HYDROGEN FLAMES IN TUBES: CRITICAL RUN-UP DISTANCES

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ABSTRACT

The hazard associated with flame acceleration to supersonic speeds in hydrogen mixtures is discussed. A set of approximate models for evaluation of the run-up distances to supersonic flames in relatively smooth tubes and tubes with obstacles is presented. The model for smooth tubes 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. This model is then supplemented with the model for the minimum run-up distance for FA in tubes with obstacles developed earlier. On the basis of these two models, solutions for the determination of the critical run-up distances for FA and deflagration to detonation transition in tubes and channels for various hydrogen mixtures, initial temperature and pressure, tube size and tube roughness are presented.

1.0 INTRODUCTION

Hydrogen releases and transport of hydrogen-containing mixtures in confined geometries, such as tubes, channels, or tunnels, represent a significant safety problem, because of the promoting role of confinement for Flame Acceleration (FA) and pressure build-up. It is well known that fast flames, which propagate with supersonic speeds relative to a fixed observer, represent a serious hazard to confining structures. 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 loads to the confining structures.

The possibility of 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 (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.

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. 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.

The first part of the paper is focused on the description of 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 [2]. The unknown constants of the model are evaluated using experimental data on flame speeds in hydrogen mixtures versus distance in tubes and channels with Blockage Ratio (BR) less than 0.1.

This model is then supplemented with the model for the minimum run-up distance for FA to supersonic flames in tubes with obstacles (BR > 0.3) developed earlier [3]. On the basis of these two models, solutions for the determination of the critical run-up distances for FA and DDT in tubes and channels for various mixture compositions, initial temperature and pressure, tube size and BR (or tube roughness) are presented.

2.0 MODEL

2.1 Smooth tubes

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.

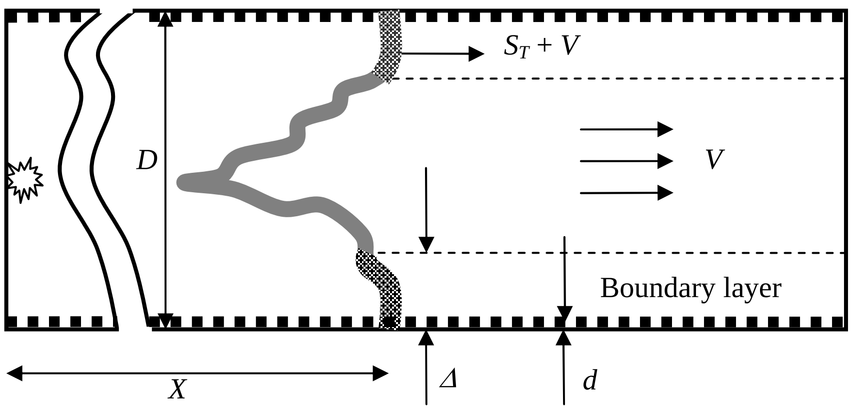

Figure 1. Schematic of the problem.

With notations shown in Fig. 1, one can write sufficiently general expression for the mass balance in the tube:

$$V\frac{\pi D^2}{4} = \alpha S_T \pi D \Delta(\sigma - 1)\left(\frac{\Delta}{D}\right)^m , \tag{1}$$

where α and m are model constants, and σ is the ratio of densities between reactants and products. The last factor in the right hand side of Eq. (1) is written to model the contribution of the flame in the core of the flow, with the assumption that this contribution is controlled by the relative thickness of the boundary layer.

The turbulent burning velocity, S_T, may be modeled using Bradley's correlation [4]:

$$\frac{S_T}{S_L} = \varphi\left(\frac{u'}{S_L}\right)^{1/2}\left(\frac{L_T}{\delta}\right)^{1/6} , \tag{2}$$

where u' is the turbulent fluctuation velocity; S_L is the laminar burning velocity; L_T is the integral length scale of turbulence; $\delta = \nu/S_L$ is the laminar flame thickness; ν is the viscous diffusivity; and φ is a coefficient. The turbulent fluctuation velocity, u', at the integral scale in a boundary layer is given by the flow speed, V, and the integral length scale, L_T, by the boundary layer thickness, Δ.

The thickness of the boundary layer grows with time while the flow interacts with the wall. The origin of the boundary layer (the head of the compression wave or the lead shock) generally propagates faster than the flame itself resulting in an increase of the boundary layer thickness as measured at flame positions along the tube, as shown in [2, 5]. The thickness of the boundary layer at flame positions along the tube can be estimated using the following expression [2]:

$$C\frac{X}{\Delta} = \frac{1}{\kappa}\ln\left(\frac{\Delta}{d}\right) + K \ , \qquad (3)$$

where κ, K and C are constants.

