# Re-ignition by Hot Free Gas Jets - A Parameter Study

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## 1 Introduction

Ignition by hot free jet flow does not only occur in the field of desired combustion when premixed fuel/air mixtures are ignited, e.g. in IC engines or when initiating detonations in pulse detonation engines [1]. Hot gas free jets can also be a potential and undesired ignition source in the field of explosion protection [2–4]. Here, one safety measure frequently applied is the protection type flameproof enclosure, where an electrical device is surrounded by a pressure resistant housing. The flameproof enclosure prevents a flame transmission from inside the housing to the ambience. However, hot exhaust gas jets may emerge from inevitable gaps and joints within the flameproof enclosure into cold ambient (fuel/air) gas leading to re-ignition.

Re-ignition by hot free jets is a complex stochastic process which involves a strong coupling of molecular mixing of two gas streams and chemical reactions. The ignition process is significantly influenced by various parameters: (pressure, temperature, species concentrations, etc.). Due to its turbulent transient nature, even small variations of these parameters might influence the re-ignition process [5]. To gain more insight into hot jet re-ignitions allowing the phenomenon to become more predictable in terms of safety, the main physical quantities influencing the ignition process are studied by means of empirical tests at simplified model systems. Within this study, technical parameters (gap geometry: $l_i$, $d_i$ and ignition location of the pre-ignition: $X_i$) which can be controlled more accurately compared to the physical quantities are varied in order to characterize the ignition process by hot free jets.

## 2 Experimental Setup and Procedure

The re-ignition events are studied by means of the schlieren technique. The test vessel consists of two interconnected cylindrical vessels, the pre-chamber (figure 1 no. 2) and a main chamber (figure 1 no. 4). Due to the large dimensions of the main chamber (11.5 l), influences of the combustion in the pre-chamber on the conditions in the main chamber can be neglected [6].

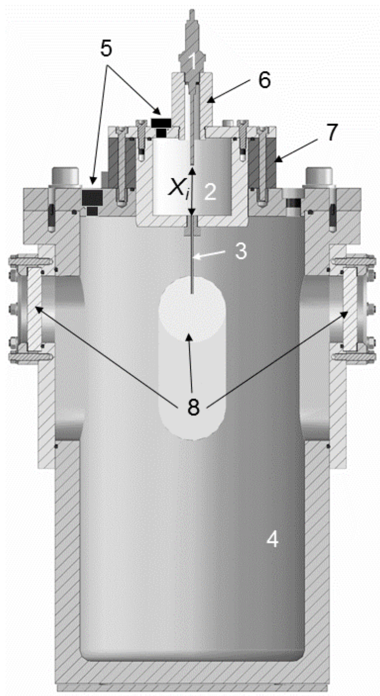



Figure 1: **Test chamber.** The pre-chamber (diameter 70 mm, volume 0.267 l) is connected by a nozzle with the main chamber measuring an inner diameter of 200 mm (height, 367 mm, volume 11.5 l).
1-Spark plug, 2- Pre-chamber, 3-Nozzle, 4-Main chamber, 5-Dynamic pressure sensor, 6-PEEK adapter, 7-Intermediate rings, 8-Quartz glass windows.

As primary ignition source in the pre-chamber, a spark plug (ZK 14-8-75 A1, Beru) with an operating voltage in the range of 15-30 kV is used (figure 1 no. 1). The vertical location of the spark plug can be varied by an adapter (figure 1 no. 6) to study the influence of the ignition source location from the nozzle ($X_i$). Two dynamic pressure sensors (6031, Kistler; charge amplifier: Type 5011 220/110V 48-62 Hz 20 VA, Kistler) (see figure 1 no. 5) measure the pressure in both chambers.

The nozzles (welded unannealed steel (1.4301) capillary tube) are attached to a M10 screw (see figure 2) and can be screwed into the bottom of the pre-chamber. The influence of the gap length on the re-ignition process is investigated by using different nozzle lengths ($l_i = 25$ mm, $l_i = 50$ mm, $l_i = 70$ mm). The pre-chamber is vertically adjusted with intermediate rings (see figure 1 no. 7) in order to keep the light path for diagnostics unchanged when varying the nozzle lengths.

The re-ignition events were investigated optically using a two collecting lens schlieren set-up ($f_1 = 200$ mm, $f_2 = 500$ mm). As a light source, a red-amber LED (Luminus, PT-54-RAX-L35-MPJ) followed by a 0.6 mm pinhole was applied. Another 2 mm pinhole was used for a schlieren stop. The schlieren images were recorded with a high speed camera system (Fastcam SA5 Type 775K-M1, Photron) with an object lens (NIKKOR-H Auto 1:2, $f = 50$ mm Koyaku Japan NO. 745721, Nikkor) at 60 000 frames per second (fps).

