Estimation of Flame Length in Lime Shaft Kilns using CFD Porous Media Model

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Understanding the flow pattern of the gas jet in packed beds can have a considerable significance in improving the reactor design and process optimization. The present study attempts to demonstrate the viability of using computational fluid dynamics (CFD) as a tool to design packed beds by visualizing the flow structure in the reacting zone. The Porous Media Model (PMM) is used as a method of flow simulations in Parallel Flow Regenerative Shaft Kiln (PFR) and Counter Flow Single shaft kiln (CFS). Current research studies focus on the influence of mixing parameters on the length of flame in lime shaft kilns. Validation of simulations with experimental results is done using a sample of a packed bed in an experiment by injecting two different gases into the packed bed. The CFD porous media model (PMM) results shows reasonable accuracy with experimental measurements. Combustion of methane, and flame length has been investigated for a PFR and CFS lime shaft kilns. The flame length was simulated for a wide number of burners. As a consequence, the flame length in PFR shaft kilns is about 5.2 m, when the 18 burners is arranged.

Keywords: Lime shaft kilns, Flame length, Porous media model,Turbulence model

1. Introduction

Design Principle of Lime Shaft Kilns

A large variety of lime shaft kiln designs have been used for centuries around the world. The two most important shaft kilns are:

1. Counter Flow Single shaft kiln (CFS)
2. Parallel Flow Regenerative shaft kilns (PFR).

Lime burning is a high-temperature process where the reactive materials are packed in a vertical shaft. Due to gravity forces, these materials move downward to pass three process zones before reaching the final product quality. In shaft kilns, the fuel is introduced by injection from burners either in radial direction (as in CFS) or in axial direction (as in PFR), depending on the kiln type. The CFS shaft kiln is used for hard burnt lime and the PFR for soft burnt lime. As shown in Figure 1(a), the counter flow shaft kiln is a vertical shaft where limestone is charged at the top of the kiln and quicklime is discharged at the bottom. To calcinate the limestone, the heat is generated by fuel combustion at the point where fuel is introduced with air by means of burner lance systems radially from outside at different heights in the kiln. Additionally, air is blown out at the discharge of the kiln to cool the product in a counter-current manner. In Figure 1(b) the Parallel Flow Regenerative Shaft Kiln (PFR) is shown. This shaft kilns are connected through a crossover channel with a rectangular or circular geometry. It utilizes the regenerative process for lime calcinations. The main features of a twin PFR kiln are:

1. Parallel flow of stone and combustion gases in the burning shaft of the kiln

2. Regenerative preheating of the packed bed in the non-burning shaft

3. Counter flow of lime and fuel and air with cooling zone.

The fuel is introduced at the upper side of the burning zone. The combustion gases flow downward in parallel flow with the stone. They leave the burning shaft through the crossover channel and flow upward in counter flow with the stone in the non-burning shaft. Here, they transfer heat to the packed bed. Because this heat transfer is transient, the mode between a burning shaft and a non-burning shaft has to be changed

2. Experimental setup and Validations

The CFD turbulence model was validated by an experiment packed bed measurement. The nitrogen was injected from bundles to the experiment packed bed at a pressure of 7 bars. The flow rate was fixed at 25 m^3/hr for all the cases. The pressure was adjusted by a ball valve, and the flow rate was adjusted using a rotameter. After that, air was injected from a blower into packed bed through air holes. The experiment measurement was performed for volume ratio $\frac{\dot{V}_j}{\dot{V}_m} = 0.1.$ When the exact flow rate of air and nitrogen was supplied, the mole fraction of O_2 was measured with the help of a gas analyzer. The schematic of the experiment measurement is shown in Figure 3. To obtain more accurate results, the different turbulent models and different turbulence intensities were applied.

1. When the two gases were injected parallel through the packed bed, the k-ε standard turbulence model with T.I=5 % shows more accuracy with the validation results.

2. When the two gases were injected radiall through the packed bed, the K-ω SST turbulence model with T.I=20% shows more accuracy with the validation results.

