Annals of the Academy of Romanian Scientists
Series on Engineering Sciences
Volume **13,** Number **2/2021** ISSN 2066-8570

A COMPUTATIONAL COMBUSTION METHOD FOR TURBULENT PULVERIZED SOLID FUEL USING LES

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Rezumat. *Combustibilii solizi sunt încă folosiţi în multe regiuni ale lumii, asigurând necesarul de energie. Actualmente, schimbările climatice impun reguli mult mai stricte legate de folosirea şi arderea eficientă a combustibililor solizi, aşa cum este cazul folosirii cărbunelui. O metodă de reducere a emisiilor este asigurarea unui proces de combustie eficient, care poate fi obţinut folosind cărbunele sub formă de pulbere. Cărbunele pulbere asigură un amestec eficient al aerului şi combustibilulului solid şi de aceea asigură o combustie eficientă şi reducerea emisiilor. Studiile experimentale ale proceselor de combustie sunt costisitoare. De aceea, metodele computaţionale oferă avantajul unor soluţii rapide şi precise ale caracteristicilor fluidului şi produşilor de combustie. În acest studiu se propune utilizarea unei metode bazată pe Large-Eddy Simulation (LES), împreună cu un model de combustie cu flacără. Studiile arată că aceste două metode asigură o bună predicţie a fluidului şi a produşilor de reacţie. Prezenta lucrare demonstrează o creştere a entropiei şi o descreştere a densităţii în zona de combustie. Temperatura scade pe măsură ce flacăra se deplasează către ieşirea din camera de combustie.*

Abstract. *The solid fuels are still used in many regions of the world and assures the energy production. Nowadays, the mitigation of climate changes require strict regulations regarding the use and efficient combustion of solid fuels such as coal and reduction of the emissions. One way to ensure reduction of the emissions is an efficient combustion, which can be obtained using the pulverized coal. The pulverized coal ensure the good mixing of the fuel and air reactants and thus, it ensures an efficient combustion and minimization of the emissions. Experimental studies of solid fuels combustion are challenging and costly. Therefore, the computational methods offer the advantage of fast and accurate predictions of the flow variables and combustion products. In this study we propose a computational method using the large-eddy simulation (LES) approach along with the flamet combustion model. The study shows that the LES approach along with the flamet model predict very well the flow variables and combustion products. The study reveals an increase of entropy and decrease of density in the combustion region. As the flame moves towards the exit of the combustion the temperature decreases.*

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Keywords: combustion, solid fuel, pulverized fuel, large-eddy simulation, flamet model

DOI https://doi.org/10.56082/annalsarscieng.2021.2.98

1. Introduction

Solid fuels still play key role and is the main source of energy in many regions of the world [1]. Nowadays, the strict regulations regarding the climate change generate significant challenges for the use of solid fuels such as coal [1]. One way to mitigate the effects of the coal combustion and the associated emissions is to ensure a full combustion process of the solid fuel [2-14]. In this way the residual toxic components emitted as a results of the burning solid fuel will be diminished. The complete and efficient combustion process of the solid fuel can be achieved using the pulverized solid fuel, pulverized coal in the case of coal combustion. Moreover, in the past decades the mixture of coal with other material such as biomass, tyre powder and plastic waster has been explored. It is assumed that the mixture of the coal with these material would enhance the combustion efficiency and hence, reduce the waste and emissions [15-20]. Previous studies showed that these additive materials act as catalysis and enhance the combustion efficiency of solid fuel. The whole idea of coal mixtures is to increase the combustion of the carbon present in coal. Thus, studies focused on the effect of the C_eO_2 and Fe_2O_3 mixture with coal and showed that the addition of these metals increase the combustion efficiency. Unfortunately, the addition of these metals to the coal combustion resulted in an increase of CO_2 emission, although the CO emissions decreased. Generally, experimental studies of solid fuels are costly and not always available. Therefore, alternative approach must be sought for the study of slid fuels combustion.

Therefore, the present study concerns the development of a computational model for the prediction of the flow variables and products of the coal combustion.

