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DEPARTMENT OF CIVIL, CHEMICAL,
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Greetings from the Local Organizing Committee Chair

Dear Colleagues and Friends,

We are pleased to welcome you to the **15th International Symposium on Hazards, Prevention and Mitigation of Industrial Explosions (ISHPMIE)** and to Naples.

The event is organized by the University of Naples Federico II, in collaboration with the National Research Council, the University of Rome, the University of Bologna and the Polytechnic University of Turin. I would like to thank the International Organizing Committee for giving us the opportunity to meet at the 15th Symposium in Naples.

We are glad to host in Naples around 200 Researchers and Scientists coming from all over the World. We would like to thank you all for your outstanding contributions! We are privileged to have a diverse array of fascinating papers from around the globe, covering a wide range of significant topics.

Here's what to expect:

- **Plenary Lectures:** Leading scientists will share their insights and the challenges they face on current topics.
- **Technical Sessions:** These sessions are organized into parallel tracks with three or four presentations each, focused on specific subjects and chaired by experts in the field.
- **Poster Session:** Join us during the coffee breaks: results from various research projects will be discussed and preliminary results from ongoing research projects are showcased.

We look forward to your participation and the enriching discussions!

In addition, we have organized an intensive social program and we hope you will enjoy our beautiful city. I wish all participants an interesting conference week with many contacts and fruitful discussions.

Almerinda Di Benedetto

Local Organizing Committee Chair

Foreword of the Proceeding Editors

It is our pleasure to present the proceedings of the 15th International Symposium on Hazards, Prevention, and Mitigation of Industrial Explosions (ISHPMIE).

We are happy to compile proceedings consisting of 111 high-quality papers that demonstrate the continuous advancements in the scientific knowledge of safety also related to emerging risk issues due to energy transition.

All articles in this volume have been subjected to a peer-review process administered by the Proceeding Editors. We are thankful to all the referees who guaranteed the professional and scientific standards expected of ISHPMIE.

After the conference, Elsevier will publish selected papers from the 15th ISHPMIE in a special issue of the Journal of Loss Prevention in the Process Industries.

We strongly believe that Naples will inspire stimulating and high quality scientific exchange between participants.

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Investigation of the thermal radiation from hydrogen jet flames

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Abstract

For industrial applications dealing with hydrogen, the definition of safety distances and the assessment of possible hazards emanating from releases is mandatory. Since hydrogen is usually stored and transported under pressure, one scenario to be considered is the momentum driven release of hydrogen from a leakage with subsequent ignition. In this scenario, the emitted heat radiation from the resulting jet flame to the surroundings has to be determined to define adequate safety distances.

For hydrocarbon flames, different jet flame models are available to assess the hazards resulting from an ignited jet release. Since hydrogen flames differ from hydrocarbon flames in their combustion behavior, it has to be checked if these models are also applicable for hydrogen.

To evaluate the accuracy of these models for hydrogen jet flames, tests at real-scale are carried out at the BAM Test Site for Technical Safety (BAM-TTS). Herein, the flame geometry and the heat radiation at defined locations in the surroundings are recorded for varying release parameters such as leakage diameter (currently up to 30 mm), release pressure (currently up to max. 250 bar) and mass flow (up to max. 0.5 kg/s). The challenge here is the characterization of the flame geometry in an open environment and its impact on the thermal radiation. Existing heat radiation data from the literature are mostly based on unsteady outflow conditions. For a better comparability with the steady state jet flame models, the experiments presented here are focused on ensuring a constant mass flow over the release duration to obtain a (quasi) stationary jet flame. In addition, stationary outflow tests with hydrocarbons (methane) were also carried out, which are intended to serve as reference tests for checking flame models based on hydrocarbon data.

Keywords: *hydrogen, release, jet flame, thermal radiation*

1. Introduction

In order to reduce global CO₂ emissions, hydrogen is becoming increasingly important as an energy carrier. Due to the enormous demand for hydrogen, the focus is shifting to safe production, transportation and storage. As hydrogen is usually transported and stored under pressure, one potential scenario is the momentum driven release of hydrogen from a leakage with subsequent ignition. The resulting high momentum driven hydrogen flame is called diffusion hydrogen jet flame. To assess the impact and hazards, the resulting jet flame must be characterized in terms of the flame geometry and emitted heat radiation. As a result, safety regulations can be derived from the knowledge gained.

