Numerical and Experimental Study on Flow Distribution in Thermal Flow Reversal Reactor

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Abstract: The prediction and improvement of flow distribution in the regenerative oxidation bed is important for the design of the TFRR. Using a combination of experimental and numerical method, the effects of the structural parameters and operating conditions on the flow uniformity were investigated. The experimental results fully substantiate the soundness of the numerical prediction. The results show that flow uniformity can be effectively improved by optimizing the structure and configuration of the TFRR.

Keywords: lean methane; TFRR; flow distribution; computational fluid dynamics

1. Introduction

Coal mine methane is not only a greenhouse gas which greenhouse effect is only inferior to the carbon dioxide but also a wasted energy resource if not utilized. Underground coal mining is by far the most important source of fugitive mine methane, and approximately 70% of all coal mining related emissions are from mine ventilation air (MVA) with a concentration of 0.1–1% methane [1]. Methane with high concentration is a kind of clean energy and could be utilized conveniently. But it is hard to utilize lean methane below 1(vol) % via combustion and to recover the energy produced. Hence, research and development on mine methane capture, mitigation and utilization should focus on methane emitted in ventilation air. With high energy recovery efficiency, thermal flow reversal reactor (TFRR) is proved to be a promising technology for lean methane oxidation, and now has been already put into use in a few coal mines [2~7].

The TFRR performance is governed by complex interactions between structural parameters and operating conditions. From the fluid dynamics point of view, the flow distribution at the regenerative oxidation bed is of special interest, which affects the efficiency and stability of the reactor. If there is the flow mal-distributions at the regenerative oxidation bed, the faster flow rate will diminish the contact time and increase minimum CH4 oxidation concentration; the lower flow rate will lead to declining temperature and even extinction [8], which can't maintain the isothermal condition and causes the reactor instability [5]. So it is important to ensure the flow field uniformity in the domain where the reactor with flow reversal can be operated, especially for the industrial scale TFRR. The use of TFRR requires therefore detailed studies to determine the reasonable structural and operating conditions. Numerical simulation and experiment of fluid distribution in TFRR is presented in this paper.

2. Experimental Reactor System

An experimental TFRR was constructed to test its flow distribution performance at different operating conditions, as shown in Fig. 1.

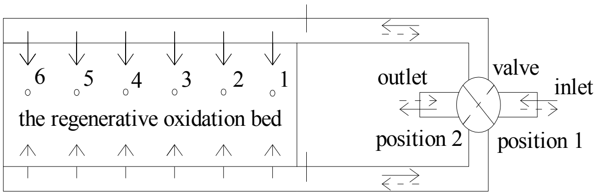

Figure 1. Configuration of the experimental TFRR

The experimental TFRR consists of a regenerative oxidation bed which is composed of a number of honeycomb ceramic, and collecting headers (the upper header and lower header, they have the same geometric parameters) which are adopted for mixture distribution because of space saving. Ambient air was used for the experimental study instead of CH_4 for safety and convenience. The volumetric flow rate of air entering the header was obtained by using a pre-calibrated rotameter. The velocity distributing inside the regenerative oxidation bed was measured by hot course and speed computer. Pressure along the collecting headers was provided by Pitot tubes and pressure transmitter together. The reproducibility in the measurement of all the variables was within 5 percent. The design details of the experimental TFRR are given in Table.1

Table.1 Properties of the experimental TFRR

Property	Value
Height of oxidation bed (mm)	H=200
Length of oxidation bed (mm)	L=600
Width of oxidation bed (mm)	W=200
Height of collecting header (mm)	b=40

Width of square hole (mm)	D=2.5
Thickness of wall (mm)	D_{wall}=0.7
Porosity (Void / %)	ϕ = 59

3. Numerical Simulation

Computational fluid dynamics (CFD) which has been widely used to provide more detailed information on the flow field as function of various design and operating parameters is a powerful tool for calculating the flow field inside the TFRR. The physical model of TFRR with collecting headers was set up, and ignored the switching valve compared with the experimental TFRR. Three-dimensional model was developed with the inlet velocity assumed to uniform.