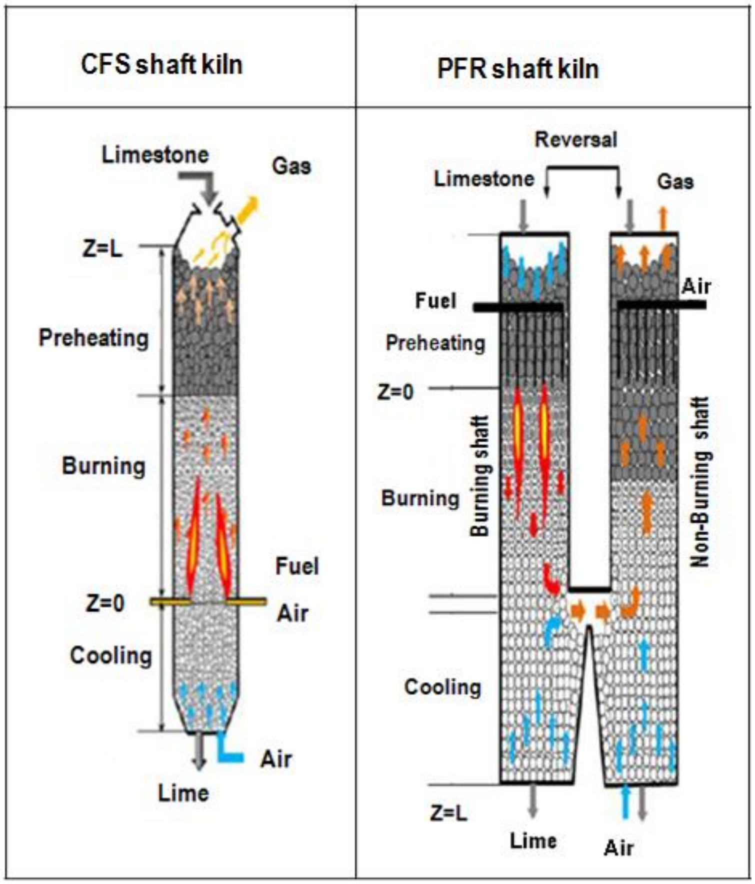

Figure 1: Schematic design of a CFS (a), and a PFR lime shaft kiln(b).

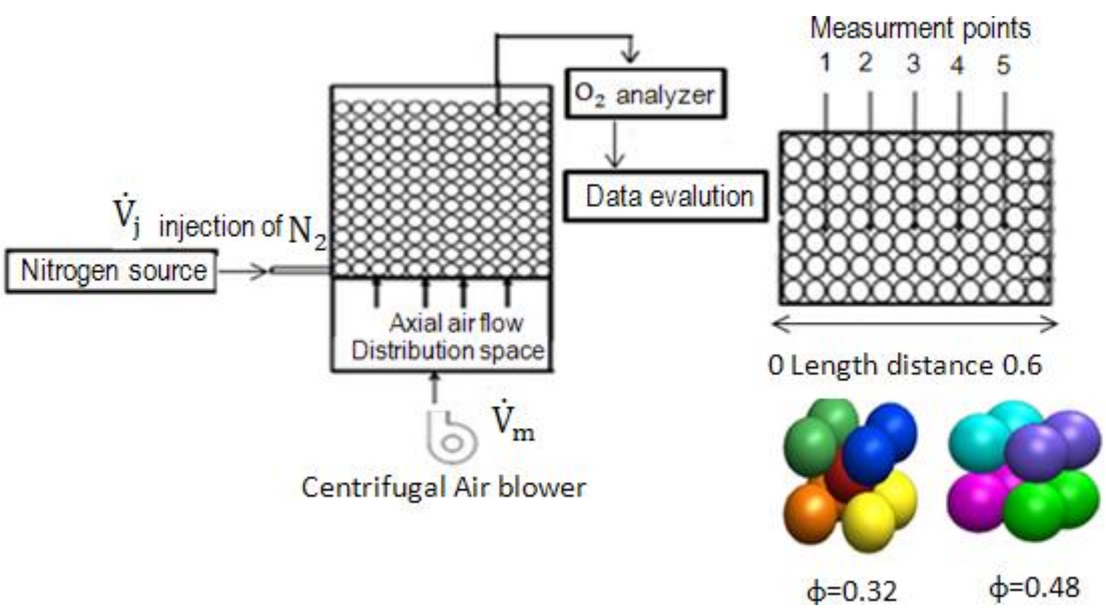

Figure 2 : Schematic description of the experimental setup.

