HYDROGEN FLAMES IN TUBES: CRITICAL RUN-UP DISTANCES

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Motivation

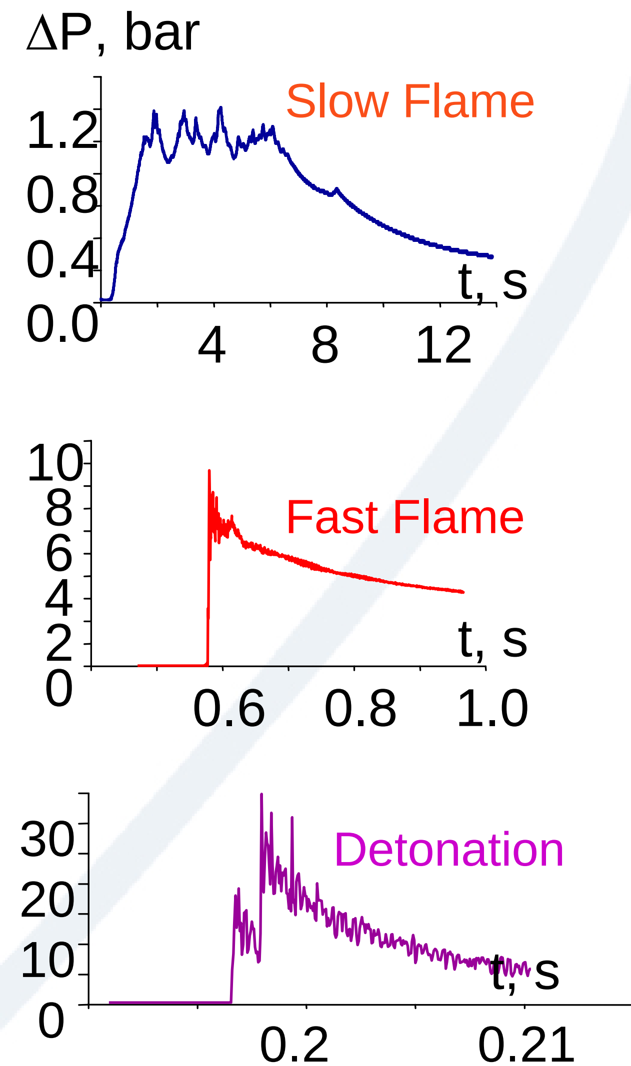
Hydrogen Safety Applications

- H_2 releases and transport of H_2-containing mixtures in confined geometries represent a significant safety problem
  - Tubes / ducts
    - Ventilation systems
    - Exhaust pipes
    - Production facilities
  - Tunnels
- Promoting role of confinement for FA and pressure build-up
- Hydrogen: special attention because of high sensitivity to FA

Motivation

Hazard

- Fast flames (supersonic relative to a fixed observer) represent a serious hazard to confining structures
- In cases of supersonic flames, DDT becomes possible
  - further increase of pressure loads
- Possibility of FA to supersonic speeds limits implementation of mitigation techniques
  - explosion suppression
  - explosion venting



Motivation

Limitations

- There are several limitations on the possibility of FA to supersonic flames and DDT
  - mixture composition
  - geometry
  - scale
  - …
  - sufficiently large run-up distance
- Important to have reliable estimates for run-up distances

Background

Run-up distances to DDT

- Historically, run-up distances to DDT were addressed in most of studies
  - Starting from Lafitte, Egerton, 1920th
  - Shchelkin, 30th
  - Followed by Jones, Soloukhin et al., Bollinger et. al., Nettleton, Campbell et al., Powel et al, Bartknecht, Fitt, Moen et al., Lee et al., Knystautas et al., Chan et al, Lindsted et al., Kuznetsov et al., Ciccarelli et al., Sorin et al.…
- Run up distances were studied in
  - Smooth tubes
  - Tubes with obstacles

