IGNITION OF HYDROGEN JET FIRES FROM HIGH PRESSURE STORAGE

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ABSTRACT

Highly transient jets from hydrogen high pressure tanks were investigated up to 30 MPa. These hydrogen jets might self-initiate when released from small orifices of high pressure storage facilities. The related effects were observed by high speed video technics including time resolved spectroscopy. Ignition, flame head jet velocity, flame contours, pressure wave propagation, reacting species and temperatures were evaluated. The evaluation used video cross correlation method BOS, brightness subtraction and 1 dimensional image contraction to obtain traces of all movements. On burst of the rupture disc, the combustion of the jet starts close to the nozzle on the outer shell of it at the boundary layer to the surrounding air. It propagates with a deceleration approximated by a drag force of constant value which is obtained by analysing the head velocity. The burning at the outer shell develops to an explosion converting a nearly spherical volume at the jet head, the movement of the centroid is nearly unchanged and follows the jet front in parallel. The progress of the nearly spherical explosion could be evaluated on an averaged flame ball radius. An apparent flame velocity could be derived to be about 20 m/s. It seems to increase slightly on the pressure in the tank or the related initial jet momentum. Self-initiation is nearly always achieved especially induced the interaction of shock waves and their reflections from the orifice. The results are compared to thermodynamic calculations and radiation measurements. The combustion process is composed of a shell combustion of the jet cone at the bases with a superimposed explosion of the decelerating jet head volume.

1.0 INTRODUCTION

Hydrogen economy is currently increasing and spreading out to all branches of energy supply and mobility and still shows gaps in safety evaluation [1-3]. They require storage, transport and handling of hydrogen at all scales. Most likely storage technologies use low and high pressure vessels, cooled liquid hydrogen tanks and solid hydrides. Releases of hydrogen might occur on failures or accidents. The origin might lie in leakages, broken fittings or connections as well as openings/holes generated by fragment impact. On severe accidents on roads, including even the complete destruction of the storage could set free large amounts of hydrogen. All types of releases might ignition is probable for due to type the broad limits range of flammability and low ignition energy [4-6]. Storage or transport types as well as the occurred openings will dominate the resulting effects.

Small leaks or holes from hydrogen tanks generate normally a low momentum and ignition forms sustained laminar or turbulent diffusion flames which are buoyancy driven [7, 8]. The resulting flames sustain under nearly constant conditions. They are similar to laminar or turbulent diffusion flames investigated in detail in laboratories (see e.g. [9-11]). High momentum drives jet fires formed on failure of high pressure storage tanks or liquid tanks at ambient temperatures (see review in [7]). Fig. 1 shows such a jet deployment from LNG tank including ignition and explosion. Similar experiments were performed at Fraunhofer ICT with an industrial 70 l cryogenic liquid hydrogen tanks for automotive industry (BMW AG), whereas some results were published [12, 13]. The resulting transient jet pulsate with subsequent overlapping and last some seconds probably because of partially exhaust blocking by the initiated deflagration. Generated pressure waves were found to be moderately in the kPa range. Temperatures obtained by evaluated fast scanning IR spectroscopy were close up to 2000 K similar to those obtained of sustained turbulent jets. Some hot spots include temperatures up to 2400 K. More details on hydrogen jets emitted from cryogenic reservoirs were published in later work by other groups [14]. The jets from high pressure tanks depend on the release conditions, mainly vessel pressure, mass flow rate and momentum. The hydrogen jet head propagates at high velocities entraining air in a turbulent way. During such hydrogen release, an early ignition of the flammable hydrogen air mixture is more likely to develop into a sustained jet-fire. Research tries to measure the size (length and width) of the fire, the radiative properties depending on the release properties and the opening [14-27].

In this paper the results of highly transient hydrogen jets from high pressure reservoirs are presented which were obtained by high speed cameras and high speed IR cameras. The evaluation uses cross correlation techniques BOS, brightness subtraction and 1-dimensional image compression to analyze the jet, flame propagation, flame profiles and combustion behavior. The results are discussed with results presented in another paper to this conference [28].

2.0 EXPERIMENTAL SETUP

The experimental set-up to generate turbulent transient jets was established at the proving ground of Fraunhofer ICT. The site is shown in fig. 1. It consisted of a pressure reservoir of a volume of 5 l, which was able to store hydrogen with pressures up to 400 bar. A picture illustrates it in fig. 2. The head is composed of two sections shown in fig. 3. One is equipped with a rupture disc which opens at a pre-selected pressure and a nozzle to form a well-defined jet, which propagates into the field of view of the measurement equipment. The outlet for the jet was mounted horizontally. The diameter of the opening nozzle was 1 cm to discharge the reservoir completely at less than 1 s. After opening the hydrogen was released into the free air. 15 experiments were carried out and the results of three are reported here with hydrogen jets starting at initial pressures of 100, 180 and 260 bar.

The related mass flow rates correlate to the initial pressure and are 1484g/s, 964g/s and 489g/s at maximum and decay exponentially within 70ms, 76ms, 80ms (to 1/e of pressure maximum).

Some oscillations were found on the pressure time curves.

The applied measurement equipment consists of high-speed-cameras from Vision Research (R) Phantom V710 with pixel 1280 x 800 and frames 7530/s full resolution. 2 high speed Infrared Cameras were applied (CEDIP) with spectral range of 1.5µm to 5.3µm, frame rate 384 fps (full frame: 320 x 256px). A filter was installed to limit the radiation to spectral ranges from 1 µm to 2 µm.

In addition, fast scanning spectrometers for recording UV spectra and NIR/IR spectra were used which are described in a separate paper [28]. The hydrogen flame jet was observed at a length of 9 m from the emitting nozzle.

3.0 DATA EVALUATION

The high-speed-cameras were used with frame rates of 18003 fps. In order to improve Background-Oriented-Schlieren-method (BOS) a regular pattern of black dots was placed on a white surface behind the centre line of the jet flame (see fig. 1). The IR cameras observed 2 overlapping section of the flame jet. The frames were joined together to provide one composed image for the evaluation.

