Numerical Simulation Study of the Influence of Flue Gases Recirculated on NO_x Emissions

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Abstract. Flue gas recirculation is considered to be one of the most promising and cost-effective NO_x reduction strategies for combustion systems. Therefore, it has great scientific and practical significances to investigate the flue gas recirculation process. Fluent was used to perform a numerical flue gas recirculation simulation on natural gas combustion in a burner, revealing the relationship between NO_x emission and circulation ratio, circulation temperature, and circulation locations. The following conclusions were drawn: the NO_x generated with gas recirculation on is less than when there is no gas recirculation; the lower the gas circulation temperature, the less the NO_x; when the circulation is 25%, the NO_x generated is low; less NO_x is generated if the gas is firstly mixed with the air before combustion.

1 Introduction

Combustion processes are typically considered as ones of the main factors responsible for the emission to the atmosphere of important air pollutants, such as NO_x, SO_2 and particulate matter. NO_x is produced during the combustion process in a high temperature region and is known as a source of major air pollution that generates ozone when it reacts with sunlight; NO_x also causes respiratory diseases [1-3]. Flue gas recirculation (FGR) is an interesting technique for reduction of nitrogen oxide (NO_x) emissions that can be applied to boilers or internal combustion engines. This technique includes recirculation of part of flue gases back to the combustion chamber; it may be responsible for various effects on combustion, pollutant formation and emissions.

CFD is an analysis of systems involving fluid flow by means of computer-based simulations. These systems may also involve heat transfer and associated phenomena such as chemical reactions. CFD simulations are based upon a numerical solution of basic equations of the fluid dynamics, conservation of mass, momentum, and energy, together with mathematical sub-models. The equations can be solved in three-dimensions. Comprehensive modelling of combustion in general requires simulation turbulent fluid dynamics, chemical kinetics as well as their interactions.

FLUENT 15 is a general-purpose CFD code, which is based on finite volumes, and the region of interest is divided into small sub-regions called control volumes. The equations are discretized and solved iteratively, providing the value of each variable (velocity, temperature, mass fractions etc.) for each control volume throughout the calculation domain.

NO_x emissions from natural gas combustion are studied, with the objective to demonstrate the applicability of stationary computational fluid dynamics simulations, including a detailed representation of gas phase chemistry, to a burner fired reactor using natural gas as a fuel.

2 Mathematical model

In this study, gas burner BT350GRF chosen is shown in Figure 1; its power is in the range of 500 kW－924 kW, and power supply pressure is between 40 and 300 mbar, power supply is 380 v/Hz, motor 7.5 kW, its size is 1500 x1080x800mm, and weight is 330 kg, with flame size 356 x275mm.

Figure 1. Structure graphing of gas burner BT350GRF

The mathematical model is based on the numerical solution of the time-averaged equations governing conservation of mass, momentum and energy and transport equations for scalars describing turbulence and combustion.

3-D Navier-Stokes equations, the energy conservation equation, and the species conservation equations are discretized by the finite volume method. The discretization method is a second order upwind scheme, and the SIMPLE algorithm is adopted for the coupling of pressure and velocity. For the calculation, the standard k - e eddy viscosity-diffusivity model is used to describe the fluid flow considering the air and fuel velocities supplied from the nozzles. The parabolic flows of the fuel and air are injected into ambient air at a standard temperature and pressure. The following pressure outlet conditions are applied to the exhaust outlet, which has the same diameter as that of the ventilation tube, zero temperature gradients, species mole fractions, and axial and radial velocities. For the wall of the chamber, no-slip conditions and zero species mole fraction gradients are applied, and convective heat transfer is applied at the wall boundary. To determine convergence of the solution, the residual in the energy conservation equation is defined as being less than $1x10^8$ and the residuals in other equations are less than $1x10^5$.

2.1 Species Transport Equations

We have chosen to solve conservation equations for ANSYS FLUENT predicts the local mass fraction of each species, Y_i, through the solution of a convection-diffusion equation for the ith species. This conservation equation takes the following general form:

$$\frac{\partial}{\partial t}(\rho Y_i) + \nabla.(\rho \bar{v} Y_i) = -\nabla.\bar{J}_i + R_i + S_i \qquad (1)$$

Where R_i is the net rate of production of species by chemical reaction (described later in this section) and S_i is the rate of creation by addition from the dispersed phase plus any user-defined source. An equation of this form will be solved for $N-1$ species where N is the total number of fluid phase chemical species present in the system. Since the mass fraction of the species must be equal to unity, the Nth mass fraction is determined as one minus the sum of the $N-1$ mass fractions. To minimize numerical errors, the Nth species should be selected as that species with the overall largest mass fraction, such as N_2 when the oxidizer is air.

