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Application of the Spectral Line-based Weighted-Sum-of-Gray-Gases model (SLWSGG) to the calculation of radiative heat transfer in steel reheating furnaces firing on low heating value gases

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Abstract. The Spectral Line-based Weighted-Sum-of-Gray-Gases (SLWSGG) model is applied to calculate the gaseous radiative properties of the aero- or oxy-combustion products of low heating value gases issued from steel making process such as Blast Furnace Gas (BFG) as well as of high heating value gases such as Coke Oven Gas (COG) and conventional Natural Gas (NG). The comparison of total emissivities shows that the 3-gray-gases SLWSGG model is in very good agreement with the Hottel and Sarofim's database. The 3-gray-gases SLWSGG model is then integrated into AnsysFluent® Discrete Ordinates method under User Defined Function and CFD simulations are performed using these combined models. The simulations are done, with full combustion-radiation coupling, for steel reheating furnaces firing on three types of gases: BFG, COG and NG. The results are compared with the simulations realized with the 1-gray-gas WSGG model available in AnsysFluent®. The comparison shows that the 1-gray-gas WSGG model highly overestimates the steel discharging temperature as compared to the 3-gray-gases SLWSGG model. Significant temperature differences are observed between the two radiative models, i.e. 116°C, 55°C and 67°C for the BFG, COG and NG cases, respectively. It can be concluded that the 3-gray-gases SLWSGG model should be used to calculate the radiation heat transfer in large industrial furnaces with more accuracy not only for low heating value gases such as BFG but also for high heating value gases such as COG and NG.

1. Introduction

Using auto-produced low heating value gases issued from steel making process in steel reheating process has a very positive impact on the environment and the energy saving. Integrated steel plants CO₂ footprint and NO_x pollutants will be reduced and natural gas (NG) will be substituted by industrial off-gases such as Blast Furnace Gas (BFG), a reusable low heating value gas. Designing combustion systems for efficient utilization of BFG in steel reheating furnaces is still a challenging

task [1]. The Computational Fluid Dynamics (CFD) plays an important role in the design phase. As in large industrial furnaces, radiative heat transfer stands for nearly 90% of the total heat transfer into steel products to be reheated, the remaining 10% is attributed to the convection. Therefore, calculating the radiative heat transfer with accuracy is essential in succeeding in the design of such combustion systems.

In the literature, much more effort was focused on method developments and applications for NG combustion. Amongst different methods available, the non-gray global model family has an important interest for practical combustion system calculations for two reasons. It is more accurate when compared to the simple gray gas model and it is more computationally efficient when compared to the Statistical Narrow Band Correlated K (SNB-CK) model [2]. The non-gray global methods consist of the Spectral Line-based Weighted-Sum-of-Gray-Gases (SLWSGG) model [3], the Absorption Distribution Function (ADF) model [4], and the more recently developed Statistical Narrow Band Full Spectrum Correlated K (SNB-FSCK) [5]. The SLWSGG model has a special interest for practical coupling with commercial CFD combustion solvers as it is an extension of the WSGG model which is largely and successfully used in Ansys Fluent® [6]. However, this model is limited to NG combustion application and no gaseous radiative properties model is available to address low heating value gases combustion. In the present study and along this line, the SLWSGG model is applied to calculate the gaseous radiative properties of the aero- or oxy-combustion products of low heating value gases issued from steel making process such as Blast Furnace Gas (BFG) as well as of high heating value gases such as Coke Oven Gas (COG) and conventional Natural Gas (NG).

In a first attempt, the quality of the 3-gray-gases SLWSGG model will be evaluated by comparing the total emissivity with the Hottel and Sarofim's database [7] as well as with the results using Soufiani and Djavdan [8] and Smith et al. [9] methods. To keep the computational efforts reasonable the SLWSGG model takes into account only 3-gray-gases. It is then integrated into Ansys Fluent® Discrete Ordinates (DO) method as User Defined Function to perform Computational Fluid Dynamics (CFD) simulations. A full combustion-radiation coupling in steel reheating furnaces firing on three types of gases: BFG, COG and NG was simulated. To reduce the computational cost, only half of the furnaces is considered in the simulations. The results will be compared with the simulations realized with the 1-gray gas WSGG model available in AnsysFluent®.

The section below describes briefly the methodology of SLWSGG model. In the next section, the results will be presented. Finally, some concluding remarks will be drawn out in the concluding section.