Background

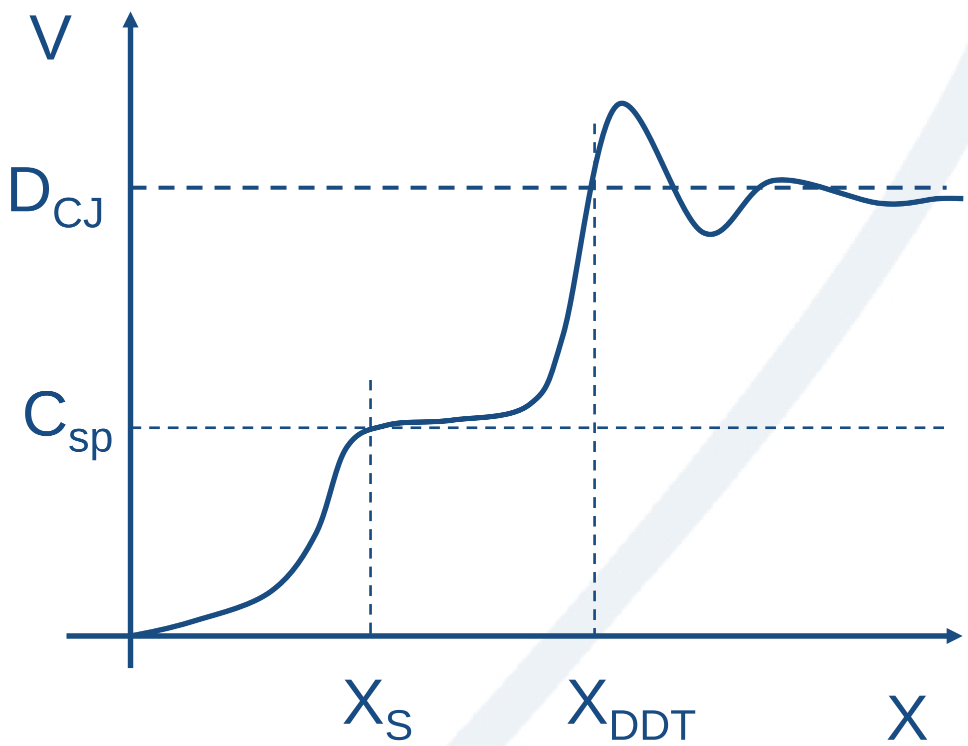
Run-up distances in smooth tubes

- Substantial experimental data accumulated
  - Mixture composition
  - Tube diameter
  - Initial temperature and pressure
- Ambiguous data on the effect of tube diameter and pressure (detonation cell size)
  - $X_{DDT} \approx 15 - 40$ D ?
  - X_{DDT} independent on D ?
  - X_{DDT} proportional to the cell size ?
- There is no universal and/or satisfactory model for the run-up distances

Background

Ambiguity of run-up distances

- Effect of tube length
  - Pre-compression or pressure piling
- Effect of tube roughness
  - Not always characterized
- Difference in governing mechanisms
  - Flame acceleration
  - Onset of detonation



Background

Run-up distances in tubes with obstacles

- Tube wall roughness and obstacles play an important role in FA and DDT
  - Chapman and Wheeler (1926) used orifice plates to promote FA
  - Shchelkin proposed a wire coil helix inside the tube
  - DDT in tubes with obstacles studied at McGill and by many other teams
- X_{DDT} and X_S are often different in tubes with obstacles

