Journal of Physics: Conference Series

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To cite this article: Ahmed K. Khodir *et al* 2025 *J. Phys.: Conf. Ser.* **3070** 012022

Journal of Physics: Conference Series **3070** (2025) 012022 doi:10.1088/1742-6596/3070/1/012022

Numerical study on the effect of fuel jet design parameters for MILD combustion characteristics

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Abstract. This study investigates the characteristics of the Moderate or Intense Low-oxygen Dilution (MILD) combustion at different design parameters related to fuel port. The effect of fuel jet diameter and number of fuel ports were investigated. The current numerical study was based on a three-dimensional geometry of gaseous burner. All computations were performed using ANSYS FLUENT 19.0. Four cases for number of fuel inlets (4,8,12 and 16 mm) were studied without any change in the fuel mass flow rate. Moreover, three different values of fuel jet diameter (2,3 and 4 mm) were analyzed. It was concluded that increasing the number of fuel ports leads to enhanced mixing and significant reduction in CO and NO emissions. Smaller jet diameter enhances the mixing of diluents, leading to more complete combustion and lower combustion temperatures. The enhanced mixing leads to effective reduction on NO and CO emission.

1. Introduction

Climate change on the planet is considered one of the most important issues in the past twenty decades and its level of risk is increasing rapidly. The observed rise in planet temperature, melting of polar ice, rising sea levels and oceans, desertification and drought, repeated floods and storms are some climate change risks. Subsequently, researchers are seeking to use new regimes and methods for combustion to reduce greenhouse gases [1,2]. Moderate or Intense Low-oxygen Dilution (MILD) combustion is a new combustion technology which used to reduce pollutant emissions. MILD regime concept is relying on the dilution of the fresh mixture using the recirculated exhaust gases (products) [3]. MILD combustion has gained significant from its ability to reduce NOx emissions [4-6] and the reduction in peak temperature. The dilution of the reactants leads to a decrease in the reaction rate and subsequently, the reaction zone increases. Also, the combustion occurs in large volume which results in homogeneity in thermal contours. In general, it can be said that the combustion rate becomes moderate through mixture dilution [7,8]. This combustion regime has been used a lot of industrial burners in different applications such as ceramic and glass melting [9,10].

Many efforts were made to enhance the characteristics of the MILD combustion. Yizhuo et al. [11,12] performed a numerical investigation to detect the major parameters of carbon monoxide and Nox of MILD regime. The mechanisms of NO and CO emissions were studied in detail in these two papers. It was concluded that the increase in entrainment ratio from 1 to 3 leads to an effective decrease in NO emissions. Li et al. [13] reported numerical and experimental study about NO emissions from CH_4/H_2 MILD combustion. It was found that increasing the mass fraction of H_2

from 5.7% to 14.4% hasn't any impact on NO emissions. Wang et al. [14] presented a novel burner which uses internal recirculation device (IRD) to create the MILD mode which improves the combustion stability and heat transfer especially, in industrial boiler. It was shown that conventional combustion the mild combustion stability increases using IRD device with a remarkable decrease in emissions. MILD combustion is often called flameless oxidation (FLOX) [15]. Yaojie et al. [16] presented an experimental study for a new configuration which depend on using an inverse-diffusion to enhance the mixing and stability of MILD combustion. Effect of thermal load and equivalence ratio were employed. The results showed that the MILD mode was unable to sustain if thermal load value less than 2 kW. Also, it was found that equivalence ratio has a small effect on MILD mode stability. CO emission was decreased with increasing the length of the combustor. Effect of combustor length on NO emissions can be negligible. Sun et al. [16] performed a numerical study for the impact of oxygen content in oxidizer of MILD combustion. It was concluded that the increase in oxygen content from 15% to 30% leads to an increase in the maximum temperature. Moreover, the length of MILD region increases significantly from 1 to 1.4 m. Sun et al. [17] reported an experimental study to show the effect of using combustor with deflector which effect on the amount of internal recirculated gases in MILD combustion. Using the deflector with arm leads to an increase in recirculated gases, hence mixture dilution has been enhanced. It was observed that NO emissions were increased with increasing arm length. Nada et al. [18] investigated the effect of burner configuration at different temperature for the oxidizer. It was observed that A further increase in inter-nozzle spacing caused flame extinction, which led to a reduction in NO_x emissions.