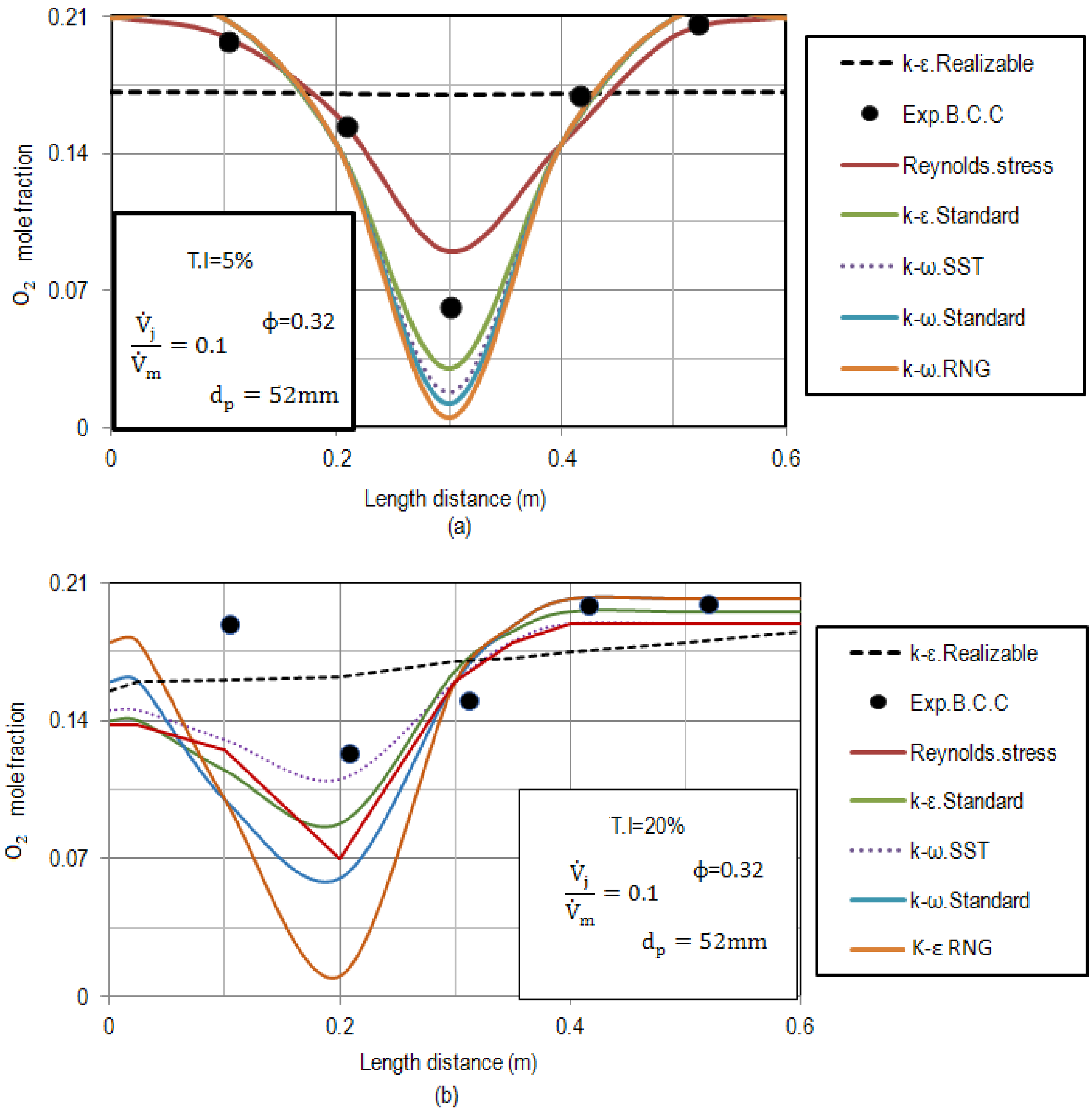

Figure 3: Oxygen profile for comparison for different turbulence models and validation (a)Parallel flow injections,(b) Radial flow injections.

