EXPERIMENTAL INVESTIGATION OF FLAME AND PRESSURE DYNAMICS AFTER SPONTANEUS IGNITION IN TUBE GEOMETRY

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Structure of the presentation

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- Experimental
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Introduction

Accidental hydrogen releases from pipe systems are one of the main hazards that occur in the handling of pressurised hydrogen.

It was shown in many publications, that in case of a sudden hydrogen release from a high pressure initial state into air self-ignition may occur if downstream the rupture location an extension pipe is present.

In experimental observations three cases are distinguished, no ignition, ignition with quenching of the reaction on the nozzle exit (failed ignition) and the self-ignition of the released hydrogen with a fully developed jet fire (ignition).

For safety applications and assessment it is important if an ignition is possible inside the tube and if this ignition leads to a fully developed jet fire in the ambient.

Objectives

The ideal shock tube theory is not able to explain all experimentally observed ignition events at the sudden release through a thin pipe.

The theoretical temperature increase is some times too low to ignite the mixture in the residential time of the mixing zone inside the tube.

It is assumed that inside miniature shock tubes other phenomena like boundary layer effects or reflection of shock waves are responsible for high temperature regions behind the shock.

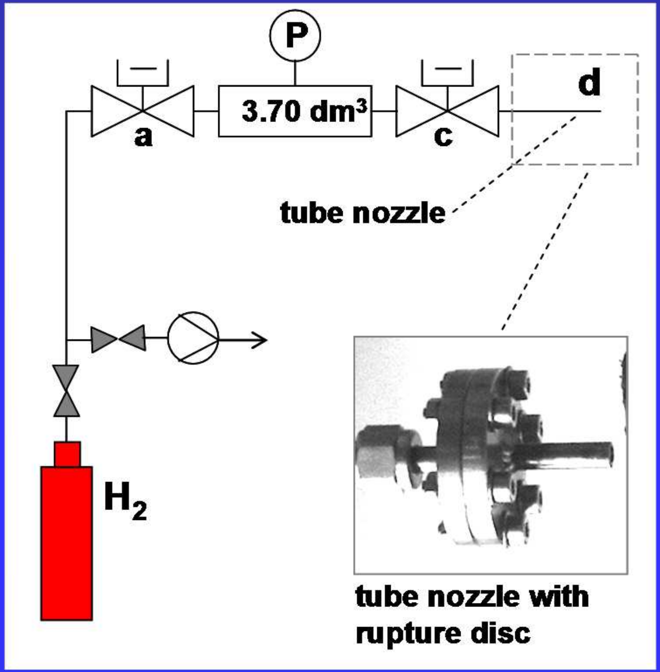
The goal of this work is to measure the pressure dynamic in 4 mm circular extension tubes downstream a rupture disc in combination with a visualisation of the radiating (reacting) zone in case of a spontaneous ignition due to the sudden release of pressurized hydrogen into atmospheric air.

Experimental set up:

The miniature open end shock tube facility:

A fast needle valve (opening time < 2 ms) is the connection between a pressurized H_2 storage vessel ($0.37 dm^3$) and a rupture disc holder.

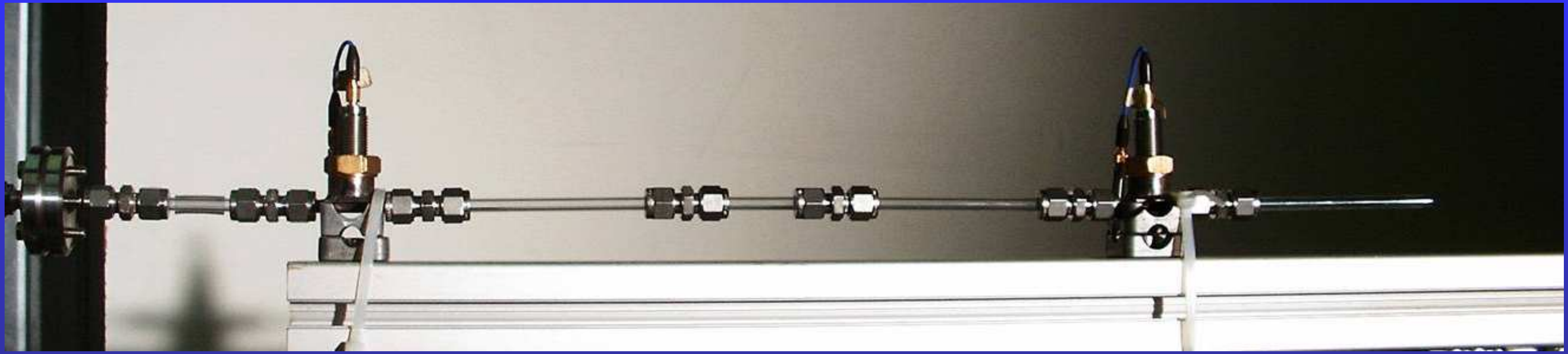
The rupture disc holder with different 4 mm cylindrical extension tubes is built from pressure sensor ports, industrial fittings and glass tubes.