2. Methodology

The concept of a Weighted-Sum-of-Gray-Gases (WSGG) model was first presented by Hottel and Sarofim [7]. In this concept the non-gray gas is replaced by a number of gray gases, for which the heat transfer rates are calculated independently. The total heat flux is then calculated by adding the heat fluxes of each gray gas. For theoretical background, the reader is referred to the comprehensive books on radiative heat transfer [5,10,11]. For latest updates on the development of the Spectral Line-based Weighted-Sum-of-Gray-Gases (SLWSGG) model, the references [3,12-17] are recommended. A brief description is recalled in the following. In the SLWSGG concept, the Radiative Transfer Equation (RTE) to be solved is:

$$\frac{dI_n}{ds} = k_n p_a (a_n I_b - I_n) \quad (1)$$

where I_n (W/m) is the radiation intensity along the direction s of the k^{th} gas, I_b (W/m) the blackbody radiation intensity, k_n ($m^{-1} \cdot atm^{-1}$) the absorption coefficient of the k^{th} gas, p_a (atm) the partial

pressure of the absorbing species, a_n the weighting factor of the k^{th} gray gas with temperature dependence and T_w (K) is wall temperature. Equation (1) is solved for each gray gas $n=1,2,\dots,N$, with the boundary condition given by $s=0: I_n = a_n I_b(T_w)$, using any standard solution method, but Discrete Ordinates Method (DOM) is commonly used. The total intensity field (or the total heat fluxes) will be determined by adding the intensities (heat fluxes) of all grey gases concerned: $I(s) = \sum_{n=1}^N I_n(s)$.

In the method of SLWSGG, the total emissivity of a gaseous mixture is written as:

$$\varepsilon(T, l, p_a) = \sum_{n=1}^N a_n (1 - e^{-k_n p_a l}) \quad (2)$$

where T (K) is the temperature, l (m) the optical thickness. The emissivity is the contribution of all gray gases. Each one is characterised by an absorption coefficient and a weighting factor commonly described by temperature dependent polynomials of J degree written in the form:

$$a_n = \sum_{j=1}^J \alpha_{n,j} T^{j-1} \quad (3)$$

$$k_n = \sum_{j=1}^J \beta_{n,j} T^{j-1} \quad (4)$$

where $\alpha_{n,j}$ is the polynomial coefficient for the weighting factors and $\beta_{n,j}$ is the polynomial coefficient for the absorption coefficient. For a transparent region of the spectrum (clear gas), the absorption coefficient is set to zero in order to account for windows in the spectrum between spectral regions of high absorptions.

In the present work, we have developed a dedicated code and used SLWSGG model to calculate the coefficients $\alpha_{n,j}$ and $\beta_{n,j}$ of the aero- or oxy-combustion products of low heating value gases issued from steel making process such as Blast Furnace Gas (BFG) as well as of high heating value gases such as Coke Oven Gas (COG) and conventional Natural Gas (NG). The main steps for determination of the polynomial coefficients in the code are: 1) for a given molar fraction of H₂O, CO₂, CO, a range of optical length and a fixed temperature, the SLWSGG model is used to calculate the total emissivity, 2) a least square method is used to calculate the absorption and weight coefficients for a fixed gray gas number to meet emissivity calculated above, 3) steps 1 and 2 are repeated for a set of N temperatures points ranging from 400K to 2400 K, and 4) the profiles of absorption and weight coefficients versus temperature obtained are used to calculate the polynomial coefficients. The parameters in the SLWSGG model are obtained from correlation of the line-by-line spectra of H₂O, CO₂ and CO. It should be additionally noted that our code can use Hottel and Sarofim's database [7] or total emissivities evaluated by SLWSGG model to calculate the gray gas weights and absorption coefficients in the form of polynomials laws. To keep the computational efforts reasonable, only 3-gray-gases were considered.

3. Results and discussion

3.1. Emissivity of the 3-gray-gases SLWSGG model

The accuracy of the 3-gray-gases SLWSGG model was tested by comparing the total emissivity with the Hottel and Sarofim's database [7], used as a benchmark, as well as with the results using Soufiani and Djavdan [8] and Smith et al. [9] methods. In the comparison shown in figures 1 and 2 for a given burnt gases mixture (H₂O and CO₂) issued from the aero-combustion of the different gases such as BFG and COG (similar result obtained for NG case but not shown here). The following gaseous compositions were used in the study (in volume percentage); BFG: 3%H₂, 20%CO, 22%CO₂ and

55%N₂, COG: 62%H₂, 25%CH₄, 6%CO, 2%CO₂, 2%C₂H₄, 1%C₂H₆ and 2%N₂, and NG: 91%CH₄, 6%C₂H₆ and 3%N₂.

