IMPLEMENTATION OF DISCRETE TRANSFER RADIATION METHOD INTO SWIFT COMPUTATIONAL FLUID DINAMICS CODE

by

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The Computational Fluid Dynamics (CFD) has developed into a powerful tool widely used in science, technology and industrial design applications, whenever fluid flow, heat transfer, combustion, or other complicated physical processes, are involved. During decades of development of CFD codes, scientists were writing their own codes, that had to include not only the model of processes that were of interest, but also a whole spectrum of necessary CFD procedures, numerical techniques, pre-processing and post-processing. That has arrested much of the scientist effort in work that has been copied many times over, and was not actually producing the added value. The arrival of commercial CFD codes brought relief to many engineers that could now use the user-function approach for modelling purposes, entrusting the application to do the rest of the work. This paper shows the implementation of Discrete Transfer Radiation Method into AVL's commercial CFD code SWIFT with the help of user defined functions. Few standard verification test cases were performed first, and in order to check the implementation of the radiation method itself, where the comparisons with available analytic solution could be performed. Afterwards, the validation was done by simulating the combustion in the experimental furnace at IJmuiden (Netherlands), for which the experimental measurements were available. The importance of radiation prediction in such real-size furnaces is proved again to be substantial, where radiation itself takes the major fraction of overall heat transfer. The oil-combustion model used in simulations was the semi-empirical one that has been developed at the Power Engineering Department, and which is suitable for a wide range of typical oil flames.

Key words: *computational fluid dynamics, discrete transfer radiation method, SWIFT, experimental furnace, oil-combustion*

Introduction

Radiation mode of heat transfer plays an important role in overall heat transfer in industrial furnaces. Thus, when trying to simulate the performance and the characteristics of combustion of such devices, an accurate modelling of the radiation field is a key factor.

The popular Discrete Transfer Radiation Method (DTRM) has shown as very appropriate for general radiation predictions. Easily embedded into CFD codes, its ability to return the desired degree of accuracy, by choosing the number of rays used in calculations, allows one to control the compromise - unavoidable in industry - between accuracy and efficiency.

The Discrete Transfer Radiation Method has been implemented into non-structured finite volume CFD software SWIFT, together with the Weighted Sum of Grey Gases Model (WSGGM) for the radiative gas and soot properties modelling. The present paper describes the verification and validation methodology used in order to qualify the software for industrial furnaces simulations, especially focusing on accuracy. The verification is performed by simulating the set of standard test cases and by comparing the results with available exact solutions. Parameter analysis (number of rays, absorption coefficient, grid size) allows one to tabulate the accuracy errors and to assess the convergence to the exact solutions. A degree of confidence on the simulation results is defined based on the influence of the number of rays on accuracy. The validation is based on the simulation of the IJmuiden experimental furnace, provided measurements on temperature and species concentrations.

Mathematical model

The discrete transfer radiation method was first presented in [7] and only short description will be given here. For more detailed description one should refer to [7].

When describing the radiation phenomena in participating media it is very convenient to represent it through radiation transfer equation (RTE), see [8]. Many methods are based on solving this equation in some manner. DTRM itself is based on solving RTE for some representative rays fired from the domain boundaries. Rays are fired from surface elements into a finite number of solid angles that cover the radiating hemisphere about each element and the main assumption of DTRM is that the intensity through a solid angle can be approximated by a single ray. The number of rays and their directions are chosen in advance and RTE is solved for each ray on its way from boundary to boundary.

An illustration is given for 2D example, as shown in fig. 1. Figure shows the domain subdivided into a finite number of control volumes. An arbitrary ray is shown for boundary face P.

The change of radiant intensity leaving point R and along the ray until it reaches P is tracked. This is done using well-known recurrence equation:

$$i_{n+1} = i_n[1-\varepsilon(T,x_i)] + i_b(T)\varepsilon(T,x_i) \tag{1}$$

Symbols i_n and i_{n+1} represent total radiation intensities at intersections of a ray with control volume faces on the way from R to P. In eq. (1) $\varepsilon(T,x_i)$ stands for total emissivity and it depends on local temperature and gaseous composition, while $i_b = \sigma T_g^4/\pi$ represents the blackbody emissivity of a fluid contained in the control volume and depends only on local temperature.