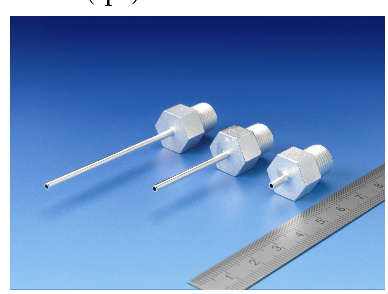


Figure 2: Nozzles used: inner diameter $d_i = 1.2$ mm; lengths $l_i = 25$ mm, $l_i = 50$ mm, $l_i = 70$ mm

The recorded images show gradients of refractive index which are caused by the difference of refractive index of hot jet gas and ambient gas at room temperature resulting from different compositions as well as temperatures. From the images jet geometries, location and time of re-ignition can roughly be deduced due to strong density gradients at the jet boundary. Further information concerning this optical diagnostic method can be found in the literature, like e.g. Settles [7].
Prior to each experiment, both test chambers were flushed with a $H_2$/air-mixture (hydrogen mole fraction 28 vol.-% $\pm$ 1 vol.-%) for about 4 minutes to ensure a minimum of five times gas volume exchange in both chambers. The composition of the test gas mixture was controlled using an oxygen analyser (Servoflex MiniHD (5200), Servomex) which was installed at the exhaust gas tube at the bottom of the main chamber. The gas mixture was generated by means of mass flow controllers (Type F-201C-FB-33-V, 10 ln/min $H_2$, 30 ln/min

air, Bronkhorst High-Tech). After filling stopped, both inlet valves (pre-chamber and main chamber) as well as the exhaust gas valve were closed after a waiting time of 10 seconds to ensure ambient pressure inside both vessels.

The experiments have been conducted under ambient temperature ($T = 22.5 \pm 4\,^{\circ}$C) and pressure ($p = 1$ bar $\pm$ 30 mbar) conditions. In case of a re-ignition, both vessels were flushed with air for 30 minutes in order to remove condensed water from the previous combustion process and to restore ambient temperature in both test vessels. If ignition occurred in the pre-chamber only, meaning that no re-ignition has occurred in the main chamber, both test chambers were flushed with air for about ten minutes.

## 3 Results and Discussion

### 3.1 Ignition Frequencies

It can be observed, that under nominally identical conditions, re-ignition occurs in one case but not in another. Figure 3 illustrates this behaviour for various experimental configurations.

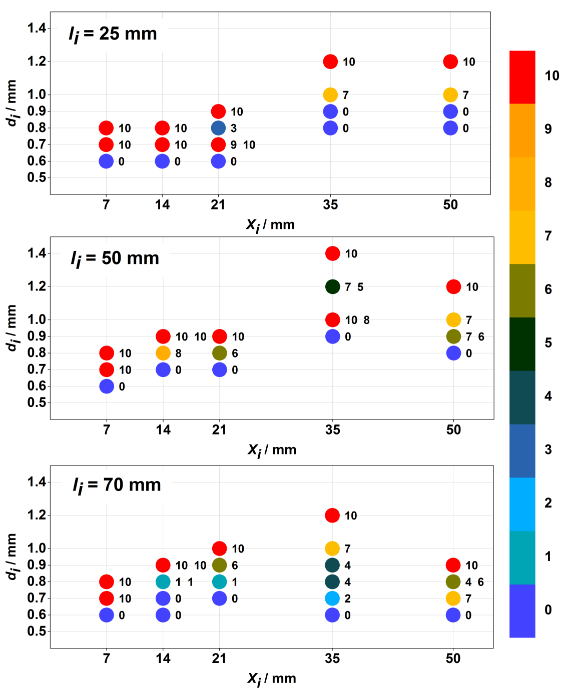



Figure 3: Re-ignition frequency maps for $l_i = 25$ mm, $l_i = 50$ mm and $l_i = 70$ mm. Colorbar: Number of re-ignitions within 10 experiments.

The re-ignition frequency in 10 tests for each parameter configuration is depicted as a function of the nozzle diameter $d_i$ and the spark plug location from the nozzle $X_i$. Each diagram represents one nozzle length $l_i$. If two re-ignition frequency values can be found next to the corresponding data point (e.g. $l_i = 70$ mm, $d_i = 0.8$ mm and $X_i = 14$ mm), a second set of 10 experiments was conducted in order to study its reproducibility.

In most cases (e.g. $l_i = 70$ mm and $X_i = 35$ mm) the re-ignition frequency decreases with nozzle diameter for constant $X_i$ and $l_i$. This behaviour was also observed by Beyer [2] and Sadanandan [4] for nozzle lengths of $l_i$=25 mm.