Most of previous studies were conducted on operating conditions such as oxidizer temperature or fuel mixture. The current study focuses on investigation the features of the MILD combustion at different fuel jet design parameters. The parameters studied are fuel jet diameter, and No. of fuel inlets. It is expected that these parameters play an important role in the mixture dilution, and subsequently all combustion characteristics.

2. Numerical simulations

Figure 1. Shows the dimensions of small-scale MILD combustor which used in the validation study. This combustor was presented by Verissimo et al. [19]. Combustor diameter was 100 mm with 340 mm length. Air was used as an oxidizer and injected at the combustor centre from a port with 10 mm diameter. Methane was used as a fuel and was injected through 16 fuel port as demonstrated in Figure 1. ANSYS FLUENT 19.0 was used in the current simulation. Finite volume method was implemented to solve the governing equations. RNG k-Ɛ turbulence model was recommended according to the turbulence model assessment which presented in the work of Khodir et al. [20]. A 3-D grid consists of 743,042 cells was generated using ANSYS mesh as shown in Figure 2 where the average values of both mesh element quality and skewness were 0.689 and $4.5e^{-2}$ respectively. The GRI-EDC (Gas Research Institute - Eddy Dissipation Concept) combustion model is a hybrid approach that combines detailed chemical kinetics with turbulence-chemistry interaction modelling for simulating combustion processes. It is particularly useful for predicting emissions such as NO_x and CO in turbulent reacting flows. GRI-EDC combustion model was used as recommended from the previous work of Khodir et al. [20-22]. The conservation of mass Equ.(1) is utilized to determine the velocity components (u, v, w) for each control volume. Additionally, the conservation of momentum Equ.(2) is employed to compute the pressure distribution across the computational domain. For combustion cases, the conservation of energy

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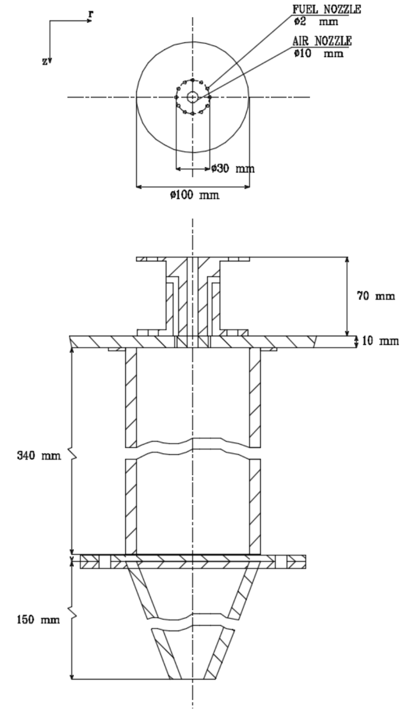

Figure 1. Schematic of MILD combustor and burner (Verissimo et al. [19]).

Equ.(3) is applied to obtain temperature results. Furthermore, species conservation Equ.(4) and the ideal gas state are also considered in the solution.

$$\frac{\partial(\rho u_i)}{\partial x_i} = 0 \tag{1}$$

where ρ is density

$$\frac{\partial(\rho u_i u_j)}{\partial x_i} = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right) \tag{2}$$

Where u is the velocity vector and μ is the dynamic viscosity.

$$\frac{\partial}{\partial x_i}(\rho u_i h) = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i}\left(\lambda \frac{x_i \partial T}{\partial x_i}\right) - \frac{\partial}{\partial x_i}\left(\rho \sum_{k=1}^{N} h_k Y_k V_{k,i}\right) + \sum_{k=1}^{N} \Delta h^o_{f,k} \dot{\omega}_k + S_H \tag{3}$$