3.1. Governing Equations

The flow and mass transfer in the collecting headers are different from those in the oxidation bed. So, the governing equations are divided into two distinct types, the turbulent flow region (free stream) in the collect headers and the laminar flow region in the oxidation bed.

1) Governing equations of the free stream region:

The flow in the collecting headers was treated as turbulent and the k-ε model was used and standard constants were adopted. The governing equations for mass, momentum balance can be written in the following general form:

$$\frac{\partial\ (\rho\phi)}{\partial t}+div(\rho u\phi)=div(\Gamma grad\phi)+S \tag{1}$$

The detailed equations may be seen in the User Manual of FLUENT 6.2

2) Governing equations of the oxidation bed region:

The dimension of the passage in the honeycomb ceramic is very small compared with that of the oxidation bed. The honeycomb ceramic was assumed as porous media, the thermo-physical property of all porous media is taken to be constants. The Reynolds number within the honeycomb ceramic channel is below 200, so the flow in the channel can be regarded as laminar and the momentum conservation equation in porous media can be described by the Darcy's law and an additional inertial loss term:

$$\Delta p=-(\frac{\mu}{a}v+C_2\frac{1}{2}\rho v^2)\Delta m \tag{2}$$

Where μ is the laminar fluid viscosity, a is the permeability of the medium, C_2 is the inertial resistance coefficient, v is the velocity in the channel, and Δm is the length of the medium. Appropriate values for a and C_2 can be calculated using the techniques described in the User Manual of FLUENT 6.2.

3.2. Boundary Conditions

A uniform velocity profile at the inlet was assumed. The turbulence intensity is 4.75×10^{-2}, and the length scale is 2.33×10^{-3}. The pressure outlet was specified. The shear condition of stationary wall was set to be no slip.

4. Results and Discussion

4.1. Definition of a flow nonuniform index

A flow nonuniform index has been defined as a criterion to quantify the in-homogeneity of flow field in the regenerative oxidation bed. It is defined as:

$$\gamma=\frac{1}{2n}\sum_{i=1}^{n}\frac{\sqrt{(v_i-v_{mean})^2}}{v_{mean}} \tag{3}$$

Where r is a flow nonuniform index, r=0 means the flow distribution is perfect, r=1 means all fluid flow through only one of the channels, n is the number of grids, v_i is the average velocity of respective grids, v_{mean} is the average velocity of integral cross section.

4.2. Comparison between experimental results and numerical predictions

In this section, the velocity profiles inside the regenerative oxidation bed, by numerical simulation and experiment, are shown in Fig. 2.

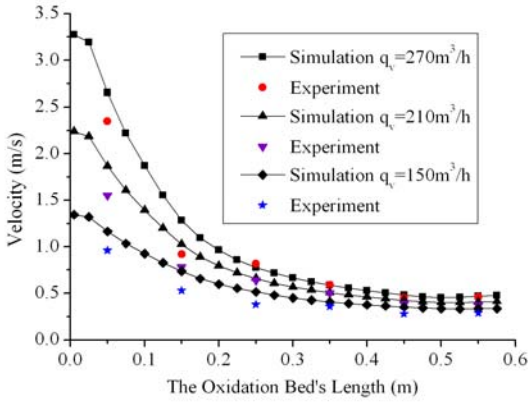

Figure 2. Velocity magnitude in the oxidation bed

Comparison between experimental data and numerical predictions, the numerical results present very good agreement with respective experimental results. It's reasonable that experimental results are a little lower than the numerical for air leak and measurement precision. Thus, the validity of numerical simulation has been performed with experimental results under specific conditions. In Fig. 2, it also can be seen that the flows inside the regenerative oxidation bed aren't uniform, and the velocity along the oxidation bed becomes lower and lower from the inlet. This fact can be explained that the flows are divided after getting into the dividing header, part of gases change the primary flow direction and get into the thin channels, and the others continue by the inertia effect as indicated early. The flow rate becomes small until stagnating on the baffle wall alone the dividing header.

