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CFD study on influence of fuel temperature on NOx emission in a HiTAC furnace ☆

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ABSTRACT

The influence of the fuel temperature on NOx formation was investigated numerically. For this purpose CFD modeling of NOx emission in an experimental furnace equipped with high temperature air combustion (HiTAC) system was studied. The comparison between the predicted results and measured values have shown good agreement, which implies that the adopted combustion and NOx formation models are suitable for predicting the characteristics of the flow, combustion, heat transfer, and NOx emissions in the HiTAC chamber. Moreover the predicted results show that increase of the fuel temperature results in a higher fluid velocity, better fuel jet mixing with the combustion air, smaller flame and lower NOx emission.

1. Introduction

In a world increasingly concerned with sustainability and the environment, energy efficiency improvements are indispensable. Improving energy efficiency is often the most cost-effective way to reduce pollution emissions in the industrial combustion systems. In this framework, high temperature air combustion (HiTAC) technology, developed by Tanaka and Hasegawa [1], can play a significant role in the mitigation of combustion-generated pollutants, whilst meeting thermal efficiency needs. The HiTAC technology, also called moderate and intense low oxygen dilution (MILD) combustion [2], or flameless oxidation (FLOX) [3]. HTAC processes try to control the pollutants formation, in particular NOx emissions, in combustion applications reducing the residence time of gases in high temperature regions of the burner, or avoiding high oxygen concentration in these regions. In the HiTAC technology, fuel is mixed with a highly diluted and heated air to create a distributed reaction zone with a reduced peak temperature. These flames have attractive features such as a uniform temperature field, yielding better product quality, higher radiation flux, and low emission of NOx.

The published experimental works on HiTAC flame properties come from studies focusing on small laboratory-scale furnaces featuring a single-gas-jet combustion in high temperature preheated and oxygen deficient air [4–7]. For example, the influence of fuel-jet dilution on combustion stability and flame structure was investigated by Prasad et al. [8]. The results obtained with low temperature air and coaxial fuel jets, which were highly diluted by nitrogen, showed increased flame liftoff distances.

Although the concept of HiTAC technology has been extensively studied, mathematical modeling of this regime has received little attention. The numerical modeling of the HiTAC technology and combustion process is a three-dimensional problem that involves turbulence, combustion, and radiation in addition to NOx modeling. Due to progress in computer hardware and software and the increase of the calculation speed, the computational fluid dynamics (CFD) modeling technique is a powerful and effective tool for understanding the complex hydrodynamics in many processes. The CFD models are founded on fundamental physical principles, and can thus predict fluid flow and heat transfer within the combustion chamber and under specific operational conditions. Moreover, submodels such as combustion, turbulence, and NOx formation can be employed for the modeling of combustion chambers [9–13]. The CFD modeling of NOx emission, HiTAC, and heat transfer in an industrial boiler was numerically studied by Khoshhal et al. [14]. The comparison between the measured values and the CFD predicted results showed good agreement, which implied that the adopted combustion and NOx formation models are suitable for correctly predicting characteristics of the HRSG boiler.

NOx formation during the combustion process is formed mainly by the oxidation of nitrogen in the combustion air (thermal NOx), by oxidation of nitrogen with the fuel (prompt NOx), and from molecular nitrogen (N_2) via N_2O (N_2O-intermediate mechanism). The research in the literature showed that NOx emission formed by a N_2O-intermediate mechanism is the main one during the HiTAC, and about 90% of the NOx formed in this condition is based on this mechanism [15,16].

NOx formation during the HiTAC conditions is very complicated, and is affected by physical and chemical phenomena such as flow, mean heat and mass transfers, mixing processes, and chemical reactions. Integrated information relating such complex phenomena to NOx formation are difficult to obtain experimentally. Therefore, it is necessary to conduct an advanced numerical study combined with experiments to obtain

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Nomenclature

E_a	Activation energy (cal/mol)
k	Turbulent kinetic energy (J/kg)
t	Time (s)
T	Temperature (K)

Greek symbols

ε	Turbulence dissipation (W/kg)
Φ	Equivalence ration

useful information on NOx formation. Mancini et al. [17] reported on the prediction of NOx emission from a large scale burner operated in flameless oxidation (MILD) mode. They compared the performance of three simple combustion models against experimental data. They reported reasonably good agreement with NOx emission and some discrepancy with the measured temperature distribution. They argued that some flow instabilities have contributed to deficiency in flow field prediction and, consequently, discrepancy in temperature.

Fuel preheated is very important for the maintaining of combustion stability when using low and medium caloric fuels. In addition, in a furnace, the vicinity of the fuel nozzle is always surrounded by hot flue gas and heated by radiation. Since the nozzle is not cooled, the fuel temperature is elevated. Temperature of the fuel jet, as high as 500 °C, was measured in the experimental single flame furnace [18]. Therefore, it is important to understand the influences of fuel temperature on NOx emission, special in the field of the industrial application.