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]. Equations (1 - 3) yield for the run-up distance:

$$\frac{X_S}{D} = \frac{\gamma}{C}\left[\frac{1}{\kappa}\ln\left(\gamma\frac{D}{d}\right) + K\right] \ , \qquad (4)$$

where 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:

$$\gamma = \left[\frac{c_{sp}}{\beta(\sigma-1)^2 S_L}\left(\frac{\delta}{D}\right)^{1/3}\right]^{\frac{1}{2m+7/3}} \ , \qquad (5)$$

where $\beta = (4\alpha\varphi)^2$. Equation (5) includes two unknown parameters, β and m, which may be determined using an appropriate set of experimental data.

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

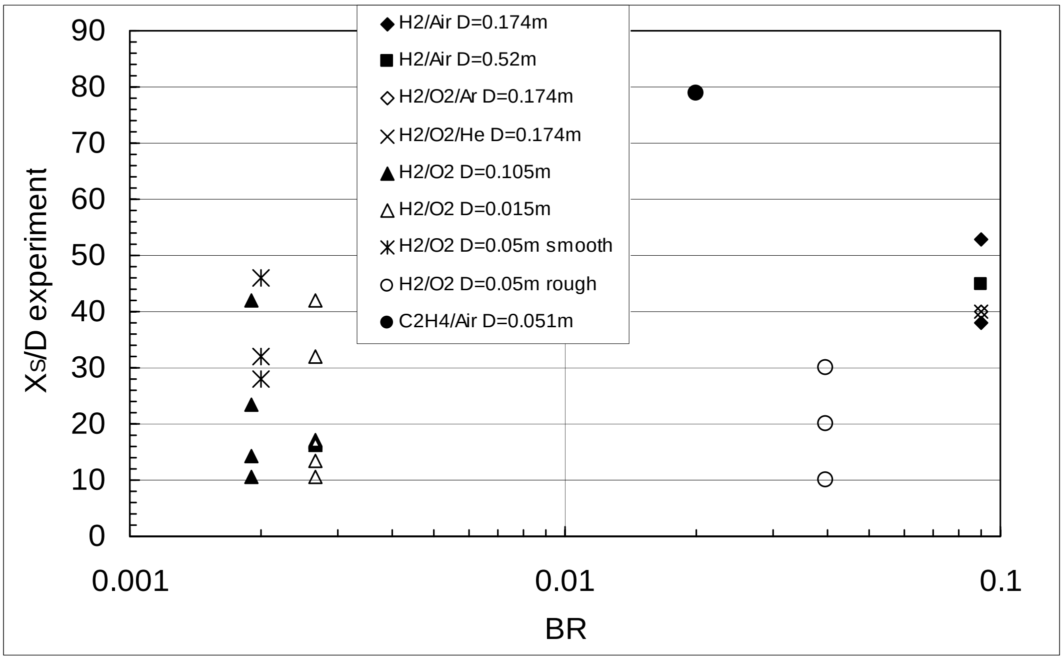

Figure 2. Experimental run-up distances over with tube diameter as a function of BR.

