On the Structure of Fast Flames in Two Types of Obstructed Channels

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The "choking regime" refers to the range of mixture compositions for which a flame in a tube filled with regularly-spaced orifice plates is observed to propagate at a quasi-steady velocity of 600 to 800 m/s. The term "choking" was first coined by Lee [1,2] to describe these fast flames, whose propagation velocities also correspond to the sound speed of the combustion products. The choice of the terminology was inspired by the streak photograph of Wagner [3] where the $u + c$ characteristics in the flow behind the "choked" flame can be seen to run parallel to the flame front itself, indicating that the flame is indeed sonic.

It was found by Lee *et al.* [1] and Peraldi *et al.* [2] that flame propagation in the choking regime is insensitive to the tube diameter and obstacle configuration. Therefore, the authors argued that choked flames are energetically driven to propagate at the local sound speed. In the experiments of Kuznetsov *et al.* [4], however, it was found that when the amount of blockage provided to the flow by the orifice plates (i.e., the blockage ratio, BR) was increased, flame velocities in the choking regime were observed to decrease slightly by 50 to 100 m/s. Also, although the propagation velocities always remained around the sound speed of the combustion products, the data showed that turbulent burning velocities may influence the propagation mechanism of choked flames. The numerical simulations of Veser *et al.* [5] suggest that the turbulent burning velocity, S_T, does indeed play a role in choked flame propagation. For a constant prescribed value of S_T, the authors found that the flame surface area adjusts accordingly such that the resulting steady-state flame speed would remain near the sound speed of the combustion products; i.e., as the value of S_T was increased, the flame surface area was found to be smaller. They also found that choked flame speeds were slightly greater (albeit always around the local sound speed) for larger values of S_T.

It is interesting to note, however, that quasi-steady choking regimes were not observed in square-tube experiments where vertical cylindrical rods arranged in a 3 x 2 offset pattern were used as obstacles [6]. The choking regime was essentially bypassed, which seems to indicate that this regime may be particular only to the orifice plate geometry.

Although choked flames are always observed to travel at velocities near the sound speed of the combustion products, it is not clear why and what mechanism controls the propagation velocity. In the present investigation, the propagation of choked flames in obstacle-laden tubes is studied numerically. The numerical results are compared to experiments in rectangular tubes with plate obstacles and in square tubes with multiple cylindrical rods in order to elucidate the propagation mechanism of choked flames.

Numerical simulations were performed using a custom solver built using the OpenFOAM CFD toolbox [7]. The code is based on a Large Eddy Simulation (LES) solver of the Naviers-Stokes conservation equations for mass, momentum and energy using a robust, implicit, pressure-velocity, iterative solution framework with a fully compressible Pressure-Implicit Split Operator (PISO) solution method [8]. A one-equation eddy-viscosity model [9] was used to model sub-grid scale turbulence.

The solver uses finite volume numerics to solve systems of partial differential equations built on 3D unstructured meshes of polyhedral cells. Second order schemes were used in space and time, central differencing for velocity, a bounded TVD scheme for scalars, and a second order backward differencing scheme in time.

The combustion model that was used is a modified form of the Weller flamelet combustion model [10], which is based on a transport equation for a regress combustion variable, b, for the unburned mixture fraction, and is given by:

$$\frac{\partial \bar{\rho}\tilde{b}}{\partial t} = \nabla \cdot \left(\bar{\rho}\tilde{\mathbf{U}}\tilde{b}\right) - \nabla \cdot \left(\bar{\rho}\mathcal{D}\nabla\tilde{b}\right) = -\bar{\rho}_u S_L \Xi \left|\nabla\tilde{b}\right|$$

where ρ is density, $\mathcal{D}$ is a diffusion coefficient, S_L is the laminar burning velocity, and Ξ is the flame surface wrinkling factor. Flame burning velocity was modeled as a product of laminar burning velocity S_L and a flame surface wrinkling factor Ξ. The value of $\Xi \times S_L$ gives the turbulent burning velocity S_T. Illustrations of the computational domains that were used are shown in Figs. 1 and 2. Adiabatic-wall boundary conditions were applied for all surfaces and obstructions in the computational domain.