2. Background

Computational methods were employed in the past in the computation of combustion processes [15-22]. Numerical simulations using the Reynolds-averaged Navier-Stokes (RANS) equations were used to compute the fluid flow associated with combustion processes. Generally, the RANS method provides a time-averaged solution and thus, it is not suitable for time-dependent processes, such as combustion. Therefore, for the computation of solid fuel combustion, numerical methods that can simulate the transient nature of the flow are desired. Numerical methods such as direct numerical simulations (DNS) provide higly accurate solution since it does not involve any turbulence modelling. However, the DNS approach poses limitations due to the fact that the grid size of the computational is proportional to the Reynolds number $Re^{9/4}$ and thus, it limited only to low Reynolds number flows. Large-eddy simulation (LES) approach mitigates the issues related to the computational cost posed by the DNS method. Moreover, the LES approach is independent of Reynolds number and thus, it can simulation high-Reynolds number flows.

3. Modeling

The governing equations of large-eddy simulations (LES) are the filtered Navier-Stokes equations, given by the equations (1) and (2)

$$\frac{\partial \bar{u}_i}{\partial x_i} = 0 \qquad (1)$$

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial}{\partial x_j}\left(\bar{u}_i \bar{u}_j\right) = -\frac{\partial \bar{p}}{\partial x_i} - \frac{\partial \tau_{ij}}{\partial x_j} + \frac{1}{R_e}\frac{\partial^2 \bar{u}_i}{\partial x_j \partial_j} \qquad (2)$$

where

$$\tau_{ij} = \overline{u_i u_j} - \bar{u}_i \bar{u}_j \qquad (3)$$

Generally

$$\overline{u_i u_j} \neq \bar{u}_i \bar{u}_j \qquad (4)$$

and

$$\tau_{ij} - \frac{1}{3}\tau_{kk}\delta_{ij} = 2\nu \bar{S}_{ij} \qquad (5)$$

where

$$\bar{S}_{ij} = \frac{1}{2}\left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i}\right) \qquad (6)$$

Smagorinsky model is an algebraic model for the subgrid scale (SGS) viscosity ν_{sgs}. The combustion model is based on the flamet-model. This model has been succesfully emplyed in the numercial simulations of combustion of highly turbulent reacting flows [1].

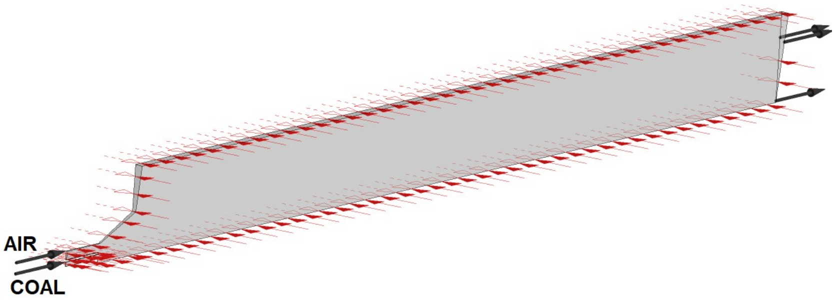

Figure 1. Computational domain

Figure 1 presents the comutational domain used for the present studies. Since the coal combustor has a circular shape, only a section of the combustor is represented in used in the present computations. The air and pulverized coal inlets are shown in Figure 1.

4. Results and discussion

Figure 2 presents the velocity field inside the coal combustor. The analysis shows that the air and pulverized coal enter the combustor at different speeds and this is due to the fact that the coal particles exhibit large inertia and may impact the combustor wall.

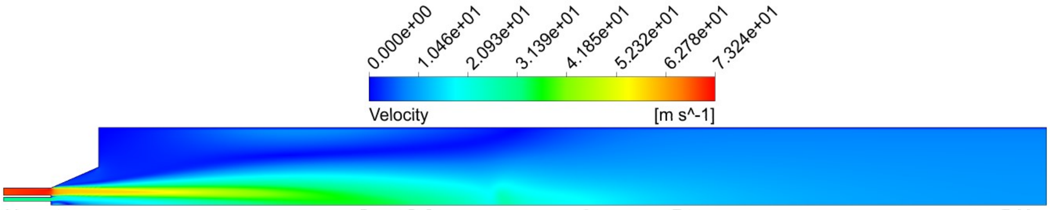

Figure 2. velocity field

As the air and coal particles interact with each other, the air flow speed decays. The air-coal mixing also causes disturbances of the flow field. It is worth to notice here that the air and coal enter at high-speeds in the combustor. Thus, the air enters at 70m/s, while the pulverized coal enters the combustor at 35m/s. the high-speeds of the air and coal are desired for an efficient mixing and combustion. In the combustion region, the second-half of the domain, the flow speed reduces to a minimum.