The frames were evaluated with various techniques of image processing especially needed as pure hydrogen jets and flames are nearly invisible in the visual spectral range. The BOS method uses a standard method of image processing [29] the cross correlation of neighboured images. It was proposed by the DLR Göttingen to the application to fluid dynamics [30, 31] and introduced to hydrogen research by Fraunhofer ICT [32, 33]. This procedure makes also very small effects in fluids visible, which are generated by fluctuations in densities.

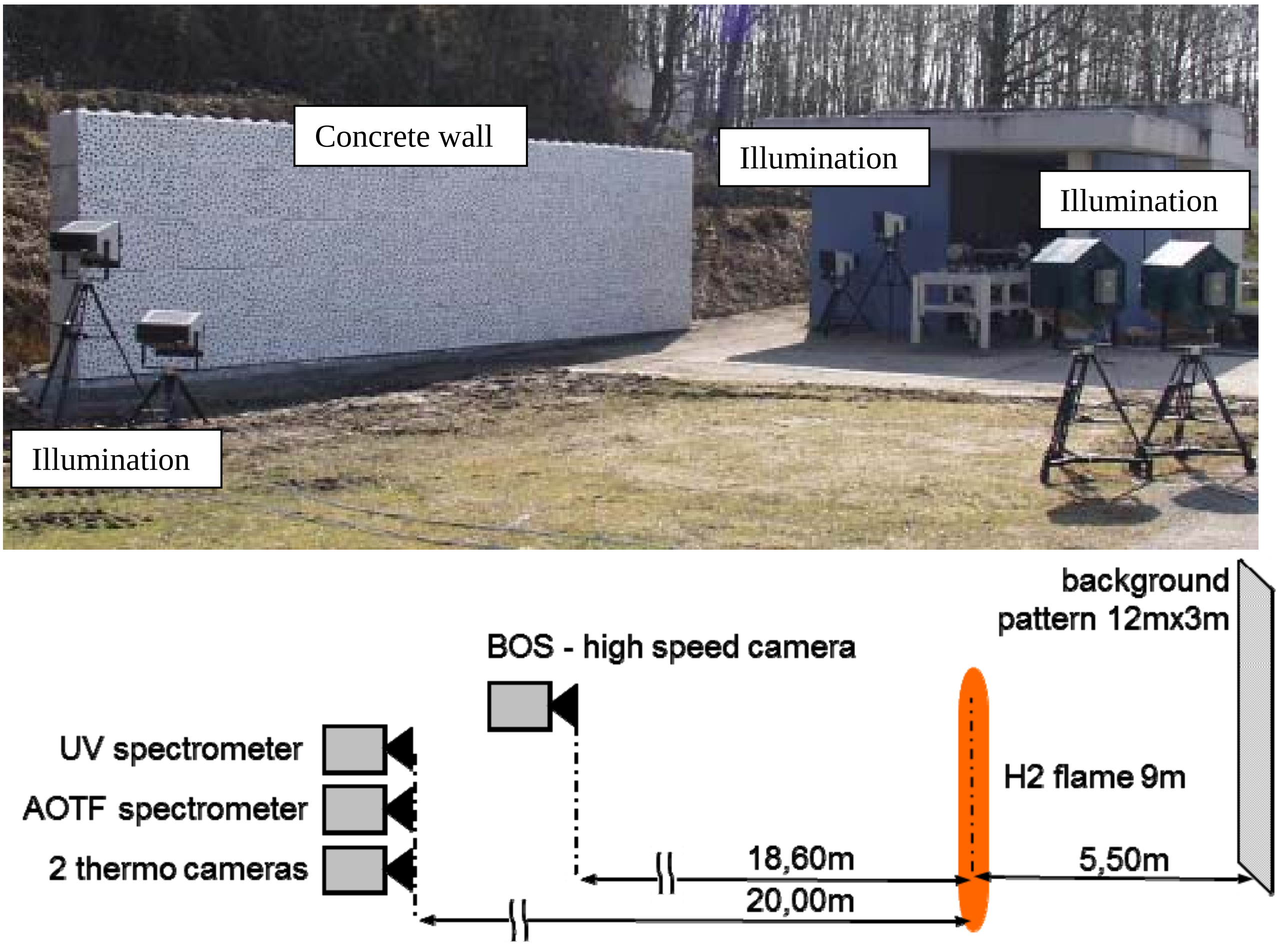


Figure 1: Proving ground at Fraunhofer ICT with a rocket test stand to be used for the pressure reservior and a scheme of the measurement equipment applied

Figure 2: 5 l reservoir usable up to 400 bar to generate hydrogen jets emitted at the left end

The brightness subtraction to achieve difference images is of a similar sensitivity which combines images from a pixel per pixel subtraction of neighboured or reference frames [34]. It is also possible to generate vector fields from the areas which are generated by the differences in the images occurring between the two involved images. The method applies for both, the high speed images as well as to IR images.

A contraction of images in 1 dimension leads to a substantial reduction of data to analyse. It was already successfully applied to quasi stationary hydrogen jets [24, 33]. It is especially useful for transient events, and delivers transient flame contours. Clear structures are obtained from difference images.