Pressure sensor:

PCB dynamic tourmaline gauges (rise time 0.2 μs).

Optical observation via high speed camera.



Example of extension tube configuration.

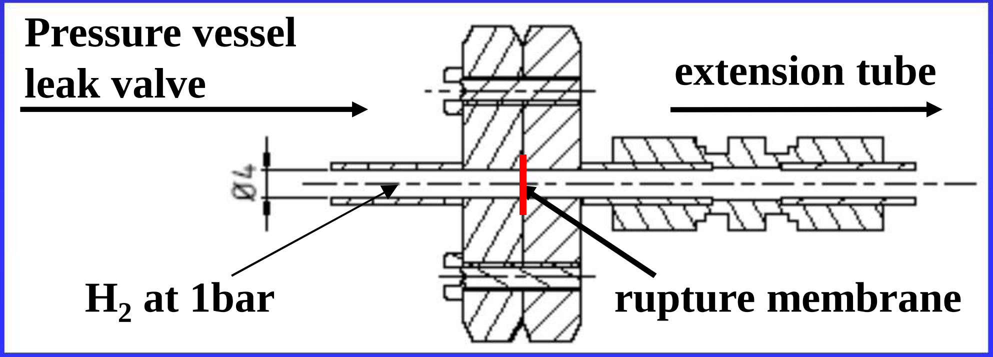
Experimental: Test Matrix

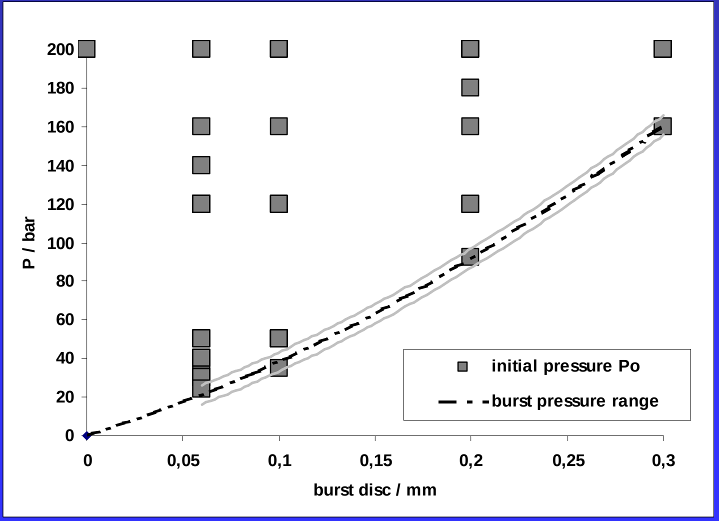
Range of bulk pressure P_0 / bar	Range of rupture disc thickness s / mm	Total tube lengths L_{total} / mm	Position pressure gauge P1 L_{P1} / mm	Position pressure gauge P2 L_{P2} / mm	Position pressure gauge P3 L_{P3} / mm	Transparent tube parts
20 to 200	0.0 to 0.3	132	80	122	-	-
50 and 200	0.0 and 0.1	1145	1093	1135	-	yes
25 to 200	0.06 to 0.3	645	593	635	-	yes
200	0.0 to 0.3	230	68	133	202	-
30 to 200	0.0 to 0.2	630	133	309	490	yes
50 and 120	0.06 to 0.2	720	52	581	-	yes
120 to 240	0.1	1040	52	-	-	yes
24 to 160	0.06 to 0.3	210	70	122		yes
120	0.06	633	52	133	494	yes

Different extension tube configurations, release pressures and rupture disc properties are used in the experiments.

