

## Effects of Operating Parameters on Catalytic Oxidation Process of Coal Mine Ventilation Air Methane

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**Abstract** - Based on the preheating catalytic oxidation device designed and built by Shandong University of Technology of China, the catalytic oxidation process of ventilation air methane in a honeycomb ceramic oxidation bed coated by catalyst Pd was numerically investigated. Influences of catalyst, methane volume concentration, preheating temperature and space velocity on catalytic oxidation process were analyzed. The results show that the catalyst can significantly improve the temperature rise of the oxidation bed and methane conversion rate. Higher inlet methane volume concentration and preheating temperature both increase the temperature rise of the oxidation bed, so the determination of the minimum volume of methane concentration and preheating temperature can guarantee the normal operation of the preheating catalytic oxidation device. With increasing space velocity, the temperature of the ceramic bed rises more slowly which causes temperature peak shift to the downstream, and the methane conversion rate decreases, so the preheating temperature should be reduced to ensure adequate temperature rise of the oxidation bed at low space velocity. Among the operating parameters, the methane volume concentration has an obviously greater effect on the oxidation bed heat dissipation flux density than space velocity and preheating temperature.

**Keywords** - coal mine ventilation air methane; catalytic oxidation; volume concentration; space velocity; methane conversion rate

### I. INTRODUCTION

Methane, the main component of coal mine ventilation air methane, is a combination of strong greenhouse gas and valuable clean energy. So coal mine ventilation air methane emissions are not only seriously harmful to the environment but also extremely wasteful on energy utilization<sup>[1]</sup>.

Because the coal mine ventilation air methane concentration is very low and at the same time the concentration fluctuation range is large, it is difficult to utilize it by any traditional combustion technology. Currently the main methods for effective treatment of coal mine ventilation air methane are thermal flow reversal oxidation and catalytic flow reversal oxidation and there have been many researches on both technologies [2][3]. Gosiewski et al [4] numerically investigated the operation process of a thermal flow reversal reactor with honeycomb ceramic regenerator by a one-dimensional model; Marín et al [5][6] studied the pressure drop and thermal stability of two catalytic flow reversal reactors respectively with packed bed and monolith bed and the effects of

four kinds of heat extraction ways on reactor performance; Feng et al [7] experimentally investigated the influence of several operating parameters including methane concentration, flow mass, reciprocating half period and wall heat loss on thermal flow reversal oxidation process on a self-developed thermal flow reversal oxidation device for low concentration gas. However, the necessary flow switch operation of reverse flow oxidation technology has led to many problems, for example, periodic fluctuation of temperature field, escape of sectional ventilation air during switch operation and high requirements on the working reliability of the reversing mechanism[8]. These problems increase the operating costs and limit the popularity of thermal reverse flow oxidation technology.

Catalytic oxidation of methane has been widely used for low reaction temperature and high conversion rate<sup>[9]</sup>. The catalysts for the oxidation of methane at low temperature are mainly noble metal catalysts Pt and Pd. Pd has more activity, lower initial reaction temperature and higher deactivation temperature

compared with Pt, so it has attracted more and more attention<sup>[10]</sup>. The preheating catalytic oxidation device developed by Shandong University of Technology of China whose working principle shown in Fig. (1) is able to achieve catalytic oxidation of coal mine ventilation air methane at low temperature through a honeycomb ceramic oxidation bed loaded by Pd catalysts and preheat fresh ventilation air methane via a recuperative heat exchanger with exhaust heat <sup>[11-14]</sup>. The operation is of high efficiency and energy saving, and avoids the disadvantages of reversing operation.

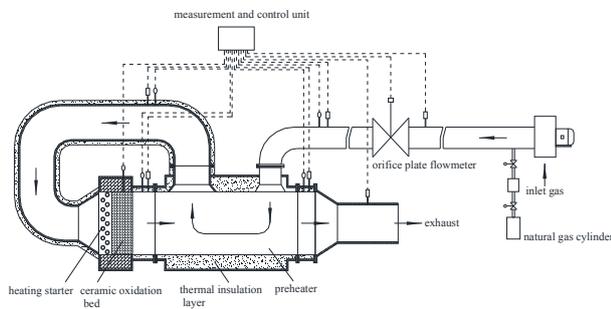


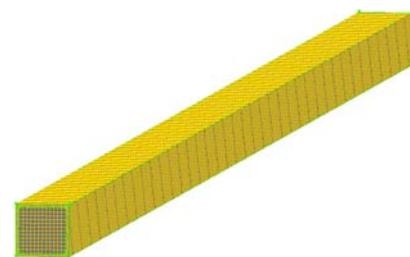
Fig. 1 The working principle of preheating catalytic oxidation device

The previous studies on methane catalytic oxidation are mainly based on experiments, yet relevant numerical simulation is few. Su et al [15] experimentally studied the influence of catalyst loading, methane concentration, preheating temperature and space velocity on the conversion rate of coal mine ventilation air methane on a monolith catalytic reactor. Shahamiri et al [16] established a one-dimensional heterogeneous model to investigate the effects of condition parameters on methane oxidation process of a fixed bed catalytic reactor loaded by Pt catalyst. Wang et al [17] studied the coal mine ventilation air methane catalytic oxidation process in a honeycomb ceramic channel whose wall coated by Pt catalyst. So far, numerical simulation about low concentration methane oxidation with Pd as catalyst is very rare.

