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Experimental and numerical study of MILD combustion in a lab-scale furnace

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Abstract

Mild combustion in a lab-scale furnace has been experimentally and numerically studied. The furnace was operated with Dutch natural gas (DNG) at 10 kW and at an equivalence ratio of 0.8. OH* chemiluminescence images were taken to characterize the reaction zone. The chemiluminescence intensity is relatively low compared to conventional flames and relatively uniformly distributed in the reaction zone due to the dilution effects of recirculated burnt gases. Visible flames were not observed. To characterize the dilution effects of burnt gases on reactions, flamelets generated with diluted fuel and diluted air, instead of flamelets based on pure fuel and air, were applied in an extended Flamelet Generated Manifold (FGM) approach. Burnt gases at stoichiometric mixture fraction rather than those at global equivalence ratio were considered as diluent, which is more appropriate for furnaces operating at lean condition. The numerical simulations were performed using the open source CFD package -- OpenFOAM.

Keywords: MILD; flameless; turbulent combustion; furnace; NOx; OpenFOAM

1. Introduction

Recycling the waste heat of flue gas is a way to improve the thermal efficiency of combustion systems, but unfortunately, it leads to higher temperature which has an adverse effect on nitrogen oxides (NOx) formation.

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Maintaining low reaction temperature is an effective way to reduce NO_x formation. Moderate or Intense Low-oxygen Dilution (MILD) combustion, also named flameless combustion or high-temperature air combustion (HiTAC), works on the principle of diluting reactants with recirculated combustion products slowing down the reactions. Reaction intensity is low and heat release is distributed over a large space which results in reduced peak flame temperature and less NO_x formation.

MILD combustion can occur when fresh air (and/or fuel) streams are sufficiently diluted by entrained combustion products before reactions take place, as shown in the regime diagram proposed in ref.[1]. MILD combustion has recently been experimentally studied on laboratory-scale setups because of scientific challenges, environmental concerns and its potential industrial applications. Three levels of experimental setup are used to study MILD combustion. Those are jet-in-hot-coflow burners[2,3], lab-scale furnaces[4-7] and semi-industrial furnaces[8,9]. Compared to the jet-in-hot-coflow burner, in a lab-scale furnace the internal recirculation patterns are represented more faithfully but the configuration is still simple enough to make detailed laser diagnostic measurements, in contrast with the more complex (semi-)industrial furnaces. Here we report on first results in a new lab-scale furnace. To obtain detailed measurements to reveal the nature of the combustion process, the lab-scale furnace presented in this study is designed to provide full optical access to perform OH* chemiluminescence, Laser Doppler Anemometry (LDA), Particle Velocity Velocimetry (PIV), Planar Laser-Induced Fluorescence (PLIF) and Coherent Anti-Stokes Raman Spectroscopy (CARS) measurements.

MILD regime is often claimed to occur at Damköhler number (Da) of an order of unity where flamelet concept is not valid and the Eddy Dissipation Concept (EDC) model is often applied to MILD combustion modeling in furnaces[10,11]. Nevertheless, experimental results especially PLIF images[4,12,13] have shown the presence of thin reaction zones or flamelets in MILD combustion. Recent DNS (Direct Numerical Simulation) results also have shown that typical flamelet-like thin reaction zones do exist in MILD combustion[14,15]. Flamelet based models such as Flamelet Generated Manifolds (FGM) approach therefore could still be attractive for MILD combustion also because these are requiring less computational resources while incorporating detailed chemistry[16,17]. The challenge of modelling MILD combustion in furnaces with the FGM approach is to include in a proper way the dilution effects by recirculated burnt gases. Dilution effects were taken into account by using diluted flamelets [18-20], but differently from those works here the diluent is not considered as the burnt gases at global equivalence ratio but as the burnt gases at stoichiometric conditions, which is more appropriate in the tabulation of possible states in the furnace.

The aim of this work is to obtain more insights on MILD combustion and extend the range of operational conditions in MILD regime based on experiments and numerical modeling. This paper reports reaction characteristics in the current furnace indicated by the OH* chemiluminescence images. In numerical modeling, an extended FGM approach including dilution effects of burnt gases was implemented in the open source CFD package OpenFOAM. In order to tabulate more possible states in furnace, dilution effects were taken into account by burnt gases at stoichiometric mixture fraction. Radiation model was also implemented with the extended FGM approach.

2. Experimental setup

The lab-scale furnace built in Delft University of Technology has a 320 mm × 320 mm square cross section and a height of 630 mm, as shown in Fig. 1. The combustion chamber is made of ceramically bonded vermiculite plates, which are 50 mm thick for the sides and bottom, 25 mm for the top. A commercial REKUMAT 150 recuperative Flame-FLOX burner is placed at the bottom of the combustion chamber. The burner nozzles are protruding 30 mm into the chamber, and the distance from nozzle tip to furnace top is 600 mm. The injectors consist of one central fuel nozzle with a diameter of 4.5 mm and 4 air nozzles with a diameter of 8.6 mm symmetrically located around the fuel nozzle. Dutch natural gas (DNG, typical composition in volume fraction being 0.813 CH_4, 0.037 C_2H_6, 0.144 N_2, 0.006 rest) is used as fuel. Flow rates are controlled by mass flow controllers. The heat extraction can be controlled by blowing cooling air on the top plate. This cooling method is chosen because it causes less flow complexity than internal cooling tubes. The furnace is designed to work in both premixed flame mode and MILD mode. Flame mode is used to heat up the furnace to 1123 K. In flame mode, fuel and air are premixed and injected into the furnace through the four air nozzles. Premixed flames stabilize on the four air nozzles. Once the temperature inside the furnace is above 1123 K, the furnace switches to MILD mode where the fuel is injected through the central fuel