INTERACTION OF HYDROGEN JETS WITH HOT SURFACES OF VARIOUS SIZES AND TEMPERATURES

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Abstract
The formation of hydrogen jets from pressurized sources and ignition has been studied by many projects, also when hitting hot devices. In the paper presented at the conference 2 years ago, the ignition was caused by glow plug a “point like source” at various temperatures, distances of igniter and source and source pressures. In continuation of that work, ignition now occurred by 1 or 3 platelets of size 45 x 18 mm at a temperatures of 1223 K. When hitting these hot platelets, the resulting flame explosions and flame jets show interesting characteristics, in contrast to the point like ignition, where the explosions drifts downstream with the jet. Parameters of the experiments vary in initial pressure of the tubular source (10, 20 and 40 MPa), distance between the nozzle and the hot surface (3, 5 and 7 m) and temperature of the hot surface (1223 K). The initial explosions stabilize already at the stagnation point or the wake of the hot platelets. Furthermore, flames propagate upstream and downstream, depending on the pressure of the hydrogen reservoir and the distance. The achieved flame velocities vary strongly from 30 to 240 m/s. With all investigated hydrogen pressures strong reactions \( v > 40 \text{ m/s} \) occur at platelet distances of 3 and 5 m. The higher values are mainly achieved with jets with 40 MPa pressure at 3 m distance. In these cases the initial explosion contours show irregular shapes. Various effects are found like explosion separation, further independently initiated explosions and two parallel flame jets upstream as well as downstream.

1. Introduction
The storage of hydrogen occurs mainly by hydrides, in cryogenic tanks or by high pressure and induces specific safety problems [1]. The reactions of jets from ruptured tanks and tubes, as well as from pressurized storage [1-9] or cryogenic tanks [10, 11] show spontaneous ignition and emit pressure waves and thermal radiation. They start as moving gas explosions depending on various parameters, continued by a shortening of the turbulent flame on emptying the reservoir. The most important roles play the configuration of the nozzle and especially the pressure in the hydrogen reservoir, the temperature of the igniting device and the distance between nozzle and ignition device, give rise to theoretical approaches [12-15] and are topics of practical use and prevention [16, 17]. The details of gas jet interaction with hot surfaces are still an interesting objective and may induce scientific theoretical studies as well as practical configuration close to hydrogen storage containers and transport tubes. Depending on the properties of release and the mixture with air or oxygen determine the subsequent effects. The explosive reactions occur in wide ranges of fuel/oxidizer compositions with flame velocities of more than 100 m/s [18, 19]. The flame velocities are strongly enhanced by turbulence, especially in spherical explosions. The mechanisms are not fully understood, but turbulence is often assumed to be responsible, especially turbulence generated by the propagating flame front or may be by a hot barrier. However, the simulations need further experiments to describe all effects in detail.

The activities reported here consider hydrogen jets from limited resources, similar as those formed by broken tubes, transporting pressurized hydrogen and being shut on both sides on pressure drop. They are a continuation of a work presented at the preceding ICHS conference two years ago [20]. The reported experiments varied the initial pressure of the source between 2.5, 10, 20 and 40 MPa, the
distance from the nozzle of 3, 5 and 7 m and temperature from 600 K to 1200 K. A glow plug, simulating a point source, ignited the jets. Shortly, the major results were: Strong reactions (explosions) occurred at temperatures above 1000 K at distances of 3 and 5 m of the orifice. Spherical explosions evolved with velocities from 80 – 185 m/s which drifted downstream with the jet head, emitting acoustic waves. Upstream and downstream propagating flames evolved with velocities of about 40 m/s at a delay of about 0.0005 to 0.001 ms. Weak explosions occurred in the same way with flame velocities of 10 to 40 m/s. The temperature profiles enable an estimation of the radiation emission and gave flame temperatures between 2000 K and 2200 K.

The experiments reported here consist of a continuation with specified hot platelets of varied size at 1223 K temperature. By combination of image processing cross correlation and differences images the videos taken at 15000 fps could clearly relate the parameters of the experiment to the ignition and explosion propagation.

2. Experimental setup and data evaluation

The experimental setup is shown in fig. 1 (photos) and fig. 2 (scheme) as already presented in the prior paper. The setup to generate turbulent transient jets was established at the open air experimental plant building of Fraunhofer ICT (fig. 1 left). It consists of gas supply system with a pressure reservoir of a volume of ~5 l, which was able to store hydrogen at pressures up to 40 MPa and a concrete wall as a background for the jet investigation.