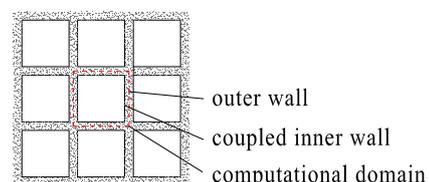
## II. NUMERICAL MODEL AND METHOD

### A. Numerical Model

The honeycomb ceramic oxidation bed contains a large number of parallel micro channels, and on the inner surface coated by Pd catalyst of these channels methane catalytic oxidation reaction occurs. In the process of catalytic reaction the inlet gas temperature and velocity in each channel can be considered approximately uniform, so the catalytic oxidation in each channel is in similar situation. In order to simplify the numerical model, one channel is selected for the numerical simulation of ventilation air methane catalytic oxidation. As shown in Fig.(2), the three-dimensional numerical model of honeycomb ceramic rectangle channel measures 1.8mm×1.8mm×350mm and its half wall thickness is 0.15mm. The channel outer wall is the center symmetry plane of ceramic wall thickness and inner wall is a coupling surface of gas and solid at the junction. The mesh number of the channel model is determined to be about 130000 after mesh number dependency research.



(a) Micro channel grid



(b) Schematic of the computational domain

Fig. 2 Grid map of computational model

### B. Numerical Method and Boundary Condition

The simulation is carried out by computational fluid dynamics software *Fluent* and  $k-\varepsilon$  standard turbulence model is adopted as the flow mass through the small size channel is large. The continuity equation is solved by the two order implicit segregated solver and the spatial discretization is performed with the two order upwind scheme. The species transport model is selected as combustion model and detailed multi-step reaction mechanism is imported.

The inlet velocity condition is used as inlet boundary condition and space velocity is in the range of 4000h<sup>-1</sup>~10000h<sup>-1</sup>. Space velocity means the ventilation air volume dealt by per cubic meter of the honeycomb ceramic substrate loaded by catalyst per unit time. The inlet temperature, preheating temperature, is in the range of 700K~900K, and the inlet volume concentration range is 0.4%~1.0%. The outlet static pressure is set as outlet boundary condition. Appropriate heat flux corresponding to operating parameter is set on the outer wall and the inner wall is set as a coupled wall. The radiation heat transfer is neglected as the reaction temperature of catalytic oxidation of methane is low. Because the ventilation air methane volume concentration is low (less than 1%), its physical parameters can be replaced by air's. The following are properties of honeycomb ceramic oxidation bed: specific heat of 1000J.kg<sup>-1</sup>.K<sup>-1</sup>, density of 3g.cm<sup>-3</sup>, and thermal conductivity of 10w.m<sup>-1</sup>.K<sup>-1</sup>.

### C. Surface Reaction Mechanism

At present, the research on methane catalytic oxidation process is mainly based on experiment and there isn't a unified reaction mechanism file of methane catalytic oxidation reaction with catalyst Pd. The catalytic reaction mechanism adopted here, including 8 adsorption reactions, 8 surface reactions and 5 desorption reactions, is obtained by Moallemi and Deutschmann *et al.*[18-20] and totally contains 21 element reactions. The reaction mechanism is

compiled into a CHEMKIN format mechanism file, which was imported into *Fluent* to achieve an accurate calculation of methane catalytic surface reaction.

### D. Heat Loss Setting

The heat loss on the oxidation bed surface, measured by the value of heat flux density has a significant impact on the oxidation bed temperature field and methane conversion rate. Under determined preheating catalytic oxidation device structure, the heat flux density is mainly affected by inlet velocity, temperature and methane volume concentration, because these three parameters dominate the heat release of methane oxidation and oxidation bed temperature field, thereby affect the heat transfer intensity of the oxidation bed with outside. In order to make the boundary conditions of calculation consistent with the actual situation, corresponding heat flux density should be set in different operating conditions. For simplicity, the heat flux density at oxidation bed surface is assumed uniform, and so is the ceramic channel outer wall. The relationship between dimensionless heat flux density, inlet methane concentration, velocity and temperature can be expressed as:

$$\frac{q}{q_0} = a \times \left(\frac{T}{T_0}\right)^b \times \left(\frac{v}{v_0}\right)^e \times \left(\frac{c}{c_0}\right)^d \quad (1)$$

