Simulation of Turbulent Combustion in a Domestic Cooker Burner using ILDM Chemistry

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ABSTRACT

A numerical study was performed to accommodate turbulence/chemistry interaction, mathematical simplification of kinetics and non-premixed reactants in three-dimensional computations. Specifically, presumed probability density function approach was combined with the ILDM technique to simulate turbulent combustion in a domestic burner. An Eulerian solution strategy was implemented in a CFD code on a structured mesh. The objective was to understand the generation and depletion of the pollutants, CO, NO$_x$ and particulate matter emission from domestic cookers.

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INTRODUCTION

Stringent legislations of EN30-1-1 and EN30-2-1 standards on emissions and efficiency of domestic cookers present a strong challenge to the burner designers who are forced to produce first prototypes with a design closer to that of the final product.

In the present project, a numerical study was performed to accommodate a reaction mechanism of 43 species and 393 reactions, which was then reduced with Homogeneous Reaction Approach (HRA) at low temperature ranges and with Intrinsic Low Dimensional Manifolds (ILDM) technique to proceed the combustion at higher temperatures. The data base formed by the chemical kinetics was used together with a turbulence-chemistry reciprocity model in a 3D flow simulation of a real cooker geometry. The Computational Fluid Dynamics – CFD – algorithm was able to calculate balance equations on a mesh with sufficient resolution. The turbulence-chemistry reciprocity will be based on the concept of the "time-layered ILDM". This model requires a time scale from a 3-D turbulent reacting flow, and is able to retrieve the corresponding local mean source values from a pre-processed data base. The main advantage of this method is to take into account non-equilibrium states of the combustion thermo-chemistry.
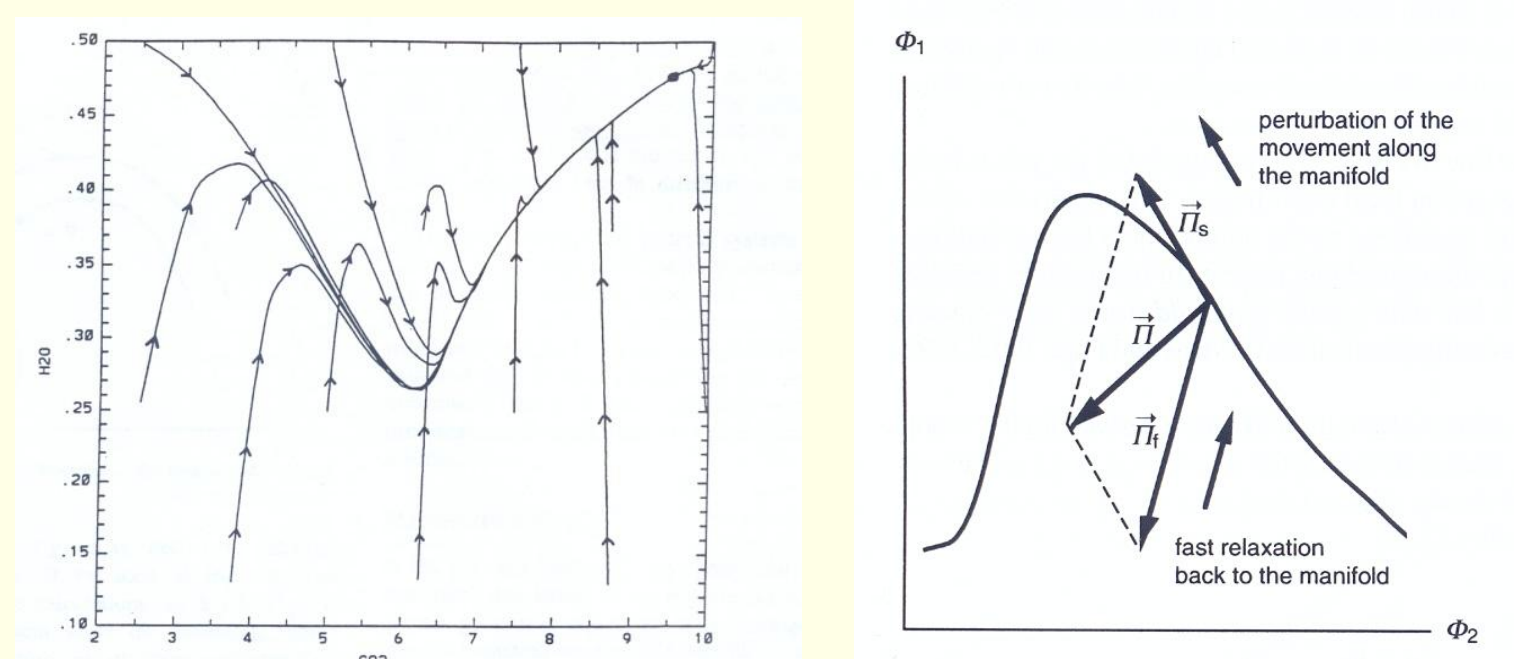
ILDM CHEMISTRY