In the Soufiani and Djavdan model [8], p_a is the partial pressure of H₂O, the absorption coefficient values are expressed in atm⁻¹.m⁻¹, and only one configuration $p_w / p_c = 2$ is available (where $w = \text{H}_2\text{O}$, $c = \text{CO}_2$). In the Smith et al. model [9], p_a is the sum of the partial pressures of H₂O and CO₂, i.e., $p_a = p_{\text{H}_2\text{O}} + p_{\text{CO}_2}$, and the absorption coefficient values are expressed in atm⁻¹.m⁻¹. Two configurations are available for this model; the configuration $p_w / p_c = 2$ is available for NG and COG, and the configuration $p_w \rightarrow 0 \text{ atm}$ for BFG.

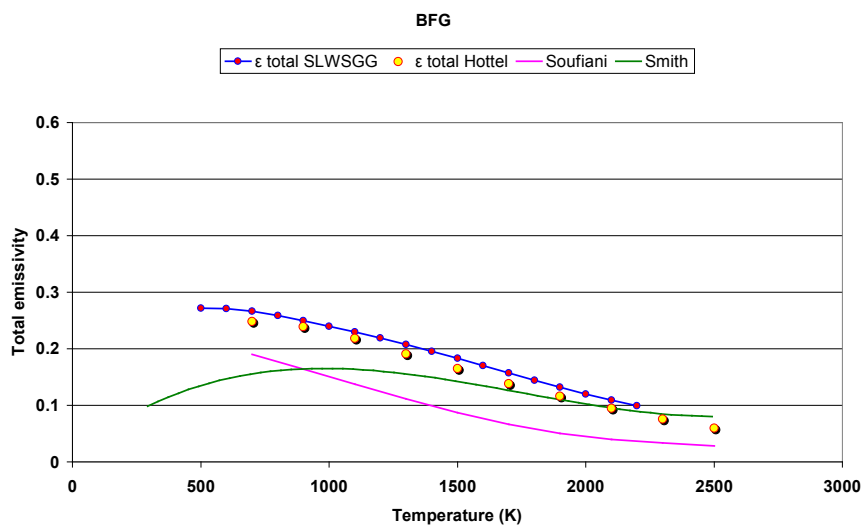


Figure 1. Total emissivity of the products from the aero-combustion of BFG.

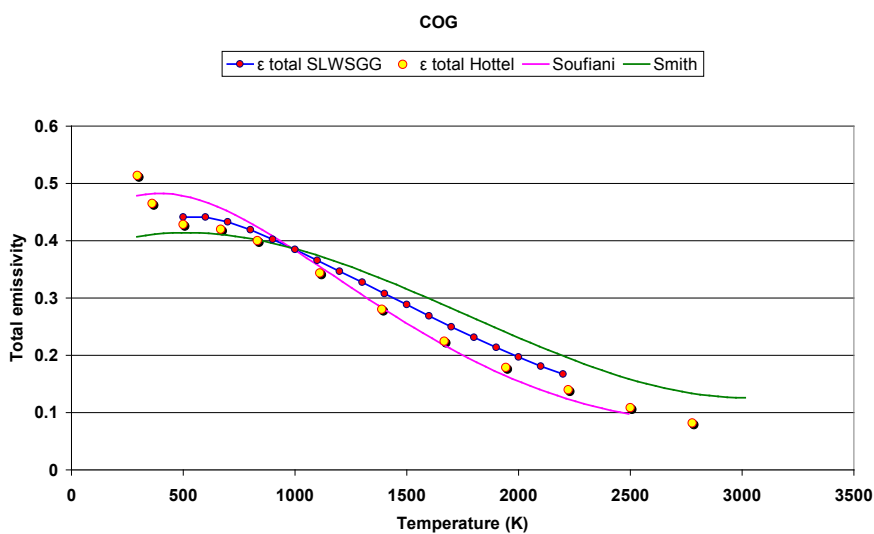


Figure 2. Total emissivity of the products from the aero-combustion of COG.