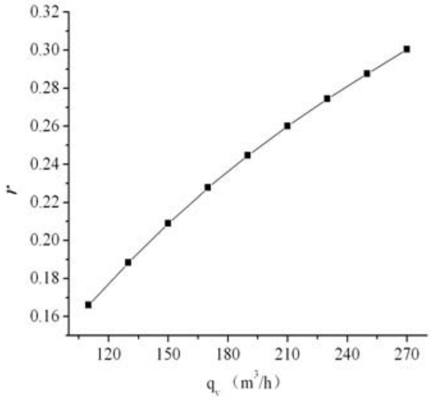

Figure 3. The flow nonuniform index under different inlet flow rate

Moreover, it also can be obtained the flow uniformity becomes worse with the increase of flow rate in the inlet. The same conclusion can be found in Fig. 3, where the flow nonuniform index of respective flow rate is shown.

4.3. Influence of structure

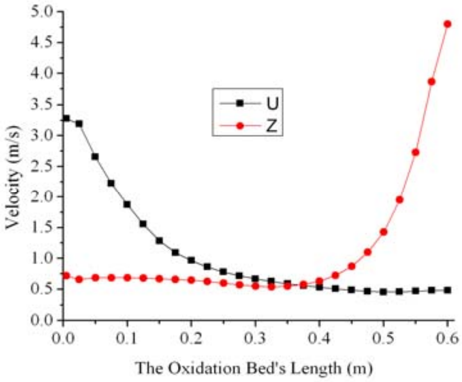

Figure 4. Velocity magnitude of different structures in the oxidation bed

Fig. 4 shows the different structures, the U-type and Z-type, have great influences on the flow distribution of the TFRR. The inlet and outlet of U-type are located at the same side, and these of Z-type are not. From the picture, it can be seen that the trend of velocity inside the oxidation bed about the Z-type, the maximum translational velocity is located near the outlet and the velocity becomes lower and lower along the oxidation bed, is different form the U-type's. The flow uniformity of U-type is better than the Z-type's.

4.4. Influence of header's height

Collecting headers are adopted for mixture distribution because of space saving. Header's height is one of most important geometric parameters to influence the flow distribution of the TFRR under the oxidation bed's length and width determined. The influence of header's height on the flow distribution inside the oxidation bed is studied, and the result is shown in Fig. 5 and Fig. 6.

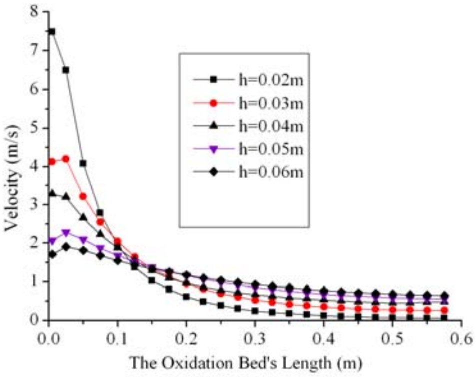

Figure 5. Velocity magnitude in the oxidation bed

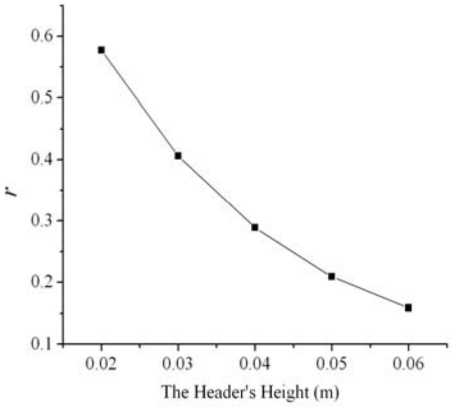

Figure 6. The flow nonuniform index under different header's height

From the pictures, we can get that the flow distribution becomes better with header's height increase. But the header's height which is high enough influences the distribution unremarkably from Fig. 6. This fact can be understood that the lower the header, the smaller the flow area becomes. It's more difficult to get to the baffle wall for more gases. The flow distribution becomes worse.

4.5. Influence of oxidation bed's length

Fig. 7 represents the results of flow distribution as the oxidation bed's length increase. As the bed's length increases, the flow nonuniform index also increases. The undesirable phenomenon is because that the longer the oxidation bed, the less the flows flux gets to the baffle wall because of resistance. More gases change the flow direction into the thin channels of honeycomb ceramic in the first part of the bed. The flow distribution becomes worse. It's necessary to choose a right length.

