NUMERICAL STUDY OF RADIATIVE HEAT TRANSFER IN A BAFFLED 2D COMPLEX HEAT RECUPERATOR

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ABSTRACT

The radiative heat transfer problem is solved for 2D complex industrial furnace of biomass pyrolysis composed by two pyrolysis chambers and heat recuperator. The fumes are a mixture of carbon dioxide and water vapor charged with absorbing and scattering particles and soot. In order to increase gases residence time and heat transfer, the heat recuperator is provided with many inclined diffuse and gray baffles of finite thickness and has a complex geometry. The Finite Volume Method (FVM) combined with the Weighted Sum of The Gray Gases (WSGG) Model of Kim and Song[1] are applied to study radiative heat transfer. The blocked-off region procedure is used to treat the geometrical irregularities. The shadow effect caused by the presence of the many baffles is discussed.

KEYWORDS Radiation, Heat recuperation, Incineration, Non gray, Soot volume fraction.

1. INTRODUCTION

Optimizing the heat transfer in recuperation systems remains the essential care of heating engineers. However, the designs of heat recuperators have a crucial effect on the efficiency of energy conversion processes generally made at high temperature in complex geometries in presence of baffles. Numerical investigation of the number of these baffles leads to adjustment of heat recuperators and could have serious advantages for the design of new thermal conversion systems.

Indeed, radiative heat transfer in geometries with segmented baffles has many engineering applications, e.g. heat exchangers, solar collectors, furnaces, internally heated turbine blades and combustors. Enhancement techniques usually employ baffles attached to the heated surface so as to provide an additional heat transfer surface area. Many investigations have been focused on the baffle-walled enclosures. Most studies discussed the optimal baffle geometry that enhance heat transfer performance for a given pumping power or flow rate. Borjini et al. [2] solved the radiative heat transfer problem in a three-dimensional partitioned rectangular enclosure containing absorbing-emitting and isotropic scattering medium in the presence of heat generation. They showed that the effect of the partition is more important in the upper half of the furnace and near the exit-end wall. A strong absorbing emitting medium attenuates the partition effect. On the other hand, the gas transmits the effect of the presence of the obstacle to surfaces that are not influenced by the shadow effect in transparent media. The emissivity of the partition has a significant effect on both radiative wall fluxes and gas temperature distributions.

In the proposed biomass pyrolysis pilot plant [3] the radiant energy transport is an essential and very predominating phenomenon. The considered heat recuperator (Figure 1) has a complex shaped geometry, so analytical or exact solutions are unable to model this phenomenon. In this paper the FVM is applied in conjunction with the blocked-off-region procedure and the WSGG model to study radiative exchanges in the heat recuperator (Figure1). The main objective is to determine which configuration of the baffles is better to enhance heat transferred to biomass in the two pyrolysis rooms, then to study the radiative heat transfer in the recuperator containing CO_2/H_2O mixtures and soot particles. The study of the effect of soot volume fraction on the inner wall radiative heat flux is presented. The effect of adding baffles inside the heat recuperator is studied and shown to have an important effect on radiative heat flux and temperature profile.

2. MATHEMATICAL MODEL

2.1 Physical model

The physical model of the studied heat recuperator is represented on Figure 1. It consists of a parallelipepedic metallic construction containing two cylindrical chambers in direct contact with gases issued from biomass pyrolysis fumes combustion. The metallic walls of the pyrolysis rooms are equipped with several baffles. The radiative heat transfer in such medium is governed by the following equation:

$$\begin{aligned} \frac{dI_\eta}{ds} &= -\left(\kappa_{g,\eta}+\kappa_{p,\eta}+\kappa_{s,\eta}+\sigma_{sp,\eta}+\sigma_{ss,\eta}\right)I_\eta+\kappa_{g,\eta}I_{b,g\eta}+\kappa_{p,\eta}I_{b,p\eta}+\kappa_{s,\eta}I_{b,s\eta} \\ &+\frac{(\sigma_{sp,\eta}+\sigma_{ss,\eta})}{4\pi}\int_{4\pi}\Phi_\eta\left(\vec{s},\vec{s}\,'\right)I_\eta\left(\vec{s}\,'\right)d\Omega' \end{aligned} \tag{1}$$

Where $\kappa_{g,\eta}$, $\kappa_{p,\eta}$ and $\kappa_{s,\eta}$ are respectively the spectral absorption coefficients of gas, particles and soot at the specific wave number η. $\sigma_{sp,\eta}$ and $\sigma_{ss,\eta}$ are the spectral scattering coefficients of particles and soot at the specific wave number η, respectively.