Where  $q$  in w.m<sup>-2</sup> is the heat flux density,  $q_0$  of 30 w.m<sup>-2</sup> is the designed heat flux density,  $T$  in K is inlet air preheating temperature,  $T_0$  of 293K is the ambient temperature,  $v$  in h<sup>-1</sup> is inlet space velocity,  $v_0$  of 10000 h<sup>-1</sup> is the designed inlet space velocity,  $c$  is the inlet methane volume concentration,  $c_0$  of 1% is the designed inlet methane volume concentration and  $a$ ,  $b$ ,  $e$  and  $d$  are all dimensionless coefficients.

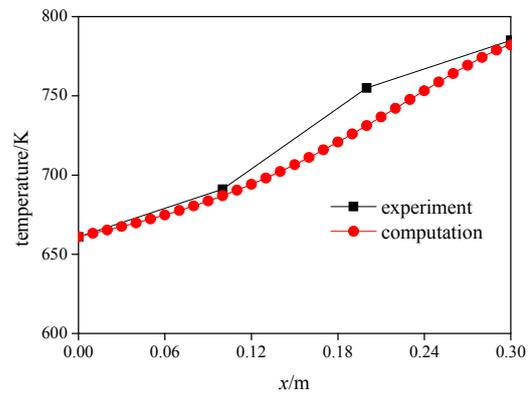
According to different operating conditions, the appropriate heat flux density can be set for numerical simulation boundary condition by means of comparison of numerical and experimental results.

In accordance with formula (1), the fitting of

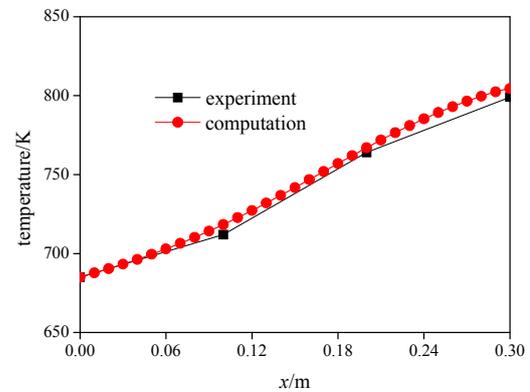
multiple independent variables function between heat flux density, inlet velocity, methane volume concentration and temperature can be obtained, then the coefficients of formula (1) is determined as follows:  $a=0.89$ ,  $b=0.094$ ,  $c=4.2$ ,  $d=0.46$ . Based on formula (1), the heat flux density corresponding to the operating parameters can be confirmed.

### III. COMPARISON OF NUMERICAL AND EXPERIMENTAL RESULTS

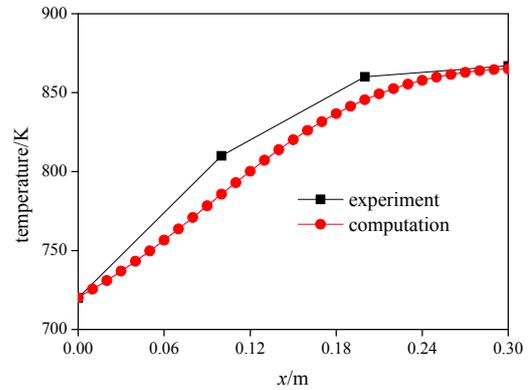
Fig.(3) shows the comparison of numerical and experimental results of temperature distribution along channel center line in the honeycomb ceramic oxidation bed under three operating conditions, in which the abscissa is distance from the channel entrance and the longitudinal is temperature at channel center line. The heat flux density is set in each condition based on formula (1). As shown in Fig.(3), the calculations fit quite well with experimental results in temperature distribution and total temperature rise and the maximum deviation of temperature is less than 4%. The reason of temperature deviation is mainly that it's the solid wall temperature measured by thermocouple during experiment process while the numerical porous media model neglects thermal non-equilibrium of solid and gas phase. Tab.(1) shows the comparison of computational and experimental results of the methane conversion rate under three conditions. It can be seen the experimental values are slightly higher than the calculated ones and the deviation is less than 5%, which is mainly caused by the good regenerative characteristics of ceramic oxidation bed during experimental process. The reliability of numerical model can be convinced from the comparison of the calculated and experimental results, so the numerical model is suitable for the study on the preheating catalytic oxidation of ventilation air methane.