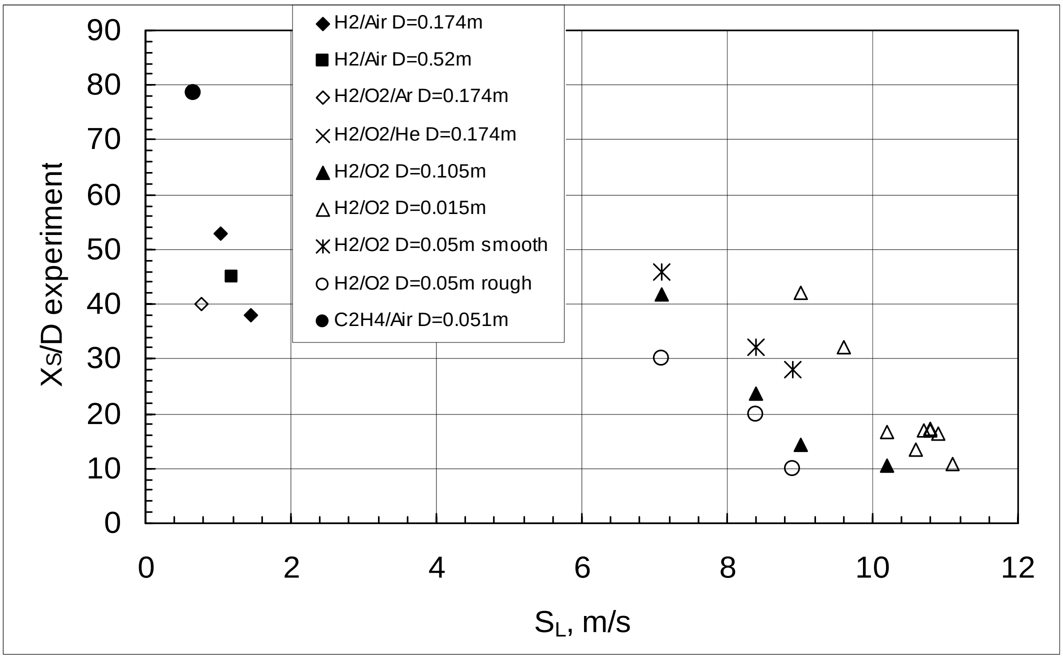

Figure 3. Experimental run-up distances over tube diameter as a function of laminar burning velocity.

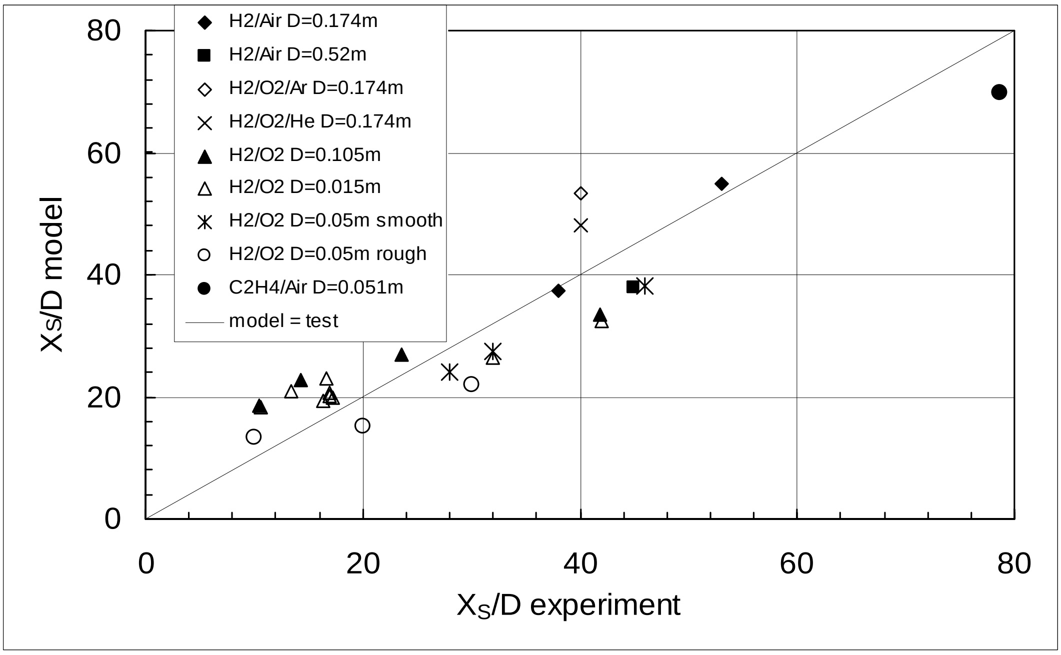

Figure 4. Correlation of model and experimental run-up distances (the same data points as in Fig. 2)

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. 4 with $\beta = 2.1$ and $m = -0.18$. 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 $\pm$ 25%.

2.2 Tubes with obstacles

A simple model was proposed by Veser et al. [3], which describes the evolution of the flame shape in a channel containing obstacles with relatively high BR. The model assumes that the flame has the form of a deformed cone, which stretches until the moment when the speed of the flame head reaches the speed of sound with respect to the combustion products. The position of the flame head at that moment gives an estimate for the run-up distance. Then the flame cone cannot stretch any more and moves down the tube at a quasi-steady velocity. An illustration of the flame shape in a tube with orifice plates is shown in Fig. 5.