3. Results

Two cases are considered for better understanding of the influencing parameters. The first one is when air and fuel do not react to each other (non-reactive flow), and the second one is when fuel and air react to each other (reactive flow). In Figure 4, the velocity profile is shown at different heights. The maximum velocity is always in the center. The higher the distance from the burner is, the more homogeneous the velocity profile becomes.

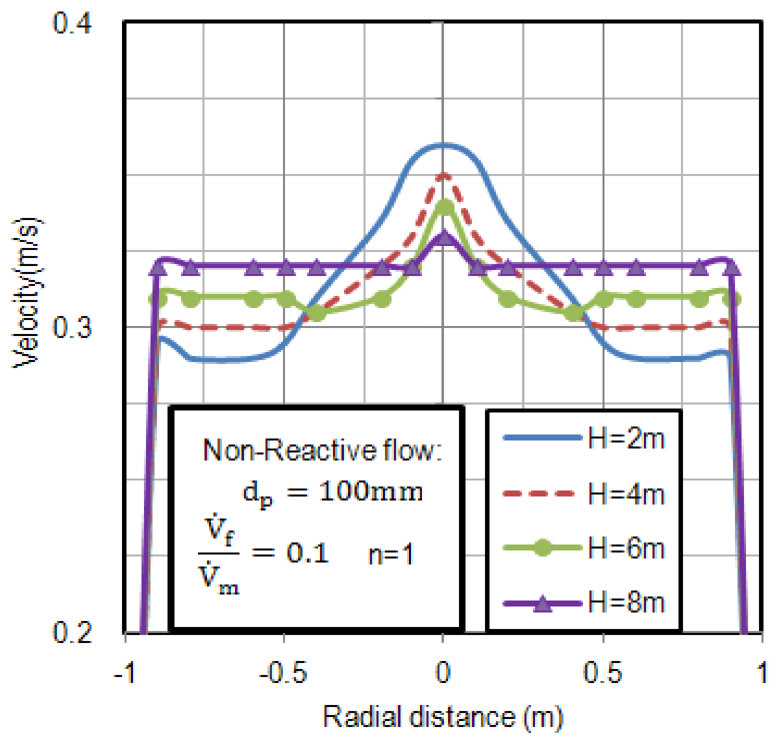

Figure 4: Velocity profile at different heights at ϕ=0.32.

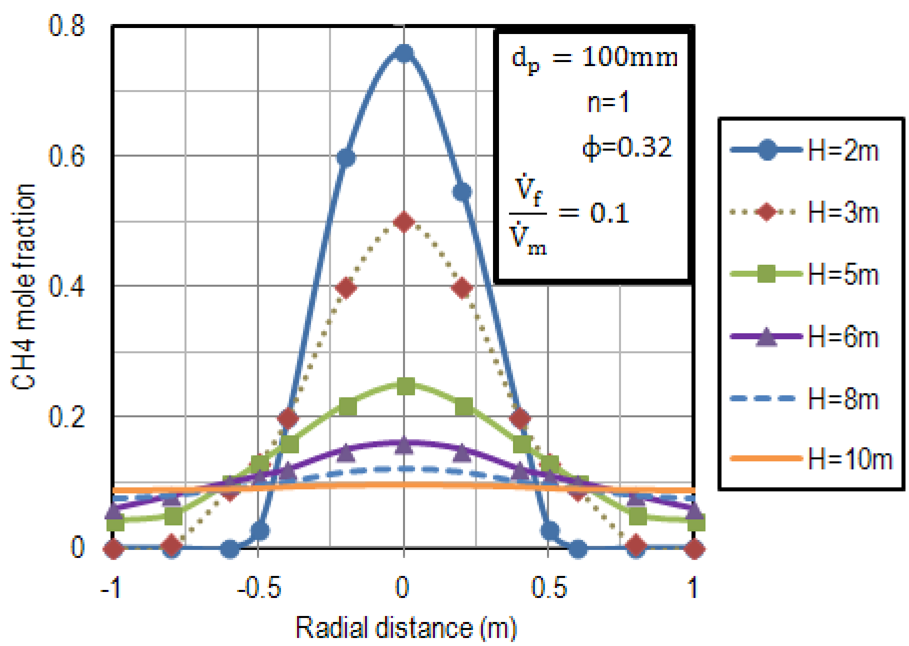

Figure 5 : Fuel distribution at different heights.