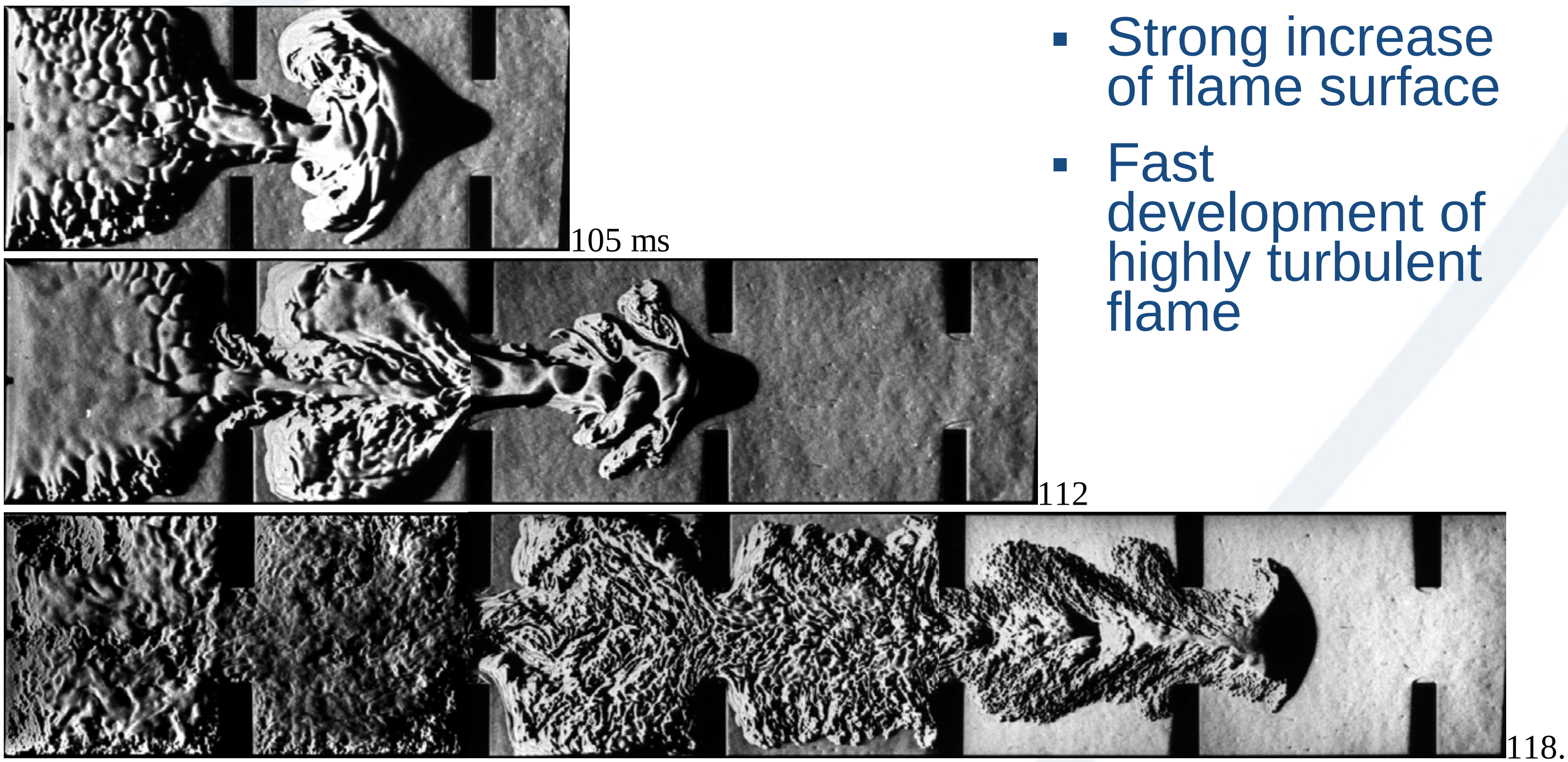
Objectives

- Present a set of approximate models for evaluation of the run-up distances to supersonic flames
  - Relatively smooth tubes
  - Tubes with obstacles
- On the basis of these models, evaluate the critical run-up distances for FA in hydrogen mixtures
  - Mixture composition
  - Tube size
  - BR and/or roughness
  - Other parameters

Tubes with Obstacles

Flame evolution

- Obstacles control FA:
  - Strong increase of flame surface
  - Fast development of highly turbulent flame

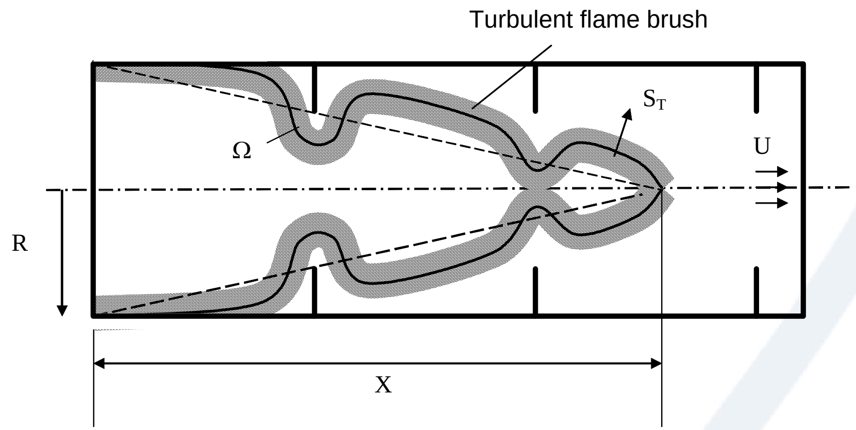


Shadow photos of Matsukov, et al.

Tubes with Obstacles

Run-up distance X_s (Veser et al. 2002)

- Flame shape is given by obstacle field
- X_S is the distance where the speed of the flame head approaches C_{sp}
- $X_S \propto D$ for given mixture, BR, and initial T, p
- Accuracy ≈ ± 25% over a representative range of data

