# Spatial distribution of thermal radiation – verification of the finite volume method

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Abstract

Thermal radiation is one of aspects of fire engineering analysis which is often treated with less attention especially by practicing fire protection engineers. The reason may be its relative complexity and non-trivial verification. Engineers often therefore rely on default models available in numerical programs they use or choose the model that involves smallest computational cost. At the same time there is no good guidance available for practitioners describing the selection or parametrization of the model for adequate accuracy in a given fire scenario. As a result quite often the accuracy remains relatively vague. Thermal radiation is a complex phenomenon especially when considered for compartment fire environment with a number of participating media affecting radiative heat transfer through absorption, dissipation, scattering, reflection and other effects. This complexity can be only addressed with well-developed numerical methods. The validation of the complete model in compartment fire environment is a very difficult task because precise measurements of key variables in multiple locations are very hard to achieve. It is relatively more achievable to study thermal radiation outside the fire compartment where absorption effects are less pronounced. This paper provides description of the verification study performed to assess the accuracy of the Finite Volume Method as it is considered to be the most widely used in fire applications . The understanding of the sources of inaccuracy is expected to lead in the future to the improvement of the method as it is implemented in the most popular CFD package for fire simulations - Fire Dynamics Simulator.

*Keywords: fire protection engineering, thermal radiation, radiative heat flux, finite volume method*

## 1. Introduction

A number of numerical radiation models can be found in literature [1,2]. Among the most often employed methods for radiative heat transfer calculations are the P1 Model, Discrete Ordinates Model (DOM), Discrete Transfer Radiation Method (DTRM) or Finite Volume Model (FVM). The arguably most popular fire engineering tool at the moment – Fire Dynamics Simulator by NIST involves a model that is closest to a Finite Volume Method. Some of these models are implemented or can be used in popular CFD programs like FDS, Ansys Fluent and OpenFoam.

One of aspects of numerical models which can be studied, analysed and compared between models is the spatial distribution of radiative heat flux around radiating objects of various shapes. It has to be noted this is just one of many complex aspects of radiation models, however even in this aspect a thorough comparative study involving effects of the selected model and its parametrization on radiation field is rather difficult to find in fire literature. To be able to produce some comparisons the radiation problem has to be simplified to a number of analytical cases. This can be done through view factor analysis for complex geometries using view factor calculations which produce theoretically exact heat flux field for any geometrical structure based on triangles. An analogic approach has been recently applied by Mason et al [4] where a flame was deconstructed into a 3D radiating surface.

## 2. Finite Volume Method

FVM, similarly to Discrete Ordinates Method (DOM), discretizes the computational domain in spatial and angular directions to account for the spatial and directional distribution of the radiation intensity. It is widely used in many disciplines as it is quite reliable and not as complex and computationally expensive as other methods. There is a number of spatial discretization schemes available for this method [5-8] The step scheme is the simplest among them however it introduces some numerical artefacts like ray effects and false scattering, especially where the radiation source is not linear. It is sometimes not recommended to be used if accurate solutions are sought. There are many references in the literature that offer improvements to this method.

## 3. Verification of FVM using view factor calculations

As the VFM in Fire Dynamics Simulator is tested in limited number of configurations as reported in the FDS Technical Documentation [3], a closer verification of the FVM method for fire related applications has been performed using view factor calculations which are then compared to FVM in the whole domain. The FVM results in this paper are based on the FVM algorithm as used in FDS with all the interfering phenomena like convection, absorption are eliminated by assuming absolute zero conditions, zero gravity (no convection) and no water vapour in the air (no absorption). These are very artificial conditions and they are only supposed to be used for testing the way the radiation energy travels in the domain in the absence of any absorbing, scattering and obstructing media. The concept of the study uses a single cell as the first approach in which the radiative heat flux is prescribed to the wall of the single cell. This setup can provide the closest understanding of how the energy travels in the domain. Then the radiating region is increased to cover more cells. The concept of the study is presented on Fig.1.