Various models already exist in the literature which describe the flame geometry and emitted heat radiation of jet flames. Most of the models currently used are based on studies by Becker and Liang (Becker, 1978) and Kalghatgi (Kalghatgi, 1984), who did fundamental research on the flame geometry of jet diffusion flames. They established dependencies on the release diameter, mass flow,

Reynolds number and the resulting flame length. Based on this, Chamberlain (Chamberlain, 1987) and Johnson et al. (Johnson et al., 1994) developed model approaches taking wind influence into account.

In addition to characterizing the flame geometry, the influence of the thermal radiation emitted into the environment was also considered here. In Chamberlain's investigations for vertical outlet conditions, mainly low momentum hydrocarbon jet flames were measured. For a horizontal release of hydrocarbon jet flames Johnson et al. (Johnson et al., 1994) carried out experiments taking into account the influence of buoyancy. Miller (Miller, 2017) extended these models to outlet angles of 45° and used weighted point sources on the flame centreline in contrast to (Johnson et al., 1994) and (Chamberlain, 1987) who used cone shaped surface emitter sources.

The models mentioned are mainly based on a large number of experimental investigations of hydrocarbon flames such as methane, ethane, propane and natural gas. For hydrogen, Molkov et al. (Molkov et al., 2009; Molkov & Saffers, 2013) developed their own approaches in which the flame lengths can be described using empirical formulas. These approaches were developed on the basis of experiments with hydrogen jet flames by Kalghatgi (Kalghatgi, 1984), Shevyakov et al. (Shevyakov & Komov, 1977), Schefer et al. (Schefer et al., 2006), Proust et al. (Proust et al., 2011), Mogi et al. (Mogi et al., 2005) and Studer et al. (Studer et al., 2009). Other studies have investigated influences such as the curvature of the flame geometry due to the buoyancy effect on horizontal jet flames (Ekoto et al., 2014). To quantify the thermal radiation emitted by a hydrogen jet flame into the environment, various approaches were developed in the work of Molina et al. (Molina et al., 2007), Houf et al. (Houf & Schefer, 2007; Houf et al., 2009), Schefer et al. (Schefer et al., 2006; Schefer et al., 2007; Schefer et al., 2009) and Proust et al. (Proust et al., 2011).

Most of the documented experimental data was obtained under transient outflow conditions (Hall et al., 2017; Proust et al., 2011; Schefer et al., 2006). Due to the decreasing pressure and mass flow during the release, the resulting jet flames do not have stationary outflow conditions. Experimental investigations with constant, stationary, outflow conditions have mainly been carried out on a laboratory scale only (Choudhuri & Gollahalli, 2003; Imamura et al., 2008; Kalghatgi, 1984; Mogi et al., 2005). A validation of existing (stationary) jet flame models for real-scale hydrogen releases is therefore currently only possible to a limited extent.

In order to close this gap, experimental investigations of real-scale hydrogen jet flames under stationary outflow conditions were carried out at the Test Site for Technical Safety at the Bundesanstalt für Materialforschung und -prüfung (BAM-TTS). The purpose of the investigations is to characterize the flame geometry and the emitted heat radiation. Furthermore, the generated data are used to evaluate existing jet flame models with regard to their suitability for hydrogen jet flames.

2. Experiments

2.1 Experimental Setup

To ensure a constant mass flow over several minutes, the test setup is supplied from 6 bundles with 12 hydrogen bottles each. These 6 bundles contain a total of $m=90$ kg of hydrogen at a pressure level of $p=300$ bar, so that an average test duration of $t = 120$ s per test can be realized. The mass flow is adjusted via a control valve in conjunction with three orifices ($d=1,6$ mm, 3,3 mm, 7,7 mm) and recorded using a Coriolis mass flow meter (Rheonik Coriolis RHE28).

