Quenching of Rotating Flames in Closed Vessel

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1 Introduction

Vorticity in reacting flows can have both beneficial as well as detrimental effects. Beneficial effects can arise from the enhanced residence time in the combustion region, or from the enhanced mixing rate induced by vortex stretching. Detrimental effects can arise if the level of flame stretch attained in consequence of the promoted vorticity becomes so large to lead to quenching. Very often vorticity in practical combustors is promoted by devices able to swirl the flow. In this situation is not vorticity to be directly realized but rigid body rotation first. The evolution of the rotating flow in the combustion chamber determines the actual level of vorticity introduced.

Apart from the need of a fine control on the mechanisms leading to the evolution of rotating flows into vortex flows, also the need of a complete understanding of mechanism of flame evolution in rotating flows arises. Previous studies have highlighted several features of flames propagating in rotating flows, like a very fast flame propagation along the axis of rotation [1], enlarged flammability limits [2], but also a strong quenching effect under the action of centrifugal forces [2]. This paper focus on this last issue by investigating the dynamics of flame propagation in a rotating cylindrical vessel (diameter 90 mm and high 20 mm) after the ignition of a flammable methane-air mixture in the center. The quenching of the flame has been studied with help of computational fluid dynamics to allows the full visualization of the flow configuration.

2 Numerical simulation results and discussion

To provide a detailed picture of the flow and thermal fields during flame propagation, numerical simulations were performed using the commercial CFD software CFD-ACE+ [3]. The governing equations are the unsteady Navier-Stokes including the balance equations for mass, momentum, enthalpy, and species in the Eulerian Control Volume formulation.

A profitable choice of the computational domain and system of reference to reduce the computational effort required was performed by exploiting the cylindrical symmetry of the experimental configuration. A full 3D vector field is computed over a 2D domain that include a 1/4 of the diameter plane. A very fine and uniform grid with a step size of 0.01 mm, to ensure an adequate resolution of the flame, is used. Perfect gas behavior and full multi-component formulations for the transport coefficients have been adopted. The reduced 3 step mechanism proposed in [4] has been adopted as chemical model.

All terms have been discretised with second order schemes. Coupling of all equations at each time step is obtained with the SIMPLEC approach [5]. Symmetry conditions are assigned on the boundaries that represents cuts of the domain on the symmetry plane. The remaining boundaries represent rigid walls

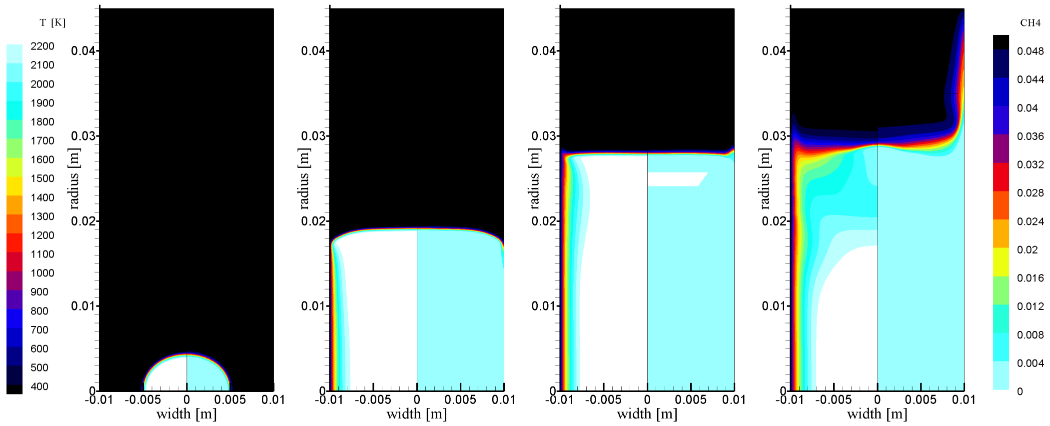

Figure 1: Temperature (left) and CH4 mass fractions (right) at time 0.51E-02, 1.50E-02, 2.48E-02, 4.96E-02; $\omega = 314$ rad/s, $\phi = 0.879$.