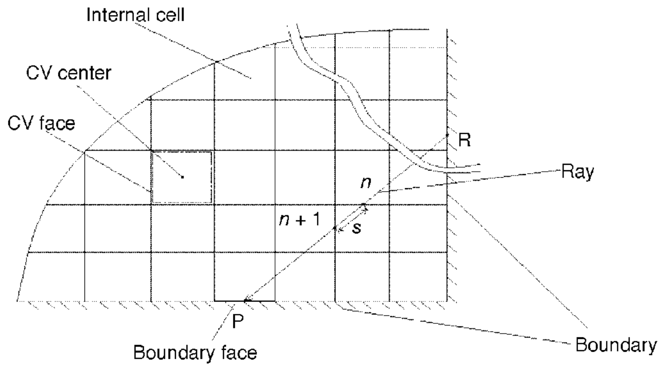

Figure 1. 2D domain; CV – control volume

Successive usage of eq. (1) from boundary to boundary is essential feature of DTRM. This procedure is repeated for all the other rays from that boundary element. If doing so also for all other boundary elements and considering the surfaces as gray diffuse, it is easy to calculate the net radiation heat flux for each boundary element. Sum of intensity changes, on the other hand, of all the rays that happen to traverse a certain domain control volume determines a radiation source term for that control volume.

To apply recurrence eq. (1) one has to know the total intensity i_0 at the beginning of the incremental path. In our example in fig. 1 this is the intensity leaving the point R. For all boundary elements (faces), thus, one has to calculate the incoming and outcoming radiation fluxes and intensities. Boundary surfaces are taken as grey Lambert surfaces, thus:

$$i = \frac{q_{out}}{\pi} = \underbrace{(1-\varepsilon_w)\frac{q_{in}}{\pi}}_{\text{refected}} + \underbrace{\varepsilon_w\frac{\sigma T_w^4}{\pi}}_{\text{directly\_emitted}} \tag{2}$$

That means that the outgoing radiation flux from a surface is composed from the diffusely reflected and directly emitted part only, without specular reflection. Incoming radiation flux q_{in} is not known before radiation calculation itself thus giving the DTRM iterative character except in case of black surfaces when $\varepsilon_w = 1$ and first term on the right hand side of eq. (2) vanishes.

In case when the net radiation heat flux is imposed as a boundary condition and not the temperature, the eq. (2) becomes:

$$i = \frac{q_{out}}{\pi} = \frac{q_{in}}{\pi} + \frac{q_{net}}{\pi} \tag{3}$$

Finally, the incoming radiation flux for some boundary element j is calculated as a sum of incident intensities for all rays as:

$$q_{in,j} = \int_{\vec{s}\cdot\vec{n}<0} i_j\vec{s}\cdot\vec{n}\,d\Omega = \sum_{i=1}^{n\_rays} i_{j,i}\cos\Theta_{j,i}\Delta\Omega_{j,i} = \sum_{i=1}^{n\_rays} i_{j,i}\cos\Theta_{j,i}\sin\Theta_{j,i}\sin(\Delta\Theta_{j,i})\Delta\varphi_{j,i} \tag{4}$$

Energy gain or loss due to radiation is given through radiation source term. For a general control volume j and for one ray (fig. 1) radiation source term is calculated as:

$$\bar{S}_j = (i_{n+1} - i_n) A_j \cos\Theta_{j,i} \Delta\Omega_{j,i} = (i_{n+1} - i_n) A_j \cos\Theta_{j,i} \sin\Theta_{j,i} \sin(\Delta\Theta_{j,i}) \Delta\varphi_{j,i} \quad (5)$$

However, overall energy gain or loss for a specific control volume is due to intensity change in it for all rays that happen to traverse it. Thus if k is the number of the rays that traverse the j-th control volume, than total radiation source term is given by equation:

$$\bar{S}_{j,tot} = \sum_{i=1}^{k} \bar{S}_{j,i} \quad (6)$$

Radiation source term, as given in eq. (6), is directly used in the energy conservation equation of the main program.

Finally, the radiative properties – total emissivity in our case, see eq. (1) – have to be modelled. As already said, total emissivity depends on local (control volume) gaseous composition, soot concentration and temperature. The weighted sum of grey gases model (WSGGM), according to [9], is employed in order to model total emissivity in current DTRM implementation in SWIFT. Detailed description of WSGGM can be found in [9, 10].

Verification tests

The verification of DTRM implementation into SWIFT code was done by simulating the radiation in simplified geometries, and for which the exact solutions could be calculated analytically. Next figures show the results for the finite cylinder, two infinite long parallel plates and 2D rectangular cavity, which are the standard test cases when testing the radiation models.