The three orifice diameters were used to allow for a same outlet mass flow at different pressure stages, enabling an optimal utilization of the gas storage. The test rig is designed for the release of hydrogen with mass flows of up to $\dot{m}=0,5$ kg/s and pressure levels of up to $p=1000$ bar. Pressure and temperature are measured at several points along the pipe section and at the outlet (cf. Figure 1).

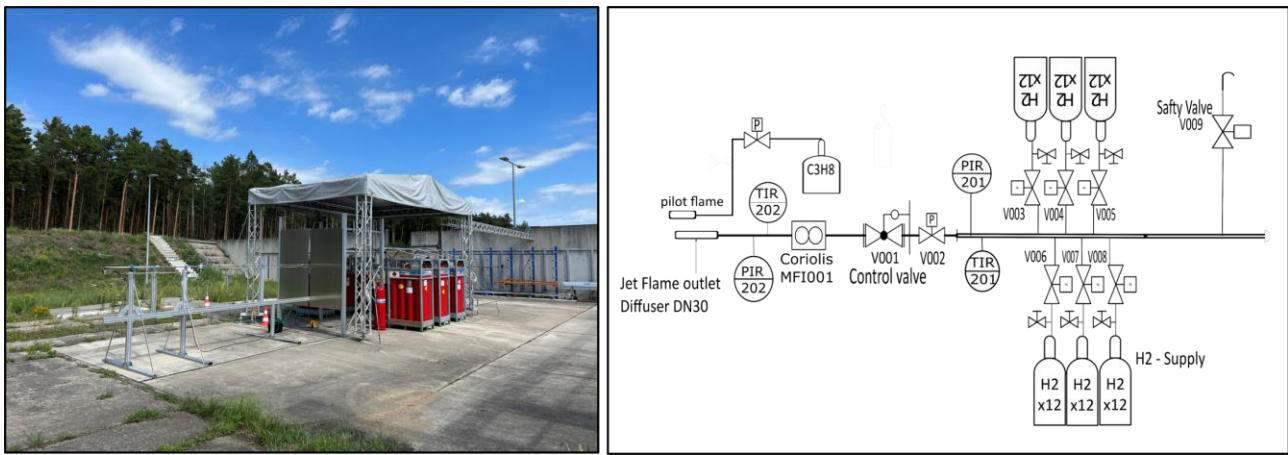


Figure 1: Test stand at the BAM TTS Size of test rig 18 m x 5 m x 4 m (Length x Width x Height) (left) and flow chart of the test stand with used monitoring equipment (right)

The flame geometry is determined using infrared (IR) cameras. Two infrared camera systems (a FLIR SC4000 with cooled IR sensor wavelength spectrum $\lambda=1,5 \mu\text{m} - 5 \mu\text{m}$ and a recording frequency of $f=200 \text{ Hz}$, and a FLIR E96 with $\lambda=7,5 \mu\text{m} - 14 \mu\text{m}$ and a recording frequency of $f=30 \text{ Hz}$) are directed at the flame from two different angles. Four thermal radiation sensors (bolometers - Medtherm Series 64) are used to measure the thermal radiation emitted by the jet flame into the surroundings.