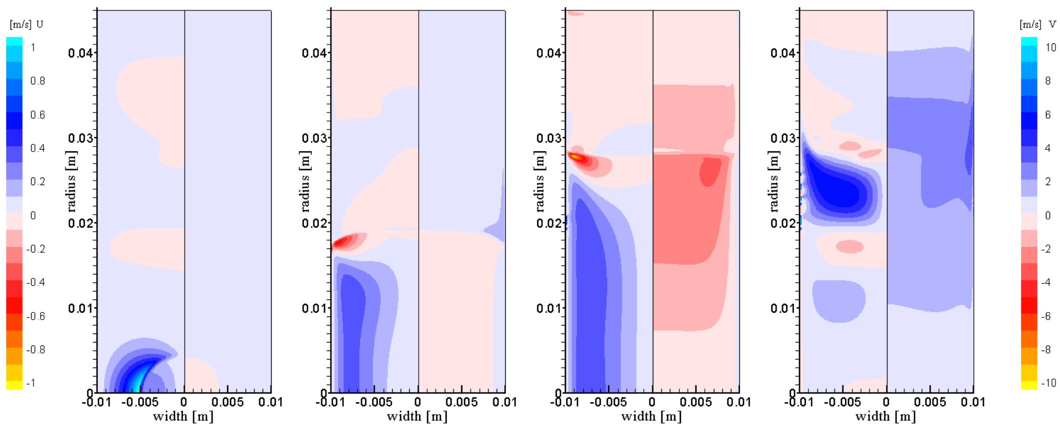

Figure 2: Axial velocity component U (left) and radial velocity component V (right) at time 0.51E-02, 1.50E-02, 2.48E-02, 4.96E-02; $\omega = 314$ rad/s, $\phi = 0.879$.

where no-slip conditions have been ensured together with isothermal conditions to ambient temperature. A preliminary computation to numerically converged rigid-body rotation of the cold flow is performed to assign initial conditions before ignition in order to ensure the absence of spurious numerical components of the centrifugal pressure field.

The numerical simulations, conducted for two mixture compositions (equivalence ratio $\phi = 0.640$ and $\phi = 0.879$) and two vessel rotation rates ($\omega = 314$ rad/s and $\omega = 628$ rad/s), have been able to capture, at least qualitatively, the whole flame propagation after ignition: from the initial fast flame propagation along the axis of rotation, to the subsequent propagation of the cylindrical flame up to the quenching well before the external cylindrical wall. Also the trends with the fuel composition and the rotation rate are in agreement with the experimental findings.

Simulation results are here presented for the case of a methane-air mixture with equivalence ratio $\phi = 0.879$ in a vessel rotating at $\omega = 314$ rad/s. This is the condition of weakest effect of vessel rotation on the flame among those simulated.

Figure 1 shows the temperature field and the CH_4 mass fraction field for subsequent time steps along the flame propagation. The flame history development is clearly recognizable: after a rapid flame propagation along the axis just after flame ignition (vortex bursting), the flame starts to develop

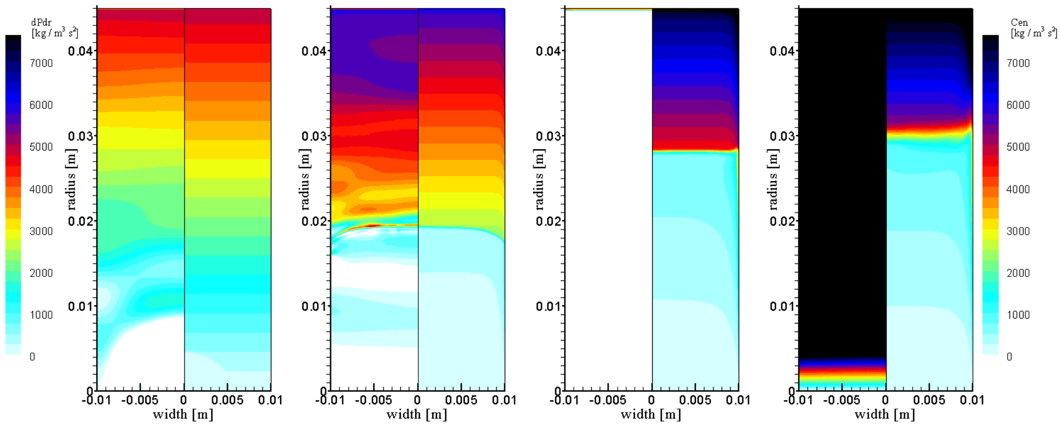

Figure 3: Radial pressure gradient (left) and centrifugal force (right) at time 0.51E-02, 1.50E-02, 2.48E-02, 3.64E-02; $\omega = 314$ rad/s, $\phi = 0.879$.

cylindrically and becomes very flat up to time $t = 0.02$s. After this time a new configuration of the flame shape develops, in which contour profiles of temperature and mass fraction at the edge of the flame near the wall separate each other: iso-contour of mass fraction are directed toward the fresh, unburnt mixture, while temperature iso-contour directed in the opposite direction.

This effect can be explained by looking at the field plots of the radial pressure gradient, $\partial P/\partial r$ and centrifugal forces, $\rho\omega^2 r$ reported in Fig. 3 with the same scale for both terms, to help comparison even if pressure gradient shows, at several moments, values well outside this range.