2.2 Mass Diffusion in Turbulent Flows

In turbulent flows, ANSYS FLUENT computes the mass diffusion in the following form:

$$\bar{J}_i = -\left(\rho D_{i,m} + \frac{\mu_t}{Sc_t}\right)\nabla Y_i - D_{T,i}\frac{\nabla T}{T} \qquad (2)$$

Where Sc_t is the turbulent Schmidt number ($\mu_t / \rho D_t$ where μ_t is the turbulent viscosity and D_t is the turbulent diffusivity). The default Sc_t is 0.7. Note that turbulent diffusion generally overwhelms laminar diffusion, and the specification of detailed laminar diffusion properties in turbulent flows is generally not necessary.

We will use the generalized eddy-dissipation model to analyze the natural gas-air combustion system. The combustion will be modeled using a global one-step reaction mechanism, assuming complete conversion of the fuel to CO_2 and H_2O . The reaction equation is

$$CH_4+2O_2 \rightarrow CO_2+2H_2O \qquad (3)$$

The reaction equation is defined in terms of stoichiometric coefficients, formation enthalpies, and parameters that control the reaction rate. The reaction rate is determined assuming that turbulent mixing is the rate limiting process, with the turbulence-chemistry interaction modeled using the eddy-dissipation model.

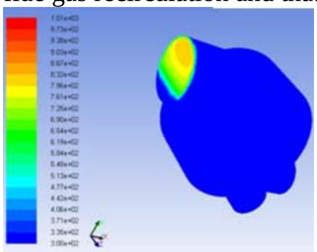
2.3 NOx Prediction

The formation of NO_x can be attributed to four distinct chemical kinetic processes [4]: thermal NO_x formation, prompt NO_x formation, fuel NO_x formation, and intermediate N_2O. Thermal NO_x is formed by the oxidation of atmospheric nitrogen present in the combustion air. Prompt NO_x is produced by high-speed reactions at the flame front. We will calculate the formation of both thermal and prompt NOx.

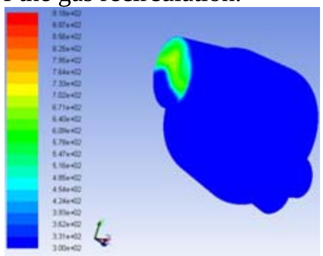
3 Effect of flue gas recirculation on NO_x

3.1 Effect of circulation ratio on NO_x

We will compare the temperature of the burner with the flue gas recirculation and that of the gas recirculation.



Contours temperature without flue gas recirculation

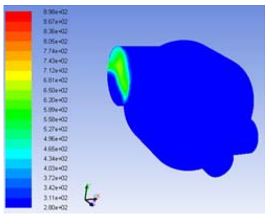


Contours temperature of flue gas recirculation

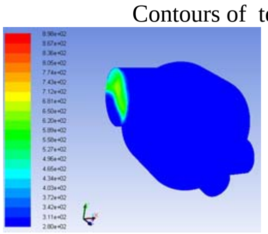
Figure 2. contours of temperature flue gas recirculation on outlet

As a result, it can be known from Figure 2, that compared with the use of flue gas recirculation, there is a certain reduction in temperature, which is due to the low temperature of the flue gas into the burner. It is necessary to reduce the temperature of the burner, and due to the addition of the flue gas, the O_2 volume fraction of the burner and the volume fraction of CO_2 can be reduced. The number increases, thereby reducing the generation of NO_x.

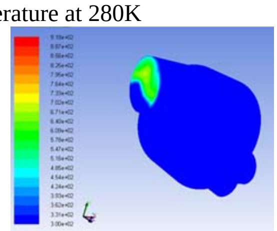
3.2 Effect of circulation ratio on No_x



Contours of temperature at 280K

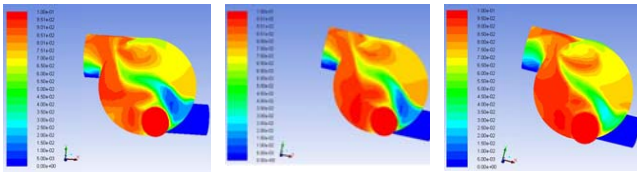


Temperature chart of 300K



Temperature chart at 320K

Figure 3. At different temperature chart gas inlet, burner, gas export



At the 280K At the 300K At the 320K

Figure 4. NO_x distribution at different temperature

According to Figure 3 and Figure 4, a different circulating temperature NO_x is in the flue gas inlet, the burner, and the content of the flue gas exports, as shown in figure 5.

