Spray combustion characteristics of a small-sized flue gas self-circulation diesel burner

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Spray combustion characteristics of a small-sized flue gas self-circulation diesel burner

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Abstract. Low NO_X combustion technology is taken more and more seriously. A new type of flue gas self-circulation low-NOx combustion structure was preliminary designed in this paper. The 3D model was established. Using the probability density function (PDF), a comparison of this data with the result of experimental can verify the feasibility of the selected calculation model. In addition, the numerical simulation of the small-sized flue gas self-circulation diesel burner' combustion process was investigated. The results show that: At the exit of the burner head, radial velocity distribution presented a "W" type substantially, the tangential velocity was an inverted "V" type distribution, and those two kinds of velocity both are tend to smooth attenuation till the distal end axially. Near the central exit of new burner, the recirculation zone becomes larger, mainly in the width direction. And circumfluence areas existed in the annular ostial of the outer cylinder. Back flow of flue gas increased. The flame length was shortened and a low NO emission was accomplished.

1. Introduction

At present, the emission standard of the oil burner is higher and higher in each country. Low NOx emissions burner is researched through various means and methods.

For light oil combustion, oil needs to be atomized prior to ignition. This is an evaporative combustion. the present study shows that[1] a good combustion state can be achieved through high-quality atomization and reasonable air distribution, and the matching degree of them determines the status of combustion. For a relatively complex structure of burner, Wu Defei et al.[2-3] accurately measured flow field, the temperature field and the distribution of the components by numerical simulation method. In terms of spray combustion research, the velocity field, temperature characteristics and distribution of the components play an important role.

NO_X produced when the light diesel is burned, more than 90 percent of which is NO[4]. The two primary modes of NO formation are as follows: One is the thermal-NO, which refer to the nitrogen from the air oxidizes; the other is fuel-NO, which is produced from nitrogen contained by oil. At lower temperatures, NO can be oxidized to NO_2. nitrogen content of light diesel oil is generally not more than 0.1%, so the main pollutants NO_X which produced during combustion is thermal-NO[5].

In addition, the literature shows that the backflow zone has a great influence on of NO emissions, which depend on the negative pressure making the flue gas emissions of the secondary combustion can obviously reduce the NO[6-10]. Xiao Zhen[11], Li Hong[12], Xia Dehong[13] and other scholar also studied some issues about small gas-fired, methane ejector burner and the flue gas from the circulation by numerical simulation and experimental methods. These studies had found that the temperature of the furnace will reduce NO emissions.

A new pint-sized burner structure with self-circulation of flue gas was designed in this paper, to reduce the temperature of the flame's high-temperature reaction zone and enhance quantity of flue gas reflux. Based on this structure, combustion characteristics of the light diesel oil burner were analyzed using numerical simulation method.

2. Burner model and numerical method

To enhance the reflux of high-temperature flue gas, in the new-style burner, an outer cylinder is over the flame holder. There is a 7.5mm wide annular outlet in outer cylinder of the combustor along the axial direction. Change the inner cylinder edge to a necking structure. features of this structure is that it can return the flue gas to the interior of combustion tube through annular opening, which taking advantage of the ejection action of peripheral airflow. A simplified Structure diagram of the combustion head as shown in figure 1. The air distribution devices both prototype burner and new burner are a swirl stabilizer with opening groove 45° as shown in figure 2.

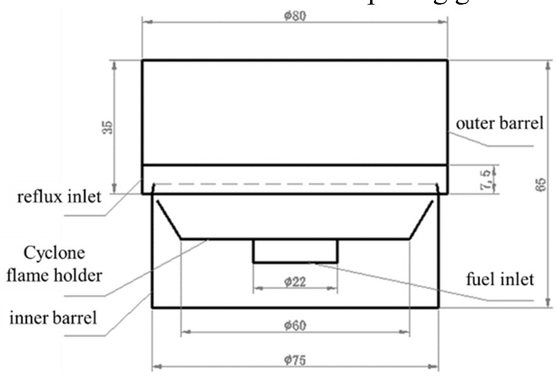

Figure 1. Structure of burner head.