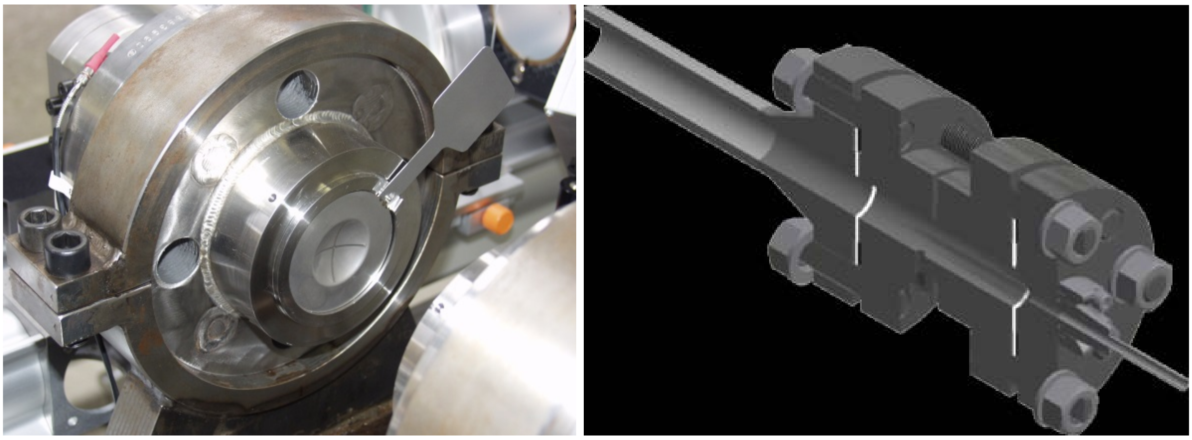
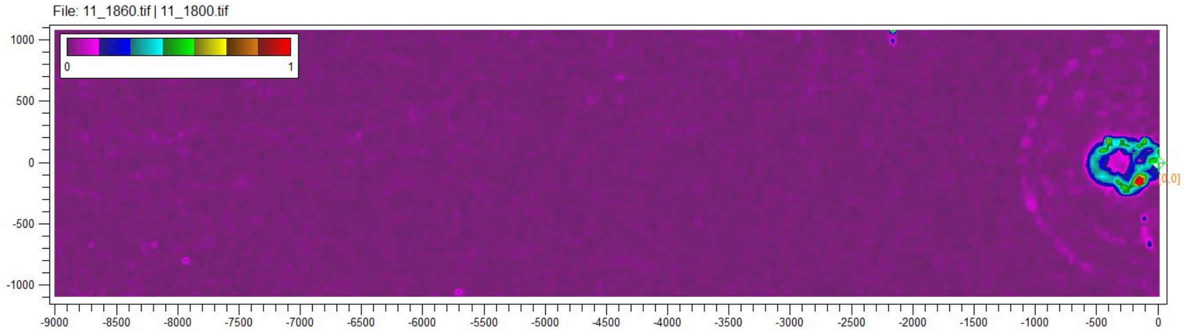


Figure 3: Rapture disc in front of the nozzle and scheme of the front end device

4.0 RESULTS AND DISCUSSION

The images of the high speed cameras provide in original version only the impression that there is something going on especially at a later stage of the event when the explosion at the jet head occurs. As expected, the BOS evaluation exhibits clearly the profile of the jet, the pressure wave from the rupture disc and the turbulent, fluctuating structures on propagation. The flame jet consists of a cone widening downstream at an angle of 25^{o} and an oval flame head. The cone shrinks with time due to the strongly decreasing hydrogen mass flow in time. Some BOS frames from a jet emitted at initial pressure of 100 bar at different deployment stages are plotted in fig. 4. The initial shock wave from the rupture burst is visible.

The time dependent profile of the jet head is obtained from the 1-D contraction of the images in direction of the jet propagation, therefor delivering a position-time curve of the jet head. A resulting contracted image series, plotted in fig. 5, shows the deceleration of the jet head according to drag. A calculated curve from a fit to a deceleration curve t(x) plotted in fig. 6 The edge fits nearly perfectly to with a constant drag coefficient. The resulting velocities decay exponentially with time. The initial velocities are 250 and 260 m/s



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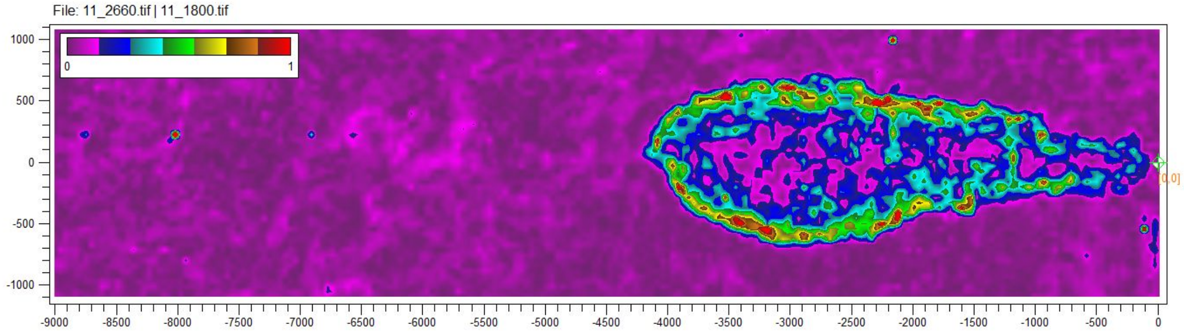

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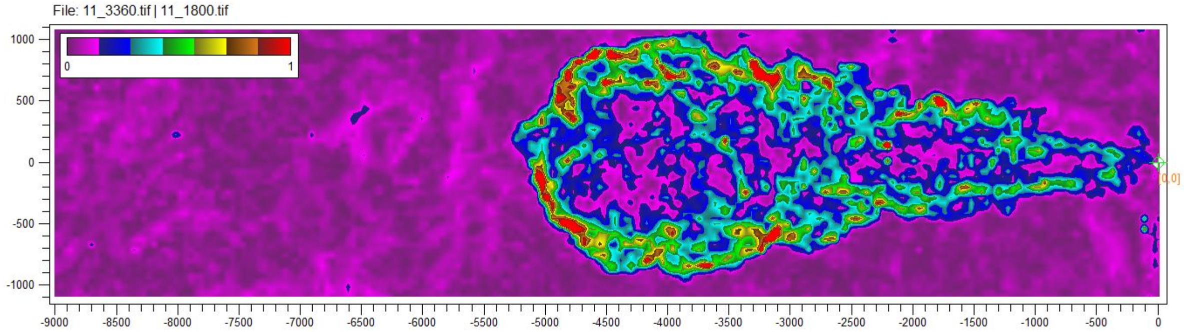