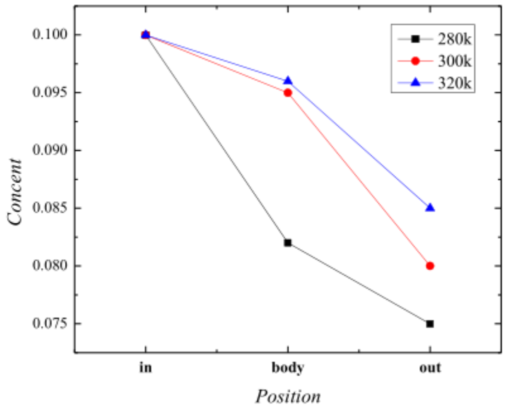
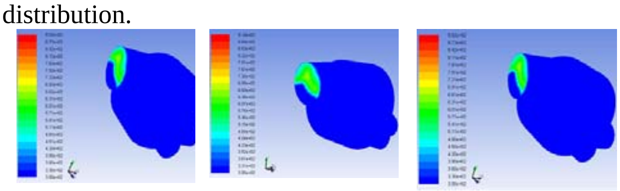


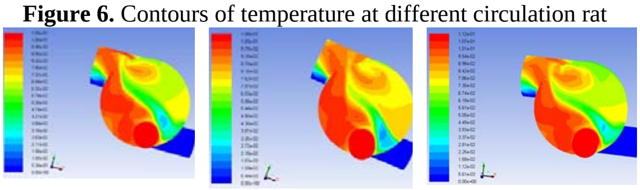
Figure 5. NOx of different circulating temperature in the flue gas inlet, burner, gas export content diagram

As shown in Figures 3-5, it is known that the lower the cycling temperature, the less NO_x. This is because when the low temperature of the flue gas enters the burner, the overall temperature of the burner is reduced to a certain extent. Then the production of NO_x. CO_2 is reduced. Under the same conditions, the circulating rate is different, comparing the results of the burner temperature contours, the velocity vector chart and NO_x distribution.



Contours of temperature at the circulation rate 15% Contours of temperature at the circulation rate 25% Contours of temperature at the circulation rate 35%

Figure 6. Contours of temperature at different circulation rat



At the circulation rate 15% At the circulation rate25% At the circulation rate 35%

Figure 7. Contours of NO_x distribution at different circulation rate

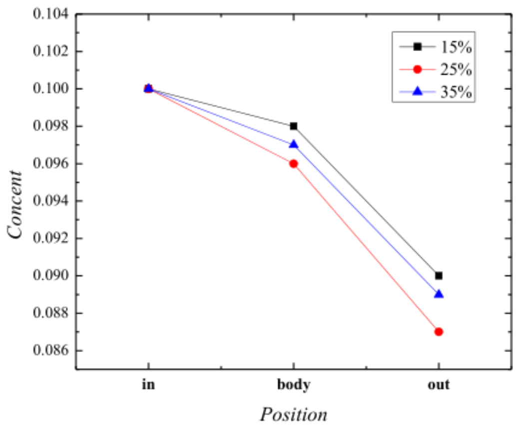
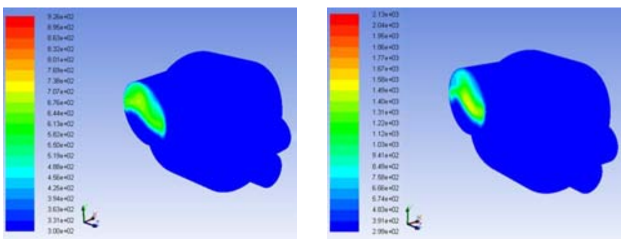


Figure 8. Content of NO_x in different circulating rate at the flue

As shown in Figures 6 to 8, NO_x is decreased and then increased with the increase of flue gas recirculation rate, at the flue gas recirculation rate 25%. NO_x is relatively small, and it can be found that the temperature is lower at the gas recirculation rate of 25%. This is due to a certain extent of flue gas recirculation to reduce the temperature in the burner. In order to inhibit the formation of thermal NO_x, and to increase flue gas recirculation, the flue gas velocity increases, so that the smoke in the flame of residence time is reduced. This also inhibits the generation of the normal NO_x. The change of firing conditions will affect the formation of fuel NO_x. Compared with the non-use of flue gas recirculation, the temperature of the burner can be reduced by using the flue gas recirculation. This is due to the low temperature of flue gas into the burner. It is necessary to reduce the temperature of the burner, due to the circulation of flue gas. With the addition of NO_x, the volume fraction of O_2 decreases and the volume fraction of CO_2 increases and then decreases. Numerical simulation of NO_x pollution emission is reduced by flue gas recirculation.