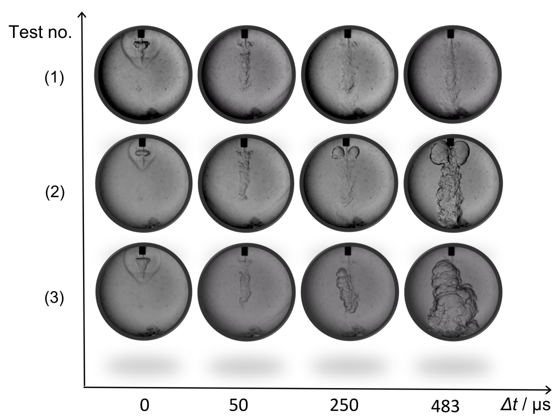
For all nozzle lengths and a spark plug location within the pre-chamber ($X_i$) of 7 mm from the nozzle, no re-ignition was observed in ten experiments for a nozzle diameter of 0.6 mm. However, for the same $X_i$, ten re-ignitions within ten tests could be observed for a nozzle diameter of 0.7 mm. For a larger $X_i$ and for smaller nozzle diameters, the re-ignition frequency declines for all nozzle lengths.

Within this study, no re-ignition was observed for a nozzle diameter of 0.6 mm (see figure 3) for varying spark plug locations and nozzle lengths. Drell et al. [8] report a quenching distance of a hydrogen/air mixture for near stoichiometric conditions to be in the range of 0.57 to 0.63 mm.

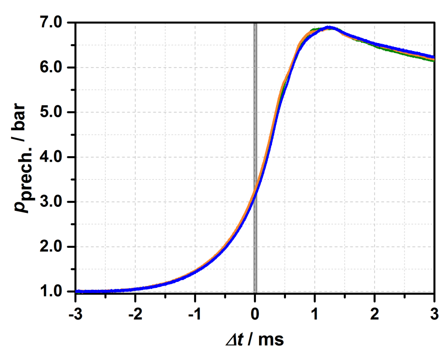
For some conditions, re-ignition or no re-ignition occurs almost equally frequent for nominally identical conditions. Also when repeating one set of experiments the outcome can vary (e.g. $l_i = 70$ mm, $d_i = 0.8$ mm and $X_i = 50$ mm). This behaviour shows the statistic nature of the re-ignition process by hot free jets. In order to investigate if the observed re-ignition frequency is statistically significant for an amount of ten experiments, 80 nominally identical experiments have been conducted for the parameter configuration $l_i = 25$ mm, $d_i = 0.8$ mm and $X_i$=21 mm. For ten nominally identical tests, 3 re-ignition events were observed according to figure 3. When increasing the number of experiments to an amount of 80 experiments in total, 22 re-ignitions equating to 27.5 % of the test being re-ignitions occurred. In this case, when increasing the number of tests by a factor 8, the re-ignition frequency decreases by 2.5%.

### 3.2 Pressure Ratio

In the current setup, the jet velocity at the nozzle exit can be varied for a given nozzle geometry by changing the distance of the spark plug to the nozzle ($X_i$). A quantity to estimate velocity differences at jet exit for varying $X_i$, is the pressure ratio of the pre-chamber and the main chamber at jet exit.
Figure 4 (a) shows the temporal development of three different free jets. The experimental parameters for all three jets were nominally equal, namely $l_i = 70$ mm, $d_i = 1.0$ mm and $X_i = 35$ mm. When having a closer look at the jet exit ($\Delta t = 0$), a pressure wave can be seen. The shape of all free jets is similar. However, re-ignition does not occur for free jet number 1, while free jet number 2 shows two ignition kernels close to the nozzle 250 $\mu s$ after jet exit. For free jet number 3 re-ignition occurs in the head of the jet. Re-ignition in or behind the head vortex of hot gas jets is observed by numerical simulations like [9, 10]. However, re-ignition locations like observed in free jet number 2 are not described by numerical simulations.




(a) Temporal evolution of free jets 1-3 under nominally identical experimental conditions. Note, that there is no re-ignition for free jet no. 1.




(b) Temporal evolution of the pressure curve in the pre-chamber for three experiments under nominally identical conditions. Green: free jet 1, orange: free jet 2, blue: free jet 3

Figure 4: (a) Three tests with identical experimental configurations ($l_i = 70$ mm, $d_i = 1.0$ mm and $X_i = 35$ mm) lead to re-ignition in two cases (jets 2 and 3) and to no re-ignition in another (jet 1). (b) However, all three pressure curves in pre-chamber have an identical shape.

The corresponding pressure traces in the pre-chamber (see figure 4 (b)) have the same shape independent of re-ignition occurring in the main chamber or not. The pressure at jet exit varies for all three curves in the range of 3.13 ± 0.1 bar to 3.27 ± 0.1 bar, indicated by the grey vertical line. It can be deduced, that the pressure in the pre-chamber alone at jet exit does not give a satisfying explanation for the question if a re-ignition occurs or not under nominally the same conditions.