In this study the combustion of methane fuel jet in a cross-flow stream of preheated and diluted air has been investigated. This paper is a continuation of the previous work [19], where a modified N_2O-intermediate NOx model was used to predict the NOx formation in an experimental furnace equipped with HiTAC system. The main aim of this work is to investigate the influence of fuel temperature on NOx emission using CFD modeling. Moreover, in the present study the flame stability limits of a methane fuel jet has also been studied experimentally.

2. Experimental setup

The experimental setup consists of an electric furnace and a combustion chamber, as shown in Fig. 1. This setup is made from fireplace bricks and completely insulated with two layers of insulation bricks. The rate of heat transfer from the inside to the outside of the apparatus was negligible, therefore an adiabatic system has been assumed. The electric furnace has height, depth and width of 0.42, 0.25, and 0.25 m, respectively. A 10 kW electric heater constructed from Kanthal wire is used as a hot gas generator to make high temperature air. It is a 0.35 m long cylindrical heater with a diameter of 0.15 m. The temperature of the preheated and diluted air was measured with an S-type (up to 1600 °C) thermocouple placed at the center of flow passage between the hot gas generator and the combustion chamber.

The combustion chamber is mounted on the exit side of the hot gas generator. The chamber has a height of 0.23 m, a depth of 0.16 m, and a width of 0.16 m. The fuel was injected into the combustion chamber by means of a stainless steel nozzle with an internal diameter of 1 mm. The fuel nozzle is placed cross-flow, with respect to high temperature-diluted combustion air. Methane was injected as fuel through this nozzle. A VARIOPLUS MRU portable gas analyzer with nominal range of 0–5000 ppm with accuracy of ±20 ppm for NO and 0–21% with accuracy of ±0.2% for O_2 was used to measure global emission levels.

In order to prepare high temperature diluted combustion air, the inlet air was mixed with nitrogen. Oxygen mole fraction in the air was varied from 21% (normal air) to 2%. The temperature mixture, after passing through the hot gas generator, reached almost 1100 °C. The main operating conditions used in the experimental work are summarized as follows.

- Preheated air flow rate: $1.63 \times 10^{-3}\,m^3/s$
- Preheated air temperature: 28, 300, 500, 900, 1100 °C

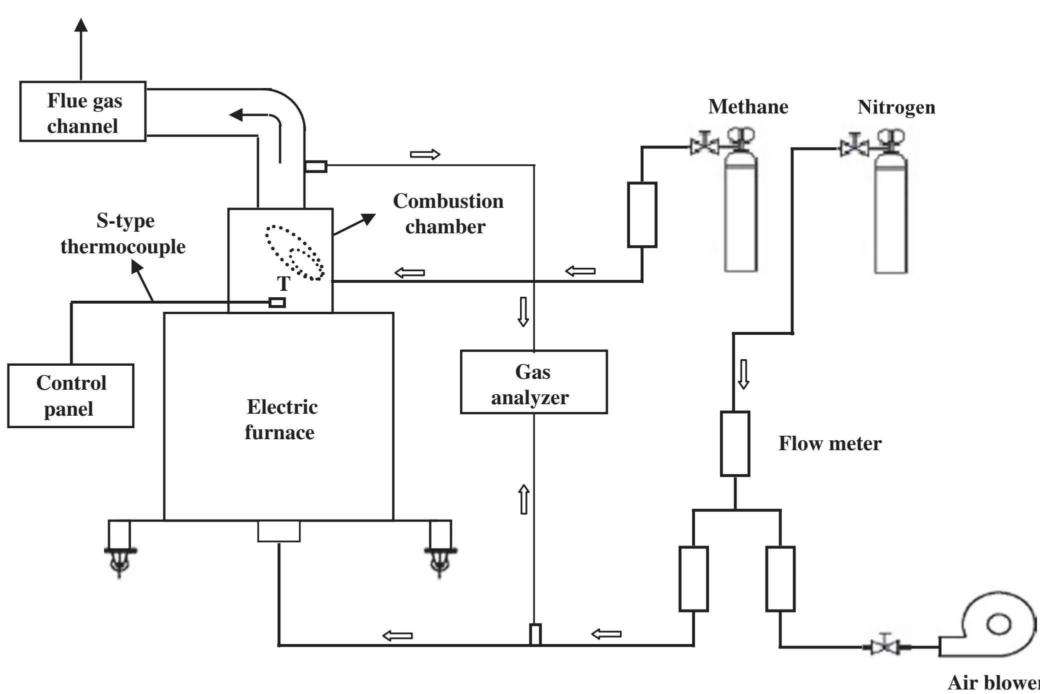

Fig. 1. A schematic view from the experimental apparatus.