In the case of BFG (figure 1), the 3-gray-gases SLWSGG model is in very good agreement with the Hottel and Sarofim's database [7], while the total emissivity obtained with Soufiani and Djavdan [8] and Smith et al. [9] methods shows an important departure from the Hottel and Sarofim's database [7]. This is due to the fact that the 3-gray-gases SLWSGG model is specifically adapted for low heating value gas combustion such as BFG, while the models used in Soufiani and Djavdan [8] and Smith et al. [9] were developed for high heating value gases. Then in the case of high heating value gas COG (figure 2), no much difference between the methods is observed in the total emissivity. However, it should be noted that the SLWSGG model always offers an advantage over the WSGG model to take into account many gray gases to calculate radiation with more accuracy.

3.2. CFD computations

The 3-gray-gases SLWSGG model was integrated into Ansys Fluent® Discrete Ordinates (DO) method as a User Defined Function and Computational Fluid Dynamics (CFD) simulations were performed for a full combustion-radiation coupling in a steel reheating furnaces firing on three different types of gases: BFG, COG and NG. The same burners characteristics are used for NG and COG cases while in the case of BFG, specific dimensional characteristics burners are used. To reduce the computational cost, only half of furnace is considered in the simulations. The overall characteristics of the half of furnace are: 37m in length, 12.8m in width and 1.79m in height. The steel slabs to be processed are of 10.5m in length and 0.22m in thickness and move through the furnaces with a velocity of 0.003241m/s which corresponds to a throughput of 212ton/h. The slabs are charged onto the furnace at 27°C in all simulations. Figure 3 shows an overview of a half of a slab reheating furnace using BFG burners.

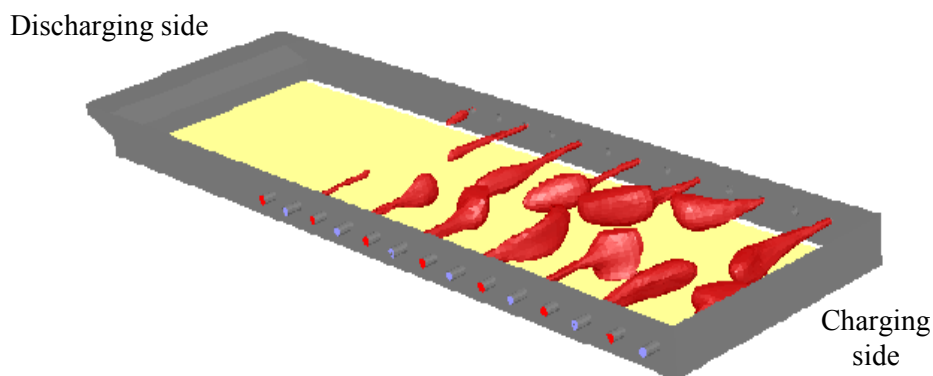


Figure 3. Overview of a half of a steel slab reheating furnace using BFG burners.

The simulations are realized for 3 gases: NG, COG and BFG. For each gas, two radiative models are used for comparison: the 3-gray-gases SLWSGG model and the 1-gray-gas WSGG model. The power is kept the same for all simulations and is of 33MW for the present study. In the case of NG and COG, the combustion air is preheated to 890°C and the gas is injected at 25°C. But in the case of lean gas BFG, both the air and gas are preheated up to high temperatures of 860°C and 730°C, respectively.

Figure 4 shows the results of the simulations obtained with the 3-gray-gases SLWSGG model for the three gases considered, i.e., NG, COG, and BFG. It is clearly noted that the highest maximum burnt gases temperature (1800°C) is observed in the COG case (Figure 4.b) due to a very high proportion of H₂ (62% in volume) in the COG composition. The lowest maximum burnt gases temperature (1537°C) is observed in the BFG case (Figure 4.c) even though the BFG is preheated to a high temperature of 730°C before injection. This low burnt gases temperature is due to the low calorific value of BFG; the gas contains about 20%CO and 3%H₂ (in volume) that are considered as reactives in its composition

and the major components (22%CO₂ and 55%N₂) are inert gases. The maximum burnt gases temperature value of the NG case lies between the values obtained in the COG and the BFG cases as expected, and takes a value of 1773°C (Figure 4.a). It is generally observed, in three cases, that the temperature of the burnt gases issued from the burners located near the charging side is lower than that of the burnt gases at the discharging side. This is due to the fact that the steel slabs are loaded into the furnaces at low temperature (27°C) from the charging side, therefore an important heat flux transfers from the burnt gases to the steel slabs, and this important heat transfer decreases the burnt gases temperature at the burners located near the charging door.