Figure 5 shows the pressure ratio of the pressure in the pre-chamber to the pressure in the main chamber, at the time of jet exit as a function of the nozzle diameter and the spark plug location. Each graph shows one nozzle length $l_i$. Each data point represents the mean pressure at the corresponding time of jet exit for a set of ten experiments. The error bars signify the standard deviation within these experiments resulting from an uncertainty in jet exit time (frame rate of the camera) and uncertainties of the pressure transducers.

It can be seen, that the pressure ratio increases with decreasing nozzle diameter $d_i$ for the same $X_i$.

The larger $X_i$, the higher is the pressure ratio at jet exit, as a greater fraction of the mixture has already reacted. This behaviour was also observed by Beyer [2] and Sadanandan [4] For $X_i = 35$ mm and 50 mm respectively, a pressure wave can be observed at nozzle exit, which can not be seen for $X_i = 7$ mm or 14 mm and partially occurs at $X_i = 21$ mm.

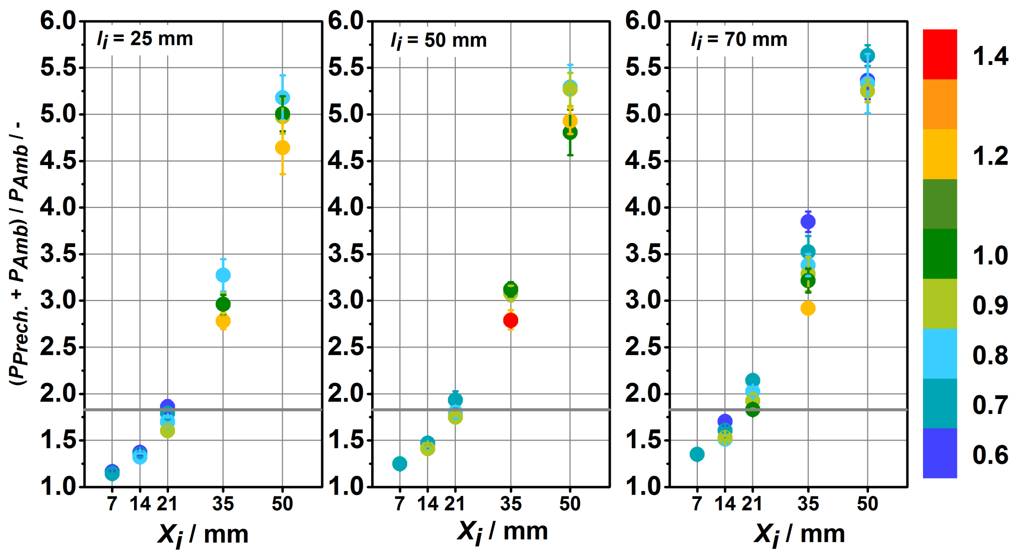



Figure 5: Mean pressure ratio of pressures in the pre-chamber and the main chamber as a function of spark plug distance $X_i$ and nozzle diameter $d_i$ for nozzle lengths $l_i = 25$ mm, 50 mm and 70 mm. ($X_i$= 35 mm, $l_i$= 25 mm and $d_i$=0.9 mm and 1.0 mm, based on 9 tests; $X_i$= 35 mm, $l_i$=70 mm and $d_i$= 0.6 mm, based on 8 tests).

## 4 Conclusions

In this study, technical parameters influencing the number of re-ignitions for ten nominally identical experiments as well as the re-ignition process itself have been studied experimentally by means of the schlieren technique. It was found that the re-ignition frequency decreases with smaller nozzle diameters for constant spark plug locations in the pre-chamber and constant nozzle lengths. The re-ignition frequency also decreases for all nozzle lengths, for spark plug locations further away from the nozzle and smaller nozzle diameters. No re-ignition was observed for nozzle diameters of 0.6 mm. Further, it was observed, that the re-ignition process is highly statistical for identical experimental conditions.

As estimation for jet exit velocities, the pressure ratio in the pre-chamber to the main chamber at jet exit was investigated. It can be seen, that the pressure ratio increases for smaller nozzle diameters for the same spark plug locations. The pressure ratio rises as well for spark plug locations further away from the nozzle. For larger spark plug locations from the nozzle, a pressure wave can be observed at jet exit.

This study reveals some insight into the re-ignition process by hot free jets. Further investigations are planed which might clarify, to which extent one can deduce re-ignition probabilities from re-ignition frequencies of ten experiments only. This may result in the fact, that statistically even an outcome of zero re-ignitions out of ten tries for certain conditions does not guarantee safeness from accidental re-ignition under these condition. In addition, jet exit velocities will be deduced from schlieren images with a higher frame rate.

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