Study of the effect of wall temperature and oxidant structure on temperature distribution and NO emission in non-premixed combustion furnace

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ABSTRACT

The aim of this study was to investigate the effect of thermal condition of furnace wall and oxidant structure on NOx emission and thermal conditions inside the non-premixed combustion furnace. For this purpose, non-premixed combustion furnace simulations have been performed using OpenFOAM software. Standard k-ε turbulence model, modified EDC combustion model and DO radiation model are used in numerical simulations. In order to analyze the results of numerical simulations, chemical calculations using well stirred reactor have also been considered. According to the results, increasing the furnace wall temperature to reach thermal insulation conditions leads to a significant increase in the average and maximum temperature inside the combustion chamber and transfers the combustion regime from flameless to high temperature. In addition, the replacement of carbon dioxide with nitrogen will be accompanied by a decrease in the combustion temperature due to physical and chemical differences between two species. According to the results, increasing the wall temperature, despite reducing the heat loss, leads to an increase in NO_x in the high temperature combustion regime. The use of carbon dioxide instead of nitrogen in oxidizer can be considered as a way to reduce heat loss while reducing NO_x emission from the non-premixed combustion furnace.

KEYWORDS

NO_x, Wall Temperature, Oxidant structure, Combustion Regime, Non-premixed Combustion.

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1. Introduction

Despite extensive studies to address the challenges of global warming due to greenhouse gas emissions, the release of NO_x and CO pollutants, and the increase in efficiency, research on combustion systems to address these challenges continues [1]. The thermal conditions of the fuel, air, and furnace walls can greatly affect the performance of non-premixed combustion systems. Xu et al. [2] investigated the effect of wall temperature on flame stability and thermal performance of non-premixed combustion furnaces under different combustion regimes. The results show that lowering the wall temperature leads to higher ignition delay time (IDT) and heat loss from the furnace wall. Lower wall temperatures also lead to a transition from conventional combustion to a flameless regime in which NO_x is significantly reduced. Oxidant structure is another parameter that is of great importance on reducing the emission of pollutants and greenhouse gases. He et al. [3] studied the effect of oxidants O_2/N_2, O_2/CO_2 and O_2/H_2O on the formation of CO and its pathways. For O_2/CO_2 oxidant, the presence of CO_2 in the reactions leads to a higher contribution of $CO_2+H \rightleftharpoons CO+OH$ and $CH_2(S)+O_2 \rightleftharpoons CH_2O+CO$ at further emission of CO pollutant. In the present study, the emission of NO_x and the temperature distribution have been studied in the non-premixed combustion chamber.

2. Geometry and boundary conditions

The non-premixed combustion furnace of the University of Lisbon [13], in which fuel is injected into the furnace from cylinders with a diameter of 4 mm and air through a circular duct with an inner and outer diameters of 6 and 15 mm, has been selected for numerical simulation. The fuel is methane and preheated air is used as oxidant. The combustion chamber is a cylinder with diameter of 150 mm and length of 300 mm. Combustion products are exited from the furnace through a chimney with a diameter of 85 mm and a length of 150 mm. Details of dimensions and boundary conditions can be founded at Ref. [1].

3. Numerical conditions

OpenFOAM software has been used to perform numerical simulations. Modelling of turbulence, combustion and radiation heat transfer have been performed using standard k-ε, modified EDC, and DO models. In addition, chemical calculations were performed using a well-stirred-reactor by considering C1C3 chemical kinetics.

4. Result and Discussion

4.1. Validation of numerical models and solver

Fig. 1 shows the radial variations of temperature and dry volume fraction of oxygen at axial distances of 90 and 210 mm. Solvers and numerical modelling are in good agreement with experimental measurements. The average error of numerical solution is less than 5% for temperature and less than 6% for dry volume fraction of oxygen.

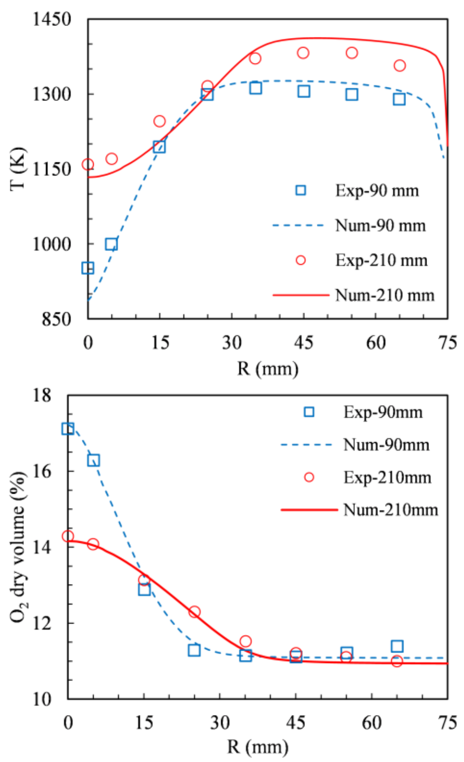

Figure 1. Comparison between radial variations of temperature and oxygen dry volume fraction with measurements at axial distances 90 and 210 mm

4.2. Effect of wall thermal conditions and oxidant structure on temperature

Fig. 2 shows the temperature contour under the use of different oxidant structures and thermal conditions of the furnace wall. By increasing the furnace wall temperature from 1200 K to the insulation wall, the heat loss is significantly reduced, which leads to an increase in the temperature of the gases in the non-premixed combustion furnace. On the other hand, the injection of carbon dioxide into the oxidant reduces the maximum combustion temperature and leads to the more uniform temperature distribution which is true in all thermal conditions. The main reason for decrease in the maximum temperature and the increase in uniformity of the temperature distribution is the difference between the physical and chemical properties of CO_2 and N_2.

