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Flameless combustion in a lab-scale furnace.
Laserdiagnostic measurements and statistical modeling.

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We present a study of flameless combustion in a lab-scale furnace combining detailed measurements and modelling. The goal of the experiments is to observe the flame behaviour and obtain velocity and temperature data using high speed imaging and laser diagnostic techniques. The goal of the modelling is to extend the Flamelet Generated Manifolds (FGM) method to take into account the effects of dilution by recirculated burnt gases. One of the cases of the Delft jet-in-hot-coflow (DJHC) burner [1,2] and the new database for the new lab-scale furnace are used for validation of the model.

This furnace consists of a WS REKUMAT 150 recuperative Flame-FLOX burner and a thermally insulated but optically accessible combustion chamber (32x32x63 cm^3). Experiments were done using Dutch natural gas as fuel and at thermal input 9 kW (fuel mass flow rate based) at three values of equivalence ratio, namely 0.7, 0.8, 0.9. The ignition and flame structure in the flameless regime have been studied by the mean and time resolved OH* chemiluminescence images. Detailed measurements of velocity have been performed with forward scatter Laser Doppler Anemometry (LDA). The forward scatter configuration significantly increases the signal strength and the effects of seeding particles depositing on the optical window become tolerable. Gas temperatures were measured using Coherent anti-Stokes Raman Spectroscopy (CARS) and wall temperatures using thermocouples.

The chemiluminescence measurements show three types of ignition behaviour, namely individual autoignition kernel, multiple autoignition kernels and ignition kernel cluster. The reaction zone (the zone with significant chemiluminescence), is a collection of these three autoignition structures which together are keeping the conversion in the furnace going. We call this situation presence of "sustained combustion". It is different from situations having flame stabilization via explicit mechanisms such as a pilot flame, a bluff body or swirl. The autoignition is depending on local conditions, namely the flow, the mixture composition and the temperature. The latter two are determined by the air dilution level and by the enthalpy deficit of the diluent. This is supported by a numerical study of counterflow flames showing that there exists a dilution range where autoignition can be achieved in a wide range of flow conditions (strain rate). This range provides the best condition to sustain a stable flameless combustion.

The burner nozzle configuration (central fuel jet surrounded by four air jets) is important to establish flameless combustion because together with the confinement it determines the way in which reactant jets are diluted by recirculated flue gas. The main reaction zone occurs in the upper half of the furnace. CARS temperature histograms show a high temperature tail, but in the chemiluminescence images stable flame front like structures are absent. The maximal mean temperature rise in the furnace relative to the reactants is less than 600 K. The instantaneous peak temperatures are lower than 1800 K, the mean of the highest 5% of the samples lower than 1700 K. NOx emissions in the exhaust gas are below 1 ppmv in all cases.

An extended FGM model called diluted air FGM (DAFGM) has been developed for describing flameless combustion in furnaces. It includes the effects of dilution on local conditions using a transport equation for a dilution variable. The reaction zones are represented by conditions retrieved from counterflow flames of undiluted fuel and diluted air including heat loss of the diluted air, computed using Chem1D. The control parameters of the FGM for the laminar case are mixture fraction, progress variable, dilution parameter and enthalpy loss (4D table) and for the turbulent case concern the mean values of these variables and the variance of mixture fraction and progress variable (6D table). Local mean radiative source terms are also stored in the table. Radiation is solved using the DOM. The radiative properties of gases are modelled with a weighted-sum-of-grey-gas (WSGG) model accounting for the local mole ratio between CO_2 and H_2O. The models have been implemented in OpenFOAM-2.3.1.

The DAFGM model first is applied to the case ‘DJHC-I Re=4100’ of the DJHC burner database using both RANS and LES approaches [1,2]. It is found that the predictions for this flame are not sensitive to the progress variable fluctuations, but that the surrounding air inlet velocity has effects on the predicted temperature profile at high axial locations. The turbulent flow field statistics and temperature predictions are in overall good agreement with experimental data, with LES performing somewhat better. Next the model is applied to the simulation of the new furnace, operated at equivalence ratio equal 0.8. It is found that in this case the RANS model predictions are very sensitive to fluctuations in progress variable (Figure 1,left, b-c). The final mean temperature rise in the reaction zone is close to the measured mean temperature rise (Figure 2, right). The DAFGM model is found to very well describe the conditions in flameless combustion both in the JHC flame and in the furnace [3].

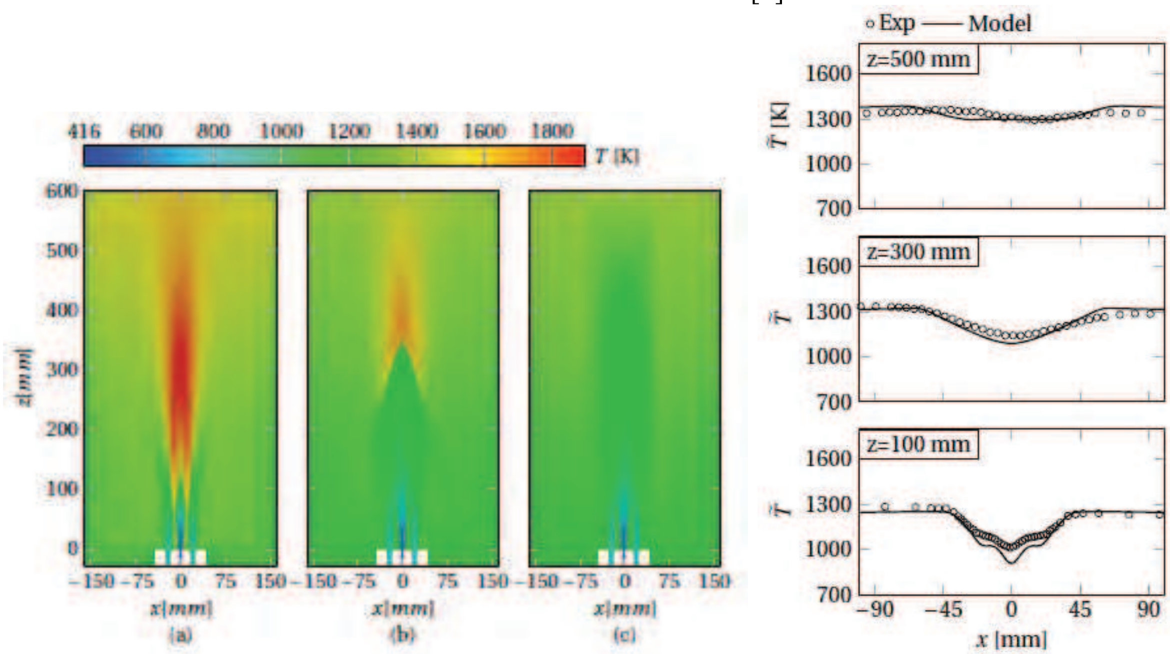

Figure 1: Left: Predicted temperature fields on the vertical mid-plane through two air nozzles: (a) excluding radiation and progress variable variance, (b) including radiation and excluding progress variable variance (c) including radiation and progress variable variance.
Right: Comparison of mean temperature predictions including radiation and progress variable variance with mean temperature from CARS measurements.

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References
[1] E. Oldenhof et al., Combustion and Flame, 2010, 157 (6), 1167 -1178.
[2] E. Oldenhof et al., Combustion and Flame, 2011, 158 (8), 1553-1563
[3] X. Huang, Measurements and model development for flameless combustion in a lab-scale furnace, PhD Thesis, Delft University of Technology, October 2018