Assessment of engineering gas radiation methods in an industrial glass furnace configuration

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Abstract. This work is dedicated to a comparison of various methods of gaseous flames radiation in a tri-dimensional configuration representative of a glass furnace studied at Saint Gobain Research Paris.

1. Introduction
Radiative heat transfer is one of the dominant modes of energy exchange in many industrial applications. In glass industry, for instance, flames are used to heat by radiation a bath of molten glass on which a blanket of raw materials is floating, continuously fed into the furnace and melting into new glass. Accordingly, in this kind of application, accurate models of flame radiation are critical to provide insight into the way glass forms and to optimize the industrial process (regarding energy efficiency and pollutant formation). Moreover, in order to simulate the full set of physical phenomena encountered in such configurations (coupled heat and mass transfer, chemistry, etc.), computationally efficient methods are required, which necessarily excludes the use of highly accurate but computationally prohibitive line-by-line (LBL) calculations.

The aim of the present work is to describe results of a project whose objective was to evaluate various approximate methods of flame radiation in order to select the most suitable for coupled calculations in glass furnaces. For this purpose, a three-dimensional Monte Carlo code was built in order to compare several contemporary approximate methods of gas radiation (WSGG, RC-SLW, Ck-7, \(\epsilon\)-distributions) to LBL calculations over selected sets of rays. The same rays, assumed to be representative of the problem studied, were used for all models, allowing a fair comparison between the approximate methods and the benchmark LBL results.

Preliminary test cases of this code were made on one-dimensional benchmarks and described in Ref. [1]. This earlier study provided the following results: 1/ the \(\epsilon\)-distribution method [2] provides nearly benchmark accuracy at a computational cost that is a small fraction of LBL simulations, 2/ the Rank Correlated SLW (RC-SLW) model [3] provides results as accurate as the Ck-7 model, but at considerably lower computational cost. The main strength of RC-SLW is that it is compatible with any arbitrary Radiative Transfer Equation (RTE) solver (e.g., Discrete Ordinates, P-N) whereas the \(\epsilon\)-distribution method is limited to ray tracing methods (either in deterministic or stochastic versions, i.e., Monte Carlo ray tracing). Accordingly, the RC-SLW model can be readily implemented in an engineering Computational Fluid Dynamics (CFD) code such as Ansys Fluent through the use of User’s...
Defined Functions, whereas the application of $\ell$-distributions would require more demanding developments. Notice, however, that the RC-SLW method, as with all other full spectrum models [4,5], is restricted to gray boundaries. This assumption will thus be made here.

The main originality of the present paper is to go beyond the one-dimensional cases usually used to compare models of gas radiation and to make fair comparisons of flame radiation methods in an actual industrial configuration representative of a furnace used at Saint-Gobain. Indeed, there are very few multidimensional solutions comparing LBL benchmark solutions to the global gas radiative transfer models described here. The input thermophysical fields (temperature and gas species concentrations) were obtained as outputs of simulations made with Ansys Fluent employing an approximate gas radiation model in the absence of soot. The test case configuration considered is described in Section 2. Section 3 is dedicated to a description and discussion of the results of the various methods.

2. Description of the test case

2.1. Glass melting furnaces
Industrial glass melting is carried out in flame-heated furnaces for flat and container glass. End-fired furnaces are widespread due to their high efficiency and mid-size capacity, ranging from 200 to 400 tons of glass produced per day. The entire furnace is made from refractory bricks; walls are thus uncooled. In an end-fired furnace, a U-shaped flame heats the combustion space above the molten glass tank. The mixture of raw materials is continuously fed into the furnace, floating on the molten glass as melting occurs. The molten glass is collected from the bottom of the tank on the opposite end. Accurate prediction of the radiative heat transfer in the combustion space is a key feature of the modelling of industrial glass melting furnaces.

Unpreheated natural gas is the most common fuel in glass melting furnaces. It is injected below the combustion air, preheated to approximately 1600 K, resulting in non-premixed, turbulent combustion. The flame and combustion products follow a U-shaped trajectory, and the gases exit the furnace at a temperature of approximately 1800 K before passing through a heat-recovery refractory stack. To improve heating uniformity, and to more effectively utilize the recovered thermal energy stored in the refractory stack, the furnace is alternatively fired from each port, reversing the combustion air flow through the hot refractory stack on each side of the furnace. Natural gas is injected below it, and the previous air inlet becomes the combustion gas outlet.

2.2. Numerical case
A simplified geometric representation of the furnace is used in this study to better focus on radiative heat transfer in the combustion space. Consequently, the glass bath is not modeled, rather, representing it by a fixed-temperature flat surface with emissivity set to 1 (blackbody). The simplified geometry used in this case is shown in Figure 1. The underlying computational mesh is adjusted to accurately capture the physics of the flame. In this study the focus will be on four lines of sight: i) along the flame, ii) vertically through the flame, iii) on the glass surface along the flame, and iv) on the glass surface along the flame and products of combustion.