Where $\boldsymbol{\lambda}$ represents the thermal conductivity coefficient and $\boldsymbol{S_H}$ is the volumetric heat sources.

$$\frac{\partial}{\partial x_i}(\rho u_i Y_k) = -\frac{\partial}{\partial x_i}\left(V_{k,i} Y_k\right) + \dot{\omega}_k \quad \text{for k=1, N} \tag{4}$$

Where $V_{k,i}Y_k$ represent the molecular penetration. Y_k is the mass fraction and $\dot{\omega}_k$ is the reaction rate.

Convergence was successfully attained for all variables, exhibiting residuals of 10^{-3}, except for the energy parameters and major species, which exhibited even higher accuracy, reaching residuals of 10^{-6}

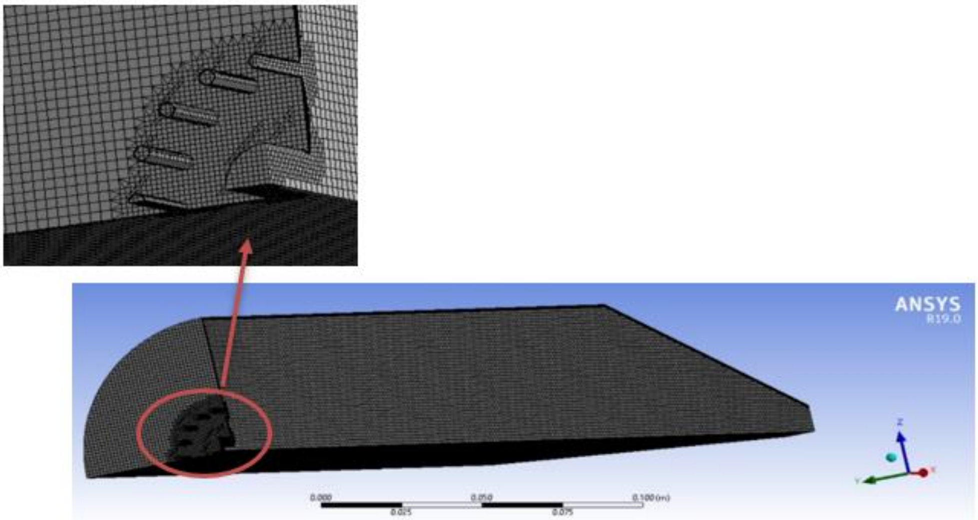

Figure 2. Computational grids.

3. Results and Discussion

3.1 Effect of Fuel Ports Number on MILD Combustion

The number of fuel inlets, or fuel injection ports, in a MILD combustion system can have several impacts on the combustion process. The current paper studied the effect of four different values of fuel inlets, 4,8,12 and ports. Increasing the number of fuel inlets can lead to reduced NOx formation as presented in Figure 3. Increasing the number of fuel inlets improves fuel-air mixing within the combustion chamber. Each additional fuel inlet promotes better distribution of fuel within the combustion chamber, leading to enhanced mixing of fuel with the oxidizer. Increasing the number of fuel inlets can enhance the mixing of fuel and air within the combustion chamber. Improved mixing promotes better combustion efficiency and a more homogeneous fuel-air mixture, which can lead to lower peak temperatures and reduced NOx formation. Also, A higher number of inlets can result in shorter residence times, reducing the time available for NOx formation. Shorter residence times help in minimizing the peak temperatures and decrease the overall NO mole fraction. Moreover, with multiple fuel inlets, the fuel can be distributed more evenly, ensuring an adequate oxygen supply throughout the combustion process. Sufficient oxygen availability helps in reducing NOx formation. When fuel and air mix uniformly, combustion is more complete, resulting in lower CO mole fractions with increasing the number of fuel ports as shown in Figure 4. Moreover, it is observed that increasing the number of gas ports from 12 to 16 doesn’t have a significant impact on CO emissions.