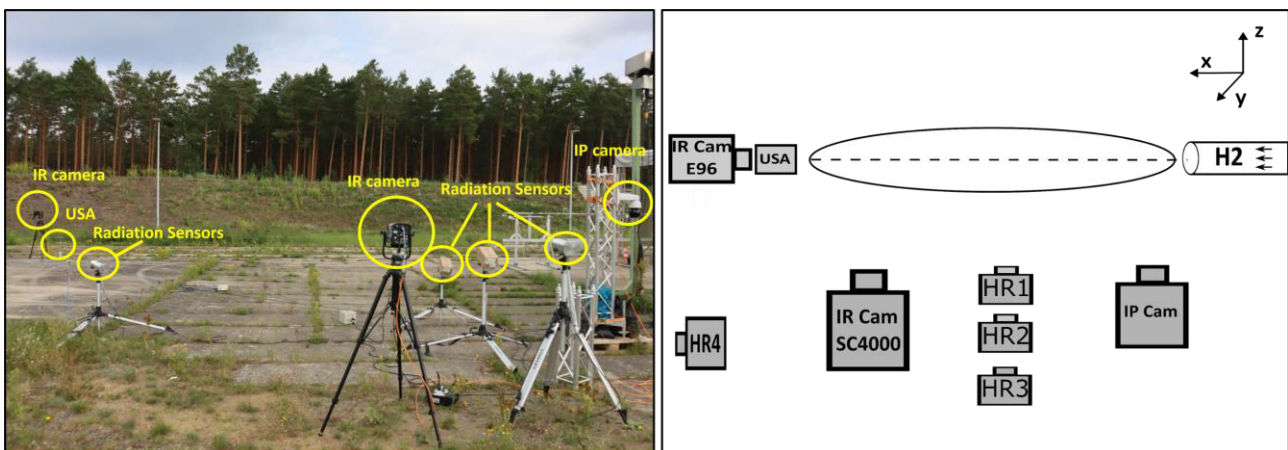


Figure 2: Measuring equipment in open field at the test area (left) and schematic illustration of the positions of the measuring equipment (right)

Three of these bolometers (cf. Figure 2 – Heat Radiation (HR) sensors) are positioned at different distances from the flame. The fourth is used to measure the background radiation of the environment (cf. Figure 2). This background radiation is subtracted as an offset from the measured thermal radiation of the three bolometers, which are aligned with the flame. The thermal radiation sensors have a spectrum of $\lambda= 0,5 \mu\text{m} - 14,5 \mu\text{m}$, a maximum frequency of $f=100 \text{ Hz}$ and are designed for a maximum irradiance of $2,25 \text{ kW/m}^2$. Each sensor has a view angle of 150° .

All three sensors directed at the flame are inclined vertically with increasing distance at angles of $\gamma=14,4^\circ$ (HR1); $10,4^\circ$ (HR2); $4,3^\circ$ (HR3). A swivelling 360° IP camera (BASCOS – 1 Dom System Plus) is installed for additional test monitoring. An overview of the position of cameras and heat radiation sensors placed at the test areas is listed in Table 1.

Table 1: Overview of the positions (distance measured to the outlet) of the thermal radiation sensors and cameras (cf. Figure 2)

Position	IR Cam E96	IR Cam SC4000	IP Cam	HR1	HR2	HR3	HR4
<i>x</i> in m	15	4,5	3,5	4,05	4,05	4,05	8,5
<i>y</i> in m	0	12,32	7	8,23	10,32	12,31	11
<i>z</i> in m	1,6	1,65	1,8	0,74	1,04	1,34	0,74

An ultra-sonic anemometer (USA - Metek type USA-1 Scientific) is used to record the wind field. The gas mixture is ignited by a propane pilot flame at the outlet with a piezoelectric high-voltage ignition. The pilot flame is switched off immediately after ignition of the jet.

2.2 Experimental Program

To date, a total of 128 jet flame tests have been carried out. Of these, 50 were tests with pure hydrogen and 78 tests with pure methane. The methane tests in particular should serve as a “reference”, since the available flame models in the literature are largely based on data from tests with hydrocarbons. Furthermore, all tests were carried out with a horizontal outlet. Only test series in which there was no headwind were used for the evaluation.

Preliminary tests showed that, for methane, there is no stable burning flame if the outlet velocity is too high (small outlet diameter, $d=4$ mm orifice, $\dot{m} > 0,043$ kg/s, $T=20$ °C). For this reason, a pipe ($l=1$ m) with an internal diameter of $d=30$ mm was placed at the outlet to serve as a diffuser (Figure 3). This made it possible to reduce the exit momentum and adapt the turbulent flame speed to the outlet velocity, allowing for a stable burning flame over the entire mass flow range from $\dot{m}=0,005$ kg/s to $\dot{m}=0,2$ kg/s.