2.2 Boundary Conditions

When using the WSGG model to study the non-gray gas behaviour, bounding walls are assumed to be gray and diffusely emitting and reflecting radiation. Under these assumptions, the radiation intensity at a given boundary node is discretized as

$$I_k(s_w,\mathbf{\Omega})=\varepsilon_w\omega_k I_{b,k}(s_w)+\frac{1-\varepsilon_w}{\pi}\int_{\mathbf{\Omega'}.\mathbf{n_w}<0} I_k(s_w,\mathbf{\Omega'})\left|\mathbf{\Omega'}.\mathbf{n_w}\right|d\Omega' \tag{2}$$

2.3 Radiative properties

The particle absorption and scattering coefficients are defined respectively by:

$$\kappa_p=\varepsilon_p\sum_i N_i\frac{\pi d_i^2}{4} \tag{3}$$

$$\sigma_{sp}=\left(1-\varepsilon_p\right)\sum_i N_i\frac{\pi d_i^2}{4} \tag{4}$$

In equations (3) and (4), N_i and $(\pi d_i^2/4)$ are the particle number density and the particle projected area pertaining to group *i*, respectively. The soot absorption coefficient used in the present work is taken in the Rayleigh scattering limit.

$$\kappa_s=\frac{3.72 f_v C_0 T}{C_2} \tag{5}$$

where $C_0=36\pi nk/\left[\left(n^2-k^2+2\right)^2+4n^2k^2\right]$, $C_2=1.4388$ cm K, while *n=1.85* is the real part of the complex index of refraction and , *k*=0.22 is the absorptive index.

The soot scattering coefficient is given by the following equation:

$$\sigma_{ss,\eta}=\frac{4\alpha^4 f_v}{d}.\frac{\left[\left(n^2-k^2-1\right)\left(n^2-k^2+2\right)+4n^2k^2\right]^2+36n^2k^2}{\left[\left(n^2-k^2+2\right)^2+4n^2k^2\right]^2} \tag{11}$$

with $\alpha=\dfrac{\pi d}{\lambda}$ is the size parameter.

2.4 Radiative heat flux. The total intensity integrated over the entire spectrum is given by:

$$I = \sum_{\eta=1}^{M} I_{\eta}\Delta\eta \tag{12}$$

where M is the number of total narrow-bands and $\Delta\eta$ is the narrow band width. The heat flux components are calculated as:

$$q_i = \int_{4\pi} \vec{n}_i.\vec{n}_0.I d\Omega = \sum_{\eta} \int_{4\pi} \vec{n}_i.\vec{n}_0.I_{\eta}\Delta\eta d\Omega \quad i\text{=x or y.} \tag{13}$$

where: $\vec{n}_i$ is the unit normal vector of a surface pointing to the gas side. $\vec{n}_0$ is the unit vector in the direction of radiation propagation.

3. RADIATIVE HEAT TRANSFER IN THE RECUPERATOR MODEL

In this study we suppose that the depth of the heat recuperator is greater to the other dimensions so that the transfers can be described by a two-dimensional model. In order to determine the best configuration of the baffles, six cases are studied (Figure 2). The main objective of our study is to peak out the case giving the greatest radiative heat flux transferred to the two pyrolysis rooms.

Case 1: The heat recuperator consists of only two pyrolysis rooms (Figure 2.a).

Case 2: We add to Case 1 one horizontal baffle which relates the two pyrolysis rooms. (Figure 2.b, Baffle 9).

Case 3: We add to Case 2 four inclined baffles on the right wall and four inclined baffles on the left wall. (Figure 2.c, Baffles number 1,2,3,4,14,15,16, and 17).

Case 4: We add to Case 3 one vertical baffle on pyrolysis room 1 and one vertical baffle on pyrolysis room 2. (Figure 2.d, baffles number 8, 13).

Case 5: We eliminate baffles number (1,2,3,4,14,15,16, and 17) from Case 4 and added three inclined baffles on pyrolysis room 1 (Baffles 5,6, and 7) and three inclined baffles on pyrolysis room 2 (Baffles 10, 11, and 12).