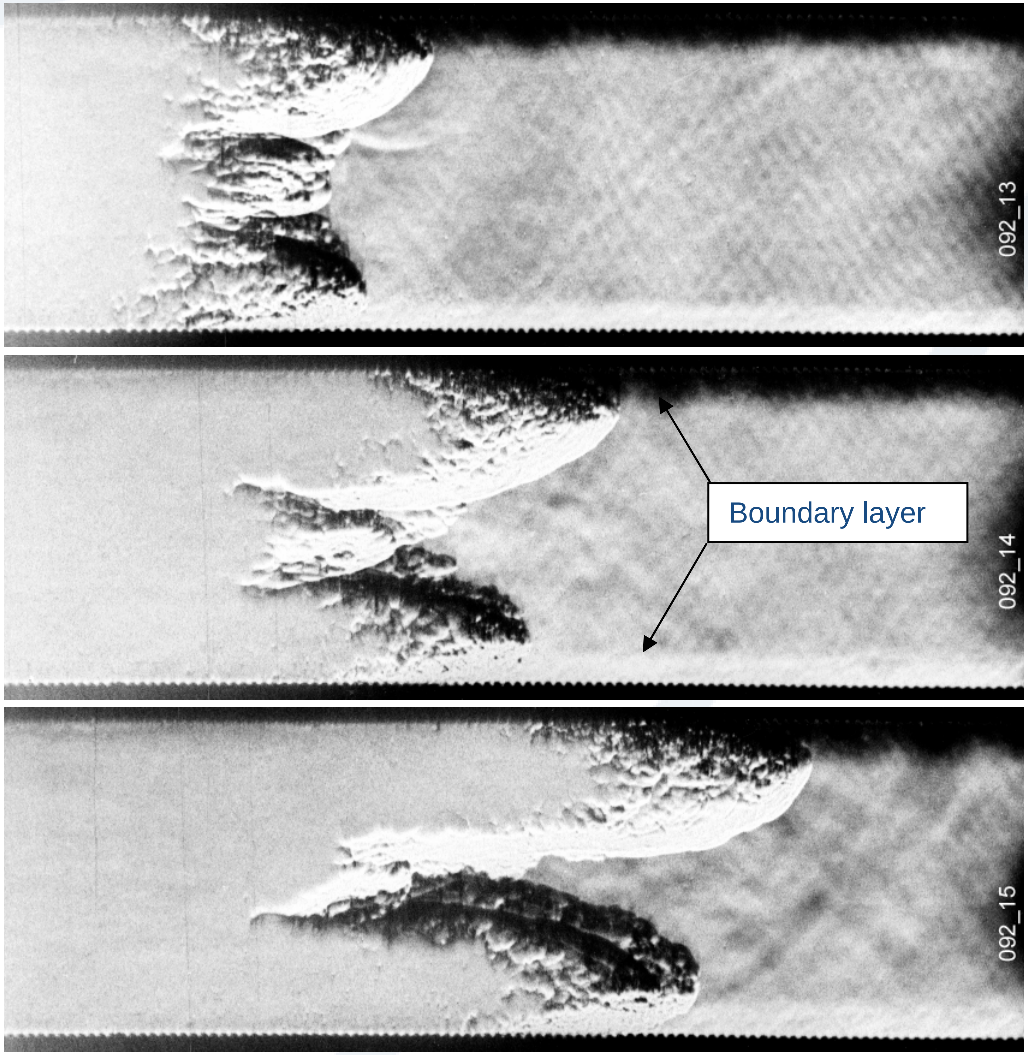


$$\frac{X_S}{R}\frac{10S_L(\sigma-1)}{c_{sp}} \approx a\frac{1-BR}{1+b\cdot BR}$$

Smooth Tubes

FA in smooth tubes

- Different from tubes with obstacles
- Boundary layer plays an important role
- Thickness Δ of b.l. at flame positions increases during FA



Shadow photos of Kuznetsov, et al.