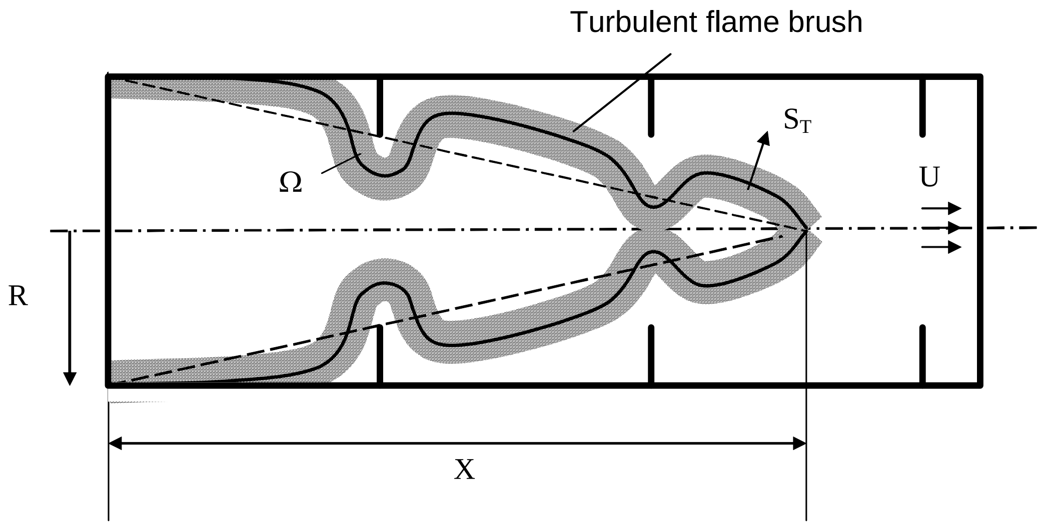

Figure 5. Schematic for estimation of flame surface Ω in tube with orifice plates.

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 reactants and products, σ, and the sound speed in the combustion products, c_{sp}. It was assumed that for relatively heavy obstructions, the turbulent burning velocity reaches its maximum saturation value of order of $S_T \approx 10S_L$ at an initial stage of FA, and the following flame acceleration is mainly due to the increase of the surface of the turbulent flame brush. The dimensionless flame acceleration distance was expressed as a function of BR:

$$\frac{X_S}{D}\frac{20S_L(\sigma-1)}{c_{sp}} \approx a\frac{1-BR}{1+b\cdot BR}\ , \tag{6}$$

where a and b are unknown parameters of the model. The scaling of the run-up distance with mixture properties as in Eq. 6 was evaluated using a wide range of experimental data and results of 3D numerical simulations in the range of BR from 0.3 to 0.75. It was shown that grouping at the left-hand side of Eq. 6 permits to collapse the data within ± 25%. The effect of BR given by the right-hand side of Eq. 6 was found to give rather good description of the data with a = 2 and b = 1.5, for the range of BR from 0.3 to 0.75.

Cases when the obstacle spacing, S, is not equal to the tube diameter, D, were not analyzed by Veser et al. [3], however, the same approach to the estimation of the flame surface with $D \neq S$ would require the term $b{\cdot}D/S$ instead of b in the right hand side of Eq. 6. This would result in a weak increase of X_S/D with S/D. In the range of S/D from 0.5 to 1.5, the change of X_S/D would be within ± 20%, which is a small variation considering the uncertainty range of the model.

3.0 RESULTS AND DISCUSSION

3.1 Hydrogen and hydrocarbon mixtures

According to Eqs. (4) and (5) the dimensionless run-up distance, X_S/D, is a function of the tube diameter due to the term δ/D in Eq. (5). This is different from the model for BR ≥ 0.3 [3], where the dimensionless run-up distance was independent of the tube diameter. Figure 6 shows, as an illustration, the dimensionless run-up distances for stoichiometric mixtures of methane, propane, ethylene, and hydrogen with air versus tube diameters.

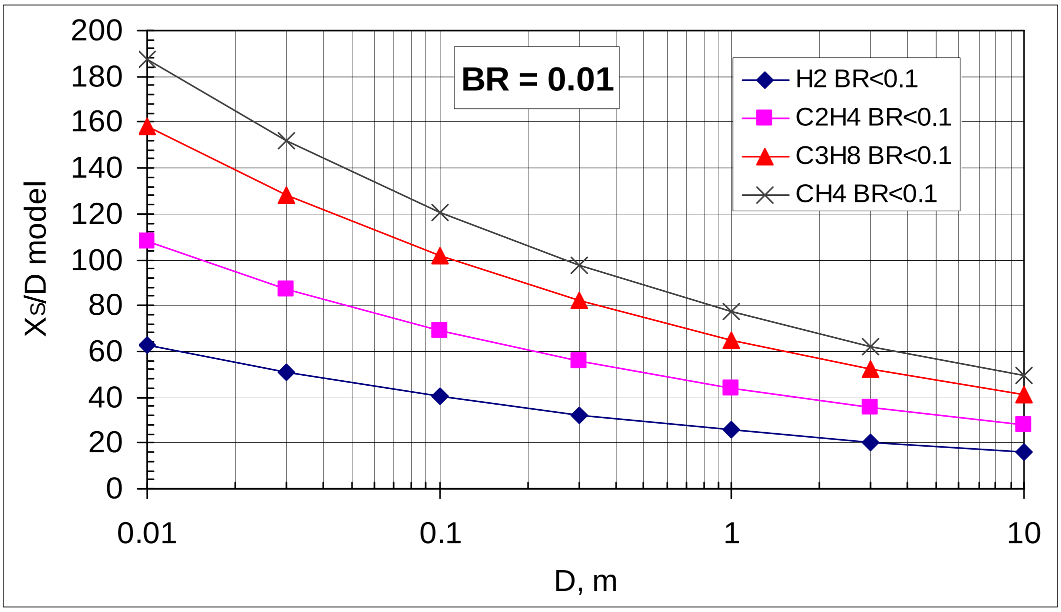

Figure 6. Run-up distances over tube diameter as a function of tube diameter for BR = 0.01