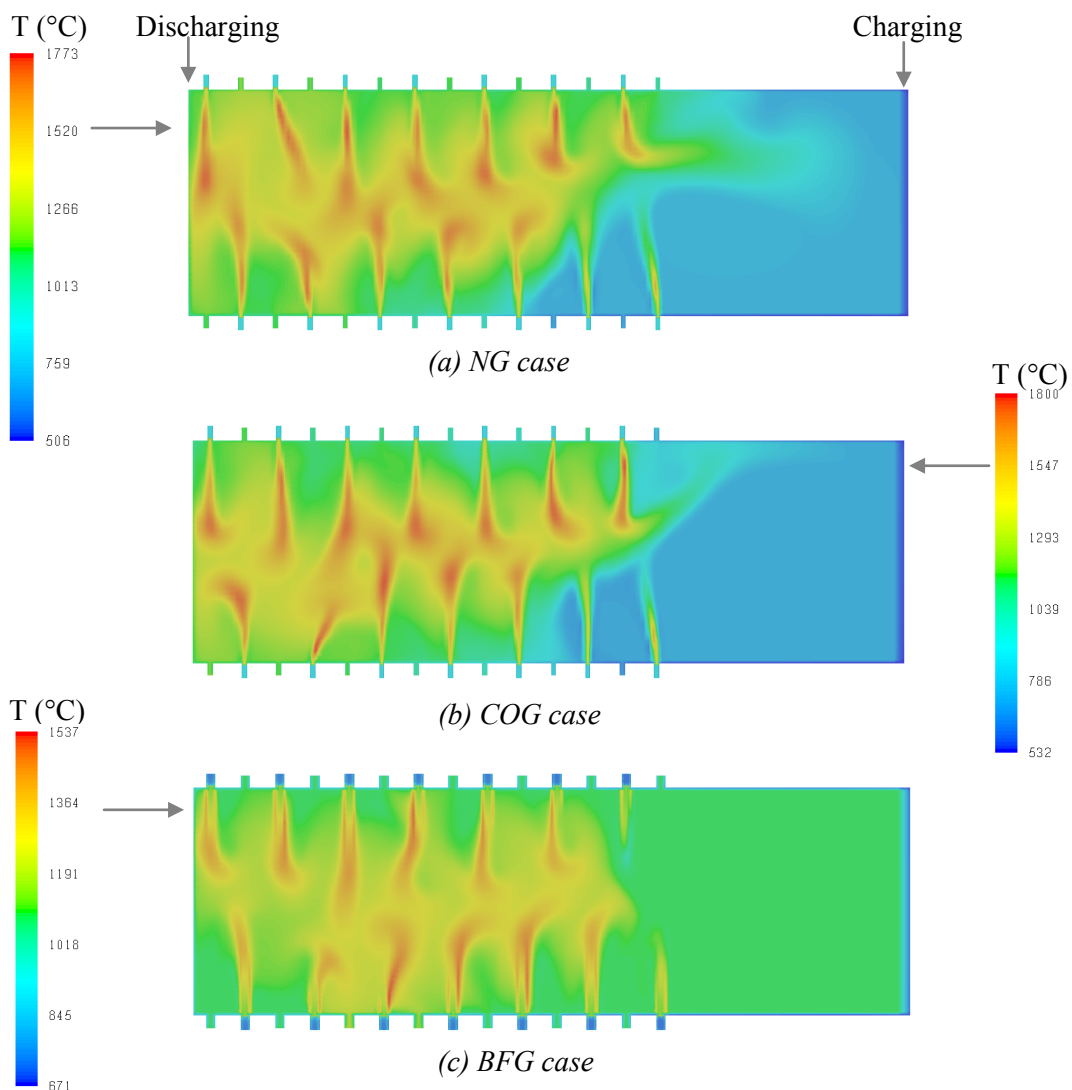


Figure 4. Burnt gases temperature in the furnaces, obtained with the 3-gray-gases SLWSGG model, for NG (a), COG (b) and BFG (c) cases.