Case 6: To case 5 we added four inclined baffles on the right wall (Figure 2.f. Baffles 1,2,3, and 4) and four inclined baffles on the left wall (Figure 2.f. Baffles 14,15,16, and 17), this case represents the real recuperator given in Figure 1.

Figure 3 gives temperature distribution inside the heat recuperator for Case 6, we can see that the numerical codes gives exactly the physical reality of the heat recuperator. Figure 4 gives the radiative heat flux inside the recuperator for the six studied cases. The hot region is located at the bottom face of the recuperator, all other zones of the recuperator are supposed to be cold. The medium absorption coefficient is taken equal to $\kappa = 0.2\text{m}^{-1}$ and the medium is supposed to be non scattering. The walls emissivities are taken equal to unity. We notice that the heat flux increases near the hot region and decreases in proximity of the cold faces. We can deduce that the developed numerical model can give accurate results which are symmetric and physically acceptable.

Figure 4.f gives the real configuration of the heat recuperator with all baffles as shown by figure 2, the complete configuration with all baffles gives the maximal heat flux transferred to the pyrolysis rooms.

4. SHADOW EFFECT

Shadow effect is defined as an area that is not or is only partially irradiated or illuminated because of the interception of radiation by an opaque object between the area and the source of radiation. In the framework of radiation between surfaces shadow effect due to surface irregularities is essential in computing radiative intensities. In order to investigate the shadow-hiding effect computer simulations are carried out inside the heat recuperator for different number of baffles to examine effects of the baffle on heat transfer distributions. First the heat recuperator contains only the two pyrolysis rooms, then one add the baffles in order to study their effect on the internal radiative heat flux and on temperature distribution. The calculations for the first case (only the two pyrolysis chambers) show that, as the baffle number increases, the medium temperature increases and the radiative heat flux on the walls of the pyrolysis rooms increases. In fact, the mean radiative heat flux versus the number of added baffles is shown in Figure 4. The baffles which are located on the walls of the recuperator contribute to decrease the radiative heat flux transferred to the pyrolysis rooms because the temperature of the recuperator walls is cold compared to the inlet temperature. Increasing the number of these baffles decreases the amount of radiative heat flux transferred to the pyrolysis rooms.

5. NON GRAY RADIATIVE HEAT TRANSFER IN THE RECUPERATOR

5.1 Effect of Soot Volume Fraction

Soot is produced in the combustion of a number of organic materials such as coal, oil, biomass, and natural gas as a result of incomplete combustion. It consists of very fine particles of carbon and solid-phase organic molecules. The size of soot particles depends on temperature and other burning conditions. In the case of the present heat recuperator the pyrolysis fumes are charged with tar, unburned particles and residual ash. Soot varies in size from very small particles which are less than 0.1 micrometer in diameter to very large aggregates. In order to analyze the effect of soot volume fraction on the wall radiative heat flux of the pyrolysis rooms, we assume that the medium contains only a mixture of gas (H_2O and CO_2) and soot; all other properties of the medium are kept unchanged. Four cases of soot volume fraction are considered in the present work ($f_v=10^{-7}$, 10^{-6}, 10^{-5} and 10^{-4}). The grid mesh is the same as in the previous paragraph. The considered spectral field ranges from 150 to 6000 μm and each band is divided into 30 gray gases and has a width of $25cm^{-1}$. The distribution of wall heat flux is illustrated in Figure 5. It is found that when the soot volume fraction increases from $f_v=10^{-7}$ to 10^{-4}, the value of wall heat flux of the combustor is shown to increase.

6. CONCLUSION

Results from numerical simulations of two-dimensional gray/non gray heat radiation in a geometrically complex heat recuperator are used to examine effects of baffles on heat transfer. The finite volume method (FVM) is used to solve the radiative heat transfer equation. The blocked-off region procedure is applied to treat the geometrical irregularities. The weighted sum of the gray gases (WSGG) model of Kim and Song is used as a non gray gas model. It springs from this study that the soot volume fraction affects strongly the radiation heat flux within the combustors of biomass pyrolysis smokes. The effect of the baffles location on radiative heat flux is also investigated and demonstrated to be advantageous. Shadow effect is studied and demonstrated to have a crucial effect on wall radiative heat flux. Also, if the baffles are located on the walls of the pyrolysis rooms near the inlet (hot regions) they will contribute to enhance the heat transfer to biomass. Whereas, if the baffles are located near the outlet or on the walls of the heat recuperator (cold regions) they will contribute to the loss of radiative energy.