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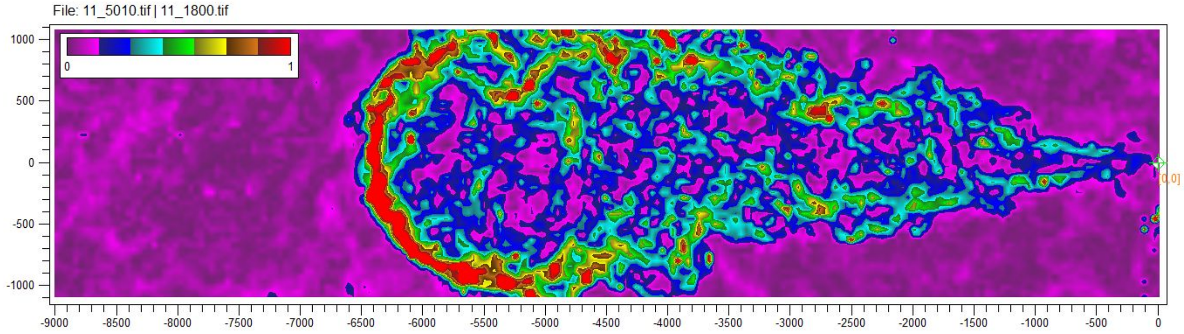

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Figure 4: BOS images from different stages of the flame jet deployment which make the structures clearly visible. Jet emitted at an initial pressure of 100 bar,

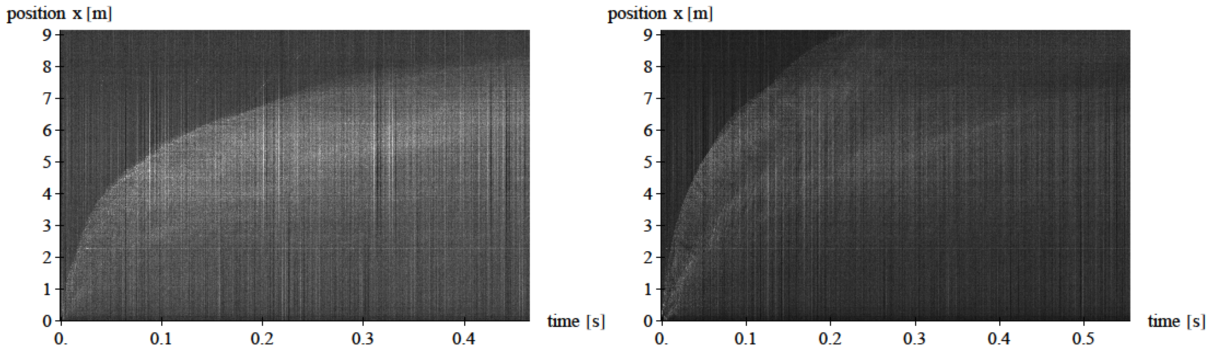


Figure 5: 1-D contracted procedure from different images to make the flame head visible, (left 100 bar, right 260 bar initial pressure)

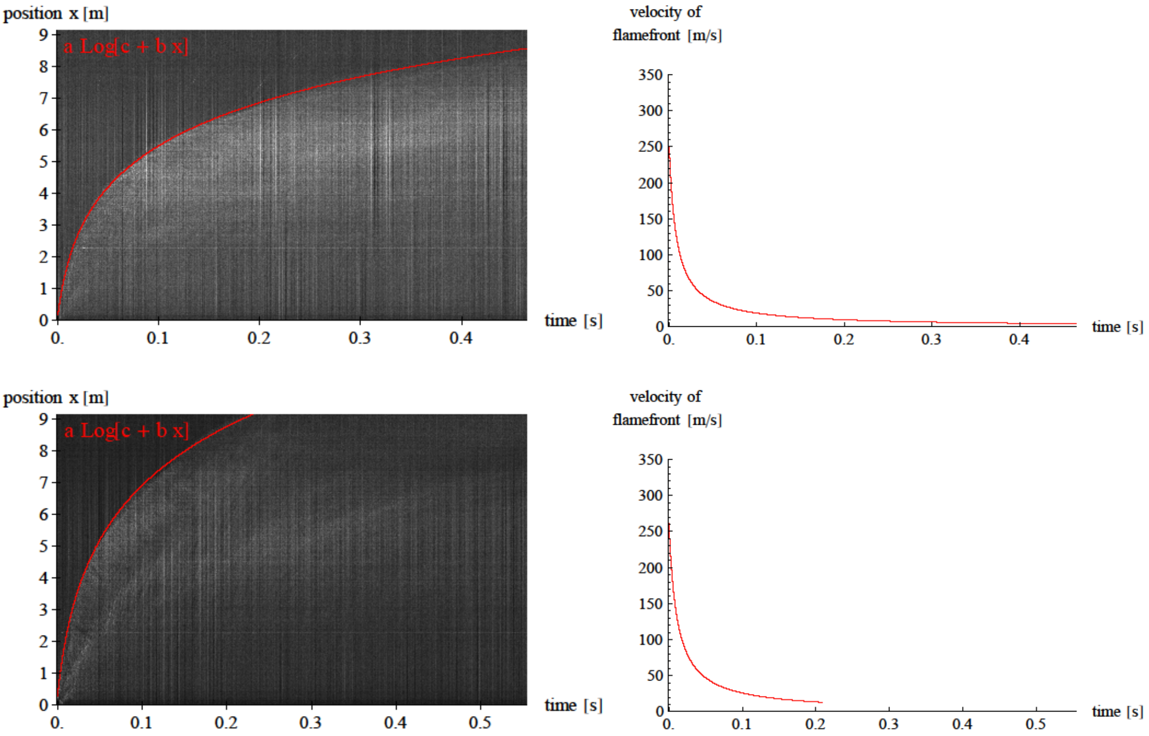
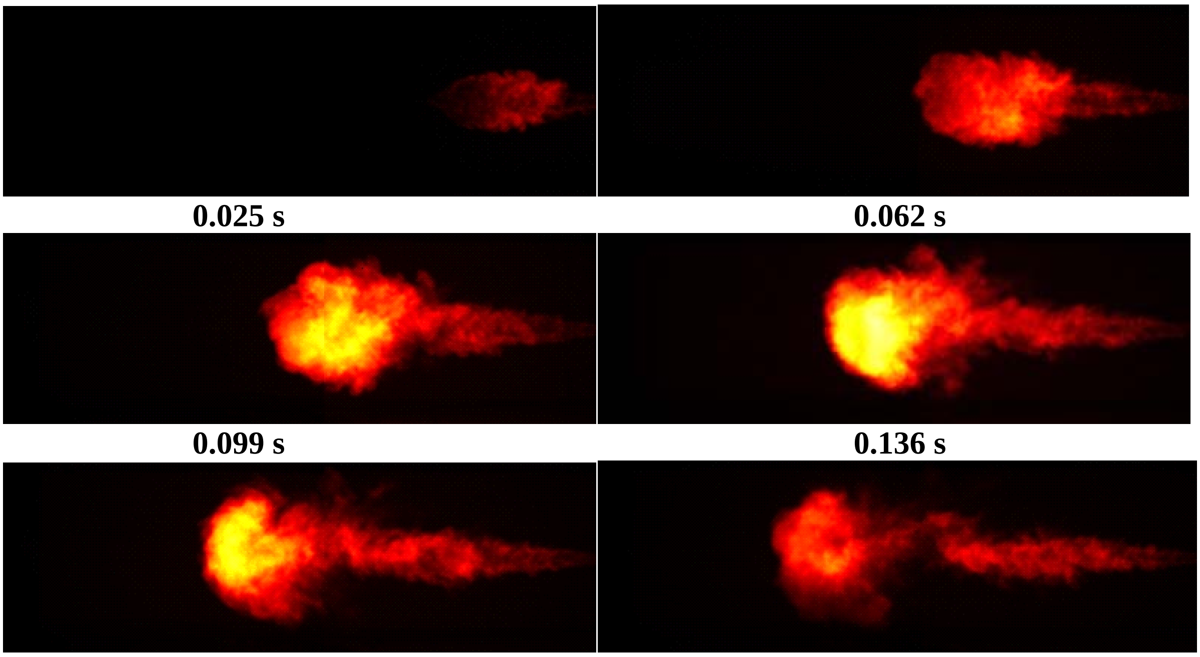