A comparison of the run-up distances predicted using Eqs. (4) and (5) (BR ≤ 0.1) with those predicted by Eq. (6) (BR ≥ 0.3) for stoichiometric mixtures of methane, propane, ethylene, and hydrogen with air is presented in Fig. 7. It is seen that the model for smooth tubes predicts relatively higher run-up distances compared to that for obstructed tubes with BR ≥ 0.3. 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. 7.

3.2 Effects of initial turbulence

Figures 6 and 7 show that in smooth tubes the run-up distances in the methane and propane mixtures are about twice as high as that in the ethylene and hydrogen mixtures. This is why there is no data available on the run-up distances for these mixtures in smooth tubes. There are data on FA in “turbulent gas/air mixtures” of hydrogen, methane, and propane, where turbulence preexists in the mixture at the time of ignition [9]. We cannot compare these data directly with the model predictions, however, if one assumes that the preexisting turbulence leads to the increase of the initial burning velocity from the laminar value, S_L, to some effective value, S_{Leff}, such a comparison can be made. Figure 8 shows that with $S_{Leff} = 2.5S_L$, which is a reasonable assumption, the “turbulent” data [9] are well described by the model. This observation gives an approximate method to account for the initial turbulence by estimating the effective value of the initial burning velocity.

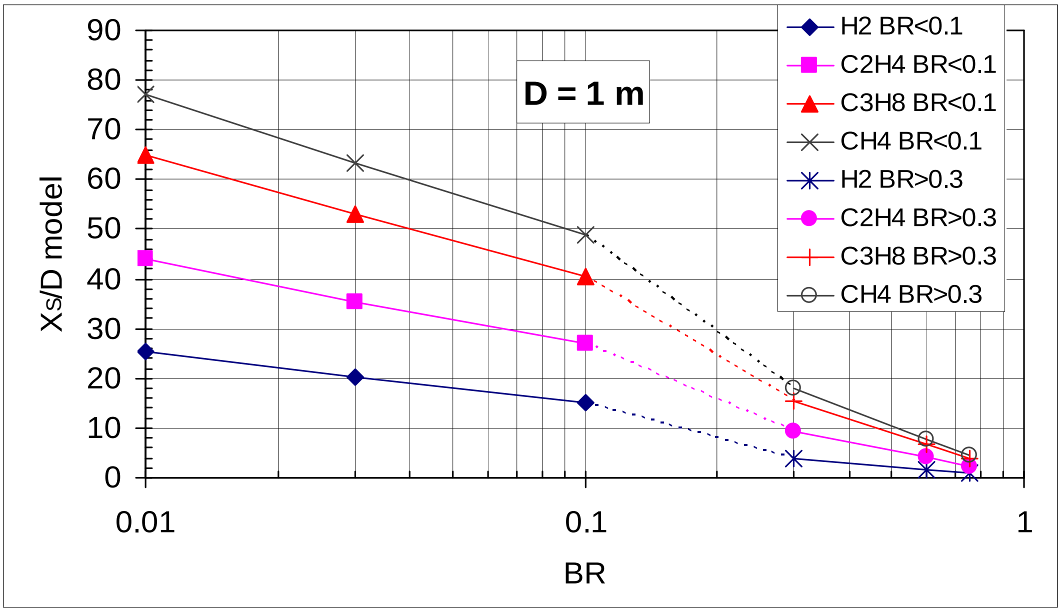

Figure 7. Run-up distances over tube diameter as a function of BR for D = 1 m.

