Run-up Distances to Supersonic Flames in Smooth Tubes

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1 Introduction

It is well known that fast flames, which propagate with supersonic speeds relative to a fixed observer, represent a serious hazard to confining structures. Generally, fast flames occur because of the intrinsic ability of combustion waves to accelerate and to undergo transition to detonation. In cases where supersonic flames are developed, Deflagration to Detonation Transition (DDT) becomes possible, which, if it occurs, results in a further increase of the pressure loads to the confining structures. The possibility of Flame Acceleration (FA) to supersonic speeds defines severe limitations on the feasibility of the practical implementation of explosion mitigation techniques, such as explosion suppression or explosion venting.

There are several limitations on the possibility of FA and DDT, which are related to the mixture composition, geometry, and scale of the enclosure containing the combustible mixture (see, e.g., [1] and references therein). Among others, the existence of a sufficiently large run-up distance necessary for the actual development of supersonic flames is one of the most important limitations.

The problem of the minimum run-up distance for FA to supersonic flames in tubes with obstacles was studied in [2]. A simple model was proposed, which describes the evolution of the flame shape in a channel containing obstacles with relatively high Blockage Ratios (BR). The dimensionless flame acceleration distance was determined in the model, which accounts for mixture properties, such as the laminar burning velocity, S_L, the ratio of densities between products and reactants, σ, and the sound speed in the combustion products, c_{sp}. This distance was expressed as a function of BR in the range from 0.3 to 0.75. The model [2] allows for estimation of the run-up distance necessary for the development of fast flames in tubes on the basis of the mixture properties and geometrical parameters. This model, however, is not applicable for relatively smooth tubes, such as those with a BR $\leq$ 0.1, where the flame shape evolution during FA is significantly different compared to highly obstructed tubes.

In highly obstructed tubes, the process of FA is affected significantly by obstructions along the flame passage, and the growth of the flame surface is the leading factor affecting FA. In circular tubes with orifice plate obstacles, e. g., the flame takes the shape of a deformed cone, anchored near the ignition end, which stretches until the moment where the speed of the flame head reaches the sound speed with respect to the products [2].

Different physical mechanisms play their roles in relatively smooth tubes or channels. In particular, generation of the turbulent boundary layer in the flow ahead of the flame is important for FA. During propagation in a relatively smooth tube the flame shape often turns into a characteristic “tulip” form with the leading edges near the tube walls. The role of the boundary layer in the DDT processes in a stoichiometric hydrogen-oxygen mixture was discussed in [3], where the run-up distances for the onset of detonations were studied experimentally as a function of the initial pressure.

The objective of the present study is to develop an approximate model for the evaluation of the run-up distances to supersonic flames in relatively smooth tubes. The model is based on a combination of ideas, which relate the flame shape evolution and the flame speed [2], with others which describe the boundary layer thickness ahead of an accelerated flame [3]. This approach is then evaluated, using a range of experimental data on FA in tubes with BR $\leq$ 0.1.

2 Model

Figure 1 shows the schematic of a flame in a tube with diameter D and wall roughness d at a distance X from the ignition point. At the stage of flame propagation shown in Fig. 1, the boundary layer is formed ahead of the flame with a thickness Δ. The flame propagates in the boundary layer with a turbulent velocity S_T relative to the unburned mixture and with a velocity $S_T + V$ in the laboratory frame, where V is the flow speed ahead of the flame. The burning velocity in the core of the flow is lower than the value of S_T in the boundary layer. The thickness of the boundary layer grows with time while the flow interacts with the wall, resulting in an increase of the boundary layer thickness as measured at flame positions along the tube, as shown in [3, 5].