Figures 5, 6 and 7 show the temperature contour on the upper skin of slaps from the charging to the discharging door, obtained with the 1-gray-gas WSGG and 3-gray-gases SLWSGG models, for three cases considered. It is important to recall that for comparison between the two radiation models, the power is kept constant (33MW) and the slabs are charged onto the furnace at 27°C for all simulations. It is systematically noted, from figures 5, 6 and 7 for each case of gas, that the temperature of the slab

at the exit of the furnace is always lower with the 3-gray-gases SLWSGG model as compared to the 1-gray-gas WSGG model. Important mean discharged temperature differences of 67°C and 55°C are noticed for the NG and COG cases, respectively. For the BFG case, the discrepancy between the 1-gray-gas WSGG and the 3-gray-gases SLWSGG is more important and attained a value of 116°C. This difference is confirmed in figure 8 that shows the core temperature profile of the discharged slab, obtained with the two radiation models, for the BFG case. It is obviously noted, from figure 8, that the 1-gray-gas WSGG model over-predicts of more than 100°C as compared to the 3-gray-gases SLWSGG model along the length of slab.

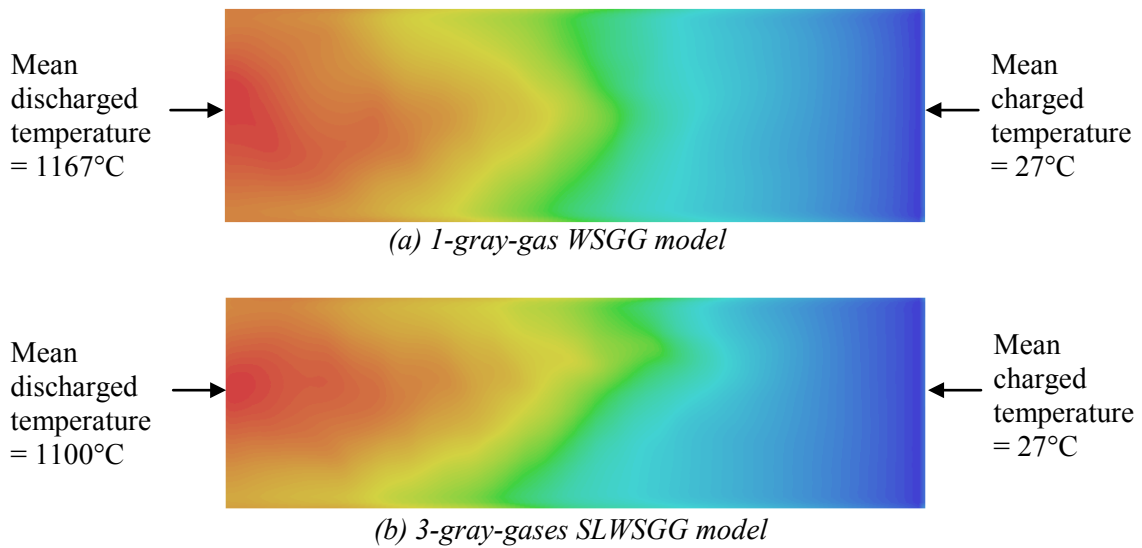


Figure 5. Temperature contour on the upper skin of slaps from the charge to the discharge, obtained with the two radiation models, for NG case.