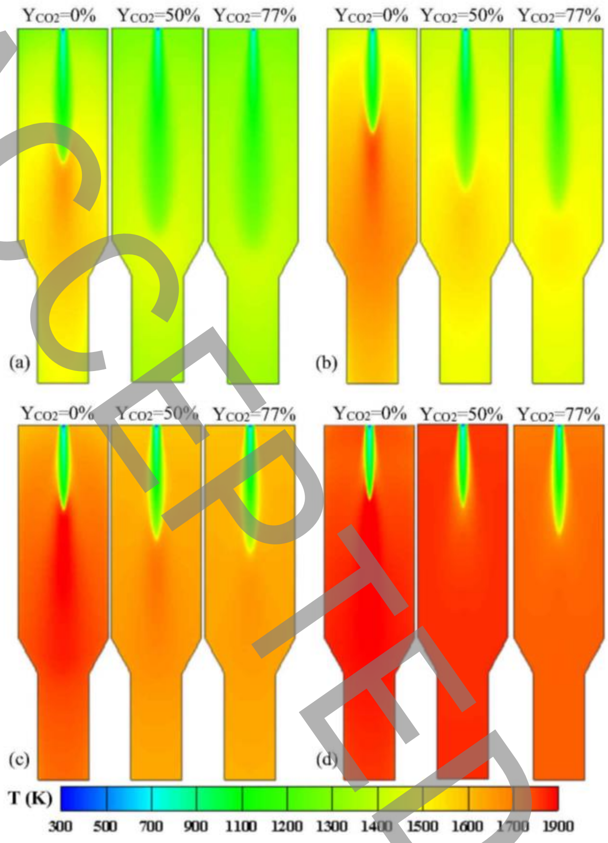

Figure 2. Temperature contours under different oxidant structure and wall thermal conditions

4.3. The effect of wall thermal conditions and oxidant structure on the NO_x emission

Increasing the wall temperature leads to a significant emission of NO_x pollutant. Changes in thermal conditions and, consequently, the reaction pathways is a major factor in the rise of NO_x emission. In all oxidant structures, NO_x emission increases significantly with the transition from flameless to high temperature combustion regime. According to the results, the use of low heat loss conditions is acceptable only under the flameless regime in terms of NO_x emission. Fig. 3 shows the sensitivity analysis of NO_x species with changes in wall thermal and oxidant structure (reactions are related to GRI3.0 mechanism). Increasing of CO_2 injection reduces the contribution of the thermal mechanism in the NO_x production. The main reason for the decrease in the maximum temperature of the combustion process is higher amounts injection of CO_2 in the oxidant. Higher heat capacity of CO_2 and the presence of CO_2 in endothermic reactions are two important factors in reducing the flame temperature.

5. Conclusions

In the present study, the effect wall thermal conditions and oxidant structure of non-premixed furnace on temperature distribution and NO_x emission has been studied. The results show that increasing the temperature of the furnace wall leads to an increase in the maximum temperature and a reduction in the IDT. Also, the main mechanism of NO_x emission under methane-air MILD regime is prompt while, the main mechanism of NO_x emission for oxygen-enriched and oxy-fuel combustion is N_2O-intermediate.

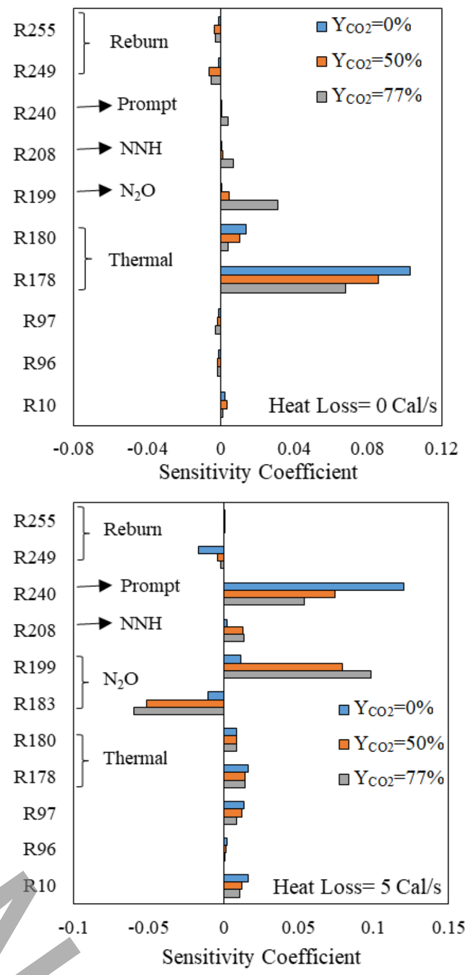

Figure 3. Sensitivity analyses of chemical reactions with heat loss values 0 and 5 cal/s under the different values of CO_2 injection in oxidant for NO_x emission

6. References

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