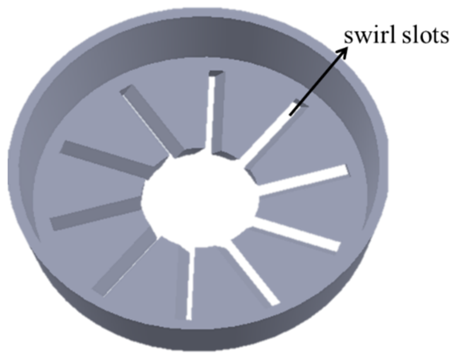

Figure 2. 3D structural drawing of flame holder.

To reduce the computational expense, 1/5-periodic boundary conditions model was used. The combustion chamber of new burner structure is consistent with prototype burner. A meshing schematic model of the combustion chamber as shown in figure 3:

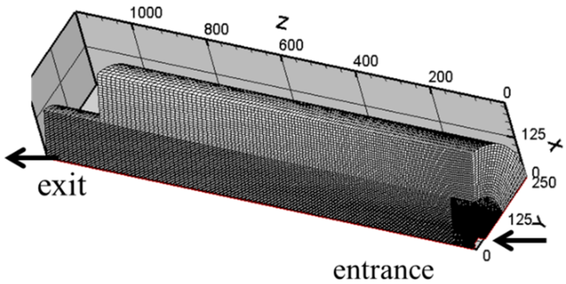

Figure 3. Meshing computation model.

For an initial design parameters and iteration adaptive, the common standard k-ε turbulence model was adopted[14]; The heat transfer process between the droplets particles and the gas phase were calculated with the coordinates of discrete optical radiation (DO) model[15] which are applicable at all scales; the combustion model adopt a simplified PDF model[16-17], It is based on the DPM model[18] and numerically simulates the droplet distribution and flow trajectories by coupling calculation of liquid and the gas phases; contaminant model adopt NOx generation model[19], wherein the generation of thermal-NO can be predicted by extended Zeldovich's mechanism. Light diesel fuel component may be simplified into a single component $C_{12}H_{23}$. the flame front is defined by calculating stoichiometric mixture fraction[20].

In this article, the mass flow rate of diesel was 7.222×10^{-4}kg/s. Calculating from the conservation of chemical mass, the theoretical air consumption was 0.010534kg/s. Chemical equivalent mixing fraction is 0.064.

3. Results and discussion

3.1 Model validation and grid independence test

The temperature and flame length were compared with that for prototype[21], both being in good agreement (figure 4 and 5). It can be seen that the flame temperature distribution of simulated result was substantially uniform with in the literature. In the same sites, there is a primary reaction zone and a secondary high-temperature reaction zone, corresponding with experimental result. The maximum simulation temperature of the flame is 1834K, the maximum value of experimental 1773K, it's within the error rang. And experiment flame length was about 455mm, numerical value was 483mm. Comparing the results, error is 6.15%. Applicability of the model was verified.

In this paper, the model is divided between 100,000 to 400,000 number grids, we found that after the maximum temperature and NO emissions are consistent when the grid is greater than 170 000. As a consequence, the grid-independent was verified. In numerical simulations of this work, the amount of mesh was 199 000.

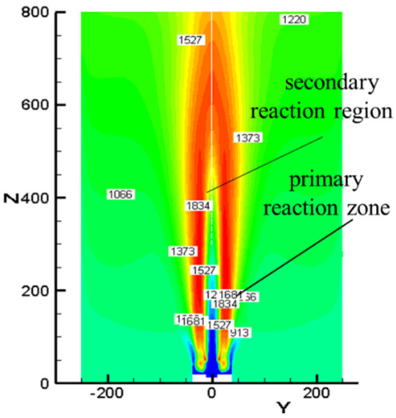

Figure 4. Simulated temperature field.

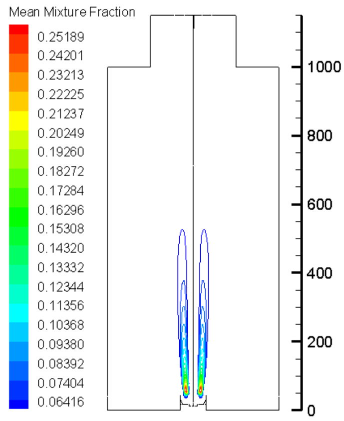

Figure 5. Simulated contour of mean mixture fraction.