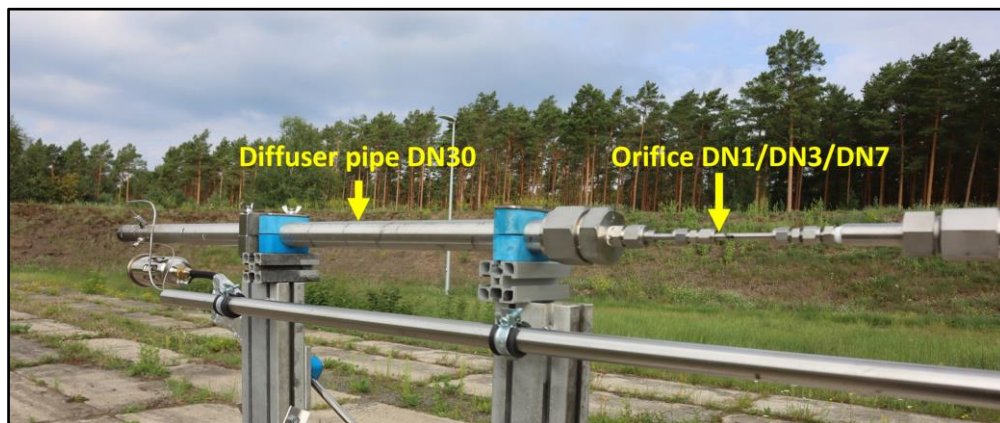


Figure 3: Diffuser pipe DN30 ($l=1$ m) attached on orifice DN1/DN3/DN7 ($l=0,2$ m)

3. Results and discussion

The focus of the experiments is the investigation the flame geometry and the emitted thermal radiation. The procedure used here is illustrated in the following example. Figure 4 shows a snapshot of a hydrogen jet flame (outlet diameter of $d=30$ mm, outlet mass flow $\dot{m}=0,172$ kg/s, $T=20$ °C) in the visible and IR range. From Figure 4 it can be seen that hydrogen jet flames do not emit any radiation in the visible wavelength range. This could be observed not only in all hydrogen experiments, but also in the experiments carried out here with methane. The flame geometry can therefore only be determined using an IR camera, which requires the specification of a temperature range and an emissivity.

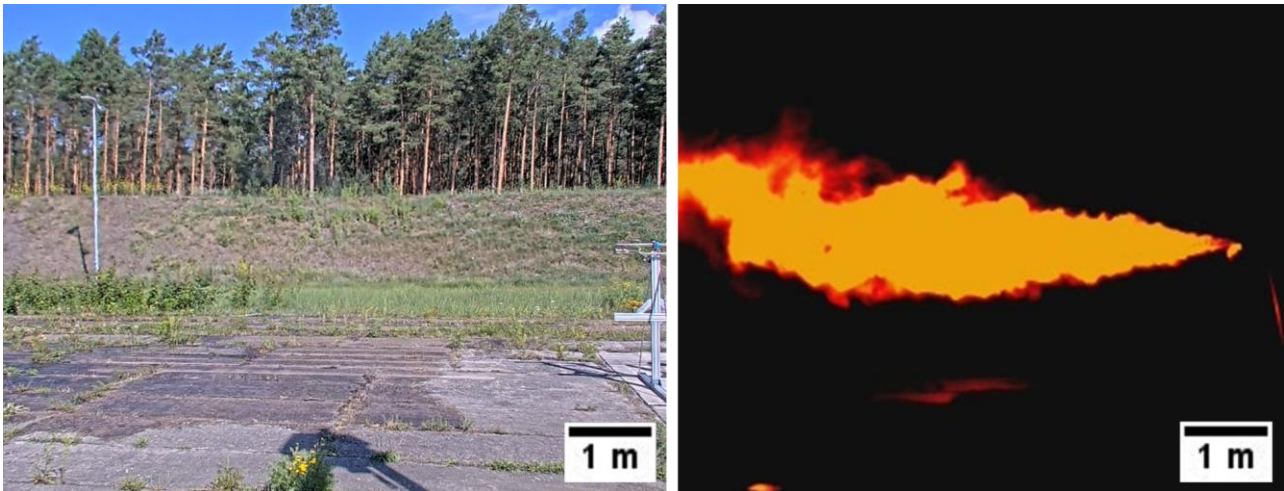


Figure 4: Comparison of the Diffusion Hydrogen Jet Flame monitored with IP Cam (left) and IR-Cam (right)

The emissivity ε of IR absorbing gases depends on many parameters such as the species concentration, the layer thickness, the temperature of the flame, the ambient pressure and the wavelength (Gore et al., 1987; Hottel et al., 1936) and is much more complex compared to measurements on solids.