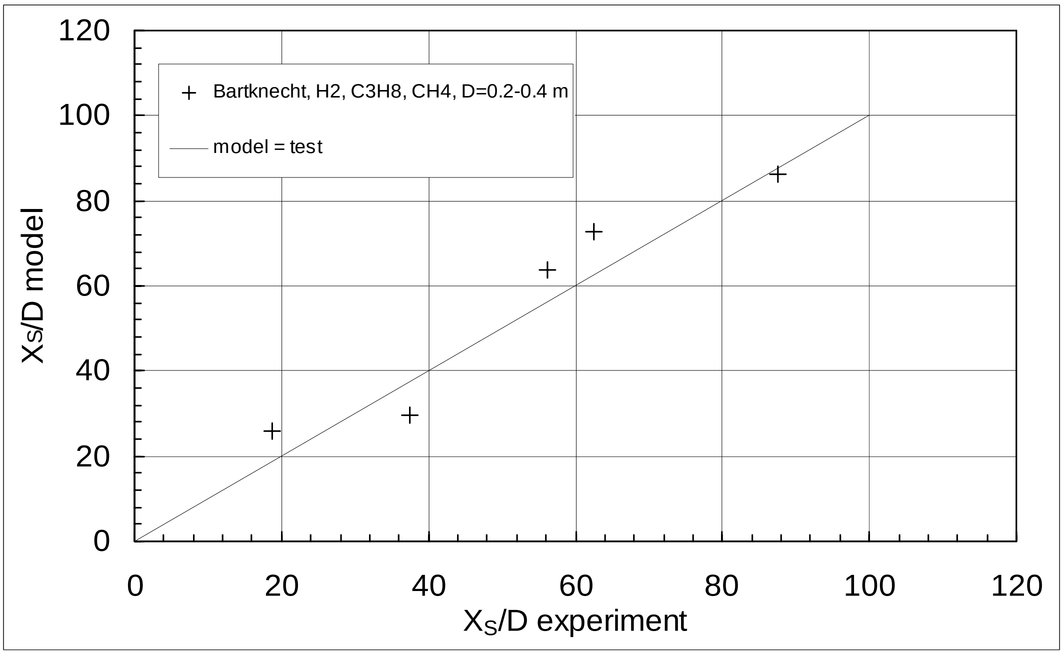

Figure 8. Run-up distances in "turbulent gas/air mixtures" [9] and model predictions with $S_{Leff} = 2.5S_L$.

3.3 Effects of tube diameter and roughness

Figure 9 shows, as an illustration, the dimensionless run-up distances versus BR for a stoichiometric hydrogen/air mixture at 298K and 1 bar initial temperature and pressure in tubes with diameters from 0.01 to 10 m. It is seen that for relatively smooth tubes with BR from 0.01 to 0.1, the dimensionless run-up distance decreases with the tube diameter. For obstructed tubes with BR > 0.3, the dimensionless run-up distance does not depend on the tube diameter, so that the dimensional run-up distance, X_S, is proportional to D.

The dimensionless run-up distances in hydrogen-air mixtures at 298K and 1 bar initial pressure as a function of tube roughness, d, for various tube diameters is shown in Fig. 10. The same set of data is used in Fig. 10 as that in Fig. 9. It is seen that as a general trend the decrease of X_S/D with the tube roughness, d, is observed.

3.4 Effects of initial temperature and pressure

Many practical applications involve cases where hydrogen mixtures are at elevated initial temperatures and/or pressures. An example may be an exhaust pipe of a fuel cell during startup operations. The initial temperature and/or pressure changes fundamental properties of a combustible mixture, such as the laminar burning velocity, flame thickness, and isobaric sound speed. These changes can result in significant variations of the critical run-up distances as predicted by Eqs. (4), (5), and (6). It is very important that the initial temperatures and pressures are properly taken into account for the determination of the critical run-up distances.

Figure 11 shows, as an example, the run-up distances in stoichiometric hydrogen-air mixtures at various initial temperatures and pressures as a function of BR for D = 0.1 m. It is seen that the dimensionless run-up distances in stoichiometric hydrogen/air mixtures decreases with the initial temperatures and pressures within the range shown in Fig. 11.

3.5 Effect of mixture composition

While the run-up distances in stoichiometric hydrogen-air mixtures are very short, especially for tubes with obstacles (see Fig. 11), the hydrogen concentration in non-stoichiometric mixtures is expected to have a strong influence on the run-up distances. The mixture composition affects significantly the properties of the mixture that are present in Eqs. (4), (5), and (6). Any reduction of the hydrogen concentration below the stoichiometry results in the significant increase of the run-up distance.

Figure 12 show the dimensionless run-up distances in various hydrogen-air mixtures at 298 K and 1 bar initial pressure as a function of BR for D = 0.1 m. It is seen that the decrease of the hydrogen concentration from 30 to 12% can lead to the increase of the run-up distances by a factor of 5 or more.

4.0 CONCLUSIONS

We have presented a set of approximate models for evaluation of the run-up distances to supersonic flames in relatively smooth tubes and tubes with obstacles. The models are based on general relationships between the flame area, turbulent burning velocity, and the flame speed. One of the models is applicable to relatively smooth tubes with BR < 0.1. Another one was developed for tubes and channels with heavy obstructions in the range of BR from 0.3 and 0.7. The models show good agreement with the data in a wide range of mixture properties and tube wall roughness (or BR).