Figure 6: The profile of flame jet head and the curve of a decelerated movement by a drag and the transient velocity. (Top 100 bar, bottom 260 bar initial pressure)

The images from the IR camera are more impressive. The event is recorded at all stages as the ignition of the jet occurs instantaneously on opening. The hydrogen jet immediately ignites and expands close to the nozzle with a weak flame contour at the shell of the jet cone. A brighter zone caches up, and after about 0.05 s, it broadens to a very intense zone of radiation with approximately spherical shape.



0.025 s **0.062 s**

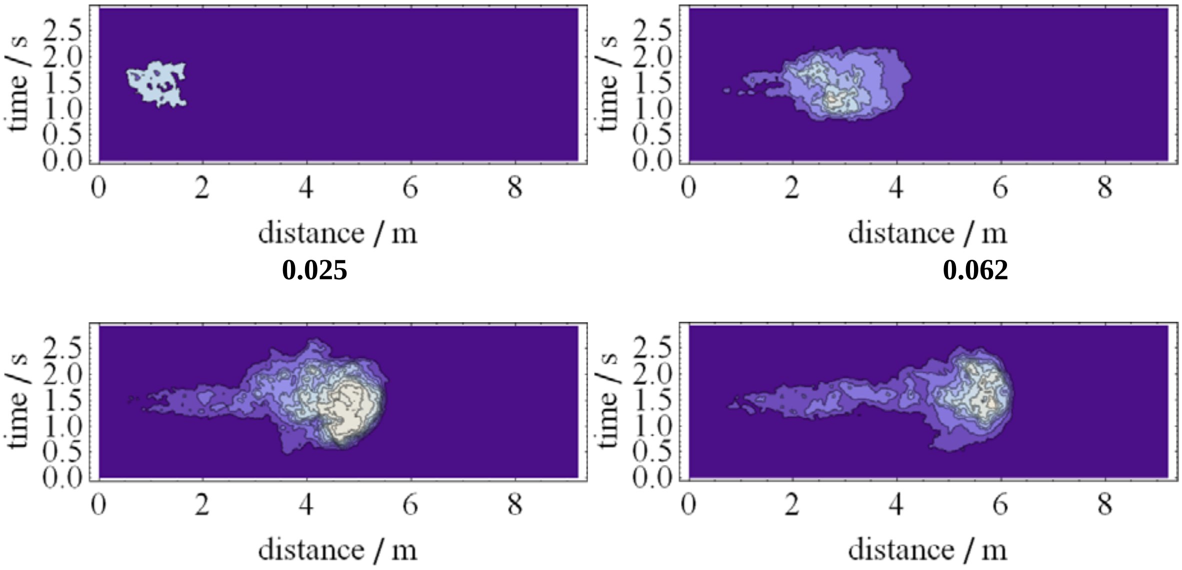
0.099 s **0.136 s**

0.173 s **0.210 s**

Figure 7: IR images at different stages from the opening of the flame jet (original direction of the jet)

The cone diameter shrinks on time and at low emission pressure the brightly emitting zone separates from the cone. At the end of the event buoyancy becomes notable. Fig. 7 depicts some stages of a jet emitted at 100 bar.