3.2combustion head outlet velocity field analysis

The cross-section locations of new burner head and chamber are marked, as shown in the figure 6. Velocity vector diagram in the burner head region is illustrated in figure 7.

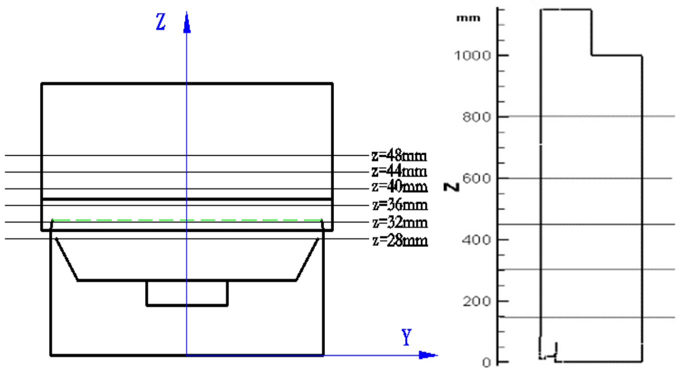

Figure 6. Sections of the burner head and combustion.

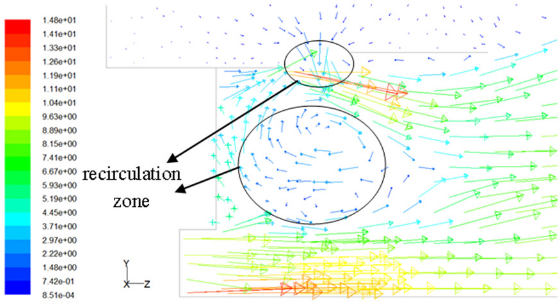

Figure 7. Velocity vector inside of burner head.

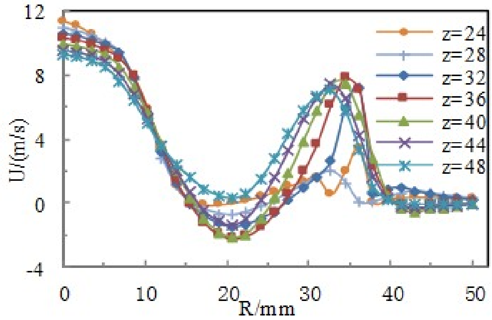

Figure 8. Distribution of axial velocity.

The combustion head region has two recirculation zones. A central recirculation zone can be clearly seen in the velocity contour. This primary recirculation zone becomes larger than prototype, especially in the width direction. It plays an important role in ignition and combustion stability. The other recirculation zone exists in the annular opening, where exist a necking structure. This is due to the ejecting airflow of the secondary edge wind. The velocity is increased abruptly at the location of necking structure, simultaneously quantity of flue gas reflux rises up significantly.

Figure 8 refers to the axial velocity diagram of combustion head region. There is a negative velocity in the radial direction (15 ~ 25mm). Through the axial velocity profile, it can be seen that the flue gas recirculation zone is constituted by two rotating opposite swirl vortices over the radial slot of flame holder. Furthermore, there is a larger secondary peak velocity in the radial direction (30 ~ 35mm), which enhanced reflux of flue gas and backflow area. In consequence, the flame stabilization can be enhanced obviously.

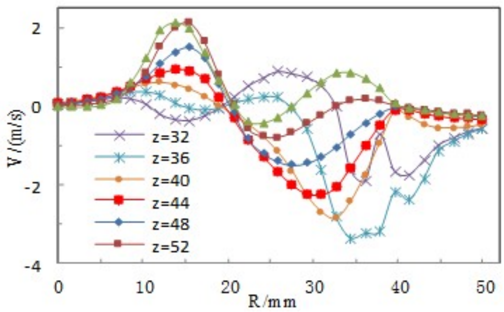

Figure 9. Distribution of radial velocity.