3.2 Effect of Fuel jet diameter on MILD Combustion

The fuel jet diameter plays a role in the mixing of fuel and air within the combustor. Three different values of fuel jet diameter were studied, 2,3 and 4 mm. A smaller fuel jet diameter can promote better mixing of fuel and air, leading to a more homogenous mixture and enhance mixture dilution as shown in Figure. 5. This improved mixing can result in more complete combustion, and, in turn, lower combustion temperatures as shown in Figure 6. In some MILD combustors, diluent gases or recirculated combustion products are used to dilute the air-fuel mixture, reducing the combustion temperature. The fuel jet diameter can affect the dispersion and distribution of these diluent gases within the combustion chamber. So, smaller fuel jet diameters can enhance the mixing of diluents, leading to more effective temperature reduction.

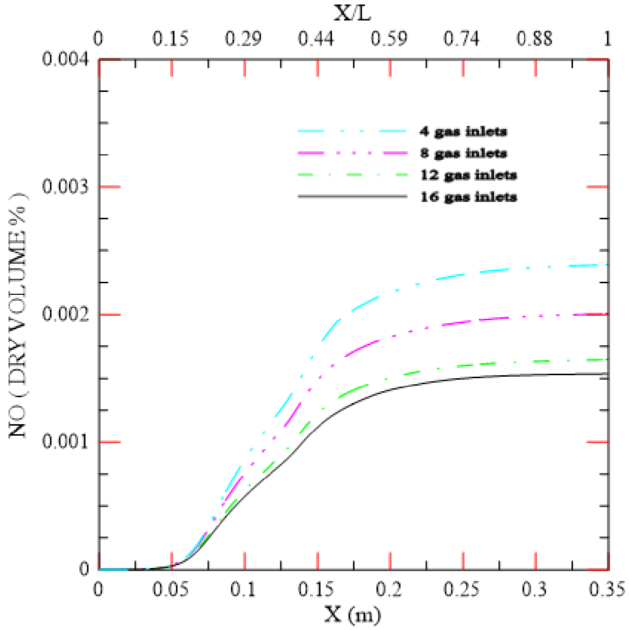

Figure 3. Predicted NO mole fraction through the combustor centreline for different number of fuels ports.

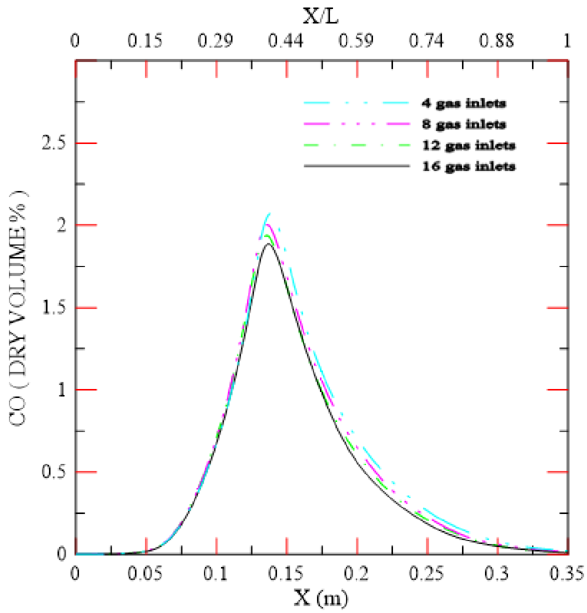

Figure 4. Predicted CO mole fraction through the combustor centreline for different number of fuel ports.