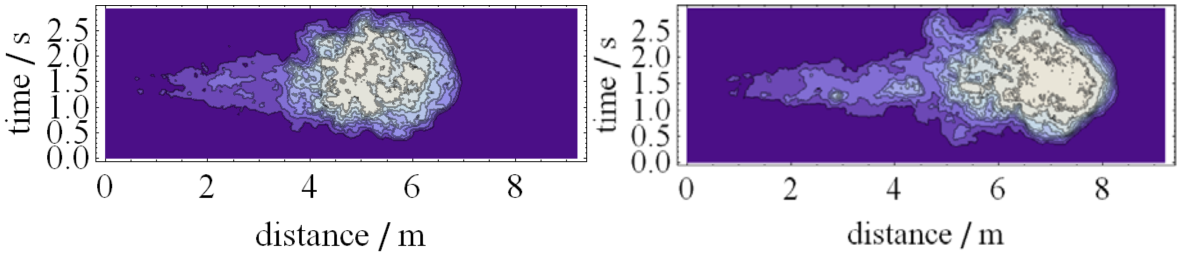
Contour plots of fig 8 and fig. 9 reveal more details and show that the bright volume at the head, the IR maximum intensity, exceeds the brightness of the cone more than twice. This bright volume at the jet head is assumed to occur as a hydrogen-air explosion. For the cone a combustion of the shell in contact with air is assumed



0.025 **0.062**

0.123 **0.185**

Figure 8: Contour plots of IR images at different stages from the opening of the flame jet (initial pressure 100 bar)



0.123 **0.185**

Figure 9: Contour plots of IR images at 2 stages of the fully deployed bright zone of the head (initial pressure 260 bar)

The bright volume at the jet head was separated by extracting the intensities surpassing the half of the maximum intensity. A morphological image processing operation recorded the centroid of the separated volume depending on time. In addition, the average volume and the equivalent radius depending on time were determined in similar way. The procedure was successful despite some scatting of data at the beginning the expasnsion of the bright zones. The centroids run parallel to the jet heads in a decelerating movement. Fig. 10 shows the results for the 3 initial pressures. The higher momenta of the higher initial pressures lead to higher distances achieved at the same time. The fronts of head are also plotted in fig 12 for the experiment with 100 bar and for that of 260 bar. The data from the front head are calculated with a deceleration parameter of 13.5 1/s for the 100 bar jet and 12 1/s for the 260 bar jet.

The equivalent radii of the bright zones are also consistent with the assumption of an explosion. After a strong rise the zone is nearly constant and then decreases because of lacking feed of hydrogen. Although the steep increases of radii show deviations from a closed volume (scattering of data), they can be approximated by linear curves which can be interpreted as flame velocities. The derived apparent flame velocities are close to 20 m/s for the various initial pressures: 100 bar =>17.8 m/s, 180 bar => 19.6 m/s, 260 bar => 21.3 m/s.

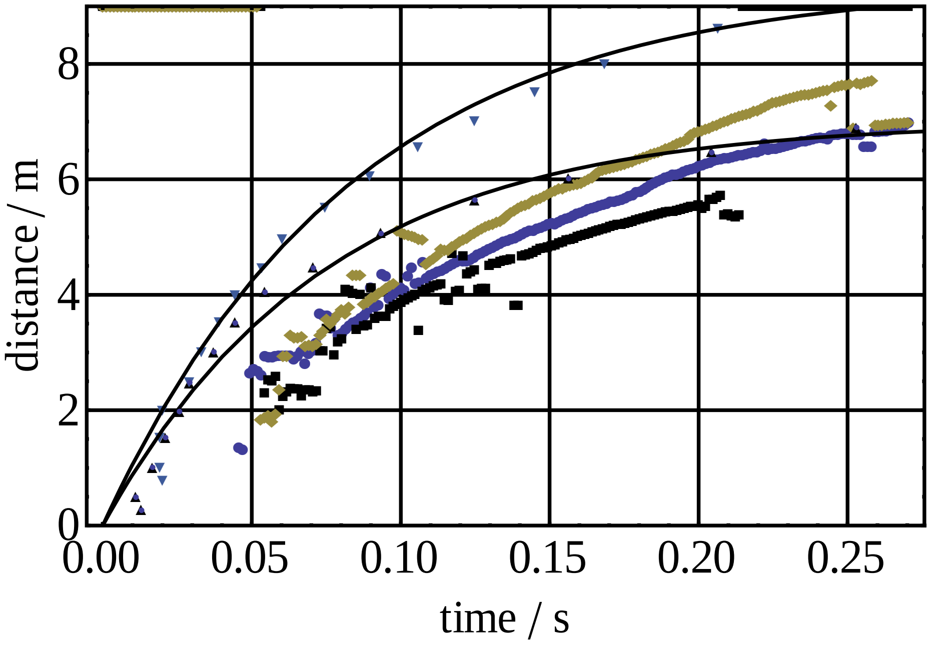


Figure 10: The position of the centroid of the bright zone versus time move similar to the advanced fronts of the jet heads (centroid: dense plot markers, front of head: sparse plot markers, calculated curves: solid lines), the higher distances always a assigned to the higher initial pressures