The distribution of the fuel in the radial direction is shown in Figure 5. The fuel concentration is reached to the stoichiometric value approximately after 7 m. In the following case, methane and combustion air react with each other. The volume flow of the fuel is increased by about 30% to $\dot{V}_f = 0.13\,\frac{m^3}{s}$, which is a typical value for a kiln with a diameter of 2 m. The radial temperature profiles and the contour for λ=1.3 is shown in Figure 6. The longer the distance from the burner is, the higher the temperature becomes (both near walls and in the center). That means combustion is not completed until the 10 m. The maximum temperature reached in the radial cross-section at different heights is always $\frac{1}{4}$ of the kiln diameter distance of the walls (0.5 m). This is also visible from the temperature contour.

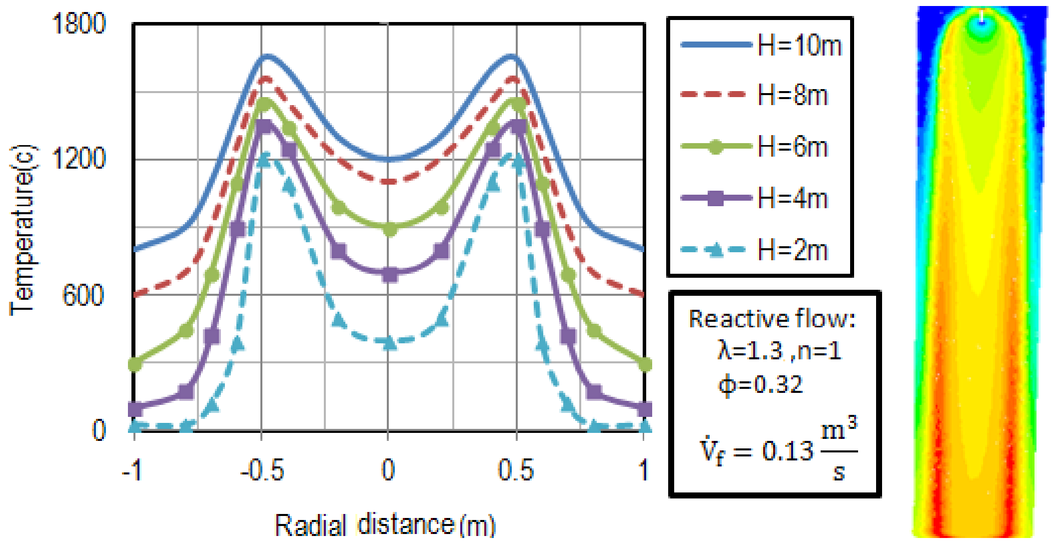

Figure 6 : Temperature profile at different heights.

The pervious section has shown that the fuel and temperature distribution in the cross-section is very inhomogeneous if only one burner is used. To shorten the flame length, the fuel diameter or outlet velocity must be decreased. To insert the same amount of fuel, more burners must be used. With more burners, the fuel distribution in the cross-section can be improved. Various arrangements are possible for burners. Here, 21 burner arrangement is used. Figure 7 shows the temperature profile at different heights. The higher the distance from the burner is, the higher the temperature becomes. It can be seen that, the temperature homogenization starts at a shorter distance from the burners. Five burners are placed radially as depicted in Figure 7.