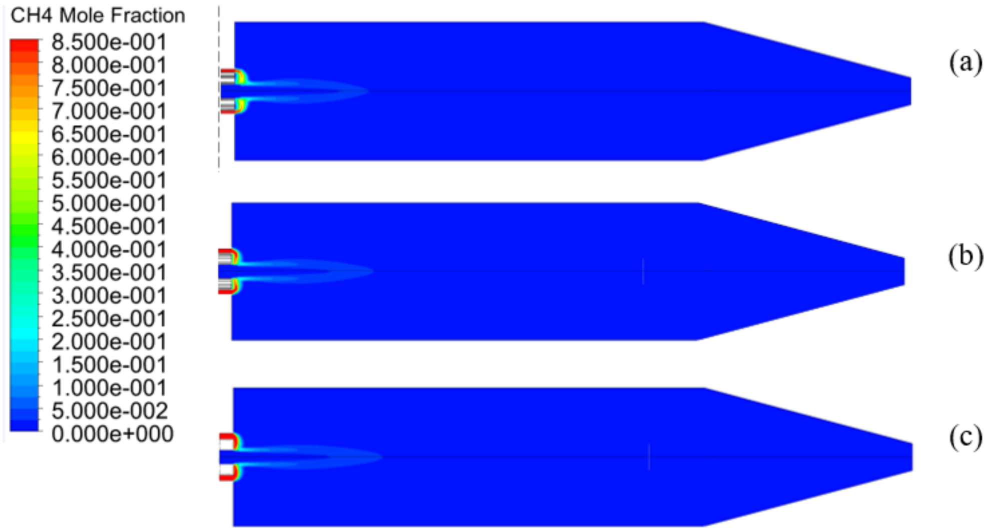

Figure 5. Predicted CH4 mole fraction contours through the combustor symmetry plane for different fuel jet diameters, (a) 2 mm, (b) 3 mm, and (c) 4 mm

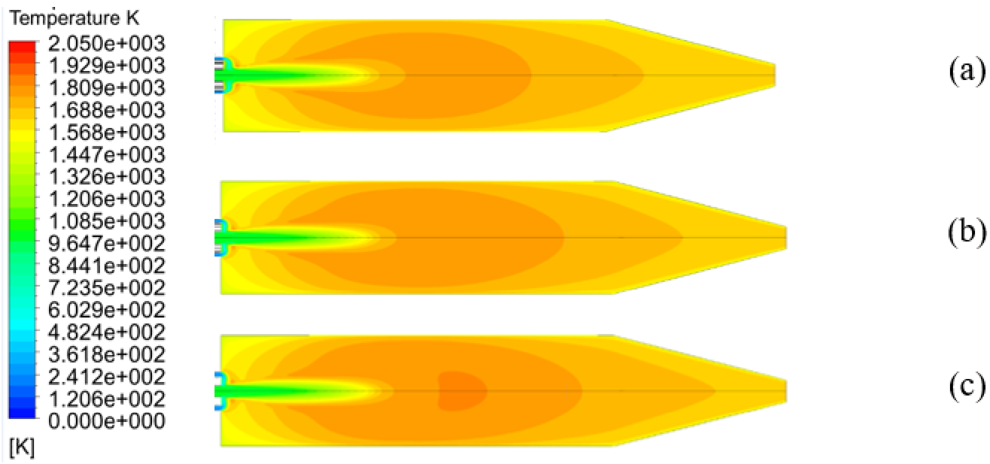

Figure 6. Predicted combustion temperature contours through the combustor symmetry plane for different fuel jet diameters, (a) 2 mm, (b) 3 mm, and (c) 4 mm

The fuel jet diameter can have an impact on NO emissions in a MILD combustor. NO emissions are a significant concern in combustion processes due to their environmental and health implications. Figure 7 demonstrates that NOx emissions decrease with reducing fuel jet diameter. As discussed in the previous paragraph, smaller fuel jet diameters tend to promote better mixing and enhance the homogeneity of the fuel-air mixture. This improved mixing helps to achieve more complete combustion, reducing the formation of NO emissions. Moreover, Lower combustion temperatures can help in reduction thermal NO formation, resulting in decreased NO emissions. Also, in the current geometry of MILD combustors, diluent gases or recirculated combustion products are used to dilute the air-fuel mixture and lower combustion temperatures, thereby reducing NO emissions. The fuel jet diameter can affect the distribution of these diluent gases within the combustion chamber.

