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CONSIDERATION OF INFLUENCING PARAMETERS ON THE FLAME LENGTH IN PARALLEL FLOW REGENERATIVE SHAFT KILNS USING POROUS MEDIA MODEL

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ABSTRACT

Understanding the flow pattern of the gas jets in packed beds can have considerable significance in improving reactor design and process optimization. This study researches the fuel diffusion in the radial direction and the flame length in a packed bed of a Parallel Flow Regenerative (PFR) Shaft kiln. This kiln is characterized that the fuel being injected vertically into the packed bed using a lot of lances in the cross-section while the combustion air is distributed continuously. The packed bed approximated as a porous media and the measured values match approximately with those calculated with the Porous Media Model (PMM). The radial mixing of fuel and air in a packed bed is relatively bad. The flame length increases a little bit with the particle diameter. The fuel velocity has a negligible influence on the flame length for values larger than 20 m/s. The flame length decreases with increasing the excess air numbers, especially for value lower than 1.2 the flame length increases very strong.

Keywords: *Burner arrangement, Flame length, Fuel velocity, Particle diameter, Excess air number*

1. INTRODUCTION

The calcination process for lime quality and energy consumption has always been optimized. Therefore, the fuel distribution in the cross-sections and the length of the flame must be known. The combustion behavior and thus, the heat release determines the calcination rate. Due to its importance, the calcination process of limestone in shaft kilns has been often simulated. The heat and mass transfer and the pressure drop in a packed bed can be calculated very well. These equations are given for example by Specht (2017). Here, also the mechanism and the modeling of the limestone decomposition are explained. HaiDo et al. (2011) simulated the limestone calcination process in the PFR kiln with a resolved lumpy particle model. The influence of a lot of parameters like stone size, energy consumption, throughput, etc. was discussed. However, the main assumptions must be used, that temperature distribution in the cross-section was perfect, and that the flame length and combustion behavior must be predicted. Krause et al. (2010; 2015) researched the calcination process in a PFR kiln with coupled three-dimensional DEM-CFD simulation. However, the packed bed must be simplified as a porous medium and only a small section of the kiln could be considered because of limited computational time.

Some other types of shaft kilns are modeled by Marias and Bruyres, (2009); Ryazanov and Madison, (2010). Always the simplifications have been made, that the fuel distribution in the cross-section is homogeneous and the length of the combustion zone is predicted. Zhengming and Jiemin (2005) showed based on measurements that the radial temperature differences in the packed bed near the burner system can be more than 200 K. As a consequence, for further optimization of the kiln process, the combustion behavior and the length of the flame in a packed bed must be known.

The flow in the gap between the particles of a packed bed was researched by Dixon and Nijemeisland (2001); Alkhalaf and Specht (2017). All studies were focused on the contact point treatment, e. q. as gap, bridge, etc., and thus on optimizing the mesh. It was shown, that because of limited computational time, the number of particles must be lower than 1000. Therewith it is not possible to simulate the flow in a packed bed of a kiln. As a consequence, the packed bed of a shaft kiln has to be treated as a porous medium.

Nield and Bejan (2005); Liu and Dong (2010) described how to calculate reactive flows in a porous medium. The requirement is always a strongly isotropic flow. This is the case if the pores are in the µm- and mm range. However, in the packed bed of lumpy stones, the pores are in cm-range. Therefore, the CFD calculations have to be validated with experiments.

Mohammadpour et al. (2021) showed that the measured values match approximately with those calculated with the Porous Media Model (PMM) and a lot of burners are needed for better temperature homogenization in the cross-section. Mohammadpour et al. (2019) investigated the injection of fuel and air in a cross-flow to a packed bed. This is the case for CSF kilns. It was shown, that the particle diameter and the ratio of combustion air (cross flow) and cooling air (vertical flow) are the main influencing parameters. The porosity is of low influence for values lower than 0.6.