Smooth Tubes

Model for X_s

- Mass balance

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

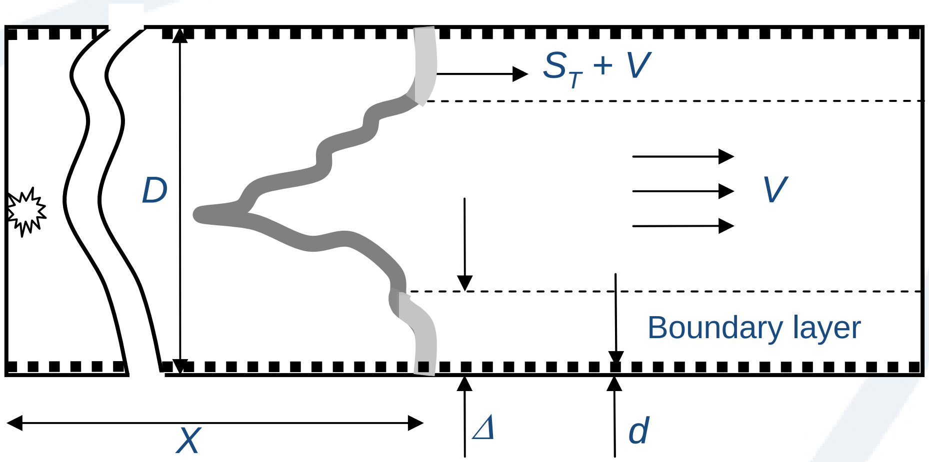
- Burning velocity S_T

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

- Boundary layer thickness

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

- X_s: $V+S_T = C_{sp}$



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

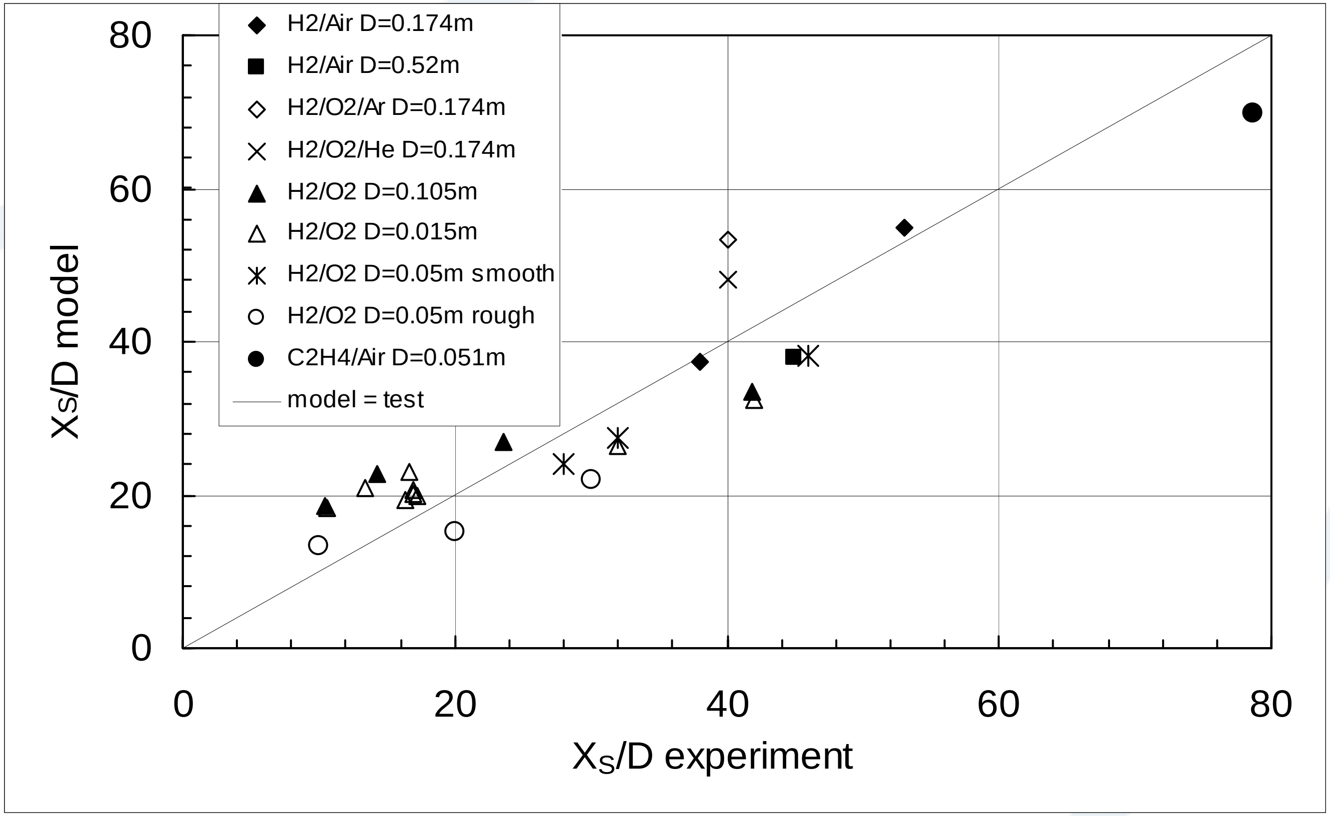
$\gamma = \Delta/D$:

