Simulation of a MILD Combustion Burner using ILDM Chemistry

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ABSTRACT

A numerical study is performed to accommodate turbulence/chemistry interaction, mathematical simplification of kinetics and non-premixed reactants in three-dimensional computations. Specifically, presumed probability density function approach is combined with the ILDM technique to simulate turbulent combustion in a burner operating at MILD combustion, which is characterized by relatively uniform temperatures with no visible flame and sound. An Eulerian solution strategy is implemented in a CFD code on a structured mesh. Modeling issues are discussed in the context of turbulence/chemistry reciprocity problem. Predictions of the mean flow field, turbulence kinetic energy, mixture fraction and its variance, temperature, and mass fraction of CO_2 and H_2O are presented.

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INTRODUCTION

The reduction of pollutant emissions and improvement of energy efficiency of practical burners are the key issues in combustion research. A better efficiency is often achieved by air preheating where energy from the exhaust gases is transferred to the combustion air [1]. Air preheating however increases peak flame temperatures and promotes thermal NO formation. The methods to reduce NO emission are based on schemes to reduce either peak flame temperature or the residence time and oxygen concentration in zones with high temperature [2,3]. It has been known for quite some time [4] that moderate or intense low oxygen dilution (MILD) combustion mode is indeed the most successful scheme to reduce peak flame temperature and NO emission. Analyses of NO_x reduction technologies for a gas turbine power station [5] showed that the use of MILD combustion burners could be much cheaper than other conventional methods like selective catalytic reduction (SCR). However, implementation of the MILD combustion technology has been precluded by the lack of understanding of its operational conditions. The purpose of the present work is to present a numerical simulation of a MILD burner based on the chemistry described by the ILDM technique.

ILDM CHEMISTRY

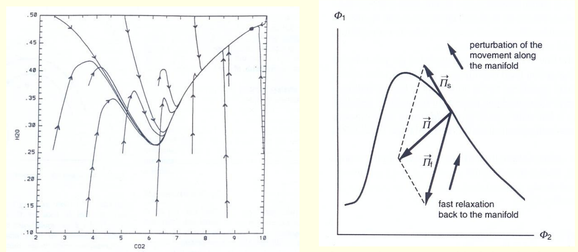

Figure 1. Fast reactions are relaxed to manifold of slow reactions [6].

From the system dynamics perspective, a chemical process with n_s species will be governed by n_s different time scales. ILDM, in principle, tries to find out the directions in which the chemical source term vector will rapidly reach a steady-state [6]. If n_f fast processes are assumed in dynamic equilibrium, the system can be described by $n_r = n_s - n_f$ degrees of freedom by mixture fraction, pressure, enthalpy and n_r progress variables which parameterize the slow movement on the manifold. This reduces the chemical system in the composition space and the number of transport equations that need to be solved and, also, reduces the dimension of the probability density function that the reaction rate needs to be integrated over in turbulent flows.

CFD IMPLEMENTATION

For steady flow, main Eulerian equations expressing conservation of mixture mass, momentum, enthalpy have the form,

$$\frac{\partial \bar{\rho}\tilde{u}_j}{\partial x_j} = 0$$

$$\frac{\partial \bar{\rho}\tilde{u}_i\tilde{u}_j}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial\left(\bar{\tau}_{ji} + \tau_{T,\,ji}\right)}{\partial x_j} + \bar{\rho} g_i$$

$$\frac{\partial \bar{\rho}\tilde{u}_j\tilde{h}}{\partial x_j} = \tilde{u}_j\frac{\partial \bar{p}}{\partial x_j} + \mu\left(\frac{\partial \tilde{u}_i}{\partial x_j} + \frac{\partial \tilde{u}_j}{\partial x_i}\right)\frac{\partial \tilde{u}_i}{\partial x_j} + \overline{\rho\varepsilon} - \frac{2}{3}\mu\frac{\partial \tilde{u}_i}{\partial x_i}\frac{\partial \tilde{u}_j}{\partial x_j} + \frac{\partial}{\partial x_j}\left[\left(\frac{\lambda}{C_p} + \frac{\mu_T}{Pr_{T,h}}\right)\right]\frac{\partial \tilde{h}}{\partial x_j} + \Sigma_{\alpha=1}^{n_s}\overline{\rho h_\alpha \dot{Y}_\alpha}$$