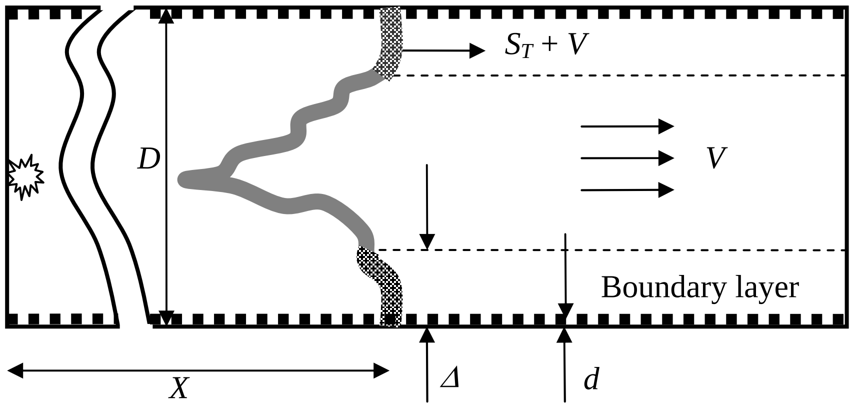

Figure 1. Schematic of the problem.

The model utilizes a general expression for the flow balance in the tube with two unknown parameters, the turbulent velocity correlation of Bradley [4], and the description for the thickness of the boundary layer at flame positions along the tube [3]. The run-up distance, X_S, is defined as the flame propagation distance where the flame speed reaches the sound speed in the combustion products, as in [2]. This approach results in the following expression for the run-up distance:

$$\frac{X_S}{D} = \frac{\gamma}{C}\left[\frac{1}{\kappa}\ln\left(\gamma\frac{D}{d}\right) + K\right], \tag{1}$$

where κ, K and C are constants taken to be: $\kappa = 0.4$; $K = 5.5$; and $C = 0.2$ [3, 5]; D/d can be expressed through the blockage ratio: $D/d = 2/(1-(1-\mathrm{BR})^{1/2})$; and $\gamma = \Delta/D$ is given by:

$$\gamma = \left[\frac{c_{sp}}{\beta(\sigma-1)^2 S_L}\left(\frac{\delta}{D}\right)^{1/3}\right]^{\frac{1}{2m+7/3}}, \tag{2}$$

where β and m are two unknown parameters, which may be determined using an appropriate set of experimental data.

3 Results

The parameters of Eq. (2) were evaluated using experimental data on the flame speed versus distance in tubes and channels with BR $\leq$ 0.1 [3, 5-8]. The data covered a wide range of BR (see Fig. 2), laminar burning velocities, S_L (from 0.65 to 11 m/s) and sound speeds in the combustion products, c_{sp} (from 790 to 1890 m/s).

Parameters β and m were determined from a fitting of the experimental data using the least squares method. The results of the fitting procedure are presented in Fig. 3 with $\beta = 2.15$ and $m = -0.17$. It is seen that the model allows for good compression of the data points with an accuracy of prediction for the run-up distances of about ± 25%.

A comparison of the run-up distances predicted using Eqs. (1) and (2) (BR < 0.1) with those from [2] (BR > 0.3) for stoichiometric mixtures of methane, propane, ethylene, and hydrogen with air is presented in Fig. 4. It is seen that the present model for smooth tubes predicts relatively higher run-up distances compared to [2]. This is qualitatively in accord with the observations that FA is strongly promoted by the obstructions. In the range of BR between 0.1 and 0.3, neither of the two models is applicable. For practical applications, one may "bridge" the range of BR from 0.1 to 0.3 as shown by dashed lines in Fig. 4.

3 Conclusions

We have presented an approximate model for evaluation of the run-up distances to supersonic flames in relatively smooth tubes. The model is based on general relationships between the flame area, turbulent burning velocity, and the flame speed combined with an approximate description for the boundary layer thickness ahead of an accelerated flame. The unknown constants of the model are evaluated using experimental data on flame speeds versus distance in tubes and channels with BR ≤ 0.1. The model shows good agreement with the data in a wide range of mixture properties and tube wall roughness.