The penetration of the pocket of burnt gases into the fresh gases is due to the impingement of the gas layer near the wall that are being cooled and dragged by the rigid rotating wall. This layer is therefore pushed by centrifugal forces more than the flow in the bulk region. As a consequence a slip flow arises on the side wall as shown in Fig. 2 where the fields of velocity components in the symmetry plane are shown. The penetration of the pocket of burnt gases into the fresh mixture is limited in the outer zone because they are surrounded by cooler fresh gases that are therefore subject to a stronger centrifugal force. This effect is stronger in the inner, burned gas zone, and is sustained by the counteracting effect of wall boundary conditions on mass and energy: heat is continuously loss at the wall while mass and mass fractions are conserved. Furthermore, the dragging exerted by the wall sustains the angular momentum near the wall.

By comparison of Fig. 3 with Fig. 4, where the azimuthal velocity field and reaction rate contour profiles are shown, it is observed that total quenching of the flame occurs in coincidence with the beginning of separation between the temperature profile and mass fraction profile as well as with the maximum values of the velocity components that are realized near the flame. During the phase of flame quenching the whole flow field is not anymore governed by the balance between the Centrifugal force and the pressure gradient, becoming the former much higher than the latter. This corresponds to a change in the structure of the entire flow field. This is more clearly illustrated in Fig. 5 where the profiles of the radial component of the pressure gradient along the midplane of the vessel are plotted. The flame front experience a high pressure gradient during the quenching phase.

3 Conclusions

Two main features have been detected and they are illustrated in the following. The first is the flow and flame structure that develops near the front and rear walls of the cylindrical vessel. The second is the flame structure that develop along the mid-plane of the cylindrical vessel. The results seems to indicate

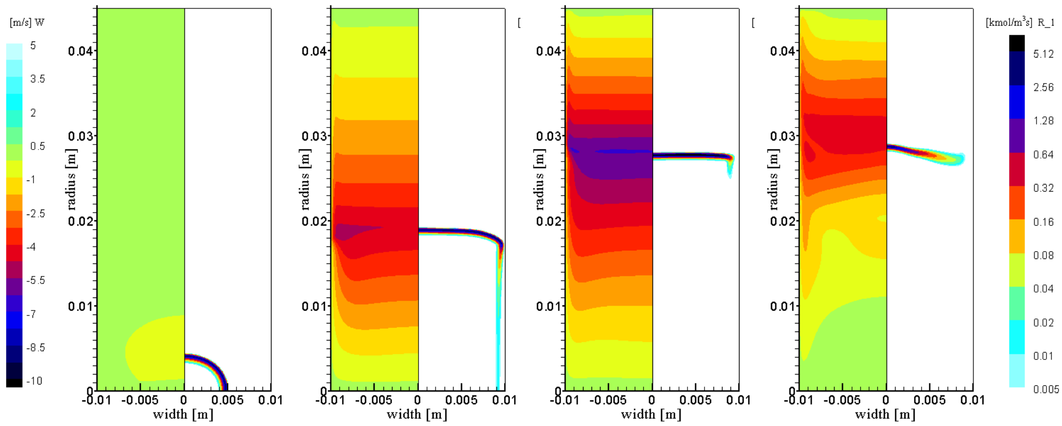

Figure 4: Azimuthal velocity component W (measured in the rotating frame of reference, left) and reaction rate RR (right) at time 0.51E-02, 1.50E-02, 2.48E-02, 4.96E-02; $\omega = 314$ rad/s, $\phi = 0.879$.

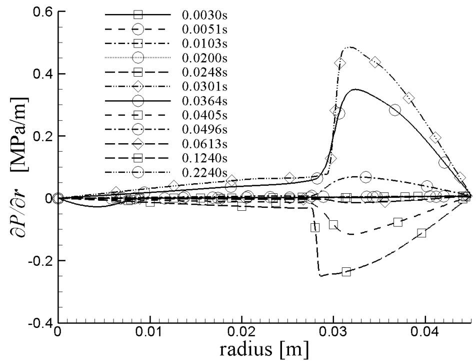

Figure 5: Pressure gradient in radial direction along the radius in the mid-plane section, $\omega = 314$ rad/s, $\phi = 0.879$.

that the flame quenching is a result of the coupled effect of both these structures.

Acknowledgments

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References

[1] Ishizuka S (2002). Flame Propagation Along a Vortex Axis. Prog. Energy Comb. Sci., 28: 477

[2] Gorczakowski A, Zawadzki A, Jarosinski J and Veyssiere B (2000). Combustion Mechanism of Flame Propagation and Extinction in a Rotating Cylindrical Vessel. Comb. Flame 120: 359

[3] CFD-RC (2005). CFD-ACE+ User Manual, Huntsville, USA.

[4] Dryer FL and Glassman I (1973). High temperature oxidation of CO and CH4, Proceedings of The Combustion Institute, 14: 987

[5] Van Doormaal JP and Raithby GD (1984). Enhancements of the Simple Method for Predicting Incompressible Fluid Flows, Num. Heat Trans.7: 147