On the basis of these two models, the critical run-up distances for FA in hydrogen mixtures were evaluated. It was shown that the run-up distances depend significantly on the mixture composition, initial level of turbulence, initial temperature and pressure, tube size, and BR (or tube roughness). It was suggested that each of these parameters should be taken into account in practical applications.

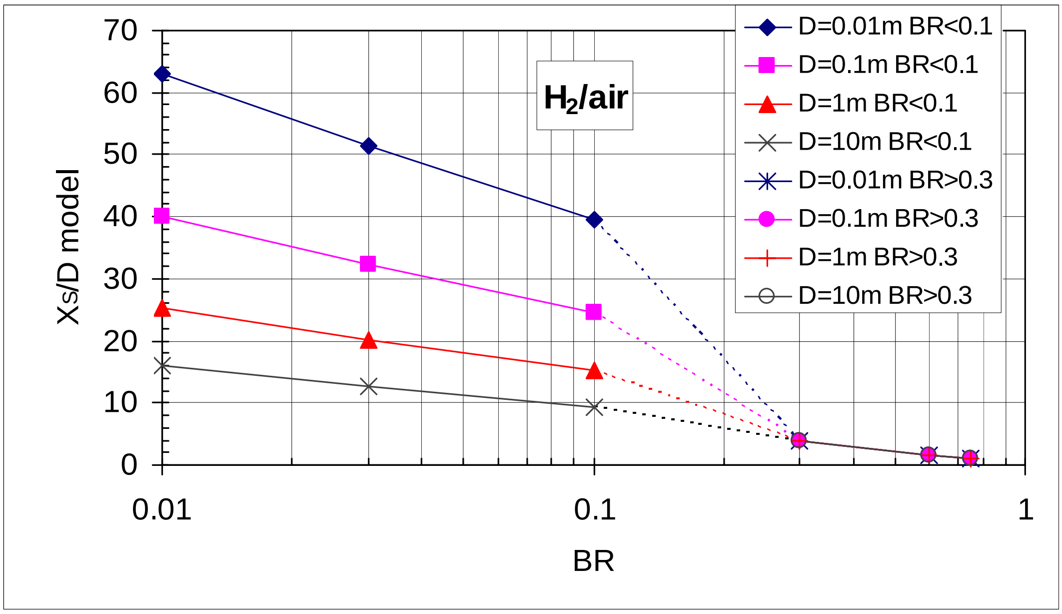

Figure 9. Run-up distances in stoichiometric hydrogen-air mixtures at 298K and 1 bar initial pressure as a function of BR for various tube diameters.

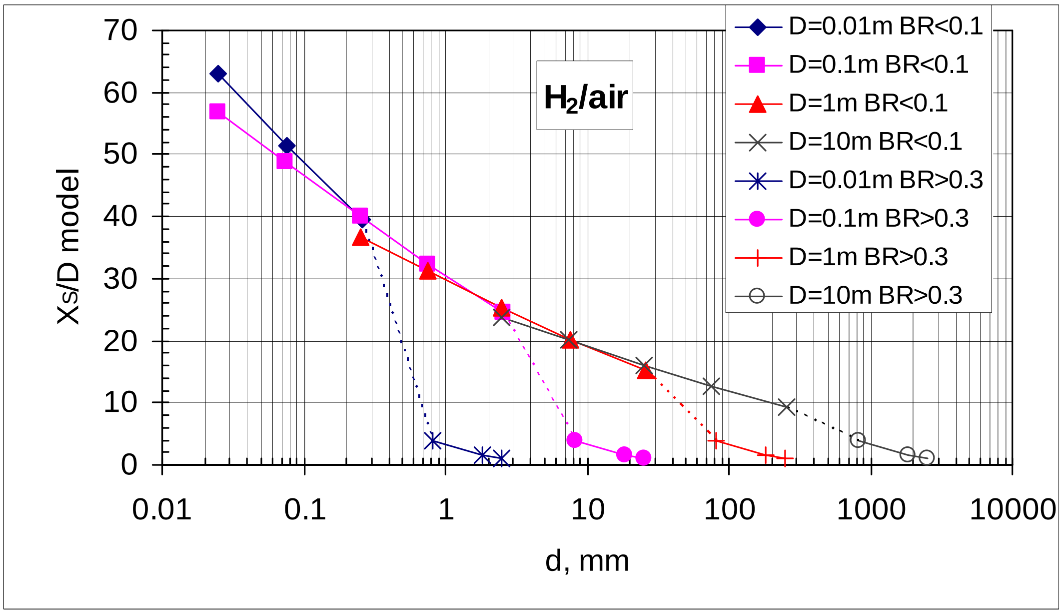

Figure 10. Run-up distances in stoichiometric hydrogen-air mixtures at 298K and 1 bar initial pressure as a function of tube roughness for various tube diameters.