References

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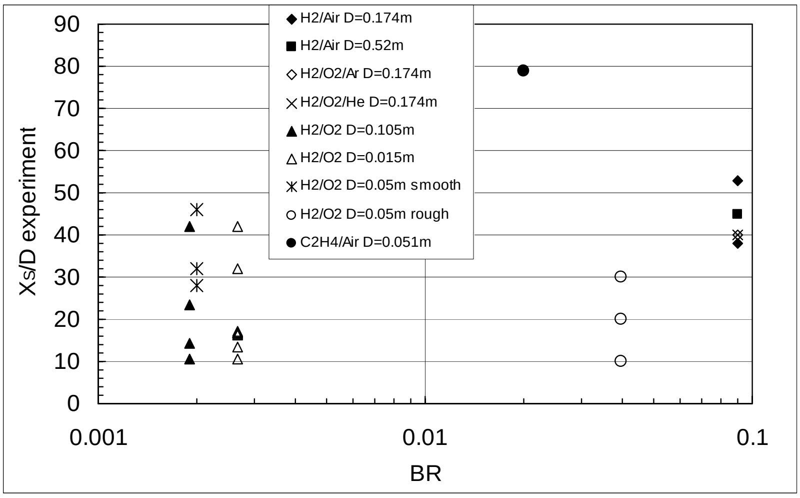

Figure 2. Experimental run-up distances over with tube diameter as a function of BR.

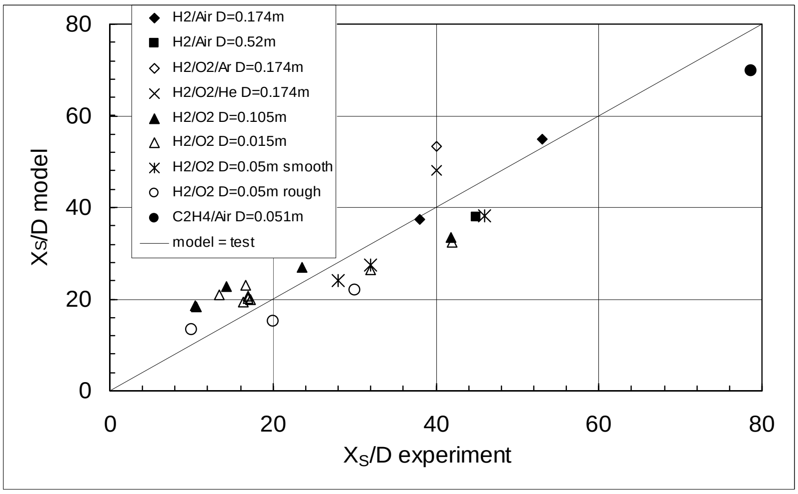

Figure 3. Correlation of model and experimental run-up distances (the same data points as in Fig. 2)

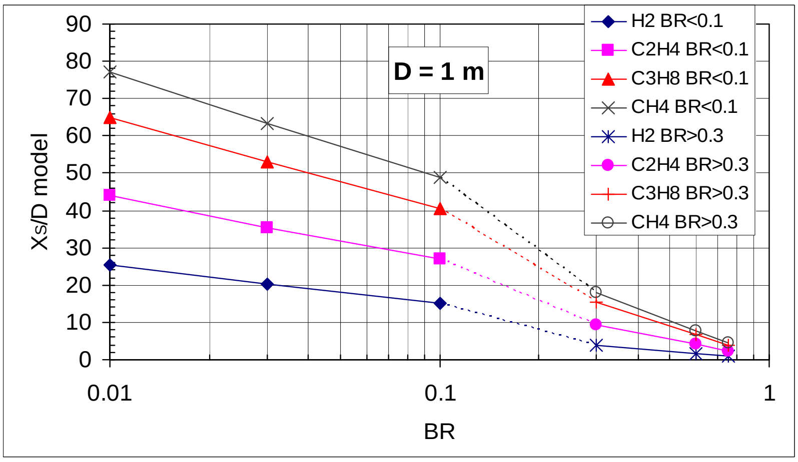

Figure 4. Run-up distances over tube diameter as a function of BR for D = 1 m.