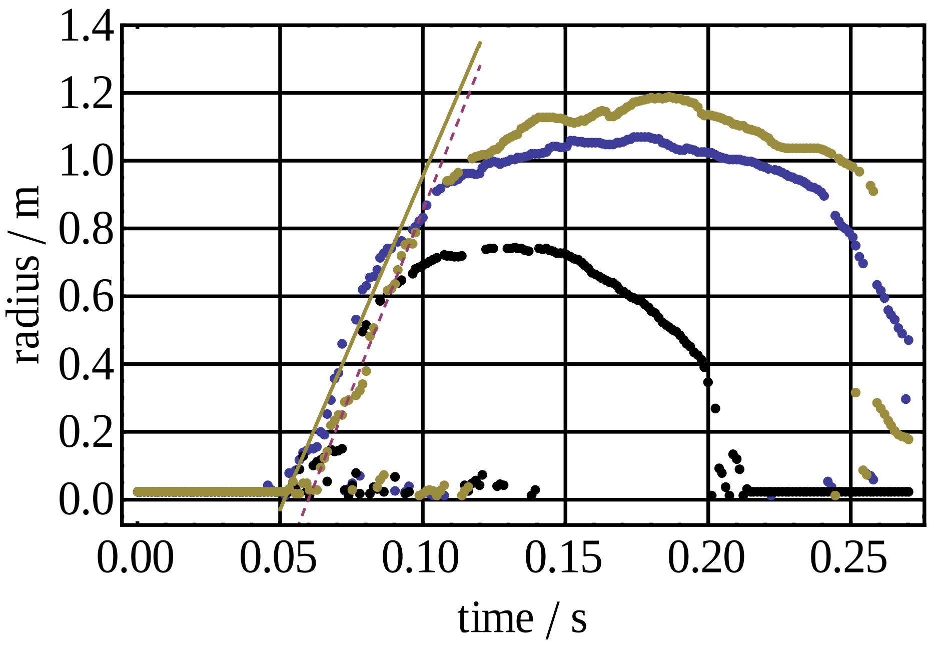


Figure 11: Equivalent radii for the deployment of the bright zone with linear rise of radii, 3 initial pressures

The 1-D contraction of the images was also applied to IR images. The edge profiles of the fronts jets are very similar to those obtained from the high speed camera (compare fig.5 and 6 with fig. 12). However, they show more details. Contracted images in direction of the height, shown with different scaling of the contour plots in fig13 exhibit clearly the deployment and movement of the bright zone at the jet head in different scales. The figure relates to the jet with 100 bar. At half scale the out flow of the hydrogen at lower pressures is revealed. Up to about 0.2 s this flow can feed the combustion in the bright zone. Above 0.2 s the cone separates from the bright zone. This separation occurs later for jets at higher initial pressures.

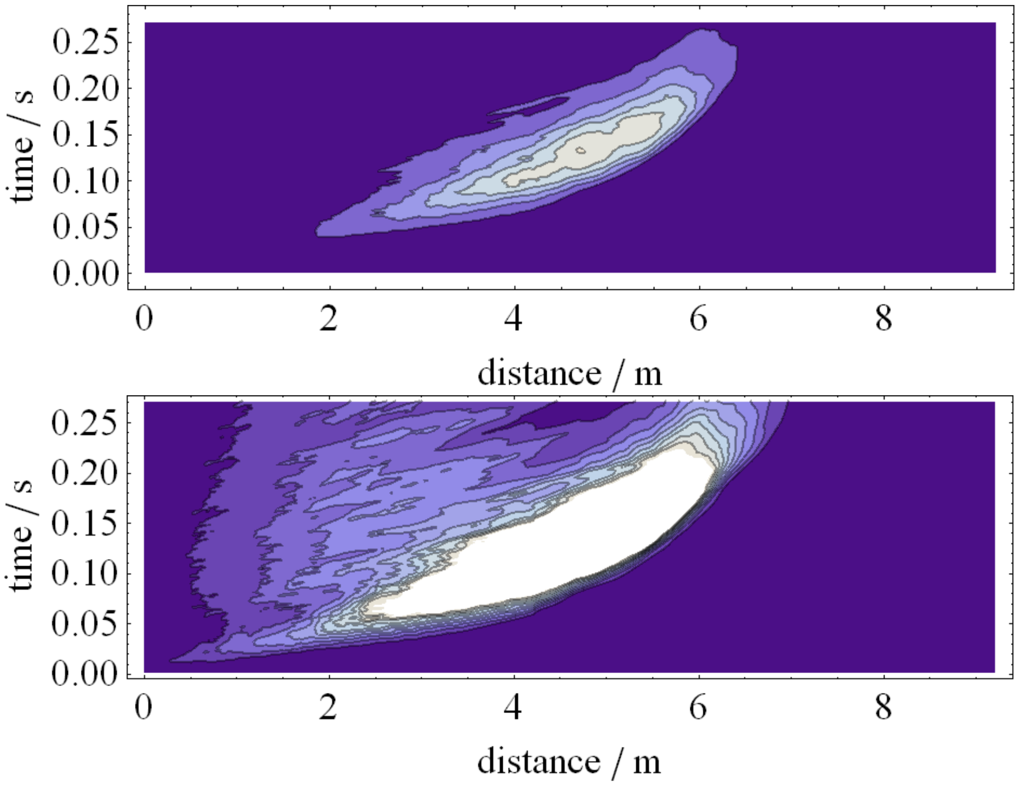


Figure 12: Contracted images in direction of the height for the initial pressure of 100 bar, shown with different scaling of the contour plots (top: full scale, bottom: cut-off at half scale)

Selected slices of the contracted images from 0.025 s to 0.123 for the initial pressure of 100 bar and 260 bar (fig. 13) confirm the assumption of a feeding cone and a occurring gas explosion. The excess intensity seems to be due to a distorted cross section of a sphere which propagates downstream.

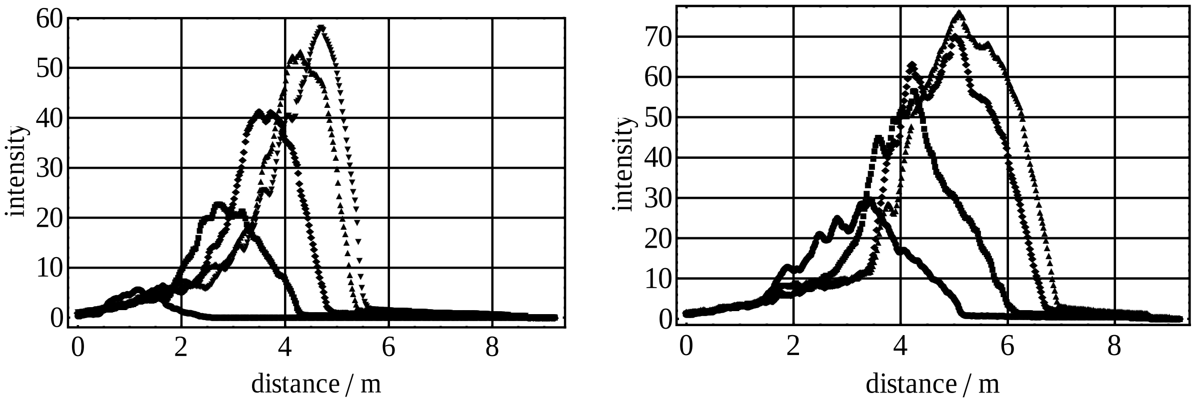


Figure 13: Selected slices of the contracted images from 0.025 s to 0.123 for the initial pressure of 100 bar (left) and 260 bar (right)

The contracted images in propagation direction show the development of the height of the flame jet as illustrated by fig. 14. Might be, after 0.13 s the jets form approximated Gaussian profiles at the bright zone with a notable buoyancy. But at the initial phase the contours in fig 15 shows 2 streams and fig 16 which shows slices of the contours with 2 peaks below 0.08 s. Such profiles are found for emissions from shells with a non-reacting core.