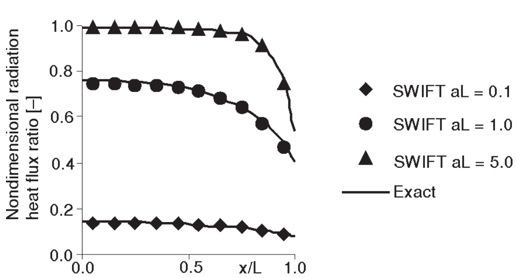

Figure 2. Nondimensional heat flux against nondimensional wall distance for different optical thicknesses (18 rays) – finite cylinder

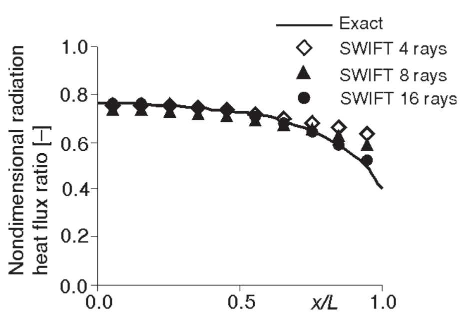

Figure 3. Nondimensional heat flux against nondimensional wall distance for varied number of rays (optical thickness = 1.0) – finite cylinder

Figures 2-6 show good agreement between simulated and exact data. In the limit of sufficient number of rays (16 or more) very accurate predictions of radiative heat transfer with DTRM can be achieved.

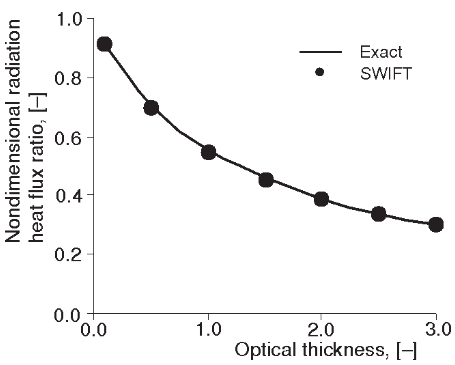

Figure 4. Nondimensional heat flux against optical thickness – two infinitely long parallel plates

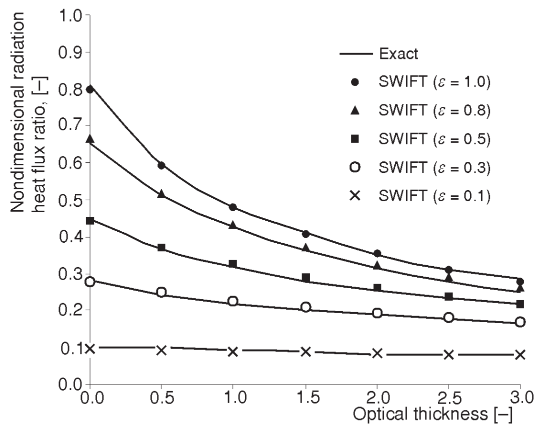

Figure 5. Nondimensional heat flux against optical thickness for different emissivities of lower wall (upper wall is held at constant emissivity 0.8) – two infinitely long parallel plates

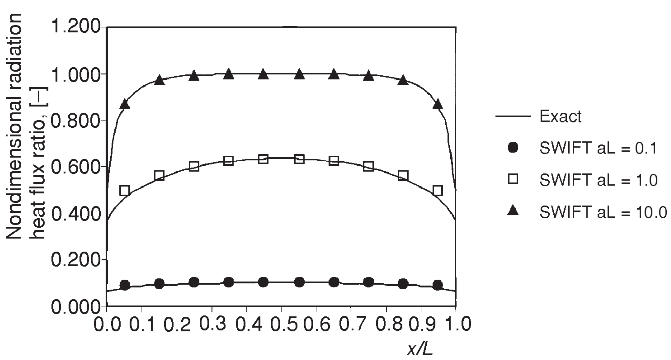

Figure 6. Nondimensional heat flux against nondimensional position for different optical thick – nesses – 2D rectangular cavity

Simulation of IJmuiden furnace – results

For the validation purpose the combustion in IJmuiden experimental furnace was simulated and the comparison with experimental data was done. The semi-empirical oil combustion model, developed at Power Engineering Department according to empirical relations from 5 and adjusted for CFD simulations, as reported in 1-4 , was used for combustion predictions. Next figures show the results and their comparisons with experimental data from 7 .