![Fig. 1: Open air experimental plant building of Fraunhofer ICT to be used for the high pressure storage tube (left) and the concrete wall, here with an ignited jet in front of it (right).](image)

The high pressure storage tube is operated using a fully remote controlled compressor system. It ensures safe operation even in black-out situations by safety positions of spring-loaded valves for depressurization of the high pressure tube, the hydrogen supply and the driving air interruption. The high pressure storage tube is opened by a rupture disc on reaching a defined pressure. Then the pressure decays exponentially in the tube. Initial pressure of the source varied between 10, 20 and 40 MPa, distance between the nozzle and the hot surface were 3, 5 and 7 m. The area of a hot platelet is 45 x 18 mm², maximum 3 platelets were placed in the given distance side by side with a resulting area of 54 x 45 mm². The experiments were focussed on one temperature of the hot platelet surfaces of 1223 K.

The jet data were similar as reported earlier [20]. The high speed video acquisition was performed using the sub-frame capability of the Phantom V710 high speed camera. Acquisition speed could be increased up to 15,000 fps at reduced resolution of 1280 x 400 px. As background for the recorded videos a mechanically stable modular concrete wall was applied. The wall was painted in white colour and stamped with an irregular black dot pattern to allow high speed video analysis of both, ignited and unignited jets under identical conditions. Together with the in total 24 kW illumination system, exposure times for the single frame of 5 µs could be realized.
The single frames of the high speed videos were evaluated with various techniques of image processing. This is necessary especially for pure hydrogen jets and flames because they are nearly invisible in the visual spectral range. First, the BOS method was applied to the recorded high speed videos. The BOS method uses a standard method of image processing, the cross correlation of neighboured images. It was proposed by the DLR Göttingen to the application to fluid dynamics [21, 22] and introduced to hydrogen research by Fraunhofer ICT [20, 23, 24]. This procedure makes also visible very small effects in fluids, which are generated by fluctuations in densities. Fig. 3 shows the results of two selected unignited 40 MPa experiments. The evaluation used image processing methods, image cross correlation [20-24], enhancing the contrast, brightness subtraction [26], de-pixeling and provide 2D contours [20]. 1-dimensional image contraction, perpendicular to the jet propagation, leads to traces of all movements [20] and gives 1D-profiles of the flames. These profiles along the jet propagation are used determine the velocities \( v \). The measurement of radiation might be obtained by time resolved spectroscopy [27-32].
and the first frame was calculated. Finally a compacting of one dimension perpendicular to the direction of movement was performed to reduce a 2D image sequence to a 1D profile of the non-compacted dimension and the time. This procedure creates an overview of the expanding jets and can derive the positions and velocities of explosions or upstream and downstream reactions in the main direction of propagation.

3. Results and discussion

3.1 Overview

Following the evaluation in the earlier paper [21], roughly, the results are classified by the criteria of observed flame speeds and pressure records and use “no”, “weak” (flames speed < 30 m/s) and “strong” (flames speed > 30 m/s) reactions. Strong turbulence mainly induced by high reservoir pressure jets is obviously a reason for “strong” reactions. Longer distances dilute the hydrogen air mixture and attenuate the reaction. The entrained air can be estimated by analysing the CO₂ emission at 4.2 µm [29]. An overview of the results is given in Tab. 2-4 in that paper [21] where also the shapes of the jets before the ignition are described, as well as flame profiles, diagrams of position versus time and flame contours. Despite some discrepancies these results in the tables show that high temperatures and pressures at small distance lead to “strong” reactions.

The 20 experiments reported in this paper focus on a temperature of the ignition source of 1223 K and the distances of 3, 5 and 7 m, however with hot platelets as ignition source. These small platelets induce already substantial effects on the ignition and flame propagation.

An Overview on the results of in detailed evaluated experiments is given in tab.1. Highest velocities are observed of jets from the 40 MPa tube at a distance of 3 m. In the initial stage the flames strongly fluctuate especially the flame evolved at the 3 platelets. The time delay of the occurrence of a first flame is very close to the arrival of the hydrogen jet head and is about 0.0001 - 0.0002 s, delay times, longer than simulated [33].

Table 1: Strong reactions with delay times after jet arrival of approx. 0.0001-0.0002 s in all cases.