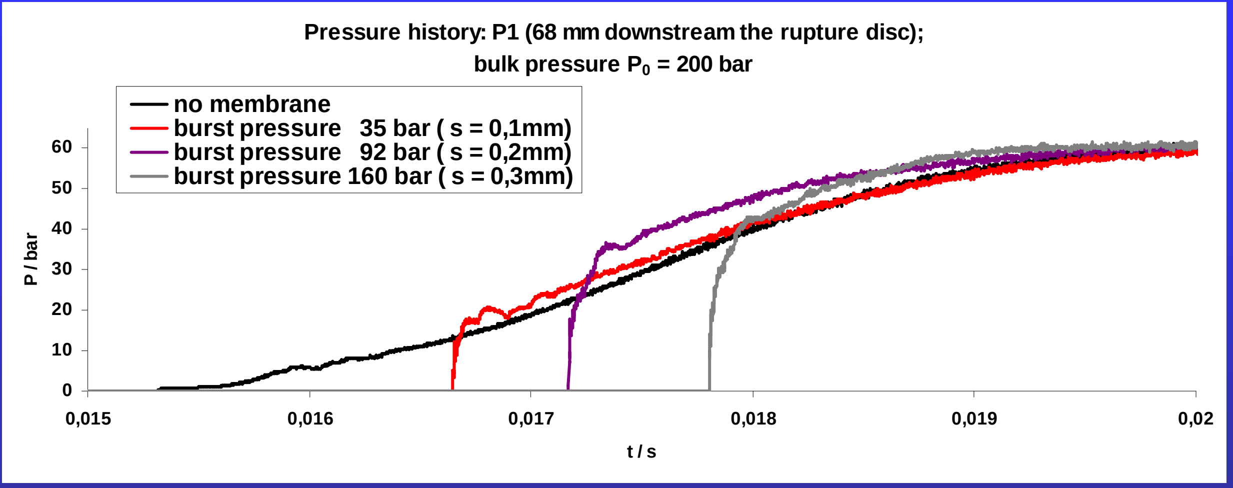
Experimental

Aluminum rupture discs (0.06 mm up to 0.3 mm) were used in the experiments.