(a) Operating condition 1 with methane volume concentration of 0.9%, space velocity of 4421h<sup>-1</sup> and preheating temperature of 660K



(b) Operating condition 2 with methane volume concentration of 1.0%, space velocity of 6189h<sup>-1</sup> and preheating temperature of 685K



(c) Operating condition 3 with methane volume concentration of 1.1%, space velocity of 7957h<sup>-1</sup> and preheating temperature of 720K

Fig.3 Comparison of computational and experimental temperature distribution

**TAB.(1).** COMPARISON OF COMPUTATIONAL AND EXPERIMENTAL METHANE CONVERSION RATE

Operating condition code	Experimental methane conversion rate	Computational methane conversion rate	Computation deviation
1	75.8%	72.2%	4.7%
2	77.2%	75.6%	2.1%
3	90.6%	86.4%	4.6%

IV. ANALYSIS OF CALCULATION RESULTS

A. Effects of Catalyst Loading

In the study of the effects of catalyst loading on the oxidation bed temperature field, the inlet methane concentration is set as a design value of 1%, the space velocity is 10000h<sup>-1</sup> as designed and the preheating intake air temperature is 800K. From Fig.(4) in which the temperature fields of the oxidation bed with different catalyst loadings are shown, it can be seen the temperature along the channel centerline gradually decreases without catalyst, while after Pd catalyst is added the temperature of the oxidation bed increases obviously in the flow direction and the heating up speed is accelerated with higher Pd catalyst loading. This is because the catalyst can improve the activity of methane molecules and then promote the oxidation of methane molecules. The methane conversion rate is further increased with higher catalyst loading and more heat is released to warm up the oxidation bed.

It can be seen from the influence of catalyst on the methane conversion rate shown in Fig.(5), the methane conversion rate is raised significantly with the increase of Pd catalyst loading. After the loading exceeds  $1.5 \times 10^{-8}$  kmol.m<sup>-2</sup>, the methane conversion rate passes 90% and the growth slows. Then the oxidation bed temperature rises to the peak at the exit, so the catalyst loading quantity of  $1.5 \times 10^{-8}$  kmol.m<sup>-2</sup> can be adopted for the oxidation bed to ensure a sufficiently high methane conversion rate and control the cost at the same time. In the following study of the effects of operating conditions on

ventilation air methane catalytic oxidation process, the catalyst loading is set to  $1.5 \times 10^{-8}$  kmol.m<sup>-2</sup>.

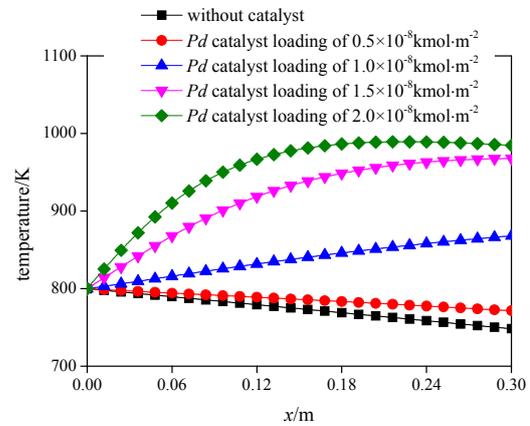


Fig.4 Effect of catalyst loading on oxidation bed temperature distribution

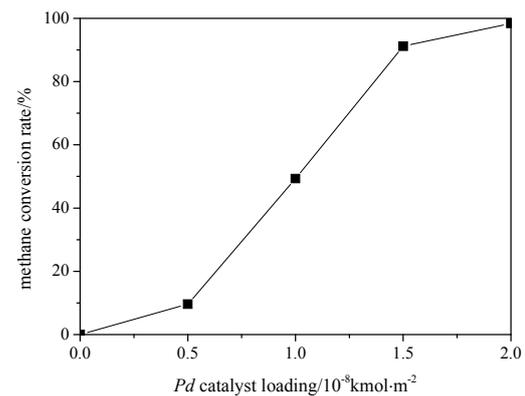


Fig.5 Effect of catalyst loading on methane conversion rate

B. Effects of Methane Volume Concentration under Different Preheating Temperatures

In the study of the effects of methane volume concentration on the catalytic oxidation process, space velocity is set as the design value of 10000h<sup>-1</sup>, the methane volume concentration is in the range 0.4%~1% and the preheating intake air temperature is of 700K up to 900K.