The case is first solved for combustion (momentum and energy equations, 2-equation RANS model for turbulence, non-premixed combustion model for chemical species) using Ansys Fluent software. Radiative heat transfer is considered in the coupled calculations to provide a realistic temperature field. It is computed with the built-in discrete ordinate model using a 4-band Weighted-Sum-of-Gray-Gases (WSGG) gas radiative property model. Boundary conditions are summarized in Table 1. All walls are assumed gray with completely diffuse reflection. Inlet and outlets are modelled as exchanging walls.

Once convergence is reached, fields of H$_2$O and CO$_2$ molar fractions and of temperature are exported and projected on a regular mesh using trilinear interpolation. These tri-dimensional fields then serve as inputs for the Monte Carlo code described in Ref. [1].
The calculation mesh contains 102,200 homogeneous isothermal cells. For the calculation of reflections by the non-black surfaces, a maximum number of reflections was set to 10, guaranteeing a maximum error on path intensities lower than 0.002 percent.

Table 1. Boundary conditions of the simplified representation of the combustion space.

| Surface               | Thermal | Radiative | Fluid  |
|-----------------------|---------|-----------|--------|
| Air inlet             | $T \approx 1600$ K | -         | mass flow |
| Combustion gas outlet | -       | $\varepsilon = 0$ | pressure outlet |
| Gas injection         | $T = 298$ K   | $\varepsilon = 1$ | mass flow |
| Side walls & Top     | Fixed heat flux | $\varepsilon = 0.2 \text{–} 0.5$ | no slip |
| Bottom                | Fixed heat flux | $\varepsilon = 0.8 \text{–} 1.0$ | no slip |

Figure 1. Geometry of the combustion space. The four lines of sight (LOS) are represented in blue.

3. Application and results
Comparisons of the various methods were made at 79 points chosen sequentially over the four lines of sight of Figure 1. 1,000 rays were randomly launched at each of these points and full model calculations were performed. LBL spectra used to define the reference solution were taken from Ref. [6]. The same database was used to generate all approximate model parameters. 16 gray gases were considered for the RC-SLW model, for which the Planck weighting temperature was set to the volume average temperature in the furnace. Narrow band methods ($C_k$-7 and $\ell$-distribution) used 998 evenly spaced narrow bands between spectral limits of 50 cm$^{-1}$ and 24,950 cm$^{-1}$. Figure 2 depicts a profile of radiative power over the first line of sight (LOS1). Table 2 provides comparisons of the methods in terms of average error on radiative power (defined as the line-of-sight average of the absolute difference between radiative powers calculated by the model and the LBL calculation, divided by the maximum LBL value of radiative power encountered along the line of sight). Computational cost (ratio of the total computation time of the approximate model to that of LBL calculation for the full set of calculation points) are provided in the caption of this table.

Results of the simulations in this realistic geometry of glass furnace confirm the results obtained previously in Ref. [1]. The smallest errors are again obtained by application of the $\ell$-distribution approach, whose computational cost is approximately one-third that of the $C_k$-7 model, and quite reasonably only 70 times that of the rudimentary WSGG model. Concerning global methods, the RC-
The SLW model is clearly more accurate than the WSGG method at a computational cost approximately 60 times that of the WSGG model. The computational cost of RC-SLW model is relatively high due to the numerous implicit equations used in its formulation. The objective of the work was to evaluate the accuracy of this method, not to optimize its cost. A full tabulation of the input data for the RC-SLW method would eliminate the need to solve implicit equations, resulting in computation times several orders of magnitude lower than those reported here. It may also be mentioned that fewer gray gases may be used in the RC-SLW method. Accurate RC-SLW solutions have been reported in one-dimensional simulations using as few as 3-5 gray gases [5].

![Figure 2. Direct comparison of profiles of radiative power along the LOS1. Top: LBL calculation, bottom: approximate methods considered in this work.](image)

**Figure 2.** Direct comparison of profiles of radiative power along the LOS1. Top: LBL calculation, bottom: approximate methods considered in this work.

**Table 2.** Relative errors (in %) on evaluation of radiative power (CPU time gain with respect to LBL calculations: WSGG: $1.2 \times 10^{-5}$, RC-SLW: $6.8 \times 10^{-4}$, $\epsilon$-distribution: $8.1 \times 10^{-4}$).

| Model     | LOS1 | LOS2 | LOS3 | LOS4 |
|-----------|------|------|------|------|
| WSGG      | 7.11 | 8.82 | 13.4 | 5.27 |
| RC-SLW    | 1.13 | 4.42 | 8.29 | 1.95 |
| $\epsilon$-distribution | 0.02 | 0.14 | 0.01 | 0.05 |
| Ck-7      | 0.85 | 2.01 | 1.11 | 1.48 |

### 4. Conclusion

The RC-SLW model can be used confidently for the accurate calculation of radiative transfer in engineering applications such as glass furnaces. A proper tabulation of the parameters of the model (weights and corresponding absorption coefficients) may be needed to maintain its cost acceptable for coupled heat transfer calculations.

### References

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