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

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 [1]. 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,

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

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

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

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, $\tilde{\xi}_v = \widetilde{\xi'^2}$

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

For reaction progress variables, α (for the present case CO$_2$ and H$_2$O), the transport is given as,

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

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

The computational setup was designed to match the standart rig for efficiency tests of domestic burners, where an Arçelik burner was used (Figure 2).
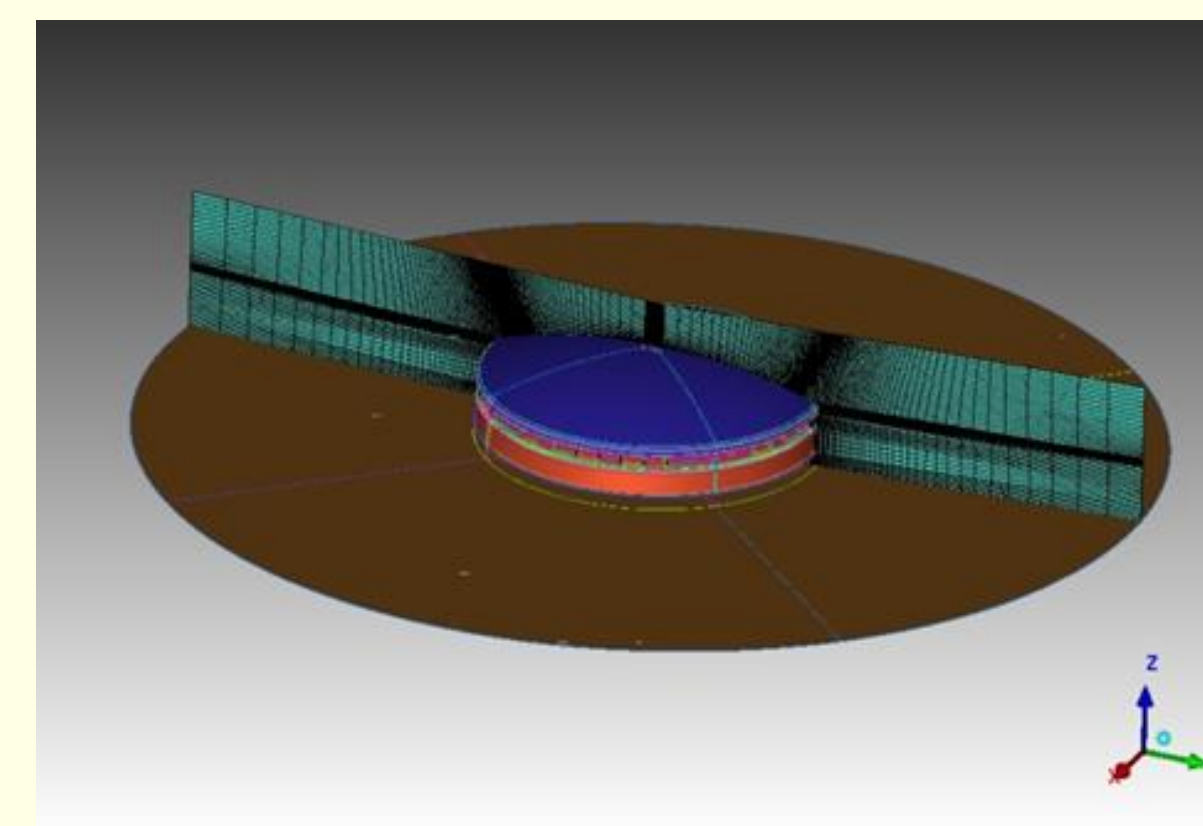

Figure 2. Arçelik burner.