<table>
<thead>
<tr>
<th>Tube pressure [MPa]</th>
<th>Distance [m]</th>
<th>Number of platelets</th>
<th>Jet arrival at hot platelets [s]</th>
<th>v of initial explosion [m/s]**</th>
<th>v upstream</th>
<th>v downstream [m/s]***</th>
<th>Ignition at</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>3</td>
<td>1</td>
<td>0.041</td>
<td>39.6</td>
<td>73.3</td>
<td>20.8</td>
<td>wake</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
<td>3</td>
<td>0.040</td>
<td>76.5</td>
<td>46.1</td>
<td>32.4</td>
<td>front stagnation and wake</td>
</tr>
<tr>
<td>20</td>
<td>3</td>
<td>1</td>
<td>0.037</td>
<td>83.2</td>
<td>54.8</td>
<td>40.4</td>
<td>wake</td>
</tr>
<tr>
<td>20</td>
<td>3</td>
<td>3</td>
<td>0.036</td>
<td>84.8</td>
<td>164.2</td>
<td>35.2</td>
<td>front stagnation and wake</td>
</tr>
<tr>
<td>40</td>
<td>3</td>
<td>1</td>
<td>0.02</td>
<td>213</td>
<td>241</td>
<td>111</td>
<td>wake</td>
</tr>
<tr>
<td>40</td>
<td>5</td>
<td>1</td>
<td>0.07</td>
<td>44.9</td>
<td>43.5</td>
<td>51.1</td>
<td>front stagnation</td>
</tr>
<tr>
<td>40</td>
<td>3</td>
<td>3</td>
<td>0.02</td>
<td>200-300 initially, 140.9</td>
<td>118.1</td>
<td>76.2</td>
<td>front stagnation and wake, irregular flame structure</td>
</tr>
</tbody>
</table>
The observations of the experiments can be summarized as followed:

1. All of the experiments with distances of 3 and 5 m led to strong reaction.
2. At least two explosions are ignited: one at ca 10 - 30 cm in front and one 10 - 30 cm after the platelets, nearly at the same time or successively. The explosions overlap thereafter.
3. The effects of 1 or 3 platelets are quite similar. They anyway act as a flame holder which means that the initiated flame stabilize with only small movement around the plates for more than 0.5 s after ignition.
4. The resulting flames are stabilized at the front stagnation point as well as at the wake and expand with varying its maximum position slightly.
5. Upstream and downstream flame propagation starts after some milliseconds at the stabilized flames. The flames are broadened or may form a double head, as compared to the results with an igniting point source.
6. Further separated explosions occur in the upstream area of the jets in some cases.

For each item above an experiment is described by flame profiles, contours and diagrams in the following section. The time scales are always from the first appearance of a flame if not otherwise specified.

The evaluated experiments were not sufficient to make any statistics on the appearance of special characteristics of the explosion evolvement. They did not allow making precise predictions but the characteristics described below might be of some preference to the condition applied.

### 3.2 Explosion in front of the platelets at the stagnation point

An evaluated jet with initial tube pressure of 40 MPa initiates at the stagnation point in front of the single platelet. Ignition occurs at the front stagnation point of the platelet 0.079 s after jet arrival. Along the jet propagation axis, the velocity of centre explosion is 44.9 m/s up to 0.0003 s (Fig. 4 and 5). Thereafter, an explosion at the wake starts with a similar velocity and unites to a single explosion after 0.00167 s.

![Flame profiles](image1)

![Distance-time graph](image2)

**Fig. 4:** (a) Flame profiles of a 40 MPa jet, ignited at the stagnation point of a single platelet at distance of 5 m from 0.000067 s to 0.00333 s after the first flame occurrence. (b) First explosion till 0.003 s with flame velocity 44.9 m/s in the wake.
Fig. 5: Explosion initiation of the 40 MPa jet at the stagnation point of the platelet.

Upstream and downstream reactions follow by 2 phases. The first phases proceed with apparent velocities of 43.5 and 51.1 m/s. For the second phase the upstream and downstream separate and proceed independently (Fig. 6 and 7).

The intensity maximum of the flame shifts to the wake. Upstream and downstream reactions are followed by 2 phases. Apparent velocities of 43.5 and 51.1 m/s are found for the first phase and 64.4 and 43.4 m/s for the second phase.
3.3 Flame development in the wake of one platelet

The evaluated jet from the 10 MPa tube, 3 m distance 1 platelet proceeds as follows: The head of the jet arrives at the platelet after 0.04 s when staring from the rupture disc. The ignitions occurs about 2 and 3 cm behind the platelet (Fig. 8).
The reaction evolves deformed but as a nearly oval explosion also beyond the platelet from 0.0002 s up to 0.002 s (Fig. 10). The intensive flame really starts to overlap from this 0.002 s to 0.009 s beyond the platelet (Fig. 10). The flame velocities are similar and imply that the disturbance by the platelet is marginal.