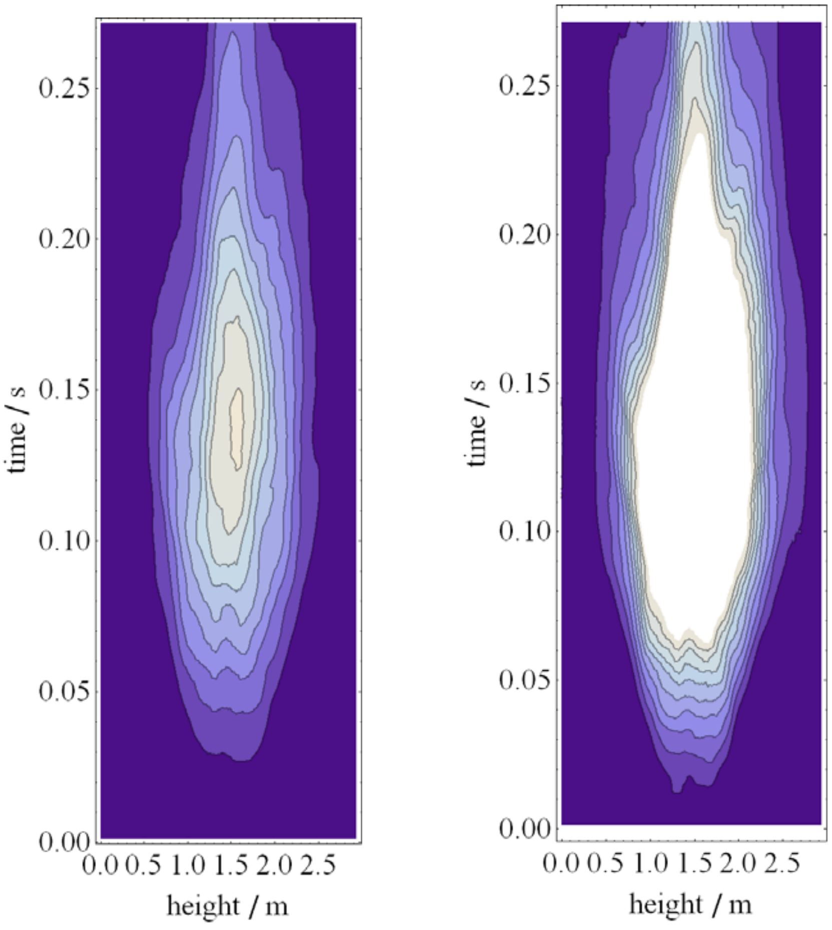


Figure 14: Contracted images in direction of the jet propagation corresponding to the height of it, shown with different scaling of the contour plots (top: full scale, bottom: cut-off at half scale)

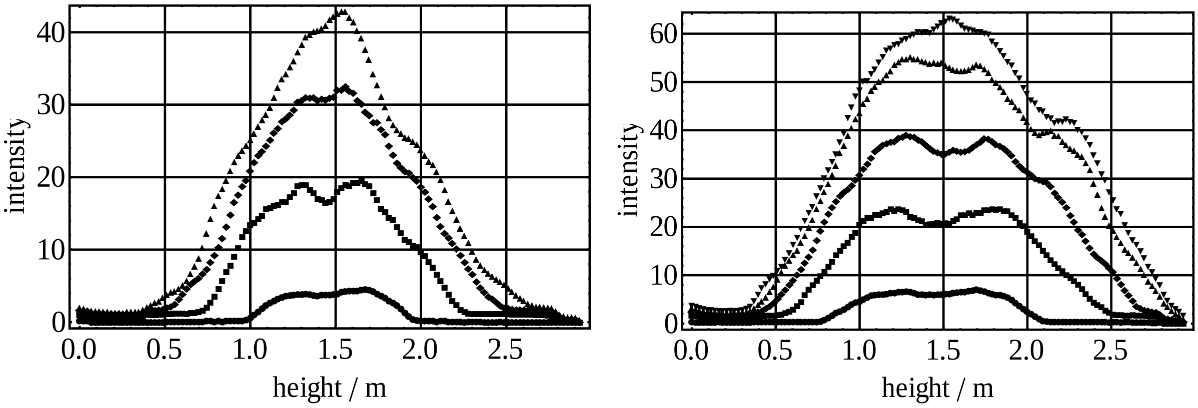


Figure 15: Selected slices of the contracted images (in direction of the jet propagation) from 0.025 s to 0.123 for the initial pressure of 100 bar (left) and 260 bar (right)

5.0 CONCLUSIONS

Transient hydrogen jets are formed on openings of high pressure tanks with a low volume related to the gas flow rate. The jet starts burning close to the opening at the outer shell. This combustion mode changes to a volume reaction forming a bright zone which might be approximated by an expanding sphere like a spherical gas explosion. The centroid of the bright zone moves parallel to the jet head. An apparent flame velocity was found to be close to 20 m/s. It moves downstream decelerated with a nearly constant drag coefficient to nearly rest and separates from the jet cone at the end. It dominates the radiation emission of the flame jet which is estimated in separate paper [28] based on this results on the jet shapes.

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