Furthermore, a jet flame is a diffusion flame that does not have a homogeneous species distribution across the layer thickness and is additionally influenced by the wind speed, direction and turbulence (Coelho, 2012). For the IR measurements, the emissivity was set to $\varepsilon=1$ and a temperature range of $T=850$ °C to $T=2000$ °C was used.

To determine the flame geometry, an algorithm was developed that averages each individual frame from the IR image over the duration of the experiment. With a recording frequency of $f=200$ Hz and a test duration of $t=120$ s, this results in averaging over 24000 frames. Figure 5 shows exemplarily the averaging procedure and result.

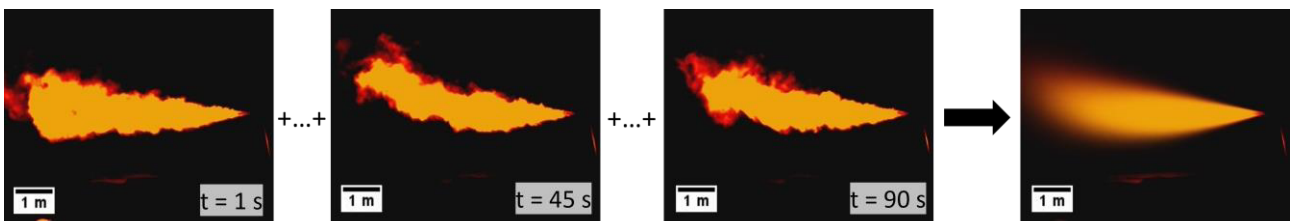


Figure 5: Numerical calculation and determination of mean flame shape over test duration

All flame parameters (flame length, mean diameter and view factor) are calculated on the basis of the generated time-averaged (stationary) flame geometry.

The flame shape (contour) is then defined via a RGB value, manually specified so that only the flame surface and no reflections from the test apparatus or the floor are visible in the image. The experimental non-dimensional flame lengths and diameters are shown in Figure 6.

The comparison of the flame geometry of hydrogen and methane in Figure 6 shows that hydrogen flames are longer and thinner compared to methane flames, which are more compressed (shorter with wider diameters). In a mass-specific comparison, this is due to the difference in density and consequently higher outlet velocity. Due to the lower density, a higher volume flow and consequently a greater outlet momentum are available with the same mass flow for hydrogen. This allows the hydrogen jet flame to spread more easily into the surrounding medium, resulting in longer flames.