The fuel distribution determines the temperature homogenization in the cross-section. Measurements of temperature and concentration are not possible. The packed beds have a diameter of up to 6m and a height of up to 18m. Because of the movement of the bed, no measuring devices can be stuck through the wall and centered in the bed. The combustion behavior is influenced by various parameters such as particle diameter, the velocity of fuel, air-fuel ratio, lance diameter, air velocity, and the number of burners. The influence of these parameters can only be researched using computational fluid dynamics. However, the simulation of the real flow between the particles requires a very fine mesh, which results in a too high computational time. As a consequence, the packed bed has to be approximated as a porous medium to model the reactive flow in the kilns. Before that, experimental validation is conducted utilizing a section of a packed bed. The experiments were done in the Institute of Fluid Dynamics and Thermodynamics, Otto von Guericke University, Magdeburg, Germany. The scope of this research is the influence of burner arrangements, fuel velocity, particle diameter, and excess air number on the combustion behavior in parallel flow regenerative shaft kilns using a porous media model. The results of this research can have considerable significance in improving reactor design and process optimization.

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2. COMPUTATION DETAILS AND GRID GENERATION

The CFD calculations are conducted using Ansys Fluent 14. Fig. 1 shows the scale of the used PFR kiln. Because of the limited computational time of three-dimensional reactive flows, a small kiln diameter of 2m was used. However, this diameter is sufficient to research the influence of all parameters. The packed bed height of 8 m is a typical height for the burning zone. The simulation of the real flow between the particles requires an exceptionally fine mesh, which results in a too high computational time. Consequently, the packed bed has to be approximated as a porous medium.

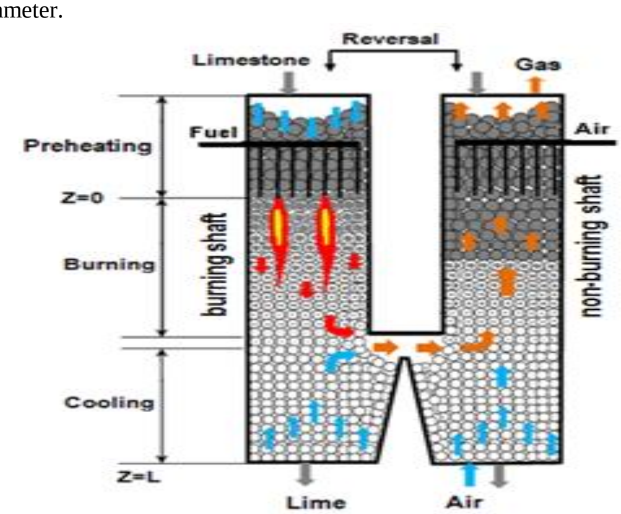
The Ergun equation is used to calculate the pressure drop in the packed bed (Mohammadpour et al., 2019).

$$\frac{\Delta P}{L} = 150 \cdot \frac{(1-\varphi)^2}{\varphi^3} \cdot \frac{\mu \cdot U}{d_p^2} + 1.75 \cdot \frac{1-\varphi}{\varphi^3} \cdot \frac{\rho \cdot U^2}{d_p} = \frac{1}{\alpha} \cdot \frac{\mu U}{dp^2} + \frac{1}{2 \cdot c_2} \cdot \frac{\rho U^2}{dp}. \quad (1)$$

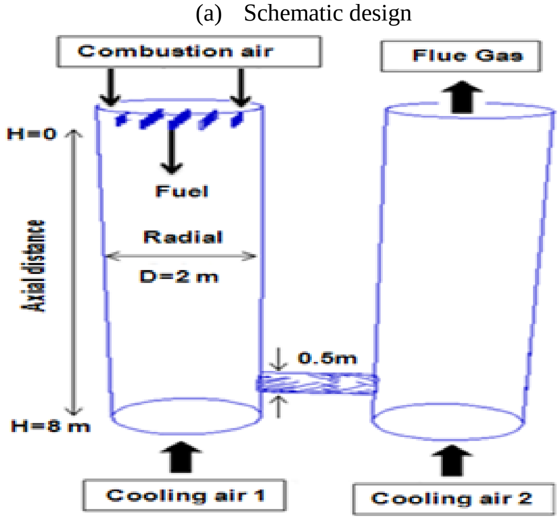
Where d_p [mm] is the mean particle diameter, ϕ [-] is the porosity, μ [Kg/(m.s)] is the viscosity and U [m/s] is the velocity. The permeability and inertial loss coefficient in each component direction can be identified as:

$$\alpha = \frac{{d_p}^2 \varphi^3}{150(1-\varphi)^2} \qquad C_2 = \frac{3.5(1-\varphi)}{d_p \varphi^3} \quad (2)$$

Both coefficients must be calculated with porosity and particle diameter.



(a) Schematic design



(b) computational domain

Fig. 1 Schematic design and computational domain of a PFR shaft kiln

The combustion air and fuel enter the burning zone with uniform velocity and temperature. In a firing system of shaft kilns, the air and the fuel are injected into the kiln by two separate flows without being premixed. Therefore, the combustion in shaft kilns is non-premixed and a non-premixed combustion model must be used. Methane is used as fuel to provide heat for calcination. The fluent solver uses a finite volume procedure, which converts the governing differential equation presented into algebraic form, together with the SIMPLE (Semi Implicit Method for Pressure Linked Equations) algorithm to solve these equations numerically. The discretization algorithm is standard for pressure, and the first-order upwind for momentum. All the convergence criteria are set to below 10^{-3}. For more detail refer to Mohammadpour et al., 2021.

Fig. 2 shows the grid generation and flame length L_f (m) related to the cell number for grid independence study of PFR shaft kilns. The mesh cells vary from 500.000 to 3.200.000. For all cells, less than 2.911.000, the flame length varies. Therefore 2.911.500 cells have been selected, which gives 616.573 nodes and 79.890 faces.