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

Two unknown parameters: m and β

Smooth Tubes

Correlation of model and experimental data



Accuracy ≈ ± 25%

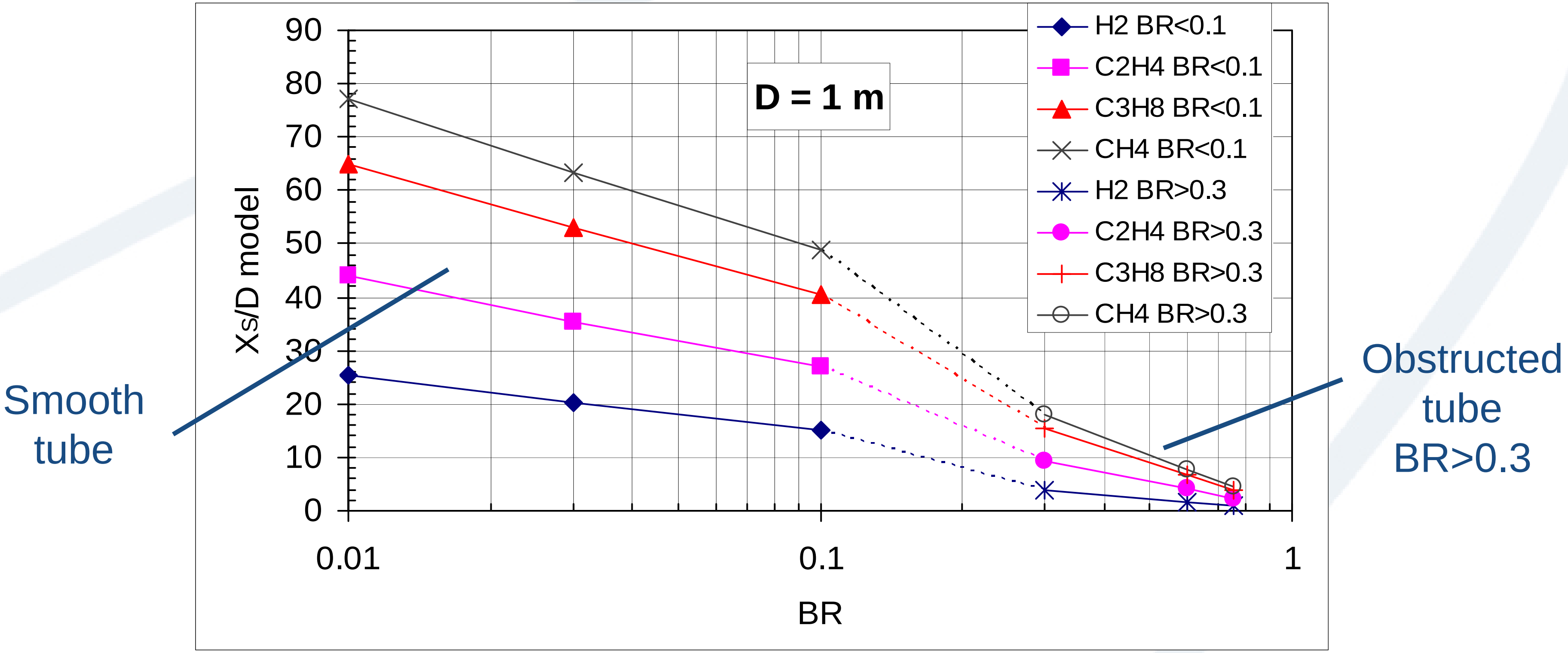
BR: 0.002 – 0.1; SL: 0.6 – 11 m/s

Csp: 790 -1890 m/s; D: 0.015 – 0.5 m

X_S/D: 10 - 80

Hydrogen and CH Fuels

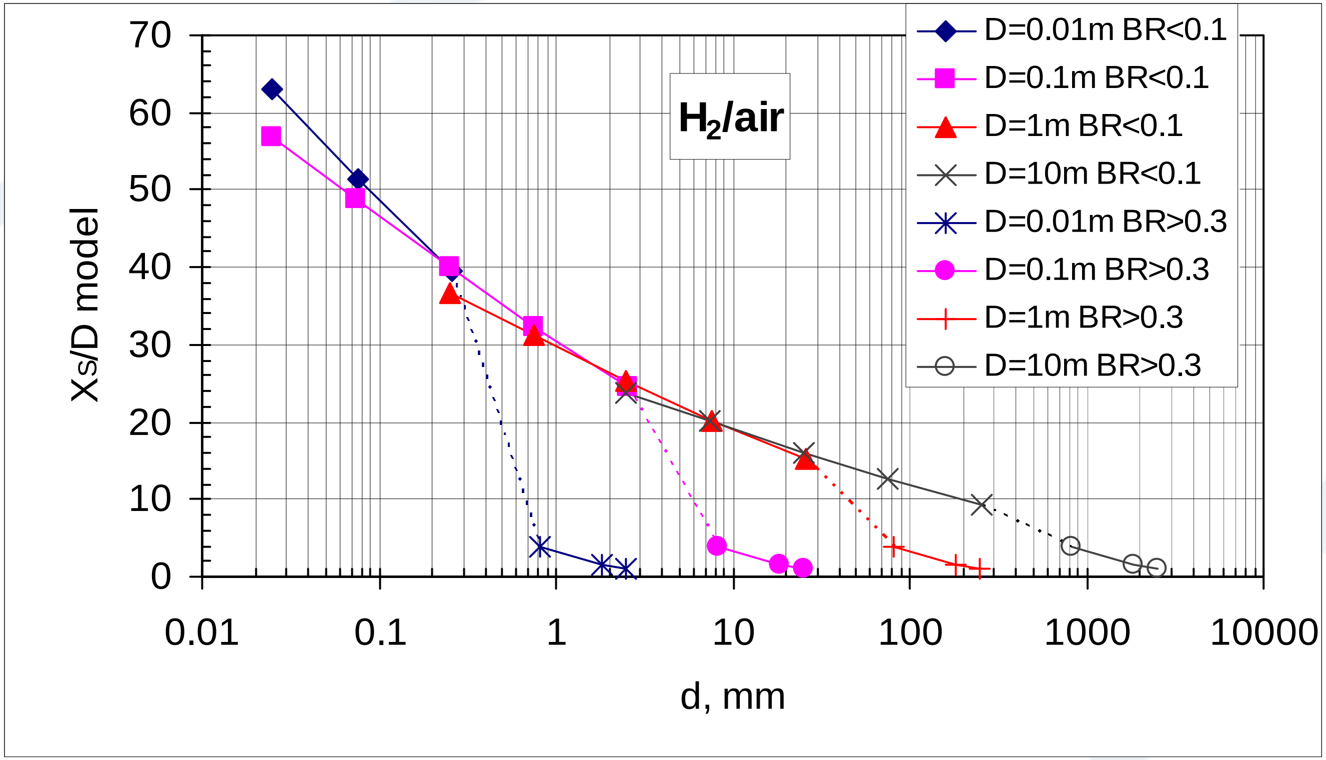
Run-up distances as a function of BR