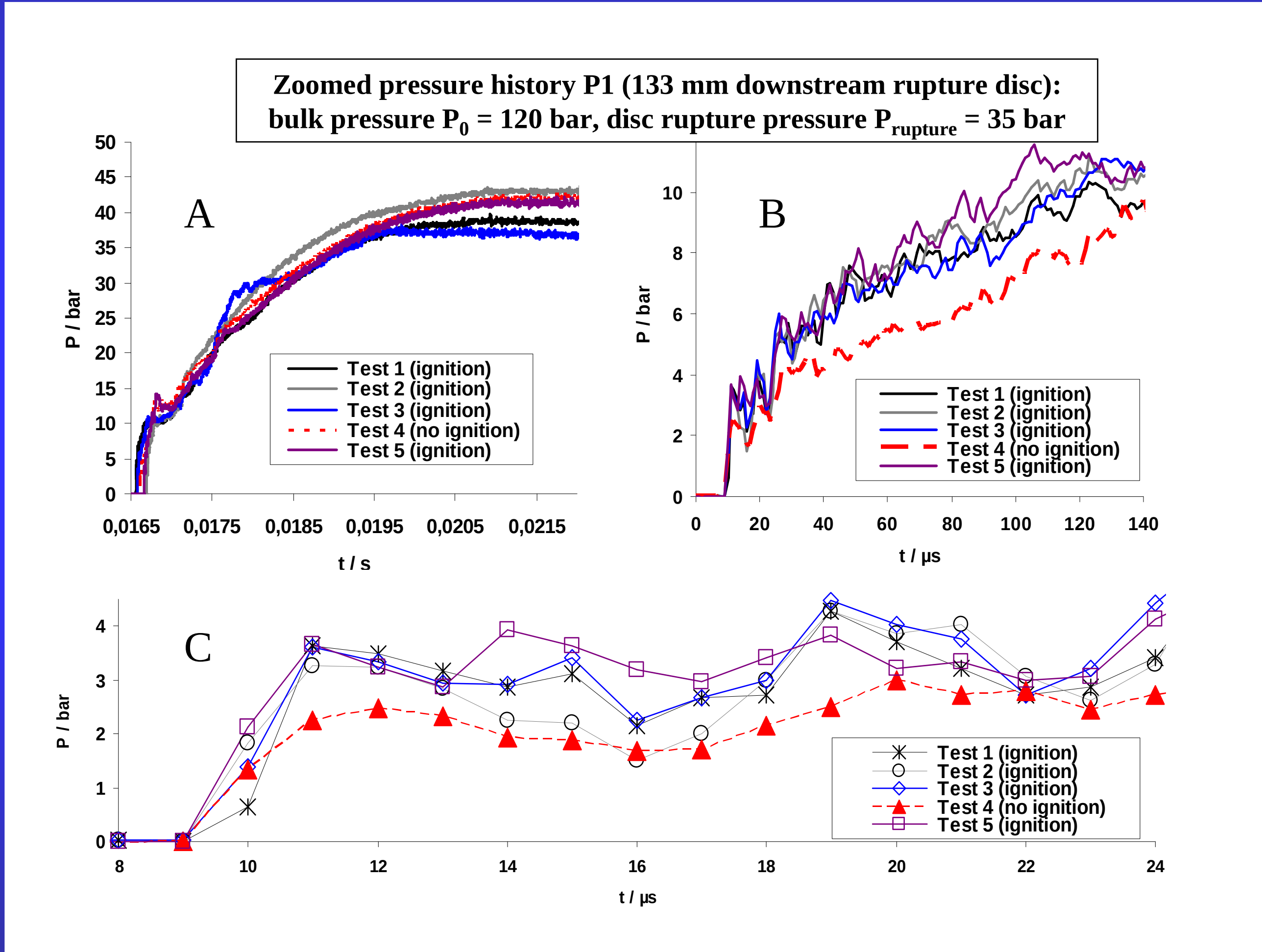


The initial flow from the leak valve first accumulates gas upstream the rupture membrane which blocks the nozzle pipe up to the point of the membrane rupture.



Test results:

Example: five experiments with the same initial conditions



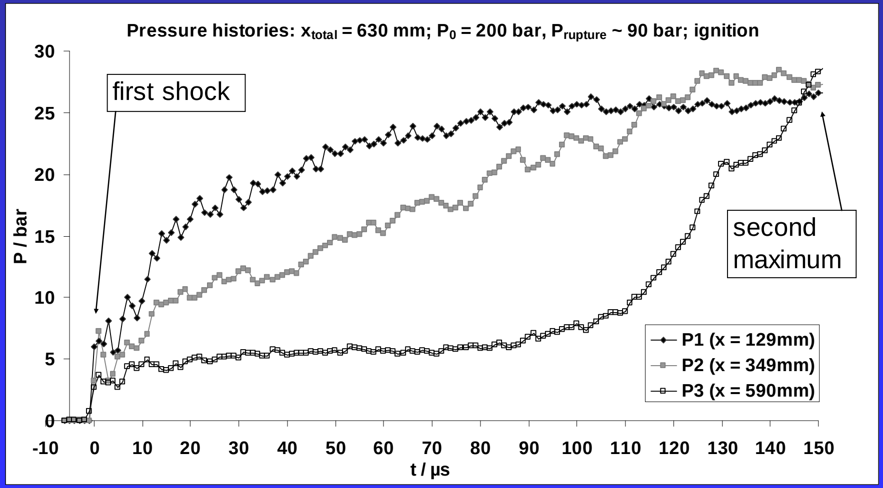
Pressure histories: 133 mm downstream the rupture disc for 120 bar initial release pressure.

Test results:

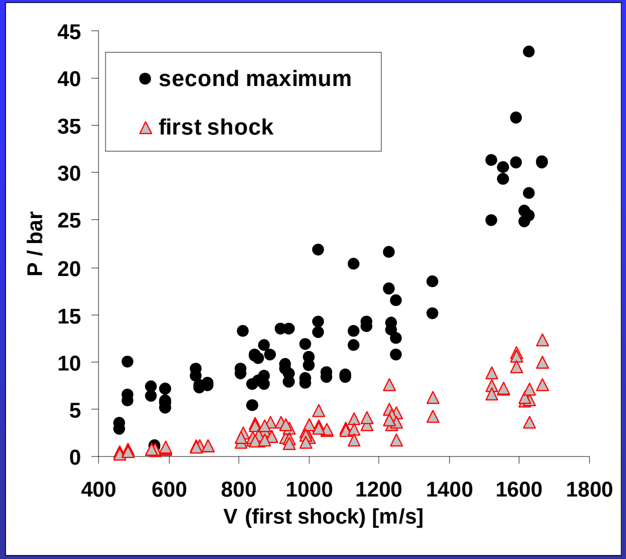
In all pressure histories two prominent points were identified:

⇨ **first shock**

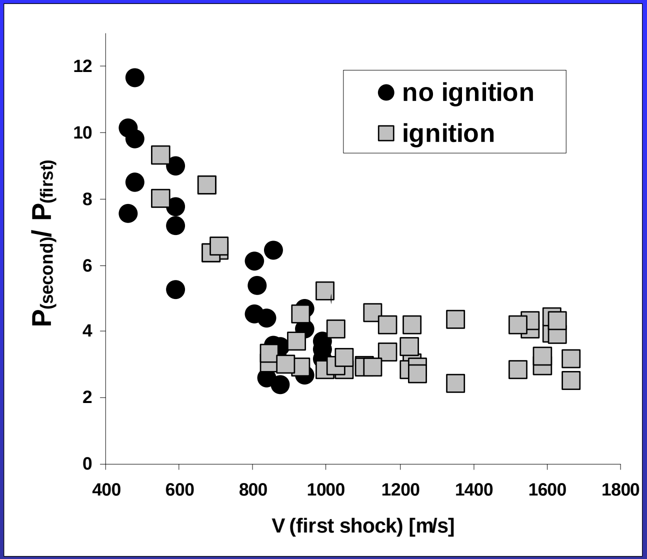
⇨ **second maximum**



Summary of the characteristic pressure levels

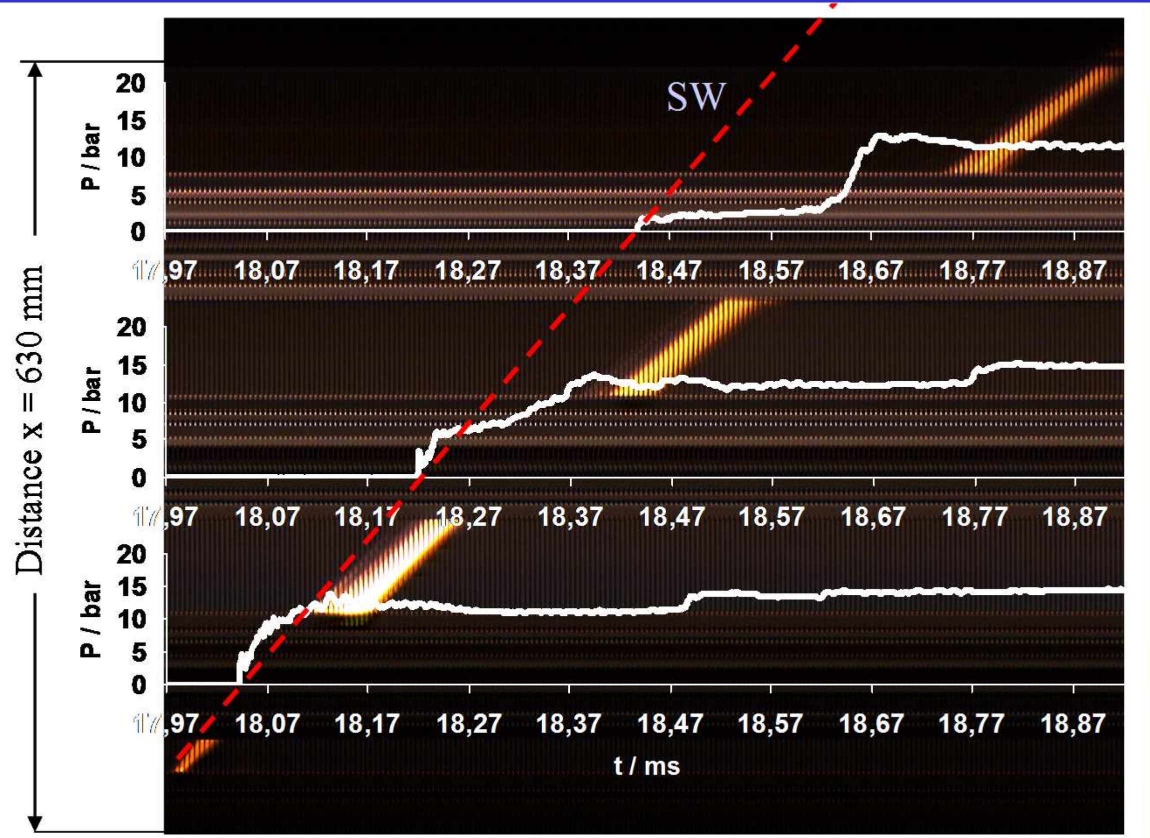


The shock wave velocities correspond to the flight time of the shock wave between two gauges.