The 3D computational domain (Figure 3) was extended radially 2 diameters from the outskirts of the burner and the calculations were made with 290 lt/h fuel (methane) mass flow rate.
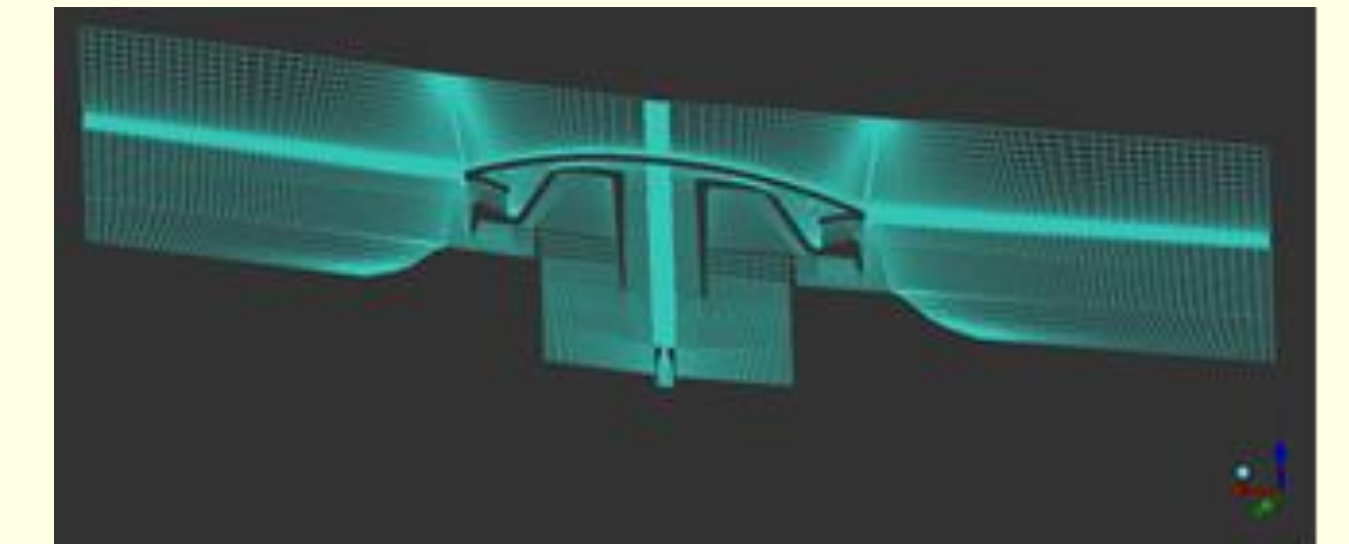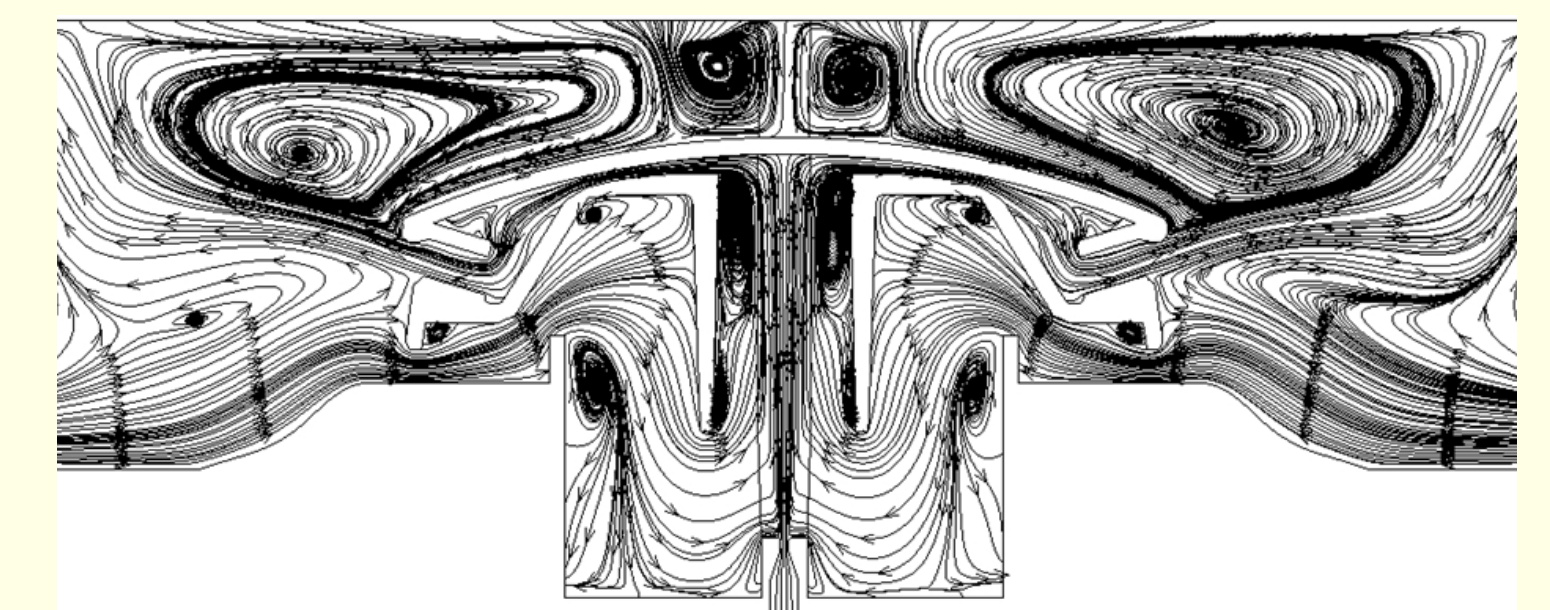