Fig.(6) shows the effects of methane volume concentration on the temperature distribution of the oxidation bed under different preheating temperatures. It can be seen the oxidation bed temperature rise

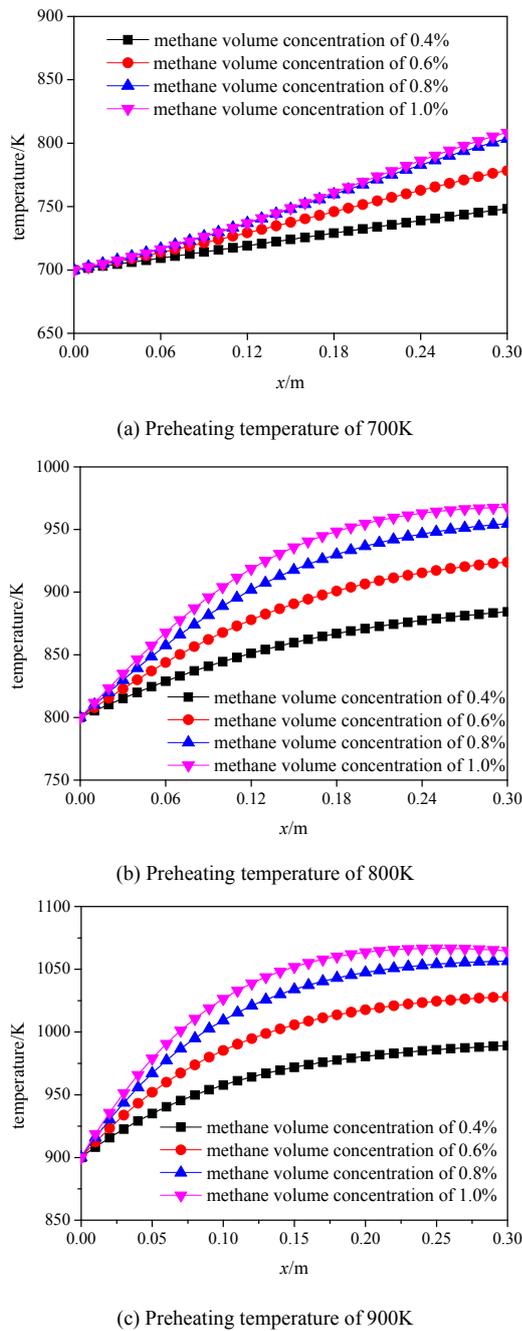


Fig.6 Effect of methane volume concentration on oxidation bed temperature distribution

speeds up in the flow direction and the temperature difference from import to export is improved obviously with the methane volume concentration increased from 0.4% to 1% under each preheating temperature. This is because the increased methane

concentration raises the contact density of methane molecule and catalyst, then the catalytic reaction is exacerbated and more reaction heat is released to accelerate the temperature rise. It can also be seen from Fig.(6) that the enhanced preheating temperature can also effectively promote the methane catalytic oxidation and accelerate the oxidation bed temperature rise. The temperature of the oxidation bed reaches the peak with the methane volume concentration of 1% and preheating temperature of 900K. Therefore when the inlet methane volume concentration is low, increasing the preheating temperature or prolonging oxidation bed length along the flow direction are both conducive to the full oxidation of methane and make the temperature reach the peak before export.

In order to make the discharged exhaust of oxidation bed effectively preheat the intake to methane catalytic oxidation temperature (about 700K) to achieve the normal operation of the preheating catalytic oxidation device, the temperature difference between the import and export of the oxidation bed should be over 150K when the space velocity is 10000h<sup>-1</sup>. At the same time, in order to prevent the inactivation and sintering of Pd catalyst at high temperature, the maximum temperature of the oxidation bed should be below 1100K. According to the temperature distribution in fig.(6), the methane volume concentration should be higher than 0.8% and simultaneously the preheating temperature should be over 800K when the space velocity is 10000h<sup>-1</sup> to maintain the smooth running of the preheating catalytic oxidation device.

The effect of methane concentration on methane conversion rate at different preheating temperature is shown in Fig.(7). It can be seen the methane conversion rate rises significantly with the increase of methane volume concentration when the preheating temperature is lower than 700K. When the preheating temperature exceeds 800K, the methane conversion is less affected by the methane concentration and the methane conversion rate is high in each concentration.

The lowest methane conversion rate is over 85% when the preheating temperature is over 800K. In the concentration range for normal operation of the preheating catalytic oxidation device, increasing the preheating temperature to above 800K can make methane conversion rate maintain stable, which is conducive to the stability of the preheating catalytic oxidation process.

