A GRAPHICS CARD ACCELERATED SURFACE-TO-SURFACE RADIATION MODEL FOR OPENFOAM

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Summary. Radiation heat transfer between surfaces is important in high-temperature processes in industry or for energy and building applications. The computational cost associated with surface-to-surface radiation model can dominate the combined mode heat transfer problems. In this study, a GPU-accelerated Monte Carlo ray tracing based surface-to-surface radiation model is developed and integrated into the open source OpenFOAM framework. The effect of the new surface-to-surface radiation model on the overall computational performance of the conjugate heat transfer solver is tested on a conjugate heat transfer scenario. The new radiation model shows a 80x speed-up advantage over the available view factor model in OpenFOAM resulting in a 7x speed-up in the overall run time of the conjugate heat transfer solver in the selected scenario.

1 INTRODUCTION

Thermal radiation, as one of the three heat transfer mechanisms, has a considerable contribution to the overall heat transfer in many physical phenomena and processes, particularly at high temperatures and as well as in energy efficiency calculations for buildings. Radiation heat transfer is very different in nature in many aspects in comparison to the conduction and convection heat transfer. Surfaces can directly transfer heat across large distances by the thermal radiation. However, conduction and convection heat transfer are much more local phenomena. Moreover, thermal radiation is also different than the other heat transfer mechanisms in terms of its dependency on the angular direction. Due to these two aspects of thermal radiation, the overall computational cost of combined mode heat transfer problems might be dominated by the thermal radiation calculation.

Radiation heat transfer between surfaces relies on view factor calculations. One of the computational methods used for view factor calculation is the Monte Carlo ray tracing method that is discussed in detail by Howell et al. [1]. This method is known with its superior accuracy and excessive computational cost. However, the suitability of the method to parallelization increases its feasibility with the use of the many-core hardware architecture.

In this study, a GPU-accelerated Monte Carlo ray tracing (MCRT) based surface-to-surface radiation model has been developed. The method is first used to calculate the view factors between the surfaces and the results are compared with the built-in view factor calculation tool within the OpenFOAM framework. Next, the developed MCRT based surface-to-surface radiation model is integrated into the conjugate heat transfer solver inside the OpenFOAM framework. After the verification of the present hybrid solver on a conjugate heat transfer scenario, the performance of the developed solver is assessed in terms of the speed-up with respect to the available conjugate heat transfer solver in OpenFOAM.

2 RESULTS

The implementation of the Monte Carlo ray tracing method is carried out according to Modest [2]. The accuracy and the speed of the developed MCRT based view factor calculator is tested on a view factor scenario between two finite plates. As shown in Figure 1, OpenFOAM's own view factor calculation tool carries out the calculation deterministically where as in the present method the rays are emitted from the top plate randomly and the view factor calculations are carried out based on the statistics of the number of hitting rays on the other plate. The accuracies of both tools are compared with the analytical solution [3].

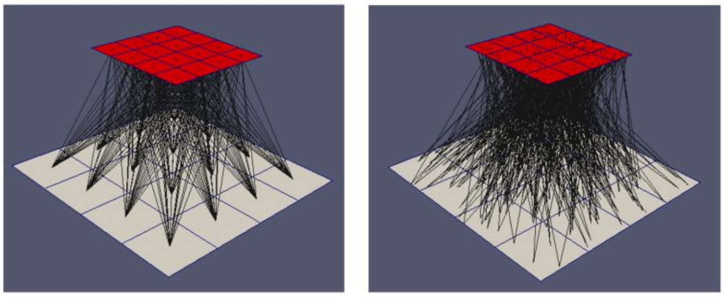

Figure 1: View factor calculations between the two planes (Left calculation was made by OpenFOAM software with deterministic ray tracing method. The right calculation was made by newly developed software with Monte Carlo ray tracing (MCRT) method.)