Fig. 10: Flame profiles of the reaction initiated in the wake expanding over the platelet.
After 0.01 s, upstream and downstream flame propagation takes place with apparent velocities of 77.3 and 20.8 m/s (Fig. 11 and 12) and continue to progress to 0.05 s.
Fig. 12: Propagation of the upstream and downstream flames and determination of the velocities (above).

3.4 Nearly spherical explosion around the platelets

A 40 MPa jet ignited in the wake of 1 platelet from 0.000067 s to 0.0067 s after the first flame occurrence. The flame formed a hemi-sphere at the wake for the beginning, after expanded beyond the platelet to deformed spherical explosion. From 0.000067 s to 0.0067 s and expansion with expansion 0 to 0.0004 s occurs with a flame velocity 213 m/s. The subsequent flame expansion also to the front stagnation point of the igniting platelet occurred from 0.001 s to 0.002 s with a flame velocity 241 m/s. A mainly downstream expansion takes place from 0.0027 s to 0.0047 s with 111 m/s (see Fig. 13 and 14).

Fig. 13: (a) Flame profiles of a 40 MPa jet, ignited at the wake of 1 platelet from 0.000067 s to 0.0067 s after the first flame occurrence. (b) First flame and expansion 0 to 0.0004 s with flame velocity 213 m/s. Flame expansion also upstream the igniting plates from 0.001 s to 0.002 s with flame velocity 241 m/s. Mainly downstream expansion from 0.0027 s to 0.0047 s with 111 m/s.
3.5 Simultaneous ignition at the stagnation point and the wake

A jet ejected from a tube of pressure 20 MPa impinged onto by 3 platelets after 0.37 ms. The jet is nearly simultaneously ignited as well at the font stagnation as also at the wake of the platelets. The centre explosion velocity is 84.8 m/s (Fig. 15 and Fig. 16). A relatively high upstream velocity is observed (Fig. 17).

Fig. 15: Flame profiles along the jet propagation and the related flame velocity.
Fig. 16: Flame contours starting from both the front stagnation point and the wake.

Fig. 17: (a) upstream velocity of 164.2 m/s, (b) downstream velocity 35.2 m/s.

3.6 Irregular flame structures
Especially with jets from 40 MPa tube pressure and at 3 m distance show irregular flame structure, influenced by the strong turbulence and jet velocity (Fig 18). A jet ignites arrival after 0.02 s after rupture disc break and ignition delay of 0.0002 s occurred. The centre flame velocity is estimated to 200-300 m/s up to 0.0004 s, followed by a velocity of 140.9 m/s (Fig. 19).
Fig. 18: Irregular flame contours at a 40 MPa jet, ignited in the wake of 3 platelets from 0.0002 s to 0.0004 s after the first flame occurrence.

Fig. 19: Centre explosion velocity of a 40 MPa jet explosion ignited by 3 platelets.
In the described case two parallel flames propagated upstream and downstream as shown in Fig. 20.

Fig. 20: Start double headed flame propagation, upstream and downstream from a jet after stabilization at the wake of 3 platelets of a 40 MPa jet.

4. Conclusions
When hitting areas, the resulting flame explosions and flame jets of a high pressure hydrogen jet show interesting characteristics. Parameters of the experiments vary in initial pressure of the tubular source (10, 20 and 40 MPa), a distance between the nozzle and the hot surface (3, 5 and 7 m) and temperature of the hot surface (1223 K). The initial explosions stabilize already at the stagnation point and or the
wake of the hot platelets. Furthermore, flames propagate upstream and downstream in dependency of the pressure in the hydrogen reservoir and the distance. The achieved flame velocities vary strongly from 30 to 240 m/s. With all investigated hydrogen pressures strong reactions $v > 40$ m/s occur at platelet distances of 3 and 5 m. The higher values are mainly achieved with jets from a 40 MPa tube at a 3 m distance. In these cases the initial explosion contours show irregular shapes. Various effects like explosion separation, further independently initiated explosions and two parallel flame jets.

5. References