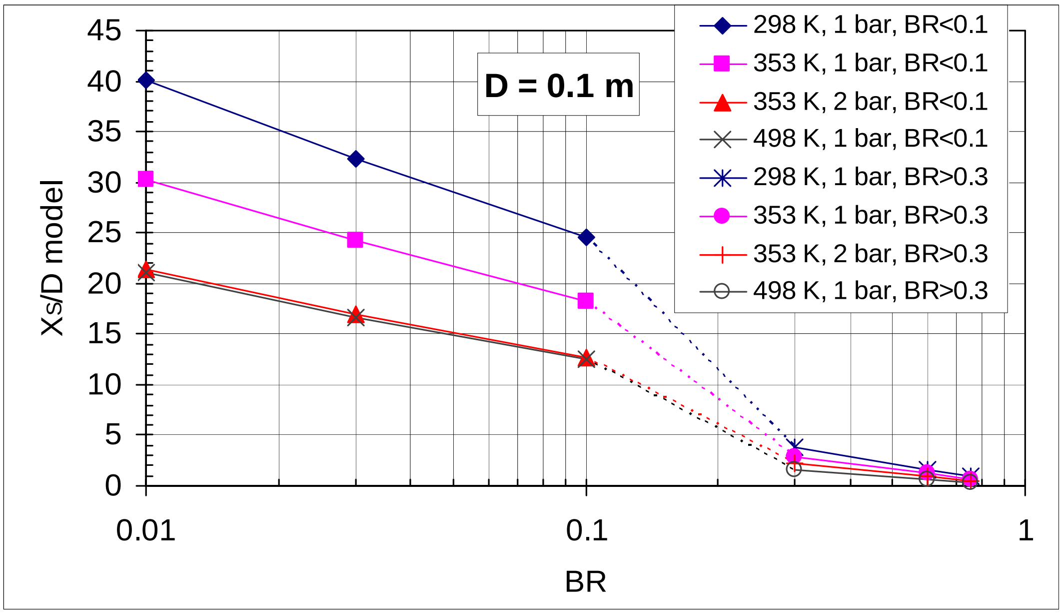

Figure 11. Run-up distances in stoichiometric hydrogen-air mixtures at various initial temperatures and pressures as a function of BR for D = 0.1 m.

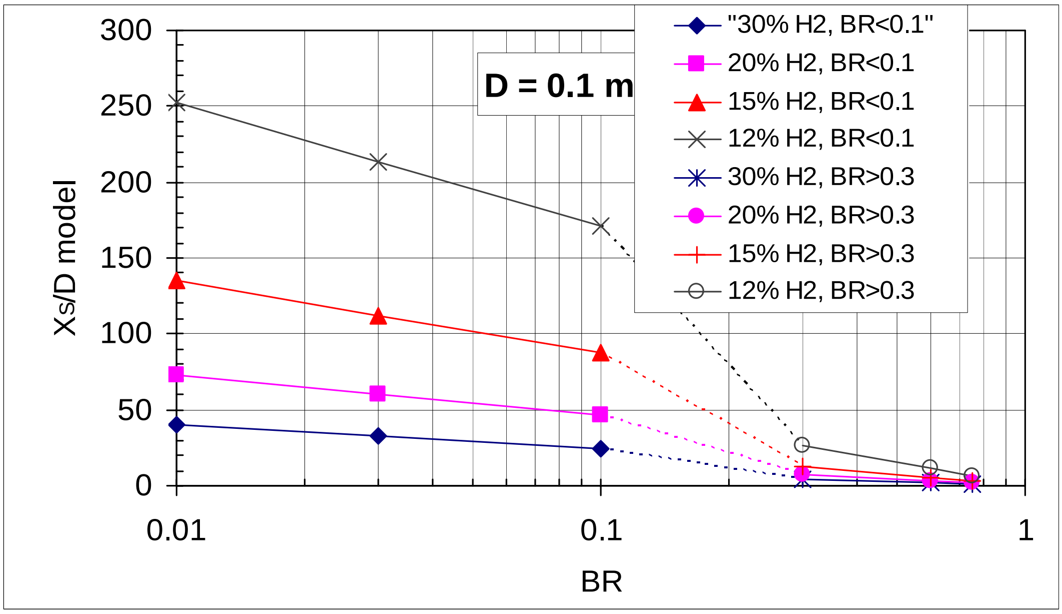

Figure 11. Run-up distances in various hydrogen-air mixtures at 298 K and 1 bar initial temperature and pressure as a function of BR for D = 0.1 m.

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