As shown in Figure 2(a), the accuracy of the OpenFOAM's view factor calculation tool can be increased with the increase in the number of cells on the plate. On the other hand, the accuracy of the present numerical tool is independent of the number of cells present on the plates but depends entirely on the number of rays used in the view factor calculations. Using 1 million rays, the standard deviation of the relative errors is measured as 10e-4 which OpenFOAM view factor calculator can only reach using a plate with 64 cells in every direction.

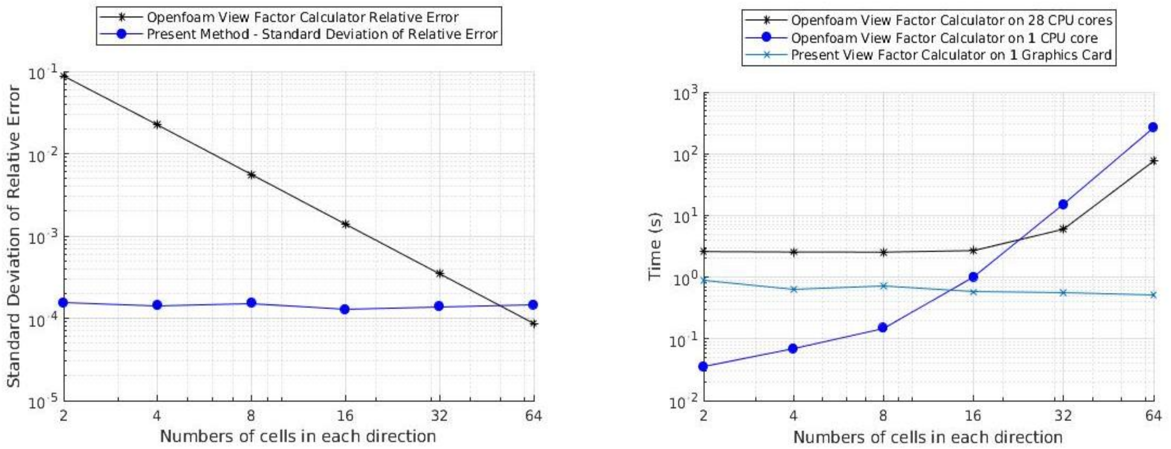

Figure 2(a): Standard deviation of OpenFoam view factor calculator and relative error of present MCRT method. (b)Comparison of the number of cells in one direction on the plane and the calculation periods required by the software for view factor calculations (These calculations are performed on a single core, on 28 cores and newly developed with OpenFOAM software.

Figure 2(b) shows the calculation times required for the different numerical tools used in the view factor study mentioned above. Using OpenFOAM's view factor calculation between surfaces divided into 64x64 cells takes around 300s on a single CPU core and 70s on 28 CPU cores. On the other hand, the present GPU-accelerated view factor calculator can carry out the same calculation at around 0.5s using Nvidia Titan-X GPU and a total ray count of 1 million.

Next, the developed MCRT based view factor calculator is integrated into the OpenFOAM framework as a GPU-accelerated surface-to-surface radiation model to replace OpenFOAM's own view factor model. The new radiation model is selected to work with the available conjugate heat transfer solver "chtMultiRegionFoam" and the effect of the GPU acceleration on the overall run time of the solver is tested on the scenario shown in Figure 3(a). In the selected computational scenario, a glass object is placed inside a hexahedral enclosure with the sides set to the temperatures 300 K and 600 K. As shown, the heating of one side of the glass through the incoming thermal radiation from the hot wall is balanced by the forced convection around the glass and the conduction of the heat within the glass is shown in Figure 3(b). In Figure 4, the total simulation times of the two conjugate heat transfer solvers utilizing the standard view factor model in OpenFOAM and the GPU-accelerated radiation model are compared. As shown, the new radiation model working on a separate GPU accelerates the thermal radiation calculation by 80x which leads to an overall speed-up of around 7x.