- X_S/D decreases with BR for given D
- FA is strongly promoted by obstructions

Hydrogen

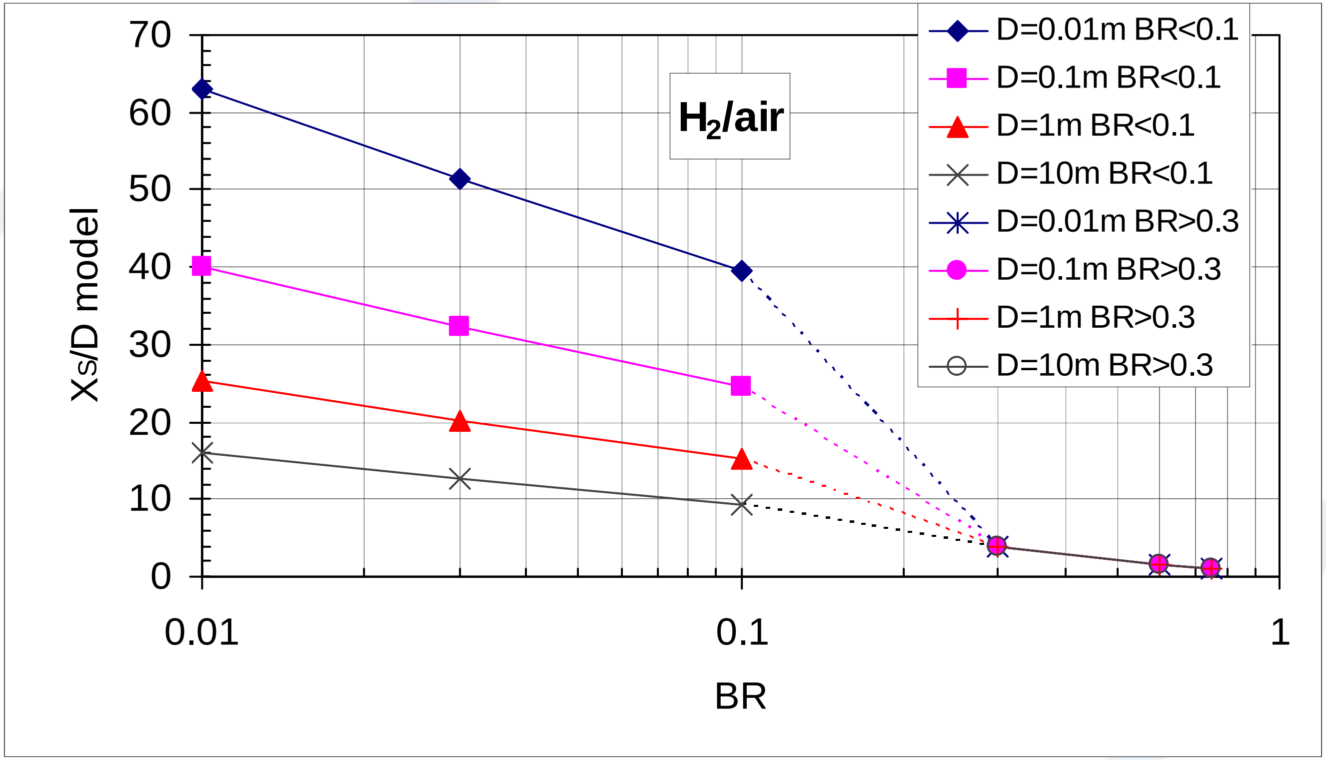
Run-up distances versus tube roughness, d



- X_S/D slightly decreases with D
- At sufficiently large d (so that BR>0.1) X_S/D drops

Hydrogen

Run-up distances for various D



- Smooth tubes: X_S/D slightly decreases with D
- Obstructed tubes (BR>0.3): X_S/D independent of D