Finally, this work can be improved by extending the present model to a 3D one and studying the non-homogenous and non-isothermal behaviour of the heat recuperator medium.

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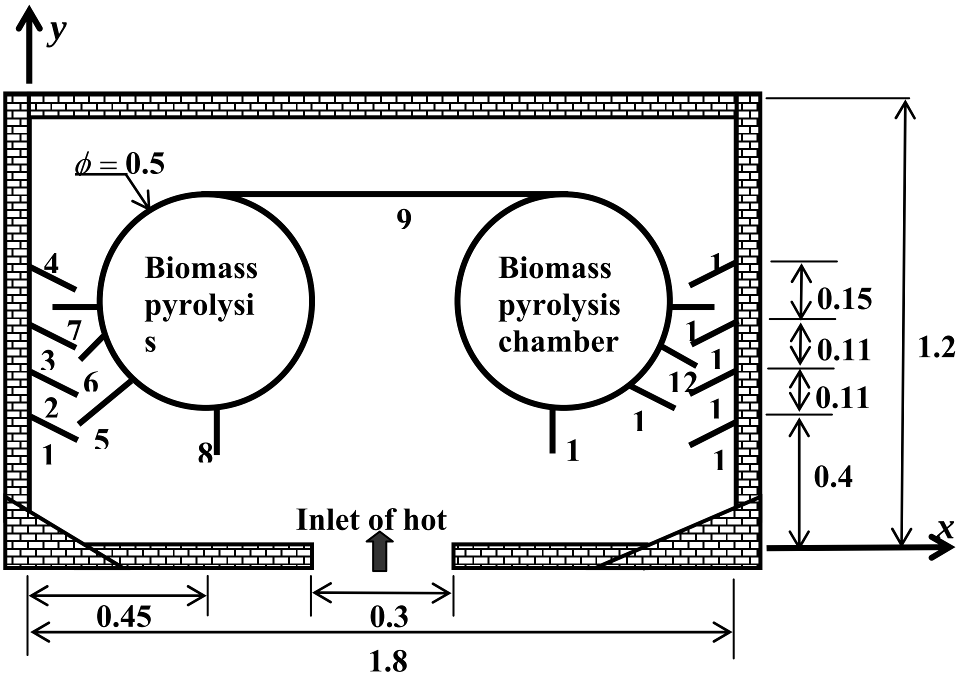
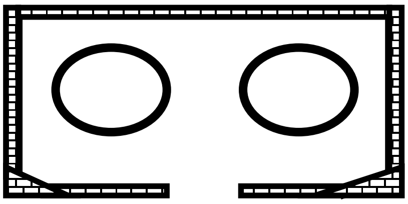
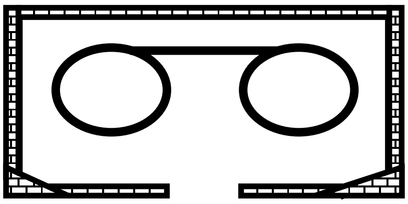


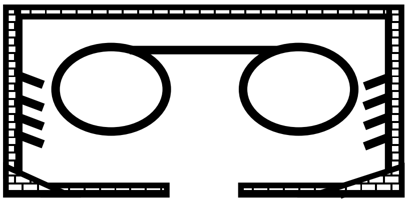
Figure 1 Geometrical characteristics of the heat recuperator



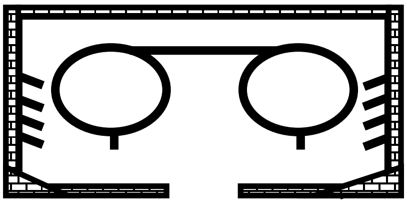
Case 1 (a)



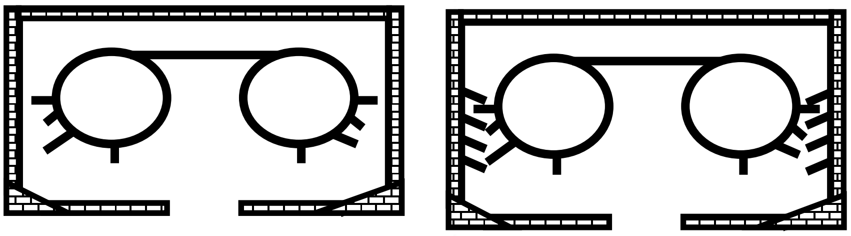
Case 2 (b)