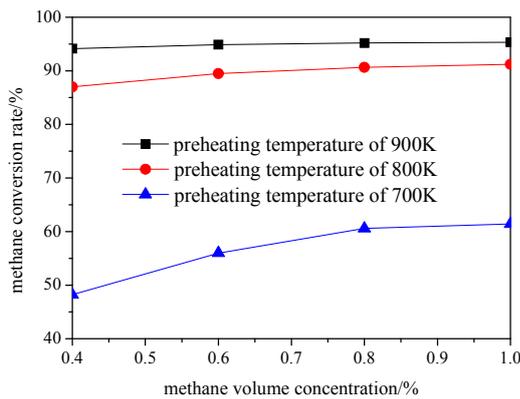


Fig.7 Effect of methane volume concentration on methane conversion rate

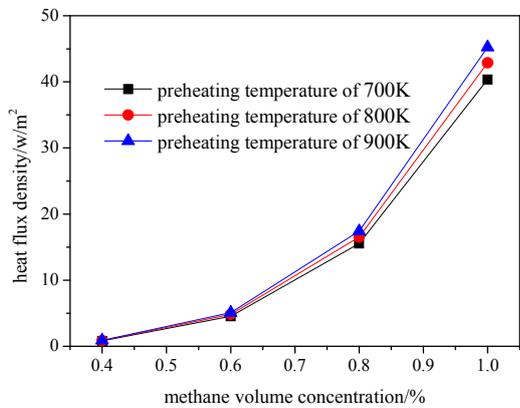


Fig.8 Effect of methane volume concentration on heat flux density

Fig.(8) shows the effect of methane volume concentration on dissipation heat flux density under different preheating temperatures. With the increase of methane concentration, the heat flux density grows rapidly, because more heat is released during methane oxidation to strengthen heat transfer between the ventilation air and oxidation bed. The preheating

temperature has obviously smaller effect on the heat flux density compared with methane volume concentration. The oxidation bed heat insulation layer design shall be carried out at the maximum concentration condition to control heat loss and ensure enough temperature rise between the oxidation bed import and export.

*C. Effects of Space Velocity under Different Preheating Temperatures*

In the study of the effect of space velocity on ventilation air methane catalytic oxidation under different preheating temperatures, the methane volume concentration is set to be the design value of 1%, space velocity ranges 4000 h-1~10000 h-1, and preheating temperature is in the scope of 700K~900K.

Fig.(9) shows the effect of space velocity on temperature distribution of the oxidation bed under several preheating temperatures, from which it can be seen the growth of oxidation bed temperature along the flow direction slows down significantly with the increase of space velocity. This is because the residence time of ventilation air in the oxidation bed is shortened and the contact time of methane molecule and catalyst reduces after the space velocity increases. Then there is not enough time for full reaction and the reaction heat release becomes less. In addition the exhaust takes away more heat from the oxidation bed under higher space velocity which also decreases the oxidation bed temperature. It can also be seen in Fig. (8) the oxidation bed temperature reaches the peak under each space velocity when the preheating temperature is improved to above 800K and the peak temperature position shifts upstream at lower space velocity. The methane in the ventilation air is fully oxidized and the reaction heat is all released where the temperature reaches the peak in the oxidation bed, then the downstream temperature decreases gradually, which reduces the export temperature and overall temperature rise and doesn't help for the exhaust to preheat the intake. Therefore, the preheating

temperature should be reduced at low space velocity to delay the temperature peak point and ensure the overall temperature rise of the oxidation bed at a high level.

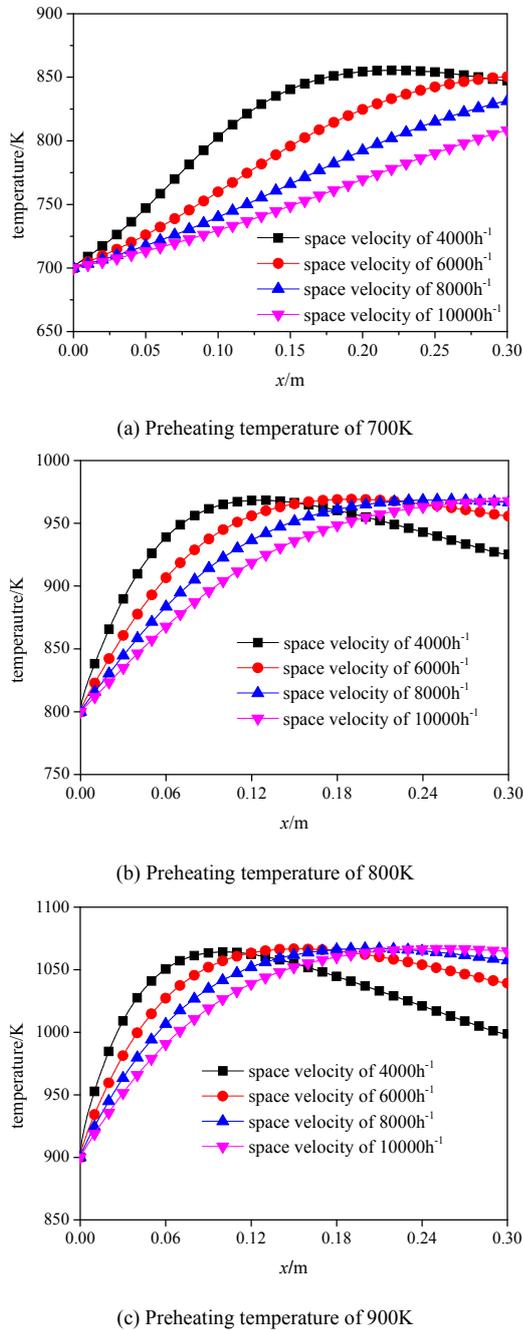


Fig.9 Effect of space velocity on oxidation bed temperature distribution

Fig.(10) shows the change of methane conversion rate with space velocity at different preheating

temperatures. It is shown the methane conversion rate drops obviously as space velocity increases and the drop reaches the maximum at lowest preheating temperature. When the preheating temperature is improved to above 800K, the effect of space velocity on methane conversion rate significantly reduces. Therefore, the high preheating temperature is able to ensure high and stable methane conversion rate within the actual operation range of space velocity.

