in the Monte Carlo calculations, the method is quite suitable for parallel programming with today's more powerful computers. The disadvantage of this method is that, as a statistical method, it is subject to statistical error.

Monte Carlo method is widely used in solar energy applications, as well. Zhou and Qiu [5] utilized the Monte-Carlo integral method to calculate the direct exchange area in the zone method for the modeling and simulation of the radiation transfer in an industrial furnace. The Monte Carlo method was used by Mazumder and Kersch [1] to model radiative transport in rapid thermal processing (RTP) and thermal chemical vapor deposition (RTCVD) reactors. The basic algorithm and a modified form of the binary spatial partitioning (BSP) algorithm was implemented to speed up ray tracing by at least a factor of 3.

Wang [6] developed an accurate stochastic algorithm to estimate view factors between canyon facets in the presence of shade trees and considered the potential of shade trees in mitigating canyon surface temperatures as well as saving of building energy use.

In the other work, Yi et al. [7] developed the Monte Carlo method for solving transient radiative transfer in one-dimensional scattering media with arbitrary distributions of refractive index exposed to a collimated short pulse-laser irradiation at one of its boundaries in which time shift and superposition principle was applied. Also, Kovtanyuk et al. [8] applied Monte Carlo method in the coupled radiative–conductive heat transfer mode in a chamber by two specularly and diffusely reflecting boundaries with anisotropic scattering medium. In this case a recursive Monte Carlo method was proposed and then the diffusion approximation of the radiative transfer equation was utilized to solve radiative heat transfer equation and an equation of the conductive heat exchange. Mirhosseini and Saboonchi [9] used the Monte Carlo method to determine view factor for the plate including strip elements to circular cylinder as a case in heating and cooling processes in material processing. The analysis displayed the differences between the numerical results obtained and analytical solutions and they indicated that smaller elements require more effort to obtain an accurate view factor.

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The heart of MCRT method is the ray tracing algorithm which the central computational issue is the determination of the intersection point between an infinite ray and a large set of discrete surface boundary elements. Thus, without doubt, acceleration of ray tracing in large geometries with a large number of boundary faces is essential. Of all the acceleration techniques reviewed by Arvo and Kirk [10], two general techniques are the most promising: bounding volumes and spatial subdivision. According to Arvo and Kirk [10], defining bounding volumes for groups of arbitrary objects would be difficult and probably not improve the efficiency especially in a domain with obstructions which several boxes will have to be checked for a given ray to find the nearest intersection point. Spatial subdivision works with a different philosophy. Two of the most popular non-uniform spatial subdivision techniques are the Octree [11] and the binary space partition (BSP) tree [12] that subdivides three-dimensional space into a finite, non-overlapping set of voxels. Octrees are created by recursively dividing a large box around the geometry into eight subordinate octants until the resulting "leaf" voxels meet the prescribed termination criteria, such as a certain maximum number of surfaces per voxel. A BSP tree is created by recursively bisecting the computational domain at each level of the tree into two pieces using a separating plane. For convenience, the planes are often aligned with the coordinate axes. In uniform spatial division (USD) [11,13] a regular three-dimensional grid of voxels of uniform size is superposed on the computational domain. Although the geometry is not divided as efficiently as the Octree and BSP methods, the next voxel is found very efficiently by incremental calculations. The USD algorithm has been used by Zeeb [14] for Monte Carlo calculations in nonparticipating media enclosed by large, complex geometries. Four complex geometries containing between 1000 and 5000 surfaces were examined for efficiency of the proposed algorithm in determining intersection points. It was shown that a good first estimate of the optimal grid is 15,000 voxels. The maximum obtained speedup ratio in this study was as great as 81. The proposed ray tracing algorithm was found to be 33% to 45% faster than the earlier version of ray-plane intersection which focused on the point of intersection instead of calculating the intersection distance.

Mazumder [15] examined BSP and volume-by-volume advancement (VVA) algorithms to accelerate ray tracing for two classical problems, namely an open box, and a box in a box, in both two-dimensional and three-dimensional enclosures. The VVA algorithm works in such a way that traces a ray from its emission point and follows up its advancement through volumetric mesh until a legitimate intersection point is found. The VVA algorithm obeyed the scaling law as $M^{1/2}$ whereas the CPU time of the BSP method scaled super-linearly. The efficiency of the VVA algorithm was found to be superior in comparison with the BSP algorithm, especially when obstructions were placed in the geometry. The maximum computational gain in case of using VVA algorithm was a factor of 334 whereas the computational gain using the BSP algorithm was found to be a factor of 52. The VVA algorithm is easy to implement without need to any preprocessing steps. The BSP algorithm, without any adaptation, will result in an unbalanced tree, which can easily lead to costly, incoherent memory accesses and cache thrashing as the enclosure boundary faces are increased.