The equation for the mean mixture fraction,

$$\frac{\partial \bar{\rho}\tilde{u}_j\tilde{\xi}}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_T}{Sc_{T,\xi}}\frac{\partial \tilde{\xi}}{\partial x_j}\right)$$

is solved together with the equation for its variance, $\tilde{\xi}_V = \widetilde{\xi''^2}$

$$\frac{\partial \bar{\rho}\tilde{u}_j\tilde{\xi}_V}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\frac{\mu_T}{Sc_{T,\tilde{\xi}_V}}\frac{\partial \tilde{\xi}_V}{\partial x_j}\right) + \frac{2\mu_T}{S_{T,\tilde{\xi}_V}}\left(\frac{\partial \tilde{\xi}}{\partial x_j}\right)^2 - 2\bar{\rho}\frac{\tilde{\varepsilon}}{\tilde{k}}\tilde{\xi}_V.$$

For reaction progress variables, α (for the present case CO_2 and H_2O), the transport is given as,

$$\frac{\partial \bar{\rho}\tilde{u}_j\tilde{Y}_\alpha}{\partial x_j} = \frac{\partial}{\partial x_j}\left(\bar{\rho}D_T\frac{\partial \tilde{Y}_\alpha}{\partial x_j}\right) + \bar{\rho}\dot{\bar{Y}}_\alpha$$

where averaged quantities are defined using four one-dimensional presumed PDFs.

The computational setup is designed to match the experiment by Özdemir and Peters [7], where the burner has 0.25×0.25 m^2 cross-section and 0.485 m height. It consists of a central fuel nozzle of 4.7 mm diameter surrounded by six peripheral air nozzles of 5 mm diameter located 40 mm away from the centerline. Inlets and a 15.5 mm wide annular exit (of 93 mm diameter) are located at the bottom of the burner. Computations were made for a non-premixed combustion with 0.38 kg/h and 6.5 kg/h fuel (methane) and air mass flow rates, respectively.

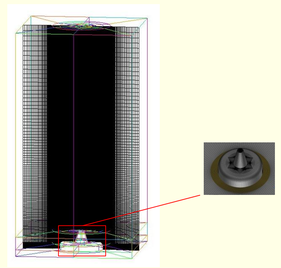

Figure 2. Computational domain.

RESULTS

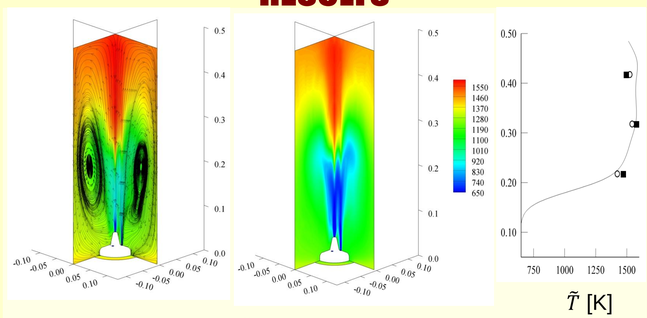

Figure 3. Streamlines, contours of temperature and temperature variation along the centerline (symbols are from [7]).

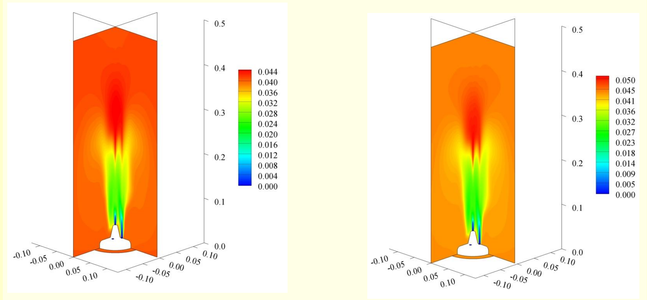

Figure 4. Contours of CO_2 and H_2O mass fractions.

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