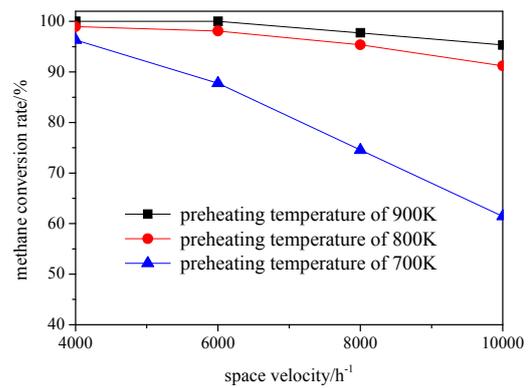


Fig.10 Effect of space velocity on methane conversion rate

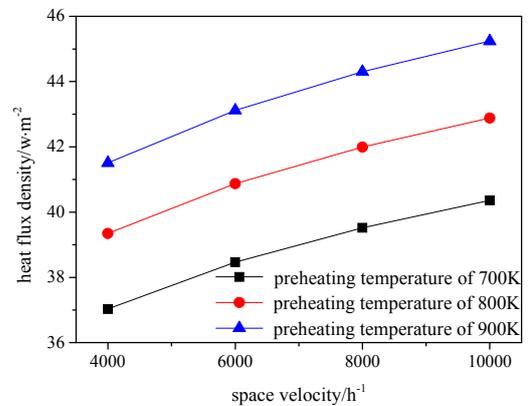


Fig.11 Effect of space velocity on heat flux density

Fig.(11) shows the heat flux density variation with space velocity at different preheating temperatures. The heat flux density variation shows a clear upward trend with the increase of space velocity due to the enhanced heat transfer between the gas and oxidation bed and has considerable rise at each preheating temperature. The heat flux increase is about 10% after the space velocity is improved from 4000 $h^{-1}$  to 10000

h-1 and about 12% after the preheating temperature is increased from 700K to 900K. Therefore the preheating temperature and space velocity have equivalent influence on heat loss in the range of operating conditions.

## V. CONCLUSION

①The influence of three operating parameters as intake space velocity, preheating temperature and methane volume concentration is considered in the numerical model of ventilation air methane oxidation, and the function relation between the heat flux and operating parameters is established to achieve good comparison of calculation and experimental results.

②With the increase of Pd catalyst loading, the oxidation bed temperature rise from import to export and methane conversion rate are both improved significantly. When the Pd catalyst loading exceeds  $1.5 \times 10^{-8}$  kmol.m<sup>-2</sup>, the methane conversion rate rise obviously slows down. So the Pd catalyst loading can be used to ensure high enough conversion rate and control production cost at the same time.

③The increase of methane volume concentration and preheating temperature both improve temperature rise of the oxidation bed significantly. The methane conversion rate has smaller change and maintains stable under higher temperature (above 800K). In order to ensure the normal operation of the preheating catalytic oxidation device at the space velocity of 10000h<sup>-1</sup>, the methane volume concentration of intake should be higher than 0.8%, at the same time the preheating temperature more than 800K.

④ After the space velocity is increased, the temperature of the oxidation bed rises slowly in the flow direction, the temperature peak shifts to the downstream, and the methane conversion rate decreases. When the methane volume concentration is 1%, the preheating temperature should be improved to above 800K to achieve the temperature peak inside the oxidation bed at each space velocity and the position

of temperature peak moves to the upstream with the increase of preheating temperature. The preheating temperature should be reduced to ensure adequate temperature rise in the oxidation bed at low space velocity.

⑤ Among the three operating parameters, the influence of methane volume concentration on surface heat loss is obviously larger than preheating temperature and space velocity. So the insulation layer of the preheating catalytic oxidation device should be designed at the condition of maximum methane volume concentration to control surface heat loss and ensure a smooth operation of the device.