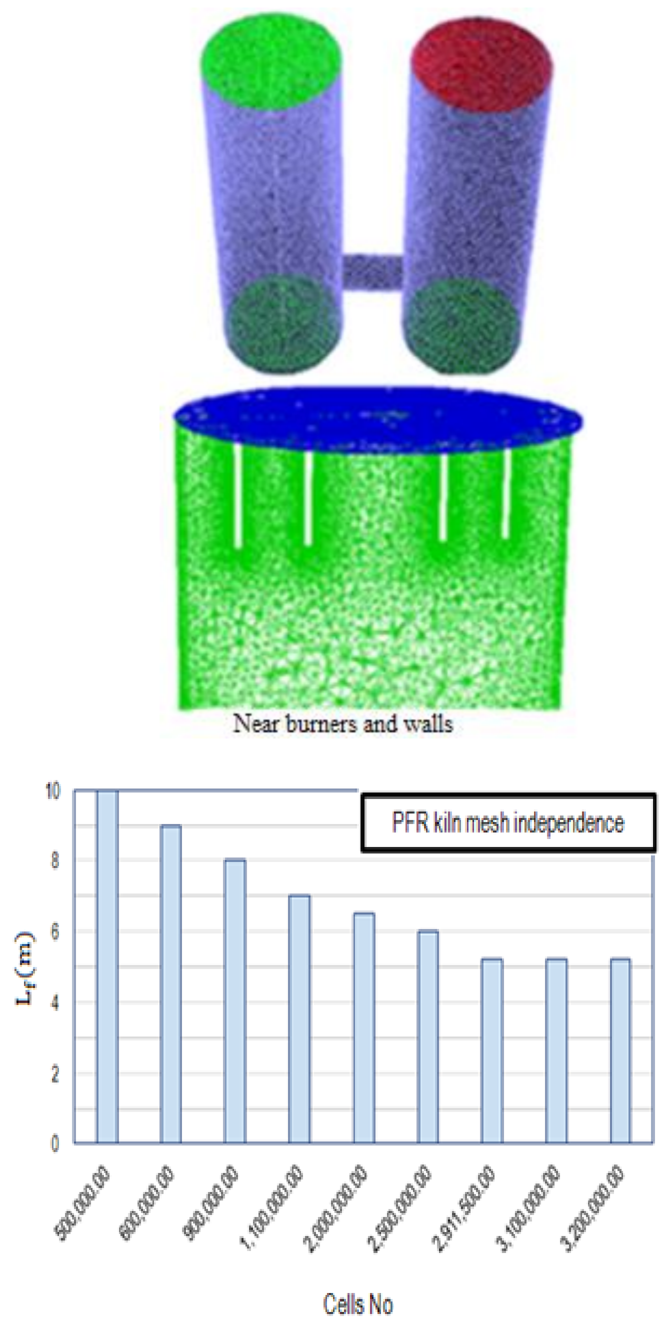


Fig. 2 Grid generation and grid independence study for PFR shaft kilns

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3. RESULT AND DISCUSSION

3.1 Experimental Validation

Experiments were done to validate the CFD simulation. Fig. 3 shows the measured oxygen concentrations as big points for the case where the ratio of the injected nitrogen to the blown-in air is 0.1 for the body center cubic (B.C.C.) arrangement. At the length distance of 0.3 m, where the nitrogen is injected (position of lance), the oxygen has its lowest concentration. This figure also includes the calculated profiles. The parameter is the turbulence model. The turbulence intensity is fixed at 5 %. The k-ε-standard turbulence gives the best fitting with the measured values. For more detail refer to Mohammadpour et al., (2021).

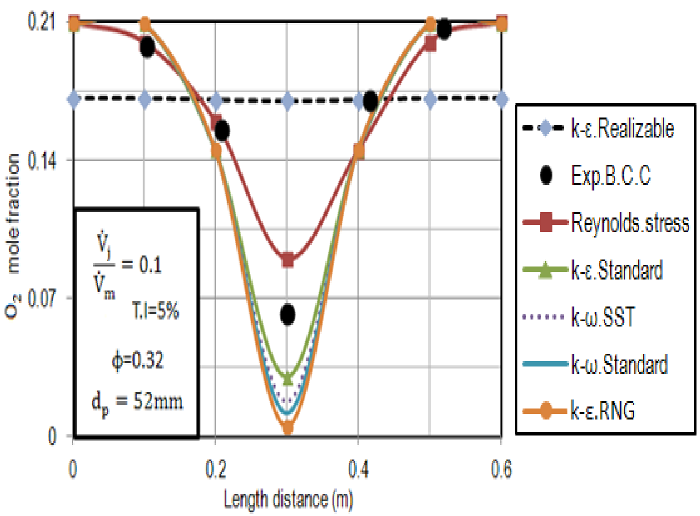
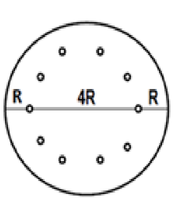
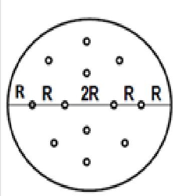
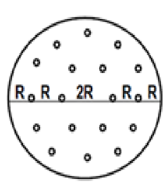


Fig. 3 Oxygen profile for different turbulence models and measured values (B.C.C. arrangement)

3.2 Influence of Burner Arrangement

Various arrangements for the burners are possible. As presented in Table 1, three principal arrangements were studied to discuss the influence on the flame length (Mohammadpour et al., 2021). The first arrangement includes ten burners placed only in an outer ring. In the second arrangement, the burners are placed in two rings, eight burners in the outer ring and four burners in the inner ring. In the third arrangement, again, two rings are used, but twelve burners are placed in the outer ring and six burners in the inner ring. The distance between the burners is R=0.33 m, and the distance up to the cross-over channel is 6 m, which is a typical length for the burning zone in PFR kilns. The diameter of the shaft is 2 m, and the fuel amount is 0.13 m^3/s. The homogenization is better in the cross-section for the higher number of burners. Hence, it can be concluded by Mohammadpour et al., (2021) that the minimum number of burners n [-] must be 18. Therefore, 18 burners are considered for further investigations.