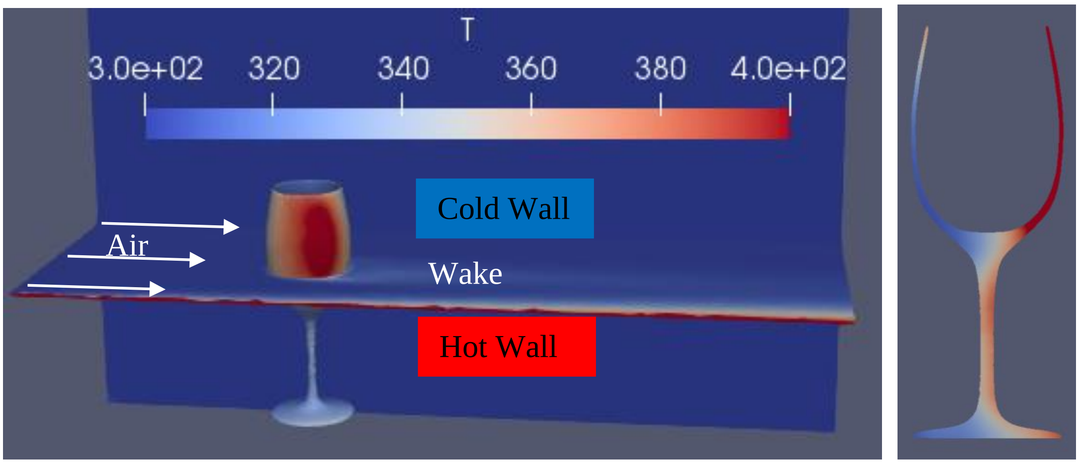

Figure 3(a): Conjugate heat transfer scenario studied to test the accuracy and the speed of the conjugate heat transfer solver with the present Monte Carlo ray tracing based surface-to-surface radiation model.
(b) Temperature distribution inside the glass

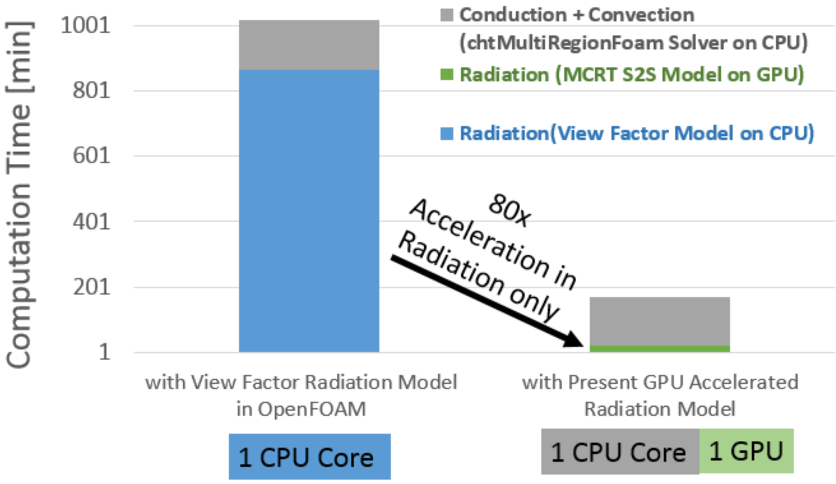

Figure 4: Computation times of the “chtMultiRegionFoam” solvers with the view factor model in OpenFOAM and with the GPU-accelerated surface-to-surface radiation model

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REFERENCES

[1] J. R. Howell, M. P. Menguc, and R. Siegel, Thermal Radiation Heat Transfer. CRC Press, 2016.
[2] Modest, M.F., Radiative Heat Transfer. 2013: Academic Press.
[3] Howell, J.R. and Mengüç, M.P., Web-Based Configuration Factor Catalog: A Listing of Relations for Common Geometries. Journal of Quantitative Spectroscopy and Radiative Transfer,3 rd Edition, 2016.