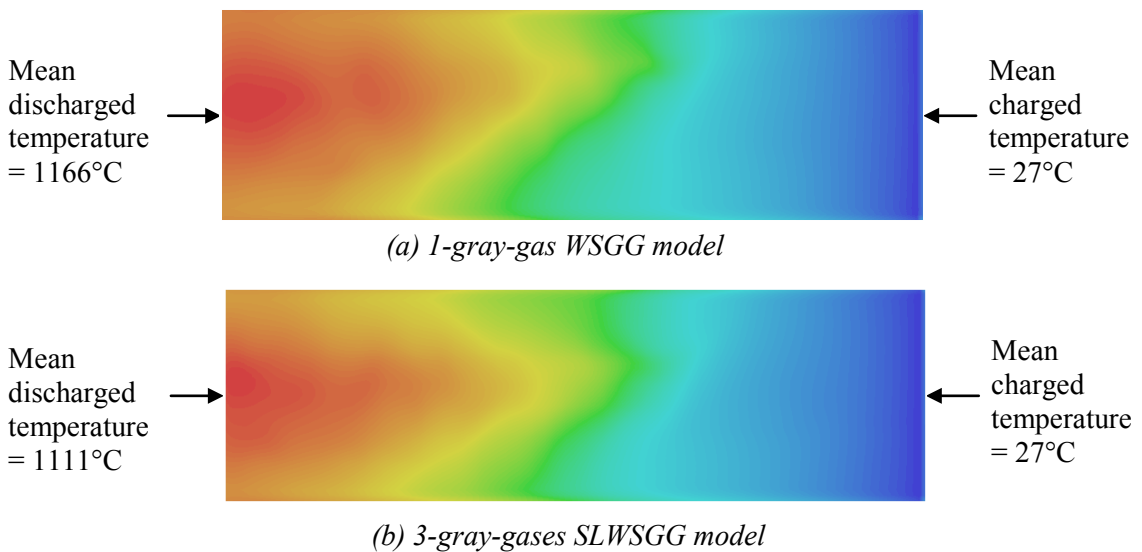


Figure 6. Temperature contour on the upper skin of slaps from the charge to the discharge, obtained with the two radiation models, for COG case.

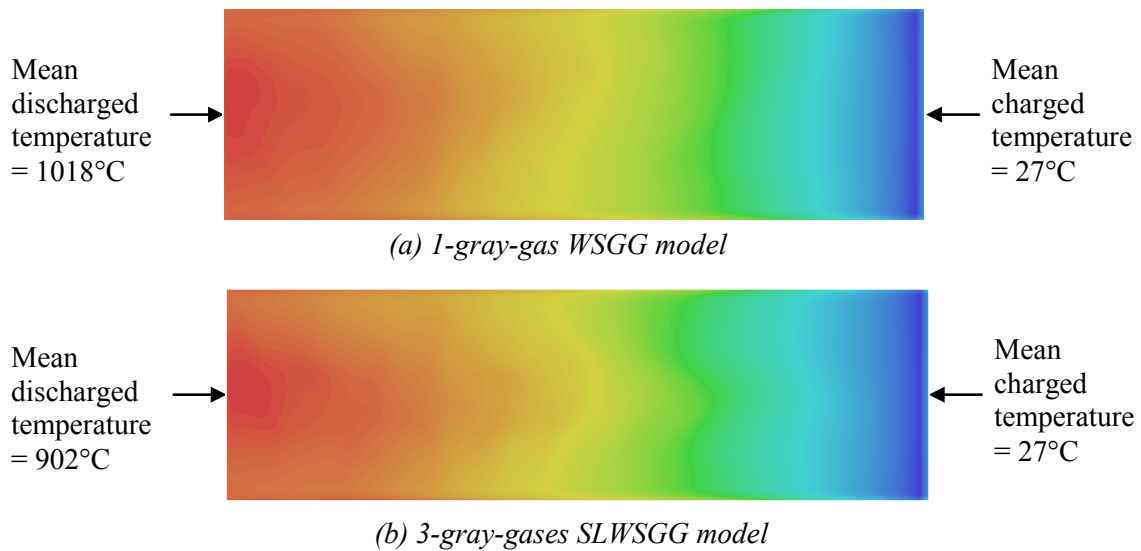


Figure 7. Temperature contour on the upper skin of slabs from the charge to the discharge, obtained with the two radiation models, for BFG case.