Table 1 Three types of burner arrangement

Number of burners	n=10	n=12	n=18
Principle arrangement R=0.33m			

3.3 Definition of Flame Length

Fig. 4 shows the CH4 and CO mole fraction contours in the vertical direction. The Figure includes not only the burning shaft but also the cross-over channel and the non-burning shaft. In the case considered here, both shafts are directly connected. In industrial applications, this exists only for rectangular shafts. For cylindrical shafts, the combustion gas is sucked off through holes in the walls. The flue gas is transported through a ring channel to the other shaft and blown in through these holes in the walls. This flow is difficult to calculate because of the complex geometry. In this study, the easier direct connection is used, because only the principal influence of the cross-over channel should be shown.

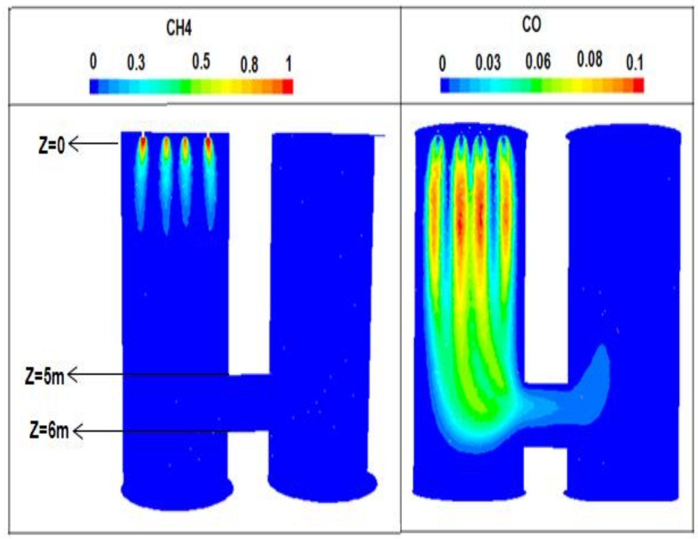


Fig. 4 Fuel contours when n=18

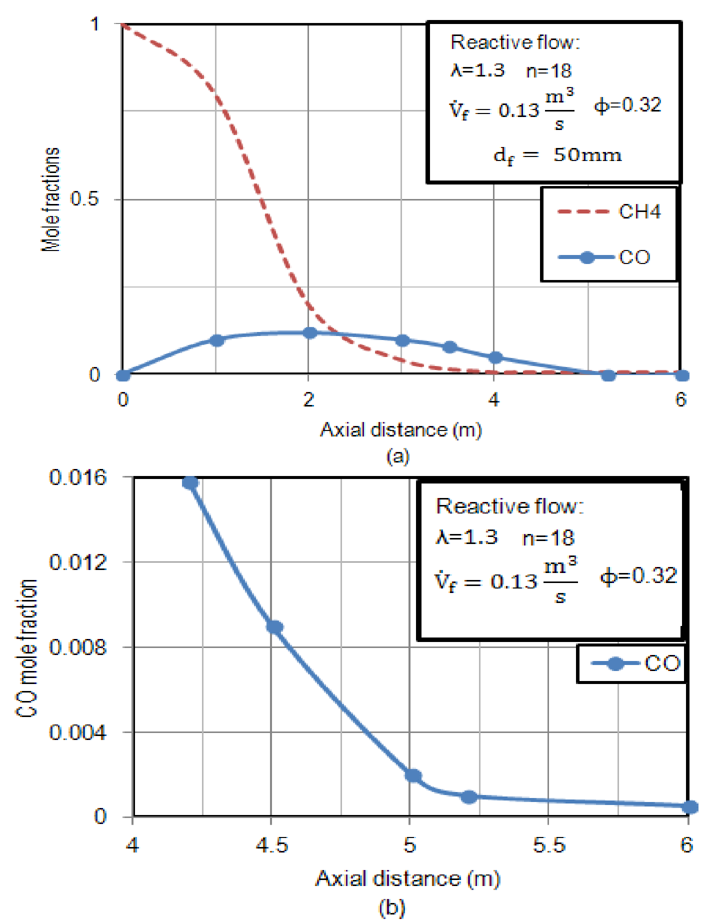


Fig. 5 (a) Axial CH4 and CO profiles, (b) CO profile of H=4-6m

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Fig. 5 (a) shows the axial mole fractions of CH4 and CO. It can be seen methane has fallen to near zero after approximately 4 m. The CO has its maximum values after a 2 m distance from the burners. The CO mole fraction doesn't reach zero because of equilibrium reasons. Therefore, Fig. 5 (b) shows the CO concentration after a height of 4 m up to 6 m in more detail. The flame length is defined here for simplification as the position where the CO mole fraction has fallen to 1 percent of its maximum value ($\frac{X_{CO}}{X_{CO_{max}}} = 0.01$). As a consequence, the flame length in PFR shaft kilns is about 5.2 m with the 18 burner arrangement. As can be seen in Fig. 4 the residual CO burns in the cross-over channel.