Test results:

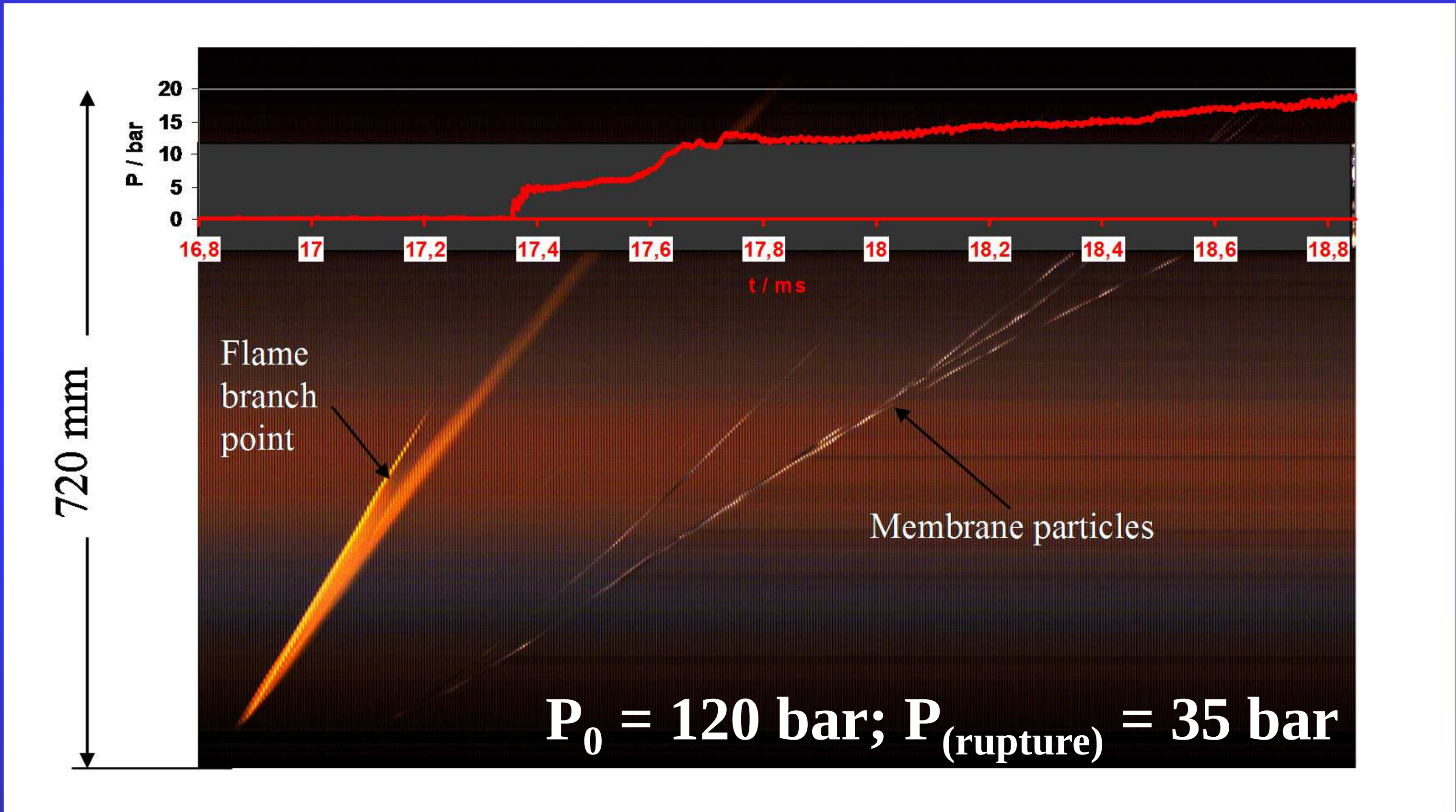
Flame propagation and pressure history



P_0 = 50 bar; $P_{(rupture)}$ = 35 bar

Test results:

Flame propagation and pressure history.