Definition of Flame Length

The flame length determines the temperature profile and that thus also the quality of the burnt lime. Methane is used as fuel where injected from burners. Figure 8 shows the axial profile of CH4 and CO mole fractions. It can be seen that, methane has fallen to the near zero after approximately 4 m. While the CO has its maximum values after a 1 m distance from the burners. Where CO mole fraction has fallen to 1 percent of its maximum value ($\frac{X_{CO}}{X_{CO_{max}}} = 0.01$) is the flame length.

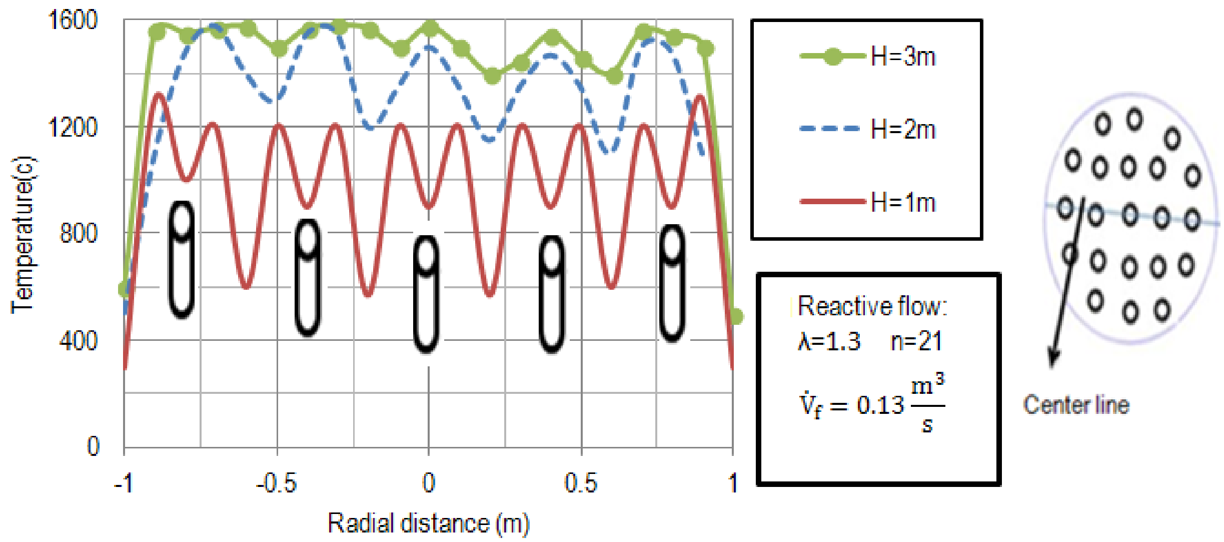

Figure 7: Temperature profiles at different heights when n=21.

As a consequence, the flame length in PFR shaft kilns is about 5.2 m, with the 18 burner arrangement.

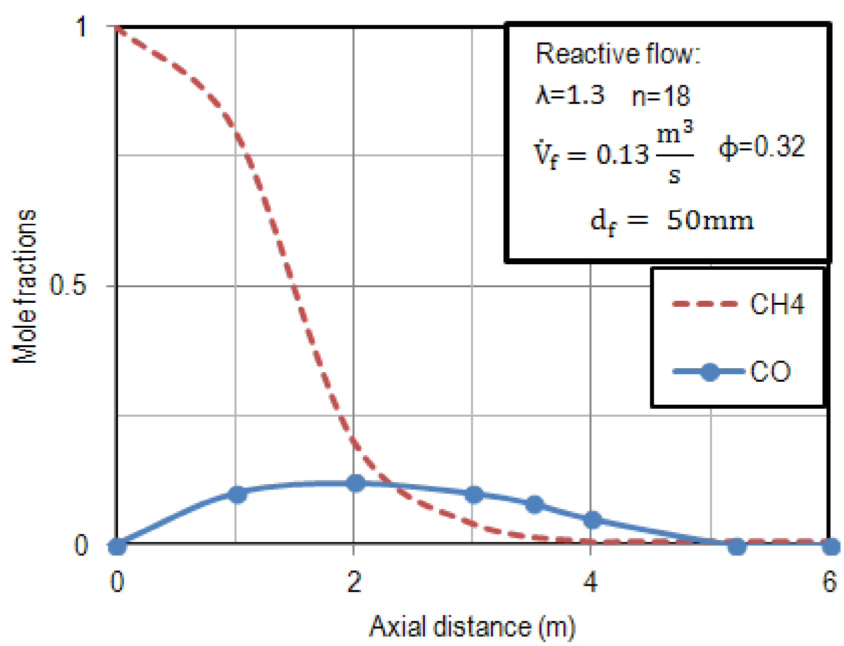

Figure 8 : CH4 and CO profiles in axial distance.