3.4 Influence of Fuel Velocity on Flame Length

Fig. 6 shows the influence of fuel velocity (a) and burner diameter (b) when the fuel volume flow (energy consumption) is kept constant. The number of burners and the excess air number are also kept constant. The fuel velocity increases from 3.7 $\frac{m}{s}$ up to 92 $\frac{m}{s}$, when the burner diameter decreases from 50 mm to 10 mm. The higher the fuel velocity is, the longer the flame length becomes. The flame length increases only a little bit with fuel velocity. For values larger than 20 m/s the flame length can be considered independent of the fuel velocity. Therefore, the flame length can also be considered independent of the energy consumption of the calcination process. The parameter in the Figure is the particle diameter. It has a significant influence. This is considered in more detail in the following section.

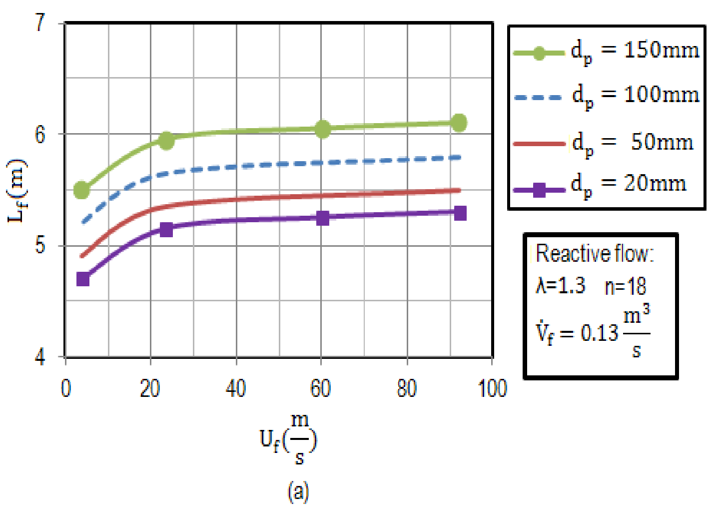

Fig. 6 Influence of fuel velocity (a) and lance diameter (b) on flame length

3.5 Influence of Particle Diameter

Fig. 7 shows the influence of particle size. Bigger particle diameters lead to longer flames. When the particle diameter increases from 20mm up to 150mm (about seven times), the flame length increased about 0.8 m. The particle diameter has the strongest influence on the flame length. In the lime industry, every kiln is operated with another mean diameter because of minimizing the pressure drop. Therefore, it should be considered that every kiln process has another flame length.