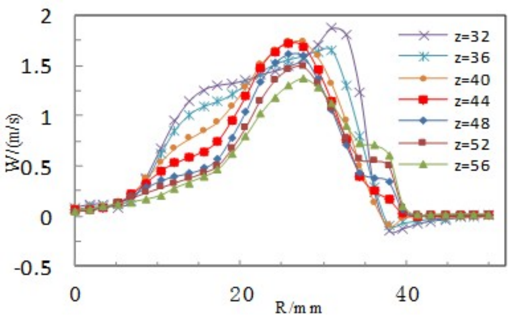

Figure 10. Distribution of tangential velocity.

The figure 9 is radial velocity of Each sections in burner head region. Radial velocity distribution of the combustion head portion is generally consistent with "W" shaped profile with the bottom value offsets to the interior direction as z increases, which is also due to ejecting airflow of the secondary edge wind at the necking of the structure. At the sectional surface of z = 36mm, valley value has a maximum because of the maximum reflux valley was appeared in this cross-sectional area. With the value of once peak of increases with increasing height of z. This is because as height increasing, reflux weakened, the radial velocity increases. However, the radial velocity tends to flat due to the smaller and smaller axial momentum along the axial direction to the distal end.

The figure 10 is tangential velocity distribution in burner head region. Tangential velocity was "inverted V" shaped profile. Tangential velocity tends to leveling off along the axial direction to the distal end because of weakening the axial momentum. maximum value of tangential velocity present to this region of R = 20 ~ 30mm, which are attributed to the swirl slot of the flame stabilizer.

On the whole, fame stabilizer and the annular opening had a direct influence on air distribution and flow characteristics. Velocity profile at the exit of the flame plate directly determines the characteristics of the flame stability and reflux.

3.3NO distribution and emission

NO volume concentration (in ppm) are distributed as follows as shown in figure 11 and 12.

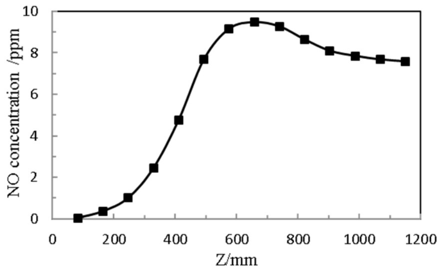

Figure 11. Distribution of axial concentration of NO.

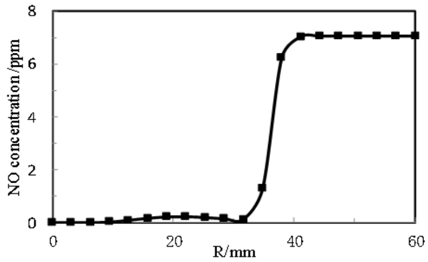

Figure 12. Distribution of radial concentration of NO on the section of z = 36mm.

NO concentration gradually increases along the axial direction to the high temperature zone, mainly in the secondary high-temperature reaction zone of flame extreme. In the recirculation zone of the burner head, NO is reflowed and burned with the flue gas reflux as a result of NO concentration reduces greatly. As is apparent from the description, the NO concentration in the burner head region is substantially zero, the concentration gradually increasing along the axial direction to the high-temperature zone. the largest NO concentration appeared in the secondary high-temperature reaction zone. This is also due to the main influencing factors is temperature. vast proportion of thermal-NO is first. The maximum concentration of NO in the combustion chamber is 9.47ppm, the average NO concentration at the outlet face is 8.08ppm. Such emissions are far below the national emission standards.

4. Conclusion

This paper mainly investigated the combustion characteristics of a new small-sized flue gas self-circulation diesel burner by numerical simulation. The main conclusions are as follows are as follows:

(1) A standard k-ε model, the discrete phase, PDF model, DO radiation model and periodic boundary conditions were adopted to simulate the Flow field, flame and NO generation of new burner in a closed combustion chamber. And the result was compared with the experiment in the literature. The reliability of the model was verified.

(2) Two reflux zones exist in annular openings and above radial slot, respectively. the radial velocity at the outlet of the burner head has a substantially "W" type profile, tangential velocity distribution tends to inverted "V" type. Both the two kinds of velocity tend to flatten axially.