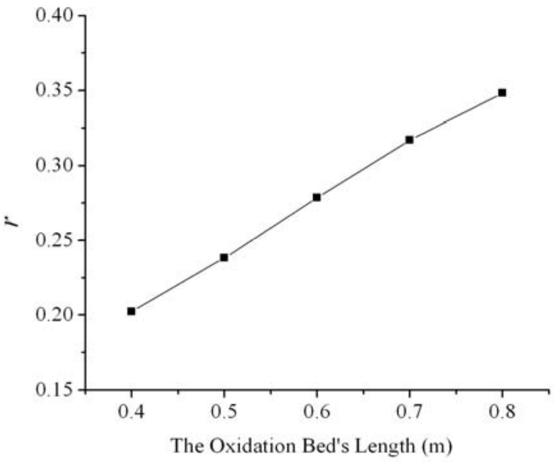

Figure 7. The flow nonuniform index under different oxidation bed's length

4.6. Influence of oxidation bed's height

How the oxidation bed's height affects the flow distribution is studied under the same operating conditions and other structural parameters there. The results are shown in Fig. 8 and Fig. 9. The flow gets more uniform with the bed's height increasing. And the influence is greatly when the height is relative low. The phenomenon can be explained that the oxidation bed's resistance increases with the height increasing. The increasing resistance makes more gases keep flowing at the primary direction relatively not changing direction, which reduces the gap between the front and rear of the flow flux. The flow distribution becomes better.

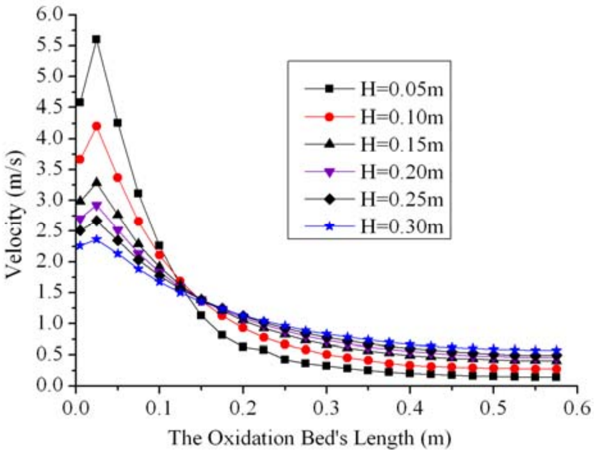

Figure 8. Velocity magnitude in the oxidation bed

5. Conclusions

The study presents the results of the effects of structural parameters and operating conditions on the flow distribution in the TFRR. Experimental evaluation of flow characteristic parameters has been carried out to support the numerical results. The flow distribution in the oxidation bed of TFRR is usually nonuniform. A flow nonuniform index is defined to describe flow deviation in the oxidation bed. The flow uniformity of U-type is better than the Z-type's. The flow uniformity becomes worse with the increase of flow rate at the inlet. The header's height influences flow distribution remarkably, and the higher the header is, the more uniformity the fluid distribution is. The proper length and height of the oxidation bed are important for the fluid distribution.

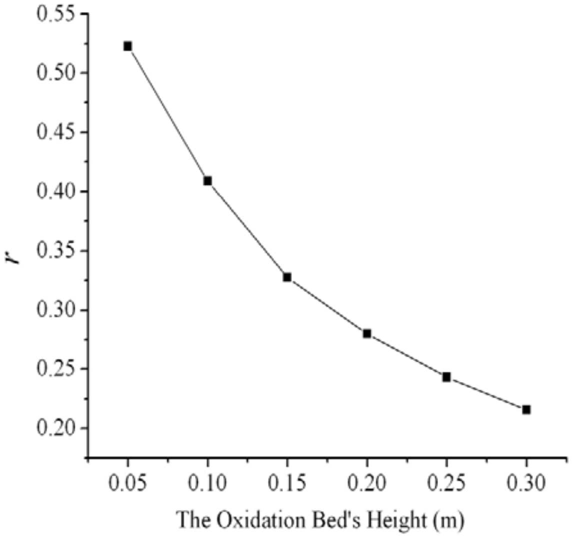

Figure 9. The flow nonuniform index under different oxidation bed's height

6. Acknowledgement

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