3.6 Influence of Excess Air Number

At least, the influence of the excess air number is discussed. Fig. 8 shows the flame length versus the excess air number. The fuel flow and the lance diameter are kept constant and the airflow is varied. It can be seen that the flame length decrease with increasing excess air numbers. Especially for a value lower than 1.2, the flame length increases very strongly. PFR kilns mostly operated with values larger than 1.3.

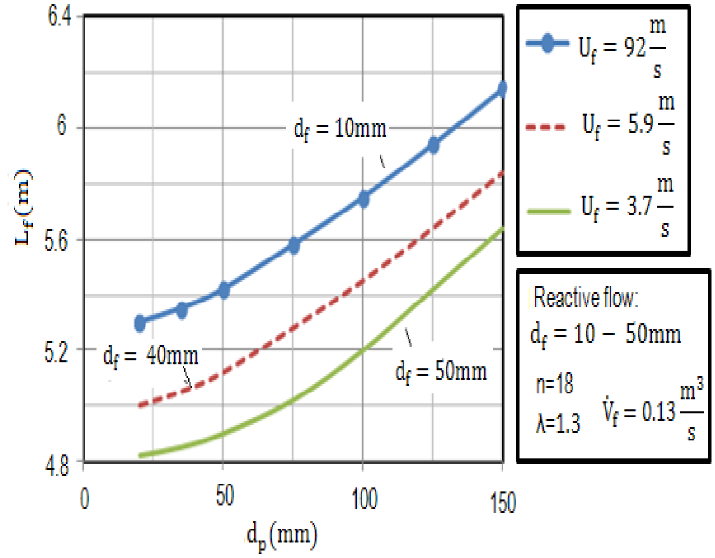

Fig. 7 Influence of particle size on flame length

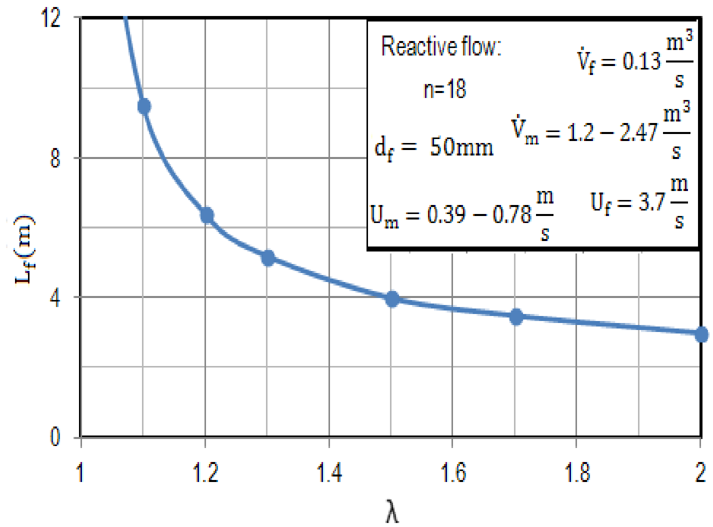

Fig. 8 Influence of excess air number on flame length.

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4. CONCLUSIONS

The research study demonstrates that PMM is a proper approach to simulate the reactive flow in the packed bed of a shaft kiln and the k-ε Turbulence model shows the best accuracy with the experimental measurements. The flame length determines the temperature profile and thus, also the quality of the burnt lime. It can be seen that the diffusion of the fuel in the radial direction is very bad in a packed bed. Therefore, a lot of burners are needed for better temperature homogenization in the cross-section. For the fuel velocity larger than 20 m/s, the flame length can be considered independent of the fuel velocity. The particle diameter influences the flame length. The flame length decrease with increasing the excess air numbers, especially for a value lower than 1.2 the flame length increases very strongly. The flame length could be in the range of 5 to 6 m depending on particle size, fuel velocity, and air excess number. These results may help to optimize the kiln design, performance, energy efficiency, and lime quality.

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