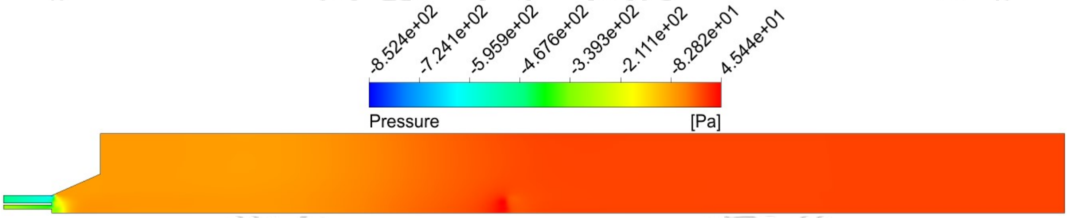

Figure 3. Pressure field

Figure 3 presents the distribution of the pressure field. The analysis shows that the pressure exhibits lower values in the regions of high velocity and higher values in the region of low velocity.

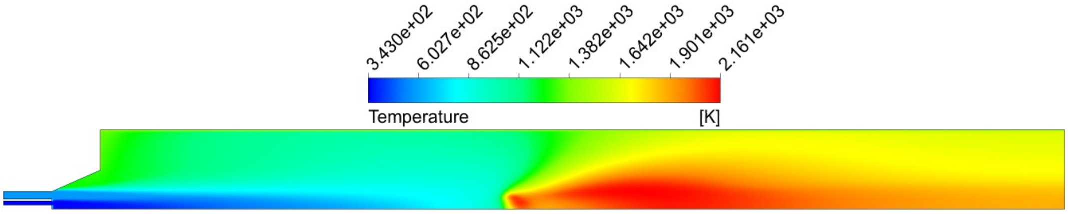

Figure 4. Temperature distribution

Figure 4 presents the temperature field inside the combustor. The analysis shows that the temperature is high in the combustion region, and temperature reaches values of 2,000[K]. The turbulent mixing inside the combustor causes a non-uniform flow and thus, it causes a non-uniform distribution of the temperature field. The temperature decays towards the exit of the combustor.

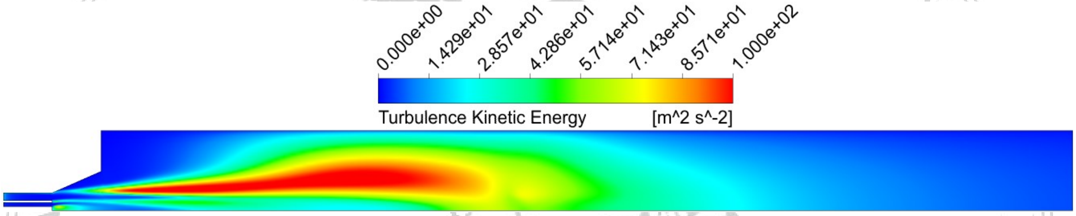

Figure 5. Turbulence kinetic energy

Figure 5 presents the turbulence kinetic energy (TKE) inside the combustor. The analysis of TKE reveals large values of TKE in the inlet region of the combustor and this is due to the high-speed of the air and pulverized coal. In this region the turbulent mixing of air and pulverized coal occurs. Usually, a highly turbulent mixing is desired for an efficient combustion and reduction of the NO_x. In the combustion region the turbulent flow is reduced since a laminar flame is desired.

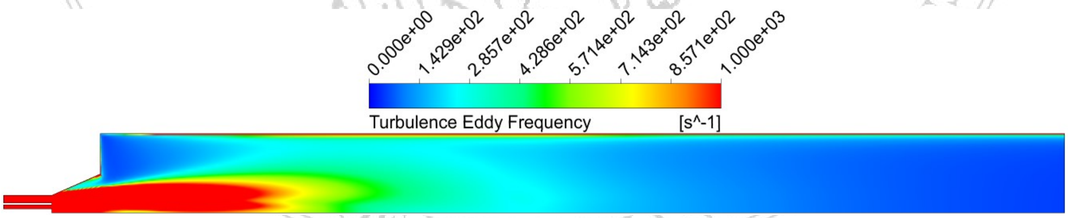

Figure 6. Turbulence eddy frequency

Figure 6 presents the turbulence eddy frequency inside the combustor. The analysis shows that the turbulence eddy frequency exhibits high values in the region of high TKE. The region of high TKE is dominated by the small turbulent scales which have high energy. The small-scale turbulent eddies have the energy to oscillate more than the large-scale turbulent eddies and thus, they exhibit larger turbulence eddy frequency.