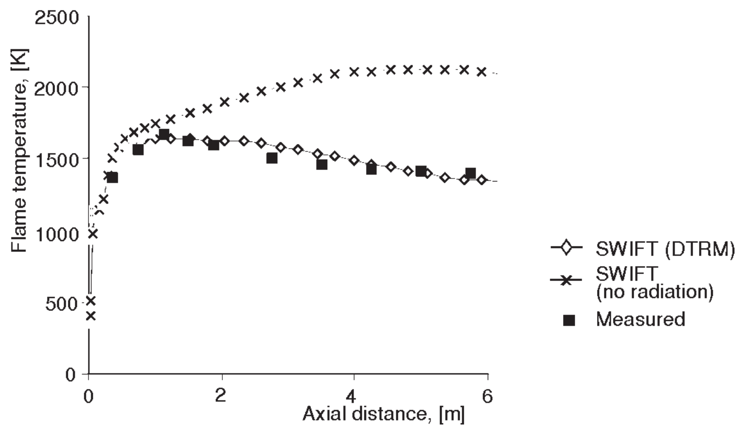

Figure 7. Flame temperature along furnace distance at axis centreline position

Figure 7 shows excellent agreement of temperature distribution along the axis when compared to experimental data. As the main heat removal in this furnace happens via radiation from the flame onto the furnace walls, calculation without radiation showed significant disagreement, as expected. WSGGM, on the other hand, has proven as suitable for emissivity calculations in combustion problems, where absorption coefficient mainly depends on flue gas composition.

Figure 8. Temperature pattern – SWIFT (DTRM)

Figures 8-11 give good illustration how important role the radiative heat transfer plays in real-size industrial furnaces. In the absence of radiative heat transfer (fig. 10) the temperature pattern looks something unnatural because the main part of the heat produced in the furnace during combustion has to go out through the outlet as sensitive heat of flue gases. Convection plays only minor role in overall heat transfer.

Figure 9. Temperature pattern – SWIFT (DTRM, walls at 300 K)

Figure 10. Temperature pattern – SWIFT (no radiation)

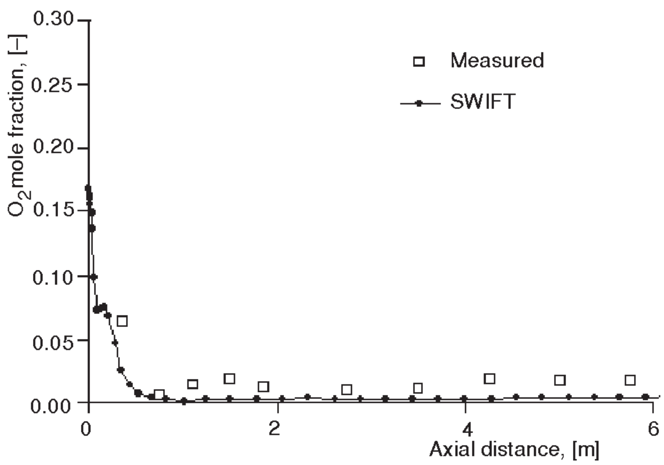

Figure 11. Oxygen distribution along the axis

Conclusion

It is shown that two rather complex physical phenomena – combustion and radiation – can be successfully modelled together within professional CFD program, and with the help of user-defined functions only. No special adjustments in the main solver had to be done and new models were implemented on simple plug-in basis. Relying on the CFD package to do the rest of the job, physically sound results were achieved. The agreement with experimental data was satisfactory well. The validation of the oil-combustion model, developed at Power Engineering Department, thus has been repeated once again and it has shown as a good choice when modelling oil combustion process in an industrial furnace. The Discrete Transfer Radiation Method has shown as a very appropriate choice when modelling radiation phenomena within real-size furnaces, where combustion products are participating in overall radiation as well. WSGGM models radiative properties of the flue gases very well.

Nomenclature

A – area, m^2
a – absorption coefficient, l/m
i – radiation intensity, W/m^2
L – characteristic length, m
$\vec{n}$ – normal vector, |m|
q – radiation heat flux, W/m^2
s – distance that a ray makes in intersecting control volume, m
$\overline{S}$ – energy source due to radiation, W
$\vec{s}$ – rays direction vector, |m|
T – temperature, K
x – position at wall, m

Greek letters

ε – total emissivity, –
Θ – polar angle, rad
φ – azimuthal angle, rad
σ – Stefan-Boltzman constant, ($= 5.67 \cdot 10^{-8}$ W/m^{2}K^4)
Ω – solid angle, sr

Subscripts

b – black body
g – gas
i – specie; ray number
in – incoming
j – boundary face
n – position of rays entrance in *n*-th control volume
$n+1$ – position of rays exit from *n*-th control volume
net – net
out – outgoing
tot – total
w – wall
0 – initial

Superscripts

' – directional
k – number of rays which intersect control volume
n_rays – number of rays emitted from boundary face

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