(3) NO was concentrated in the terminal vicinity of the flame high- temperature zones. The NO emissions of the new burner are below 10ppm.

Acknowledgments

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5. References

[1] Xuchang Xu, Junfu Lü, Hai Zhang. (2012) Combustion theory and combustion equipment (The second edition). Science press, Beijing.
[2] Wu Defei, Mao Yu, Jiang Hua. (2003) Numerical simulation of three-dimensional flow field and combustion conditions in complex structure gas burner. Journal of the University of Petroleum, 27(2): 93-97.
[3] Zhou Guijuan, Mao Yu, Wang Juan. (2006) Three-dimensional numerical simulation of turbulent flow and combustion in the outlet of oil burner. Acta Petrolei Sinica (Petroleum Processing Section), 22 (4): 49-55.
[4] Veynante D, Vervisch L. (2002) Turbulent combustion modeling. Progress in energy and combustion science, 28 (3): 193-266.

[5] He Hongzhou. (2005) A study on technology of decreasing the generation of NOx during oil combustion. Techniques and Equipment for Environmental Pollution Control, 6(12): 77-81.
[6] SHINOMORI K, KATOU K, et al. (2011) NOx emission characteristics and aerodynamic structure of a self-recirculation type burner for small boilers. Proceedings of the Combustion Institute, 33: 2735-2742.
[7] Qi Fenglei. (2012) Development and investigation of Low-NOx coal gas burner with flue gas recirculation. China University of Petroleum, Qingdao
[8] ELDRAINY YA, SAQR KM, et al. (2011) Large eddy simulation and preliminary modeling of the flow downstream a variable geometry swirler for gas turbine combustors. International Communications in Heat and Mass Transfer, 38 (8): 1104-1109.
[9] Yan Zhen. (2011) A thesis submitted in partial of fulfillment of the requirements for the degree of engineering. Huazhong University of Science and Technology, Wuhan.
[10] Shinomori K, Katou K, Shimokuri D, et al. (2011) NOx emission characteristics and aerodynamic structure of a self-recirculation type burner for small boilers. Proceedings of the Combustion Institute, 33 (2): 2735-2742.
[11] Xiao Zhen, Guo Yincheng. (2008) Studies on NOx emission in a natural gas pilot boiler with internal flue gas recirculation. Journal of Engineering Thermophysics, 29 (10): 1780-1782.
[12] Li Hong. (2008) Flue gas from burning cycle of the design and experimental. Hebei University of Technology, Tianjin.
[13] Xia Dehong, Xue Genshan, Shang Yingchun. (2009) Numerical simulation of a low oxygen burner with self-circulation of flue gas. Journal of University of Science and Technology Beijing, 31(12): 1616-1619.
[14] Kurreck M, Willmann M, Wittig S. (1998) Prediction of the three-dimensional reacting two-phase flow within a jet-stabilized combustor. J. Eng Gas Turb Power, 120: 77-83.
[15] Truelove JS. (1987) Discrete-ordinate solutions of the radiation transport equation. Journal of Heat Transfer, 109 (4): 1048-1051.
[16] Repp S, Sadiki A, Schneider C, Hinz A, Landenfeld T, Janicka J. (2002) Prediction of swirling confined diffusion flame with a monte carlo and a presumed-PDF model. Int J Heat Mass Transfer, 45: 1271-85.
[17] Jiang LY, Campbell I. (2005) A critical evaluation of NOx modeling in a model combustor. Journal of engineering for gas turbines and power, 127 (3): 483-491.
[18] Wu Chao. (2009) Study on applicability of turbulent combustion model in the numerical calculation of combustor. Shenyang Aerospace University, Shenyang.
[19] Bazdidi-Tehrani F, Zeinivand H. (2010) Presumed PDF modeling of reactive two-phase flow in a three dimensional jet-stabilized model combustor. Energy Conversion and Management, 51 (1): 225-234.
[20] Turns S. R. Yao Qiang, Li Shuiqing, Wang Yu translate. (2009) An introduction to combustion concepts and applications (Second edition). Tsinghua university press, Beijing.
[21] Li Depeng. (2012) Research on combustion technology under extreme environmental conditions [D]. China University of Petroleum, Qingdao.