However, it is important to mention here that the small-scale turbulent eddies are also more prone to dissipation. Figure 7 presents the turbulence eddy dissipation and it can be seen that the turbulence eddy dissipation exhibits high values in the region of high TKE and turbulence eddy frequency.

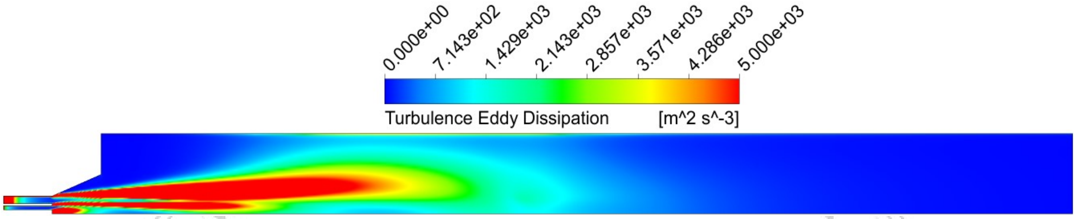

Figure 7. Turbulence eddy dissipation

Figure 8 presents the density variation inside the combustor. The analysis reveals that the density is very low in the combustion region and this is due to the fact that the increase of temperature causes an increase of entropy and hence, a decrease of density.

Figure 9 presents the entropy distribution inside the combustor. The analysis reveals the increase of entropy in the combustion region and as already mentioned this is due to the increase of temperature.

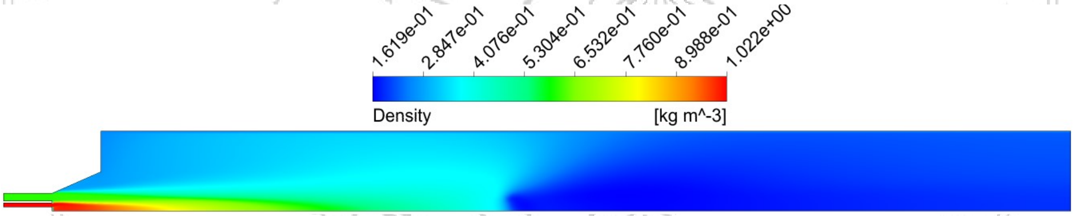

Figure 8. Density distribution

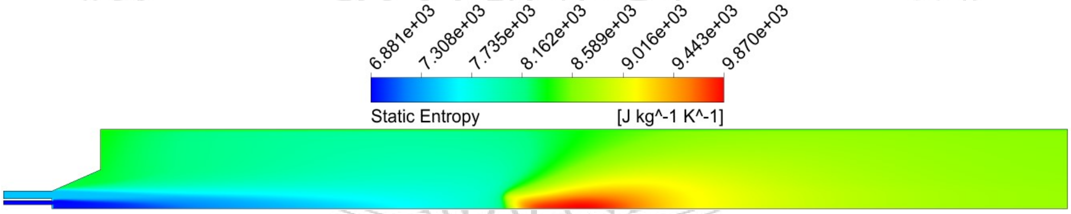

Figure 9. Entropy

Figure 10 presents the thermal radiation and it can be seen that it is high in the combustion region of the combustor. As the combustion flame moves towards the exit of the combustor region, the temperature decays and thus, the entropy decays as well.

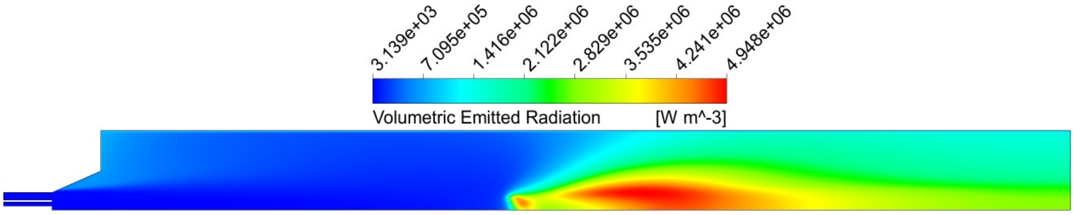

Figure 10. Radiation distribution

Figure 11 presents the distribution of the CO_2 inside the combustor. As shown in Figure 11, the CO_2 is present only in the combustion region since it is a product of the combustion process.