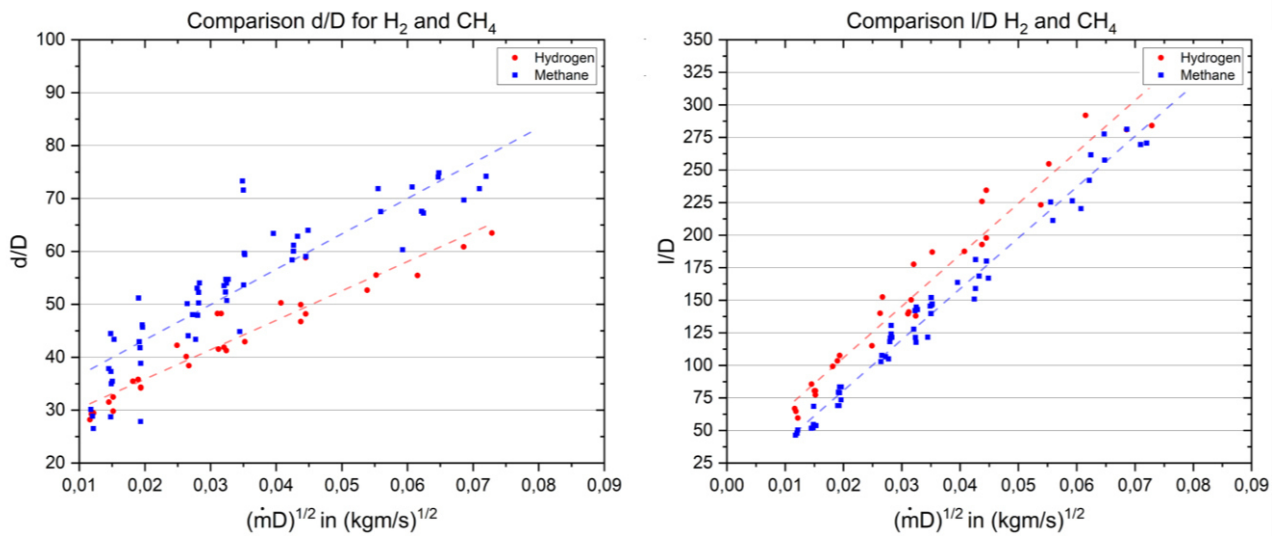


Figure 6: Comparison of hydrogen and methane regarding to non-dimensional parameter flame diameter/outlet diameter (d/D) over nominated parameter mass flow/outlet diameter $(\dot{m}D)^{1/2}$ (left) and non-dimensional parameter of flame length/outlet diameter (l/D) over nominated parameter mass flow/outlet diameter $(\dot{m}D)^{1/2}$

From the geometric data of the flame and the heat radiation intensity Q_{rad_Sensor} in W/m^2 measured by the bolometers (cf. Figure 7), the SEP of the flame can be determined using Eq. 1

$$SEP = \frac{Q_{rad_Sensor}}{\tau_{1_2} \varphi_{1_2}} \quad \text{Eq. 1}$$

with the view factor φ_{1_2} (unitless) and the transmittance τ_{1_2} (unitless) of the air are required (index "1_2" refers to the path between emitter "1" and receiver "2").

The transmittance τ of the air was calculated according to Wayne et al. using Eq. 2 (Wayne, 1991).

$$\tau_{1,2} = 1,006 - 0,01171(\log_{10}X_{H_2O}) - 0,02368(\log_{10}X_{H_2O})^2 - 0,03188(\log_{10}X_{CO_2}) + 0,001164(\log_{10}X_{CO_2})^2 \quad \text{Eq. 2}$$

$$\text{with } X_{H_2O} = \frac{R_H L S_{mm} 2,88651 \cdot 10^2}{T} \text{ and } X_{CO_2} = \frac{273L}{T}$$

where $\tau_{1,2}$ is the transmittance (unitless), X_{H_2O} parameter for water vapor in the atmosphere (unitless), X_{CO_2} parameter for CO₂ in the atmosphere (unitless), R_H relative humidity (unitless), L the path length between emitter and absorber (in m), S_{mm} vapor pressure of water (in mmHg) and T the air temperature (in K).

The view factor $\varphi_{1,2}$ is calculated numerically, based on the determined flame geometry (cf. Figure 5, right). Assuming a radially symmetrical flame, the flame geometry is divided into vertical slices with the width of one pixel of the IR image. The view factor is calculated as a function of the distance of the slice from the bolometer according to the relationships given in (VDI, 2010). The overall view factor of the flame is then calculated from the sum of the individual view factors of each section. Thus, the SEP of the flame can be determined from the temporal average of the measured thermal radiation of the individual bolometers. Ideally, the SEP values of the flame calculated from the different bolometer signals should be identical. Under atmospheric conditions, this is only achieved within a certain accuracy limit, but with satisfactory agreement.

Figure 7 shows a comparison of the SEP values determined from the measurements for methane and hydrogen. A trend can be seen here that hydrogen jet flames have higher SEPs than methane jet flames. For methane, SEPs in the range of 7 kW/m² - 9,5 kW/m² and for hydrogen SEPs between 10 kW/m² - 15 kW/m² were determined.