Discussion:

Calculated temperatures from experiments:

For a leading shock wave followed by a second compression, the temperature increase in the mixing zone can be formulated as a two step procedure.

first shock ⇨

$$T_{SW} = \frac{T_U(2\cdot\gamma\cdot M^2)\cdot((\gamma-1)\cdot M^2+2))}{(\gamma+1)^2\cdot M^2}$$

second maximum ⇨

$$T_{\max} = T_{SW}\cdot\left(\frac{P_{\text{second maximum}}}{P_{\text{firstshock}}}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}$$

Calculated values of ignition delay times (H_2/air):

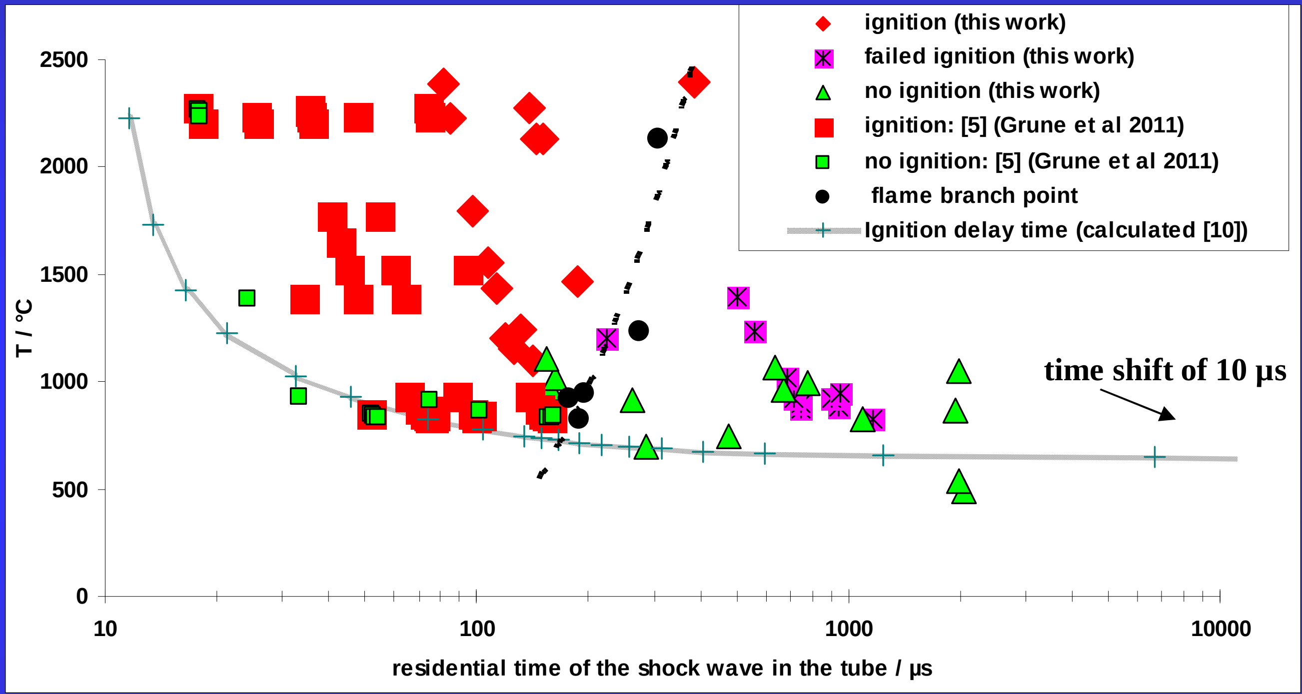
Cantera code with Lutz mechanism (1 bar and 20 ° C).

Goodwin, D.G., Cantera User's Guide, California Institute of Technology, Pasadena, CA, November, 2001

Lutz, A.E., Sandia Report SAND88-8228 (1988). K.A. Bhaskaran, M.C. Gupta, T. Just, Combust. Flame 21 (1973) 45–48.

Discussion: :

Summarized mapping of the experimental results:



Calculated ignition delay times vs. temperatures are plotted with a time shift of +10 µs.