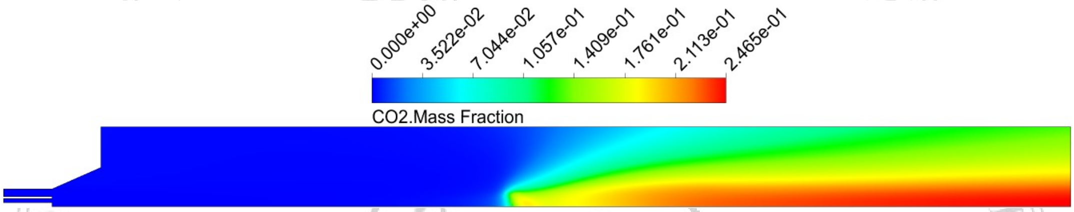

Figure 11. CO_2 variation

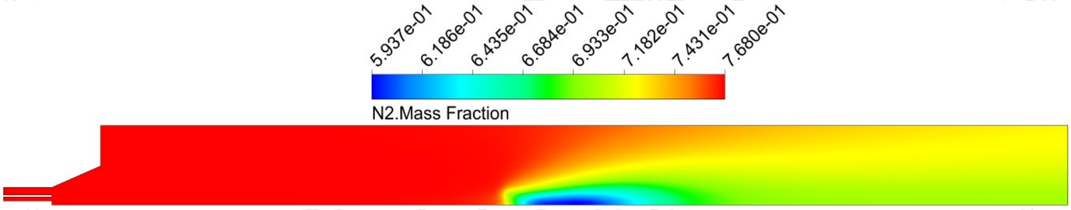

Figure 12. N_2 distribution

Figure 12 presents the distribution of the N_2, inside the combustor. The analysis reveals that the N_2 exhibits high values in the region of the inlet of pulverized coal and this is due to the fact that the nitrogen is already present in the chemical composition of the coal.

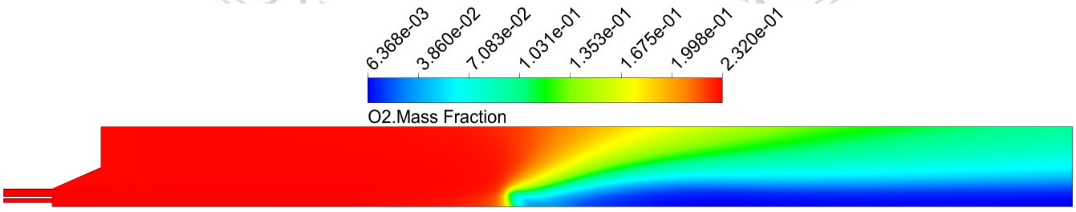

Figure 13. O_2 distribution

Figure 13 presents the variation of the O_2 inside the combustor. The analysis reveals that the O_2 is dominant in the inlet region and this is due to the fact that the oxygen is present in the chemical composition of both, air and coal. As a result of the coal combustion, the values of the O_2 are low.

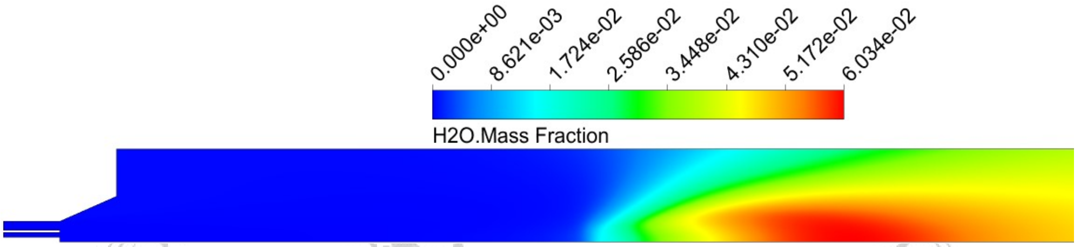

Figure 14. H_2O distribution

Figure 14 presents the variation of the H_2O inside the combustor. It is worth to mention here that generally the H_2O is a result of the combustion processes. The analysis reveals the presence of large values of H_2O in the combustion region.

Conclusions

An efficient computational approach, large-eddy simulation (LES) along with the flamet combustion model is developed for the computations of combustion of solid fuels. The study shows that the LES along with the flamet model can predict very well the flow characteristics and combustion phenomenon. The analysis shows that the high-speed incoming air and pulverized coal cause a highly turbulent mixing in the inlet region. The highly turbulent mixing is desired since it defines the combustion process and ensures efficient combustion and thus, reduction of the emissions. The study reveals that the temperature exhibits high values in the combustion region. An increase of entropy is also observed in the combustion region, while a lower density is observed as well.

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