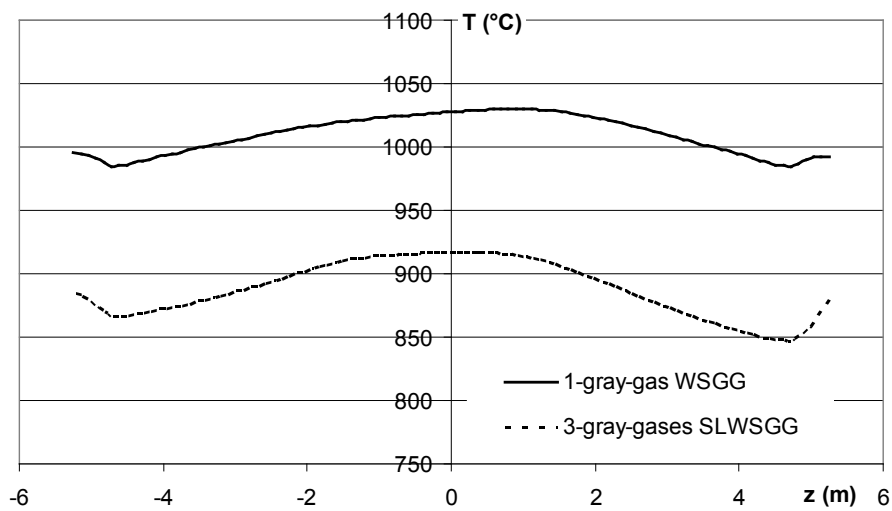


Figure 8. Discharged slab core temperature profile along the length of slab, obtained with the two radiation models, for BFG case.

In large-scale steel reheating furnaces, radiation dominates convection and stands for nearly 90% of the total heat transfer from hot gases to products to be processed. In this line, Table 1 shows the radiative heat transfer (in %) from burnt gases to steel slabs, obtained with the two radiative models, for three cases of gas. If we consider the 1-gray-gas WSGG model, it is noted that the radiation heat transfers are 92%, 91.8% and 90.2%, respectively for NG, COG and BFG cases (the remaining is of

convection) and less than 2% of difference is noted between the rich gases (NG and COG) and the lean gas BFG. If we consider the 3-gray-gases SLWSGG model, we observe that the radiation heat transfers are 88.5%, 89.3% and 84.6%, respectively for NG, COG and BFG cases, and nearly 5% of difference is noted between the rich gases (NG and COG) and the lean gas BFG. This 5% in radiation difference reflects the authentic result obtained with the 3-gray-gases SLWSGG because the total emissivity of burnt gases issued from BFG combustion is largely smaller than that from rich gases such as NG and COG (comparing figure 1 with figure 2). That explains the lower heating quality of BFG as compared to the rich gases NG and COG.

Now, if we compare the two radiation model for each gas, it appears from Table 1 that the 1-gray-gas WSGG model overestimates the radiation heat transfer in comparison with the 3-gray-gases SLWSGG model. Differences of 3.5%, 2.5% and 5.6% are noted for the NG, COG and BFG cases, respectively.

Table 1. Radiation heat transfer proportion from burnt gases to steel slabs.

Model	NG	COG	BFG
1-gray-gas WSGG	92.0 %	91.8 %	90.2 %
3-gray-gases SLWSGG	88.5 %	89.3 %	84.6 %
Difference between two models	3.5 %	2.5 %	5.6 %

4. Conclusion

The Spectral Line-based Weighted-Sum-of-Gray-Gases (SLWSGG) model was applied to calculate the gaseous radiative properties of the aero- or oxy-combustion products of low heating value gases issued from steel making process such as Blast Furnace Gas (BFG) as well as of high heating value gases such as Coke Oven Gas (COG) and conventional Natural Gas (NG). The quality of the 3-gray-gases SLWSGG model was evaluated by comparing the total emissivity with the Hottel and Sarofim's database [7] as well as with the results using Soufiani and Djavdan [8] and Smith et al. [9] methods. The comparison shows, in the case of BFG, that the 3-gray-gases SLWSGG model is in very good agreement with the Hottel and Sarofim's database [7] while the total emissivity obtained with Soufiani and Djavdan [8] and Smith et al. [9] methods shows an important departure from the Hottel and Sarofim's database. This is due to the fact that the 3-gray-gases SLWSGG model was specifically adapted for low heating value gas BFG combustion, while the models used in Soufiani and Djavdan [8] and Smith et al. [9] were developed for high heating value gases. In the case of high heating value gases of COG and NG, no much difference between the methods is observed in the total emissivity. However, it should be noted that the SLWSGG model always offers an advantage over the WSGG model to take into account many gray gases to calculate radiation with more accuracy.

The simulations performed for steel slab reheating furnaces burning on BFG, COG and NG indicate that the 1-gray-gas WSGG model highly overestimates the steel discharging temperature in comparison with the 3-gray-gases SLWSGG model. Important mean discharged temperature differences are noted between the two radiation models, i.e. 116°C, 55°C and 67°C for the BFG, COG and NG cases, respectively. It can be concluded that the 3-gray-gases SLWSGG model should be used to calculate the radiation heat transfer in large industrial furnaces with more accuracy not only for low heating value gases such as BFG but also for high heating value gases such as COG and NG.

5. References

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