Case 3 (c)



Case 4 (c)



Case 5 (e) **Case 6 (f)**

Figure 2 Different studied configurations

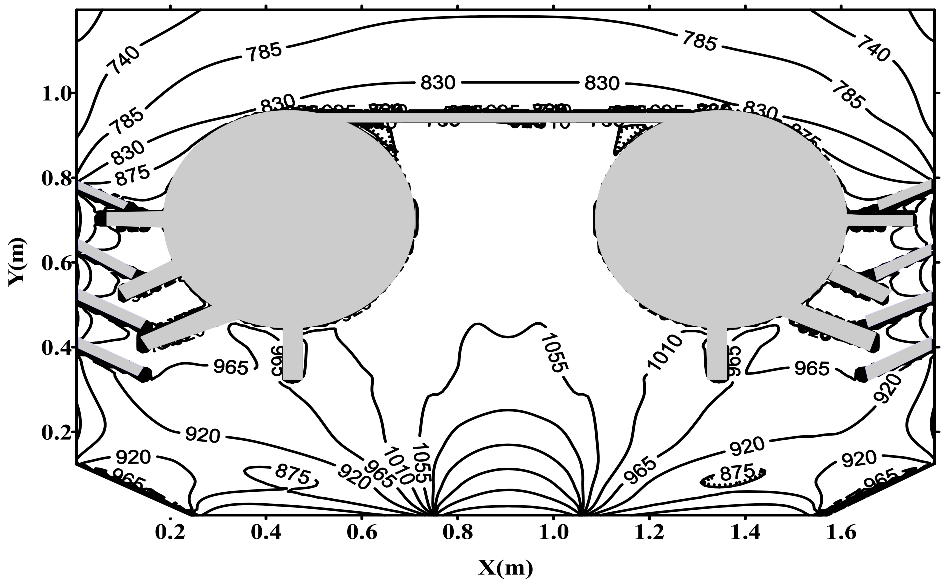


Figure 3 Temperature distribution inside the heat recuperator for Case 6

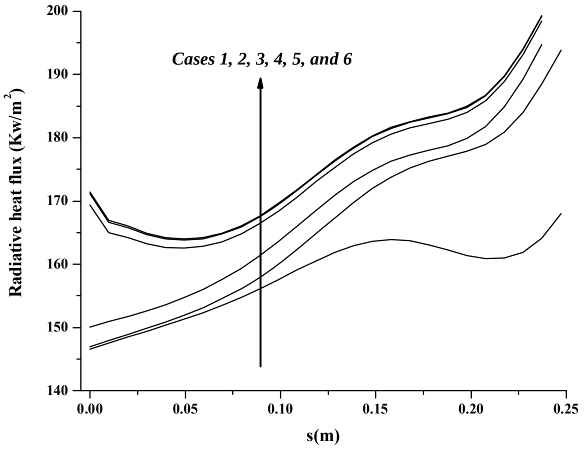


Figure 4 Radiative heat flux on the walls of the pyrolysis rooms for the different considered cases

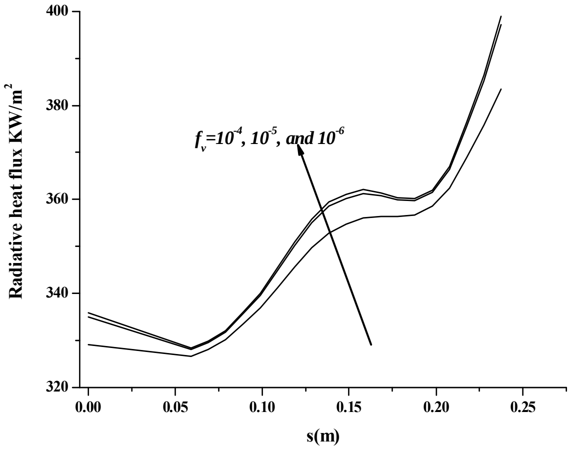


Figure 5 Effect of soot volume fraction on radiative heat flux on the walls of the pyrolysis rooms