Figure 9 shows the influence of fuel velocity when the fuel volume flow is kept constant. The number of burners and the excess air number are kept constant. Fuel velocity is increased from 3.7 $\frac{m}{s}$ up to 92 $\frac{m}{s}$. For this aim, the burner diameter is decreased from 50 mm to 10 mm. The higher the fuel velocity is, the longer the flame length becomes. When the fuel velocity is increased from 3.7 $\frac{m}{s}$ to 92 $\frac{m}{s}$ (by about 20 times), the flame length is increased by 0.6 m. This was studied for various particle sizes (d_p=20 to 150 mm). As a consequence, the bigger the particle diameter is, the longer the flame length becomes.

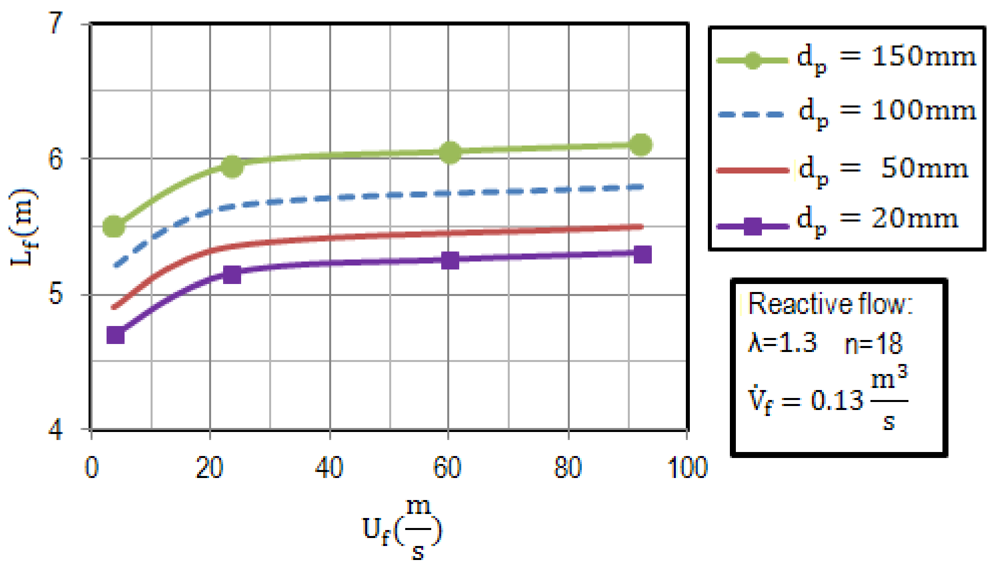

Figure 9 : Influence of fuel velocity on the flame length.

4. Conclusion

This research study demonstrates that the PMM is a proper approach to simulate the reactive flow in lime shaft kilns. The k-ε standard and k-ω SST turbulence models showed the best accuracy with the experimental measurements. The advantage of PMM model is that it can be used in simulation of reactive flow of shaft kilns with real dimension of about 10 meters in height without limitation in the number of nodes and computational times. The fuel and temperature distribution in the cross-section is very inhomogeneous if only one burner is used. Therfore, the more burners must be used. The flame length was simulated for a large number of burners for both PFR and CFS shaft kilns. In PFR kilns, the flame length was calculated at about 5.2 meters when methane was injected from 18 burners. Fuel velocity and particle diameter are two main influencing parameters on the flame length. The higher the fuel velocity is, the longer the flame length becomes. The bigger the particle diameter is, the longer the flame length becomes. These parameters cannot be provided by measurements. These results may help to optimize the kiln design, performance and operational modes in terms of high temperature distribution and energy efficiency.