Figure 3. Computational domain.

RESULTS

Figure 4. Streamlines in and around the burner.

Temperature
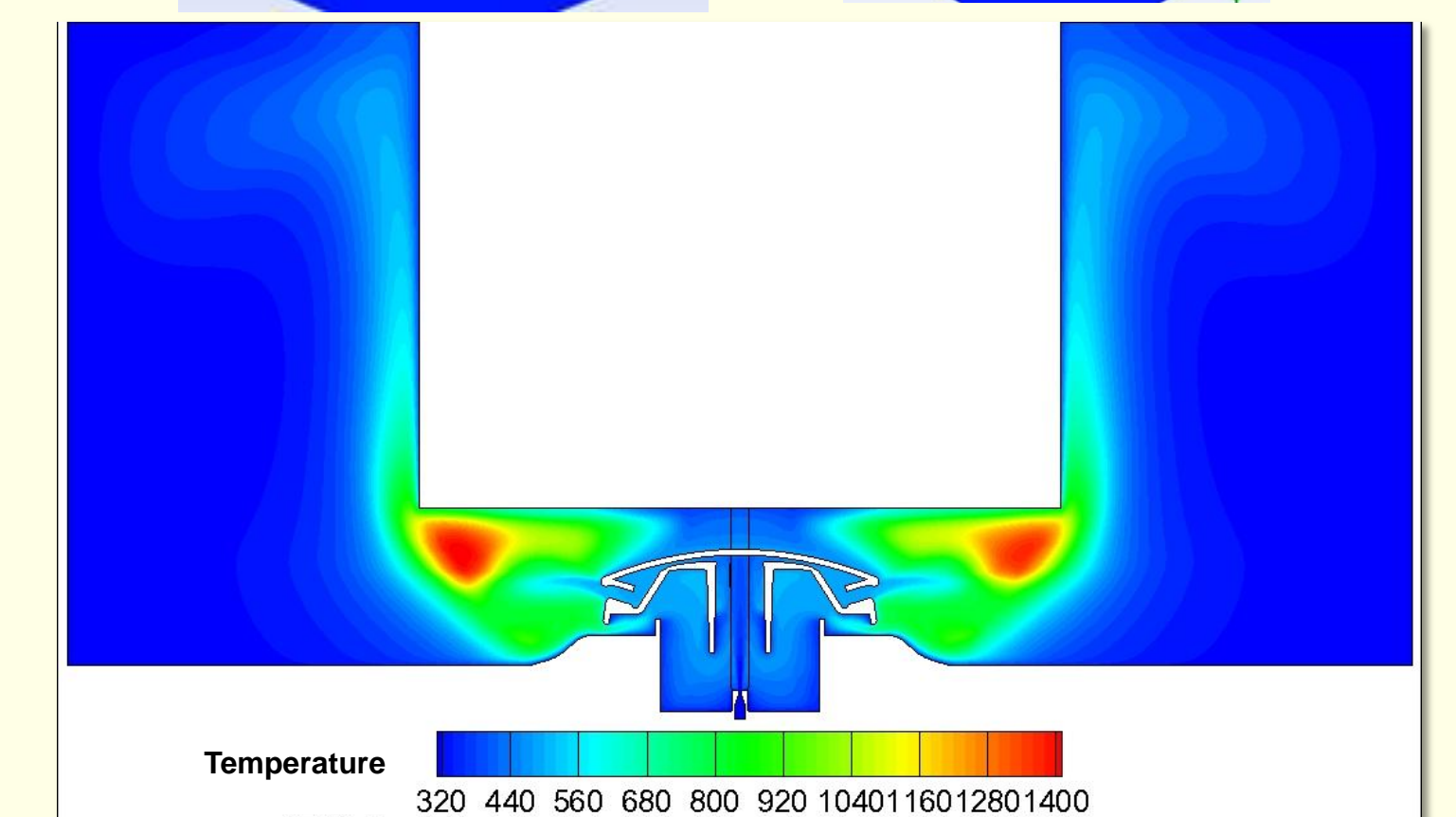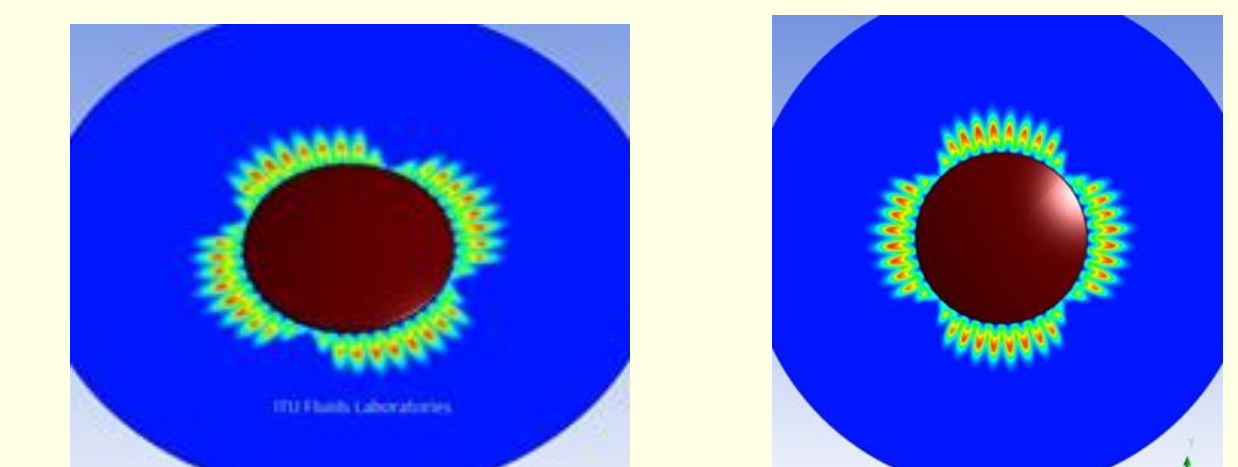320 440 560 680 800 920 1040 1160 1280 1400

Figure 5. Contours of temperature [K].

REFERENCES

[1] U. Maas, S.B. Pope, Simplifying chemical kinetics: Intrinsic low-dimensional manifolds in composition space, Comb. Flame 88 (1992) 239-264.