Naeimi and Kowsary [16] developed a new ray-object intersection algorithm based on the well-known Simplex method from linear programming. In this algorithm, feasible region is defined by a set of plane equations of enclosure boundaries. Intersection point is the one that maximize the line equation of the emitted ray as the objective function. The advantage of this ray-object intersection method was that it is easy to implement and by using this algorithm number of objects which must be checked in complex geometries will be reduced considerably although the computation time of this method may be a bit higher than the conventional time for simple objects.

In more recent work an optimized and accurate Monte Carlo method was examined by Naeimi and Kowsary [17] for simulation of 3D complex radiative enclosures. The performance of the Monte Carlo method was enhanced by implementing efficient algorithms to find location of emission and direction of emission. Next, the best acceleration ray tracing algorithm was determined by comparing timing results of the USD, the BSP, the Simplex and the VVA algorithms while the constrained maximum likelihood estimation was used to enhance its accuracy. Although the USD algorithm was found to be 20% to 32% slower than the VVA algorithm, it is very easy to implement with respect to VVA algorithm in the Monte Carlo code.

In this article, the macro-voxel algorithm is introduced for the first time and is discussed in significant detail. Timing results are computed for a typical three-dimensional radiation furnace composed of several tens of thousands of boundary faces to demonstrate the efficiency of the new algorithm. This in-depth study is completed with recommendations about optimally applying the proposed algorithm to large radiative geometries.

2. Method of analysis

As a case study, heat exchange in a black box and a typical three-dimensional radiation furnace with diffuse gray surfaces is considered using the Monte Carlo method by estimating "distribution factors" [4].

Radiation transport between one surface or volume element to one of other surfaces or volume elements of the enclosure can be described by a radiation distribution factor, D_{ij}, which is defined as the fraction of the total radiation emitted from surface element i that is absorbed by surface element j, due to both direct radiation and all possible reflections within the enclosure. If the estimated distribution factor and the exact distribution factor are denoted by $\widehat{D}_{ij}$ and D_{ij}, respectively, they may be related as

$$D_{ij} \approx \widehat{D}_{ij} = N_{ij}/N_i \quad (1)$$

where N_i is the number of emitted bundles from surface i, and N_{ij} is the number of these bundles which are absorbed by surface j, directly or indirectly. N_{ij} is calculated using the Monte Carlo method.

Total diffuse-specular radiation distribution factor obeys the conservation of energy, reciprocity and closure relations. Applying these principle relations, the net radiative heat transfer rate on surface element i may be written as

$$Q_i = \varepsilon_i A_i \sum_{j=1}^{M} (\delta_{ij} - \widehat{D}_{ij}) \sigma T_j^4 \quad (2)$$

where M is the total number of boundary faces, and ε_i and A_i are the hemispherical, total emissivity and surface area of emitting surface. T_j is the temperature of jth face, and δ_{ij} is the Kronecker delta.

2.1. The Monte Carlo ray tracing method

Monte Carlo ray tracing method is a statistical approach in which advancement of any emitted energy bundle is followed from its emission point until it is absorbed either after direct travel or after any number of reflections or until it leaves the enclosure.

2.1.1. Location of emission point

In order to estimate the radiation distribution factors we need to determine emission point for each energy bundle. This emission point is obtained from random surface emission routine by Turk [18]. By using two uniformly distributed random numbers between zero and one, R_1 and R_2, and three vertices of triangle, V_1, V_2 and V_3, following relations are used to determine the emission point, R_0:

$$\begin{aligned} R_0 &= (1 - R_1 - R_2)V_1 + R_1 V_2 + R_2 V_3, && R_1 + R_2 \le 1, \\ R_0 &= (R_1 + R_2 - 1)V_1 + (1 - R_1)V_2 + (1 - R_2)V_3, && R_1 + R_2 > 1. \end{aligned} \quad (3)$$

In order to reduce the overhead of calculations of the code each boundary face is divided into triangles and considered as a constant temperature surface in thermal radiation calculations. This separation