The fuel jet diameter in a MILD combustor can influence not only NO emissions but also carbon monoxide (CO) emissions. CO is a harmful pollutant that forms during incomplete combustion and poses risks to human health and the environment. Figure. 8 demonstrates that CO emissions decrease with reducing fuel jet diameter. It was noticed that CO decreased by reducing fuel jet diameter for the same reasons stated in the previous paragraph which related to complete combustion, reduced combustion temperature, shorter residence times, mixture dilution and improved mixing.

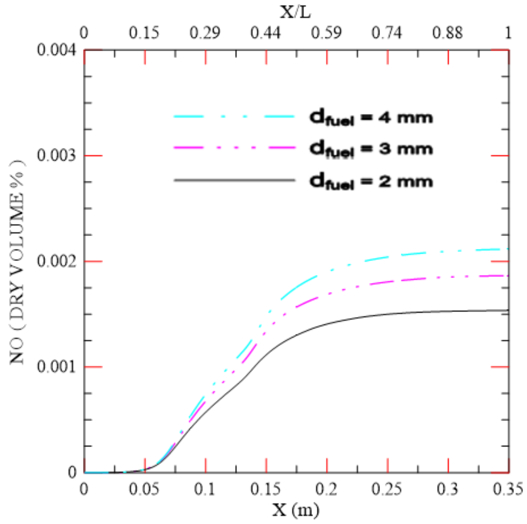

Figure 7. Predicted axial NOx emissions through the combustor centreline for different fuel jet diameters.

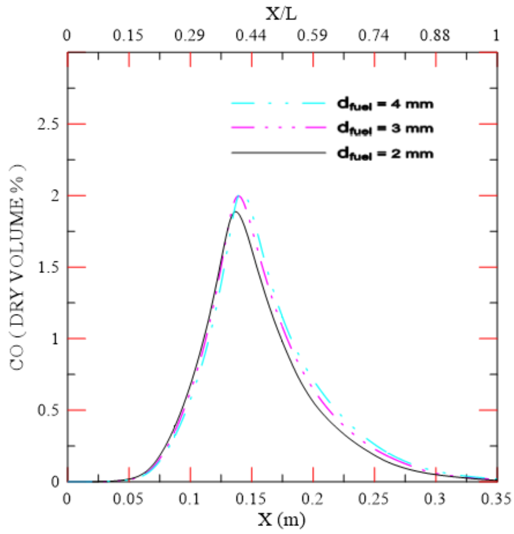

Figure 8. Predicted axial CO emissions through the combustor centreline for different fuel jet diameters.

4. Conclusions

In the present study, the impact different fuel design parameters on MILD combustion were investigated theoretically. The significant results can be summarized as follows:

1. A smaller fuel jet diameter can promote better mixing of fuel and air, leading to a more homogenous mixture and enhance mixture dilution.
2. A significant reduction in NO and CO emissions was obtained by decreasing the fuel jet diameter.
3. Increasing the number of fuel inlets improves fuel-air mixing within the combustion chamber. Each additional fuel inlet promotes better distribution of fuel within the combustion chamber, leading to enhanced mixing of fuel with the oxidizer. Improved mixing helps to distribute the heat release more evenly, reducing the formation of hotspots and slightly lowering the peak combustion temperature
4. The number of fuel inlets affects the residence time of the fuel-air mixture within the combustion chamber. Multiple fuel inlets can promote longer residence times by increasing the tortuosity of the flow path, allowing more time for fuel and air to mix and react. Longer residence times generally result in more complete combustion and lower peak temperatures, subsequently NO and CO emission were decreased.

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