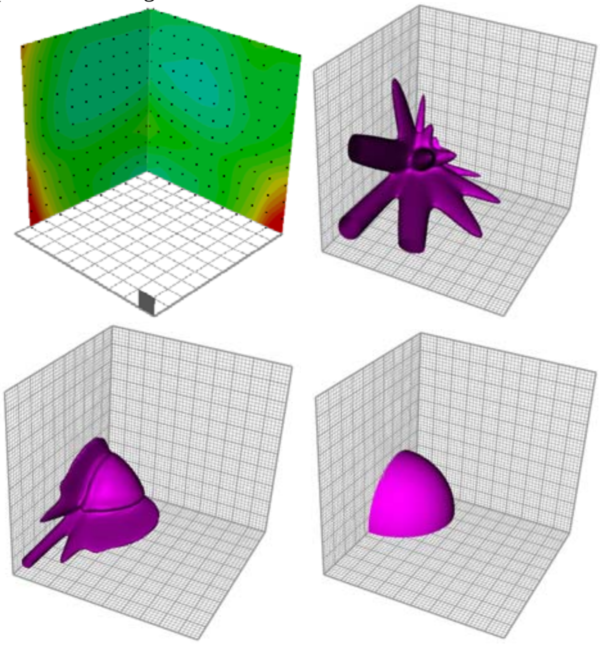

Fig.1 Heat flux contours and isosurfaces for a single radiating cell (100 angles, 1000 angles, exact view factor calculations)

It is clear from results on Fig.2 that the increase in angular resolution causes reduction of error, although it is not uniform in the whole domain. It has also been observed that the relative error is distributed in a way that it does not depend on the spatial resolution itself but rather on the ratio between the cell count from the source to target to the size of the radiating source (cell count). So best results are observed within the cell distance more or less comparable to the size of the radiation source (in cell count), which can be seen on Fig. 2. Further away (in far field) results deteriorate with lower angular distributions. In higher angular resolutions the relation between the error and the distance is less pronounced as seen on Fig.3

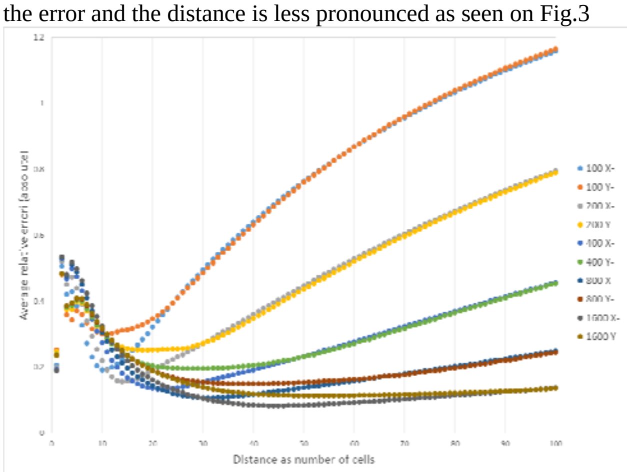


Fig.2 Error vs. distance from radiator for various angular resolutions

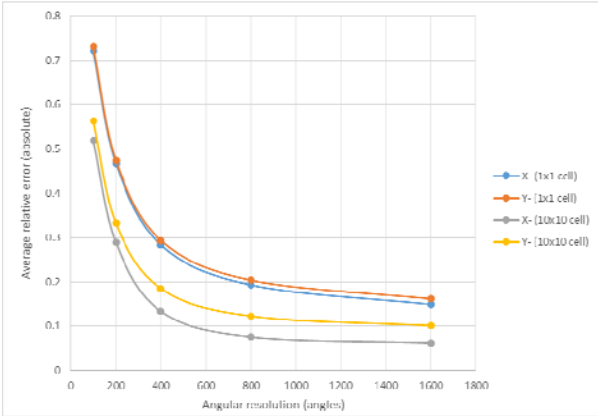


Fig.3 Average error vs. angular resolution for two radiator sizes and receiver orientations

## 4. Conclusions

The error in FVM calculations depends on the location in space in relation to the radiation source and the ratio between the source resolution and the distance to target. In the far field (where ratio of distance cells/source cells is high, the error is significant for lower angular resolutions).

With the increase of angular resolution the error generally decreases but in a non-uniform way. Eventually with high resolution only areas located in perpendicular directions in respect of the radiation source are slightly excessive while other directions exhibit small negative error.

Default angular resolution of 100 angles produces significant error by creating areas of significantly excessive flux and areas of very low flux (ray effect). Ray effect is significant for radiation sources of low spatial resolution and low angular resolution. The default resolution should not be used for applications where radiative heat transfer is critical.

Calculations and phenomena where heat flux is critical should be based on high angular resolution of approx.. 2000-4000 angles or an appropriate error tolerance should be used depending on the location and the distance to the target.

The verification approach used in this paper can be used to improve FVM in FDS or testing other alternative numerical methods.

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