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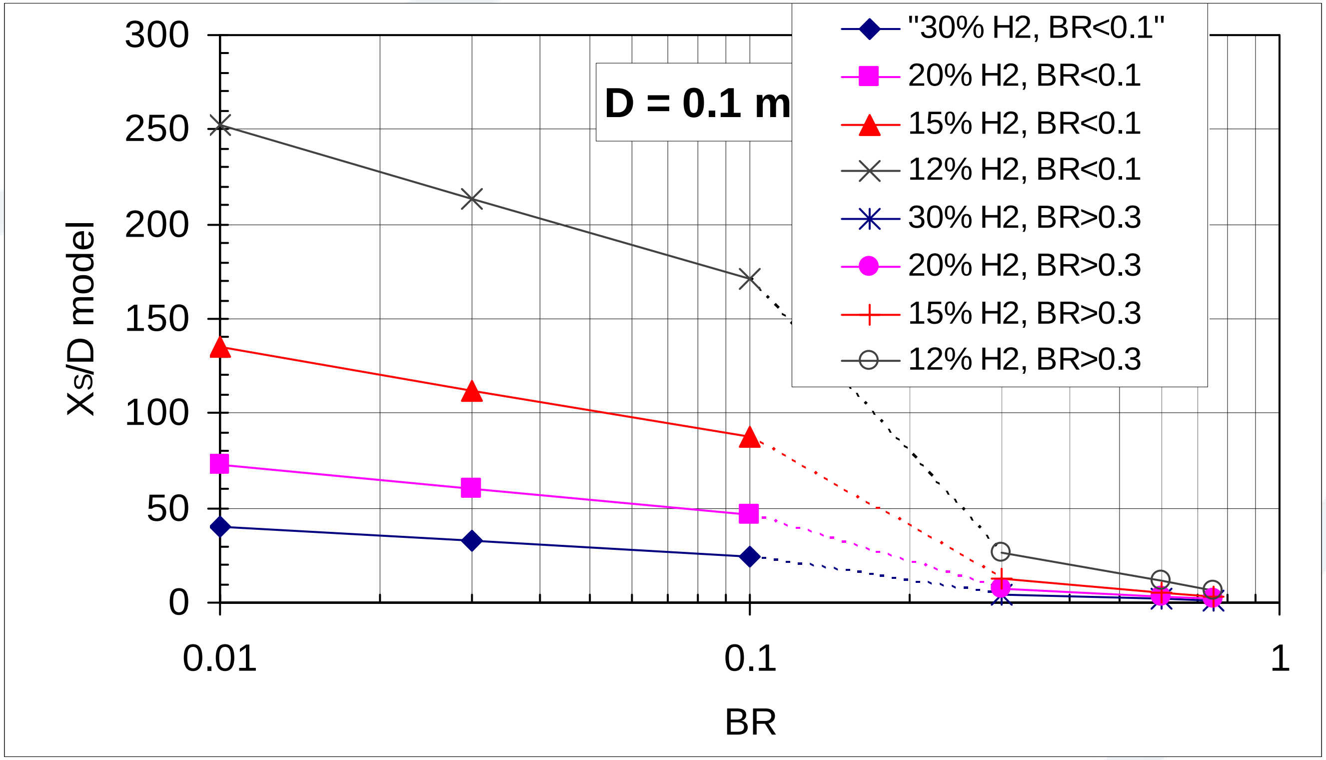
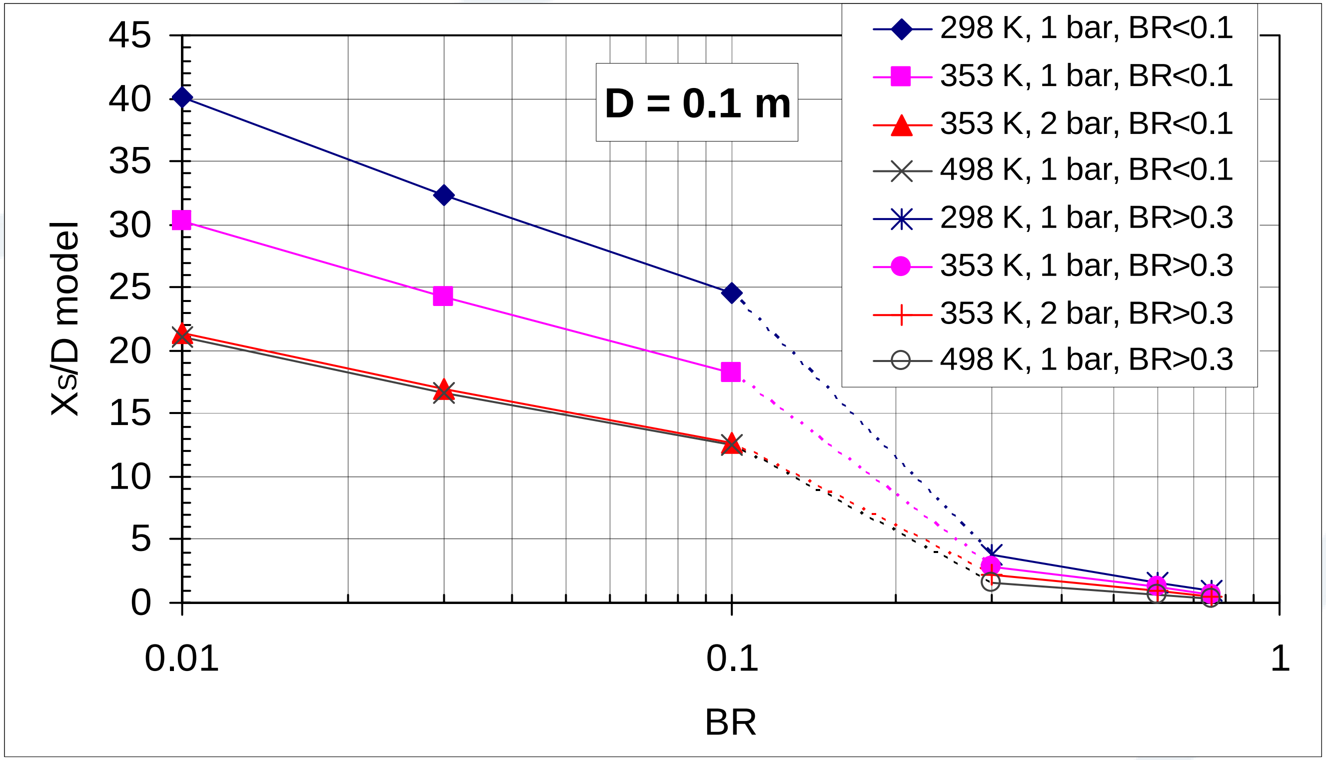
Effect of mixture composition



- Decrease of the H2 from 30 to 12% leads to the increase of the run-up distances by a factor of 5

Hydrogen

Effect of T and P on run-up distances



- Initial T and p affect S_L, C_{sp}, and σ
- Changes are specific to particular mixture

Concluding Remarks

- A set of approximate models for the run-up distances to *supersonic flames* in relatively smooth and obstructed tubes has been presented
  - These models attempt to capture physics relevant to FA in smooth and obstructed tubes
  - Show good agreement with the data in a wide range of mixture properties and tube wall roughness (or BR)
- The run-up distances depend significantly on:
  - mixture composition
  - initial T and P
  - tube size, and BR (or tube roughness)
- Each of these parameters should be taken into account in practical applications

Questions?