The properties of the simulated fast flames, such as turbulent burning velocity and the speed of sound in the combustion products, were varied; their effects on the flame propagation speed, the length of the flame cone, and the flow field in general were studied. Existing experimental data was then used to verify that the behavior observed in simulations matched the physical phenomena seen in tests. These results are used to discuss the structure of fast turbulent flame obstructed channels and the mechanisms responsible for the choked flame regime.

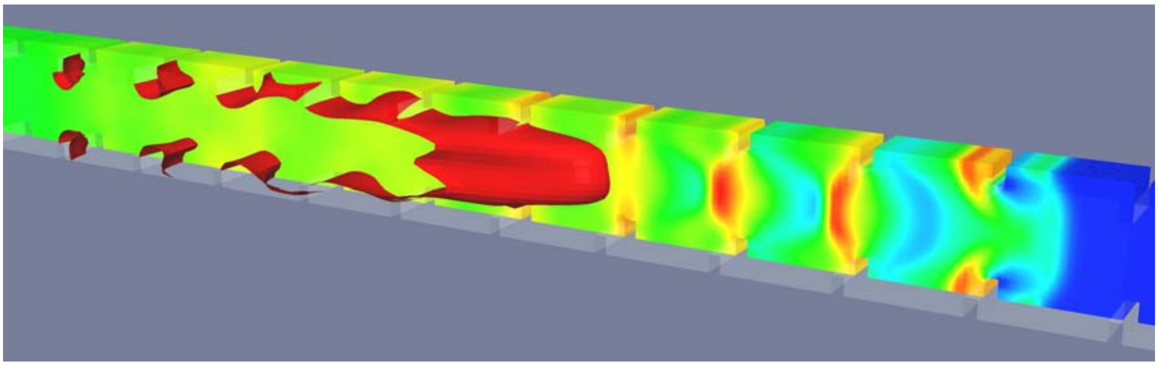

Figure 1. Illustration of the square channel with orifice plates geometry. An iso-surface contour colored red shows the flame surface and a cut down the center of the channel is colored by pressure.

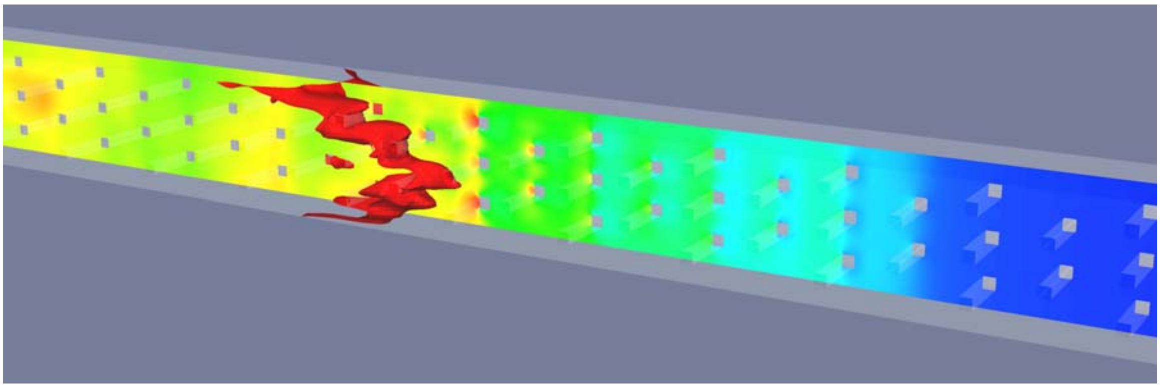

Figure 2. Illustration of the square tubes with cylindrical rods geometry. An iso-surface contour colored red shows the flame surface and a cut down the center of the channel is colored by pressure.

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