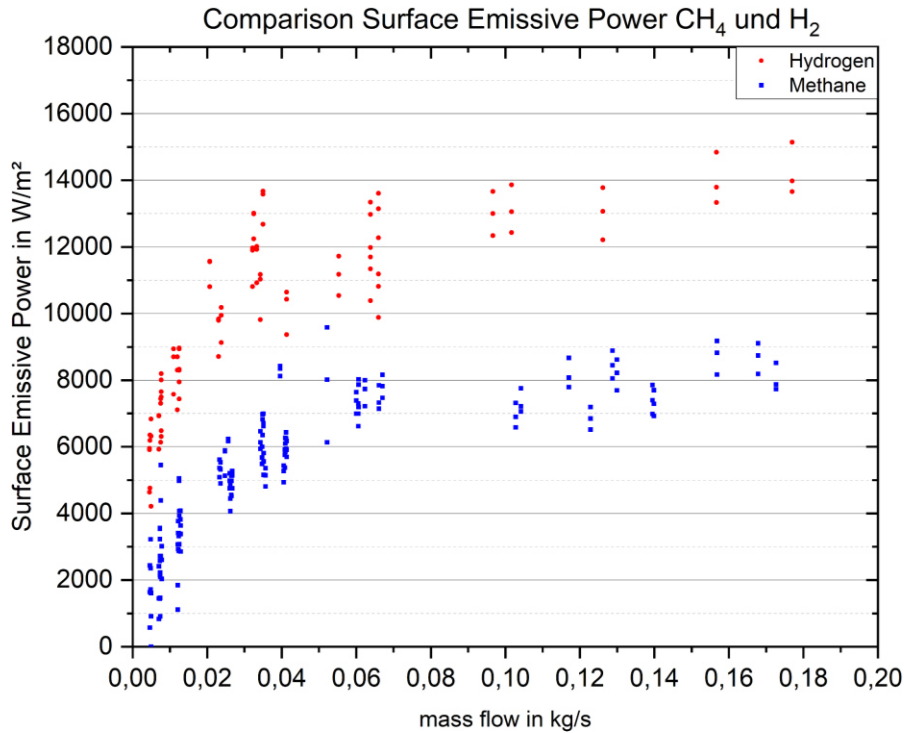


Figure 7: Comparison of Surface Emissive Power for hydrogen and methane drawn over mass flow

In the literature (Chamberlain, 1987; Fishburne & Pergament, 1979; Mogi et al., 2005; Proust et al., 2011; Schefer et al., 2006; Schefer et al., 2007) the radiant heat fraction of the flame is derived from the measured heat radiation of the flame and the total energy (heat release rate) produced during combustion which can be calculated from Eq. 3:

$$Q_{Combustion} = \dot{m}\Delta H_c \quad \text{Eq. 3}$$

with the mass flow (\dot{m}) and the lower heating value (ΔH_c). The lower heating value is $\Delta H_{c_{H_2}} = 120$ MJ/kg for hydrogen and $\Delta H_{c_{CH_4}} = 50,3$ MJ/kg for methane (Uwe Riedel, 2018).

The radiative fraction can only be calculated indirectly via the measured thermal radiation and the flame area. Here, x_{rad} is calculated according to Eq. 4, where A_{flame} is the flame area. The product of x_{rad} and ΔH_c can be understood as the radiant heat energy that is converted into thermal radiation during combustion.

$$x_{rad} = \frac{SEP_{exp} A_{Flame}}{\dot{m}\Delta H_c} \quad \text{Eq. 4}$$

This could be due to the fact that mainly visible (luminous) methane flames have been examined in the literature. In contrast, in the present work only non-visible (non-luminous) flames have occurred so far. Studies on the differences between luminous and non-luminous flames with regard to thermal radiation have only been examined sporadically in the literature. One of the early investigations performed by (Hottel et al., 1936; Sherman, 1934) with natural gas showed a lower thermal radiation for non-luminous flames in comparison to luminous flames due to differences in the radical species and emissivity of the flame.

4. Conclusion

From the test results presented here, initial findings regarding flame geometry and heat radiation have been made.

1. Hydrogen jet flames have a longer and thinner flame than methane jet flames for the same mass flow.
2. Hydrogen jet flames show higher thermal radiation values for the same mass flow rate compared to methane jet flames.
3. The radiant heat fractions of the hydrogen jet flames determined so far correspond to the values given in the literature, whereas those for methane are significantly lower than the values given in the literature (rather at the lower limit), which may be due to the non-luminescence of the flames in this work.

Outlook: The difference of heat radiation between luminous and non-luminous flames will be investigated further as well as releases with different outlet angles and outlet diameters. The results obtained will be used to check the applicability and accuracy of jet flames models and, if necessary, the further development of these.

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