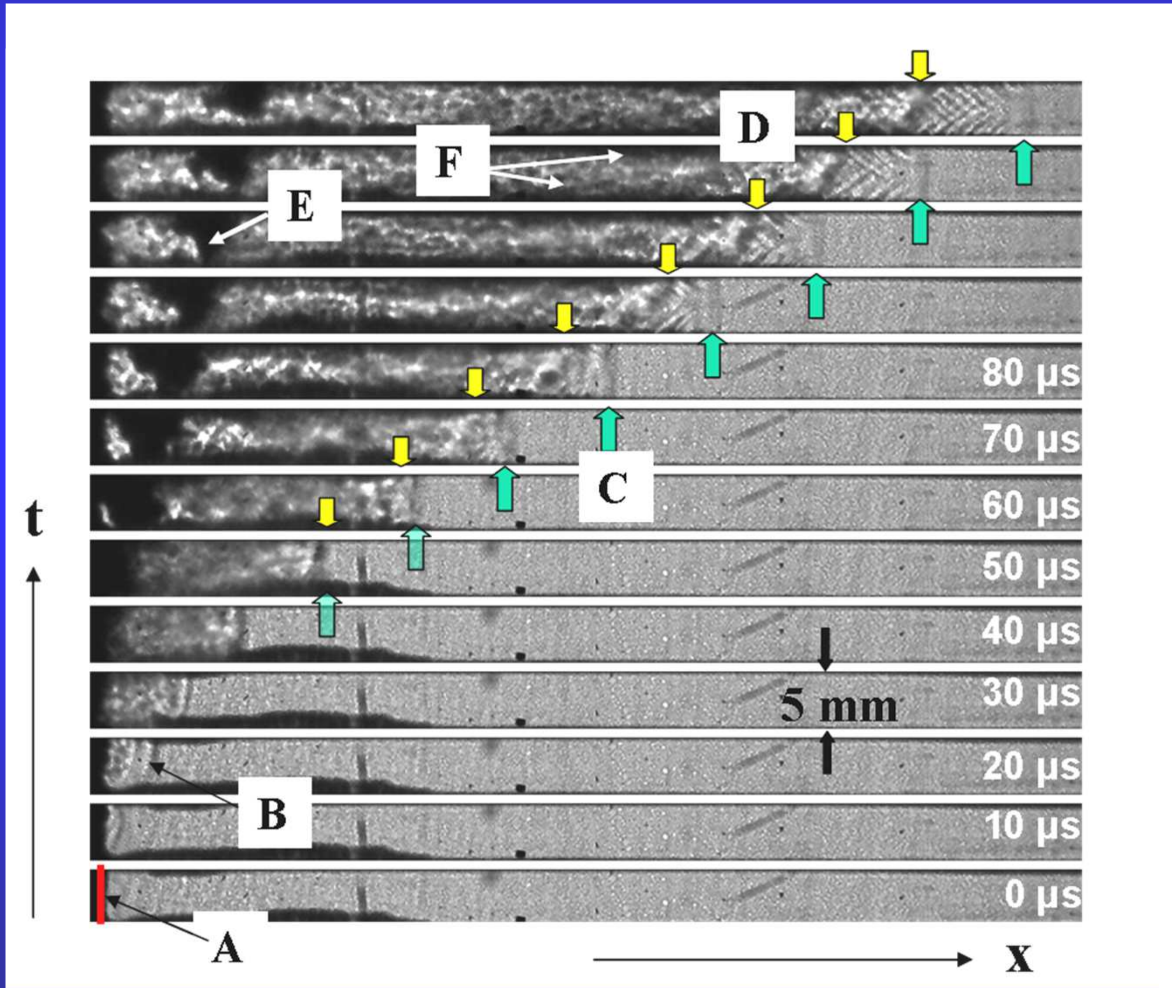
Flame branch point separates the ignition events with resulting jet fire from the cases without a resulting jet fire (failed ignition).

Flow visualisation via shadow graphs in a rectangular 5 mm tube

A distance of 2 to 3 tube diameters is necessary for the formation of a relatively planar leading shock

⇕

Start up time of the shock wave formation in a 4 mm circular tube is expected to be 10 µs to 20 µs.



Summary

An experimental investigation of the pressure dynamic in 4 mm circular extension tubes downstream a rupture disc in combination with the visualisation of the reacting zone in case of a spontaneous ignition due to the sudden release of pressurised hydrogen into atmospheric air was presented.

An ignition due to the sudden release of pressurized hydrogen into air was observed for a H_2 release overpressure of 30 bar inside a 645 mm long extension tube. In a shorter extension tube (42 mm) the limit for an ignition was found to be 25 bar.

The flame fans out with increasing distance of the flow in the nozzle exhaust direction. In long tubes a branching of the flame fan out in two directions (leading shock and main contact surface) was observed. If the point of the flame branching is reached no jet fire on the nozzle exit takes place.

The pressure histories measured inside the extension tubes downstream of the rupture membrane show non ideal shock tube characteristics.

Two prominent points were identified in the pressure histories: a first leading shock and a level of the second compression.

Temperature increase due to the first shock wave followed by adiabatic compression, demonstrates the possibility for a successful self-ignition and lies in a good agreement with theoretical predictions of ignition delay times.