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## REFERENCES

- [1] I. Karakurt, G. Aydin, and K. Aydiner, "Sources and mitigation of methane emissions by sectors: A critical review", *Renew. Energ.*, vol.39, pp.40-48, 2012.
- [2] I. Karakurt, G. Aydin and K. Aydiner, "Mine ventilation air methane as a sustainable energy source", *Renew. Sust. Energ. Rev.*, vol.15, pp.1042-1049, 2011.
- [3] C. Ö. Karacan, F. A. Ruiz, M. Coté, S. Phipps, "Coal mine methane: A review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction", *Int. J. Coal. Geol.*, vol.86, pp. 121-156, 2011.
- [4] K. Gosiewski, A. Pawlaczy, and M. Jaschik, "Thermal combustion of lean methane-air mixtures: Flow reversal research and demonstration reactor model and its validation", *Chem. Eng. J.*, vol.207-208, pp.76-84, 2012.
- [5] P. Marín, M. A. G. Hevia, S. Ordóñez, and F. V. Díez, "Combustion of methane lean mixtures in reverse flow reactors: Comparison between packed and structured catalyst beds", *Catal. Today*, vol.105, pp.701-708, 2005.
- [6] P. Marín, S. Ordóñez, and F. V. Díez, "Procedures for heat recovery in the catalytic combustion of lean methane-air mixtures in a reverse flow reactor", *Chem. Eng. J.*, vol.147, pp.356-365, 2009.
- [7] T. Feng, P. F. Wang, X. L. Hao, L. J. Chen, and P. Y. Ma, "Experimental Study on thermal flow-reversal oxidation of coal mine ventilation air low concentration methane", *Chin. Saf. Sci. J.*, vol.22, no.10, pp.88-93, 2012.

- [8] K. Gosiewski, A. Pawlaczyk, "Catalytic or thermal reversed flow combustion of coal mine ventilation air methane: What is better choice and when?", *Chem. Eng. J.*, vol.238, pp.78-85, 2014.
- [9] G. Lapisardia, L. Urfels, P. G  lin, M. Primet, A. Kaddouri, E. Garbowski, S. Toppi, and E. Tena, "Superior catalytic behaviour of Pt-doped Pd catalysts in the complete oxidation of methane at low temperature", *Catal. Today*, vol.117, pp.564-568, 2006.
- [10] A. Trinchero, A. Hellman, and H. Gr  nbeck, "Methane oxidation over Pd and Pt studied by DFT and kinetic modeling", *Surf Sci*, vol.616, pp.206-213, 2013.
- [11] Y. Q. Liu, R. X. Liu, Y. X. Wang, Z. Q. Gao, and B. Zheng, "A Preheating Catalytic Oxidation Reactor for Coal Mine Ventilation Air Methane", China Patent CN202113840U, January 18, 2012.
- [12] Y. Q. Liu, R. X. Liu, Y. X. Wang, B. Zheng and Z. Q. Gao, "A Preheating Catalytic Oxidation Reactor for Coal Mine Ventilation Air Methane with Multiple Reaction Chambers", China Patent CN102205207A, October 5, 2011.
- [13] Y. Q. Liu, R. X. Liu, Y. X. Wang, B. Zheng and Z. Q. Gao, "A Preheating Catalytic Oxidation Reactor for Coal Mine Ventilation Air Methane with Burner Startup", China Patent CN102225321A, October 26, 2011.
- [14] Y. Q. Liu, R. X. Liu, Y. X. Wang, Z. Q. Gao and B. Zheng, "The Intake and Exhaust Deflector Device of Preheating Catalytic Oxidation Reactor for Coal Mine Ventilation Air Methane", China Patent CN102230393A, November 2, 2011.
- [15] S. Su, J. Agnew, "Catalytic combustion of coal mine ventilation air methane", *Fuel*, vol.85, pp.1201-1210, 2006.
- [16] S. A. Shahamiri, I. Wierzba, "Modeling catalytic oxidation of lean mixtures of methane-air in a packed-bed reactor", *Chem. Eng. J.*, vol.149, pp.102-109, 2009.
- [17] P F Wang, T Feng, X L Hao, "One-dimensional numerical simulation of thermal reverse flow oxidation of ventilation air methane in coal mine", *J Min. Saf. Eng.*, vol.29, no.3, pp. 434-439, 2012.
- [18] F. Moallemi, and G. Batley, "Chemical modelling and measurements of the catalytic combustion of CH<sub>4</sub>/air mixtures on platinum and palladium catalysts", *Catal. Today*, vol.47, no.1-4, pp.235-244, 1999.
- [19] Deutschmann, R. Schmidt, F. Behrendt, and J. Warnatz "Numerical modeling of catalytic ignition", *Proceedings of the 26th International Symposium on Combustion*, The Combustion Institute, Pittsburg, vol.26, pp. 1747-1754, 1996.
- [20] T. Engel, and G. Ertl, "A molecular beam investigation of the catalytic oxidation of CO on Pd(111)", *Journal of Chem Phys*, vol.69, no.3, pp.1267-1281, 1978.