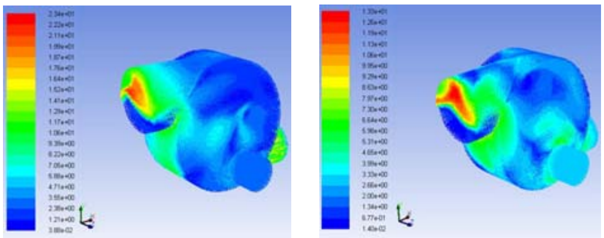
3.3 The effect of cyclic position on NO_x

On the same conditions, the circulation position is different, comparing the results of the burner temperature contours, the velocity vector chart and NO_x distribution.



Contours of natural gas, air, flue gas at identical inlet temperature Contours of natural gas, air, flue gas at different inlet temperature

Figure 9. contours of natural gas, air, flue gas at inlet temperature



Contours of natural gas, air, flue gas at identical inlet velocity

Contours of natural gas, air ,flue gas at different inlet velocity

Figure 10. Contours of natural gas, air, flue gas at identical inlet velocity

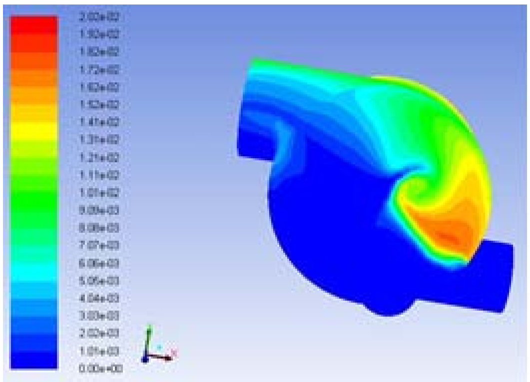


Figure 11. Natural gas air flue gas with inlet NOx distribution

As shown in Figure 9-11, when the outlet temperature is relative to the same inlet of natural gas, air and gas are lower. The relatively slow rate of export, to a certain extent, inhibits the formation of NO_x, so that the amount of NO_x is reduced.

4 Conclusion

In this paper, effects of flue gas recirculation ratio and fuel types on NO_x are investigated, and the effects of air preheating temperature and oxygen concentration on NO_x have also been discussed. According to the predicted results, flue gas internal recirculation is an effective method for reduction of NO_x, and NO_x is rapidly decreased with an increase in the recirculation ratio. The influence of air preheating temperature and oxygen concentration on NO_x emission is negligible when the flue gas recirculation ratio is high enough. The temperature of the circulation is 280K, 300K, 320K, the cyclic rate is 15%, 25% and 35% respectively. And under the same conditions in the case of different circulation of the 4 types of discussions, we can get the following conclusions: 1) The NO_x produced by the use of flue gas recirculation is less than that of non-use of flue gas recirculation for the low temperature flue gas returns to the gas supply system, and the gas mixture is reduced. The concentration of oxygen, heat absorber, the combustion temperature become too high, thereby inhibiting the generation of nitrogen oxides. 2) The lower the temperature of the flue gas is, the lower the NO_x is. When the flue gas enters the burner, the overall temperature of the burner is reduced to some extent, and the combustion is suppressed. And the production of NO_x is reduced. 3) At the circulation rate of 25%, NO_x is less. When the flue gas recirculation rate is higher, the combustion will be unstable, and the heat loss will increase, and the NO_x yield will be affected. 4) The gas and air mixed with the first mixture will produce less NO_x .

With the previous 4 conclusions, we can clearly know that flue gas recirculation is important for NO_x production and influence. The principle of flue gas recirculation is simple and easy to understand, the device is easy to install, and the price is not very high; therefore, in natural gas, gas pollution reduction has an important role. Flue gas recirculation is an important way to reduce NO_x, and it is also an important way to reduce pollutants in the future. If in the future we should carry out a deeper research, the research results will be used to achieve the greatest possible reduction of emissions of pollutants.

References

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