SAFEKINEX

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Experiments on explosion safety

Deliverable No. 11
Effect of turbulence on explosion severity ($K_g$ –value)

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 Responsible Partner:
Universität Karlsruhe (TH)
Engler – Bunte – Institut
Lehrstuhl und Bereich Verbrennungstechnik
Engler – Bunte – Ring 7
D–76131 Karlsruhe

Authors:
Dipl.-Ing. Maximilian Weiß
Prof. Dr.-Ing. Nikolaos Zarzalis
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1 Introduction

It is well known that turbulence influences combustion processes. Turbulence is used to increase the energy release rate for controlled combustion processes like the combustion of fuel gas within the cylinder of car engines, the combustion of kerosene in aircraft engines, the natural gas combustion in gas turbines or the coal combustion in a power plant in order to generate electricity. Therefore several scientists try to understand the influence of turbulence on the heat release rate (or turbulent burning velocity) and work on correlations for the turbulent burning velocity on the conditions of flow.

Due to the significance of turbulence for the heat release rate of controlled combustion processes, the research focus has been on controlled combustion processes and not regarding to safety analyses. Additionally our knowledge on safety parameters like AIT (auto ignition temperature), MIE (minimum ignition energy) or $K_g$-value is limited and till now not comprehensively understood. Furthermore the dependencies of those safety parameters on the gas-mixture and conditions (pressure, temperature) are encyclopaedically. Therefore fewer scientists have investigated the effect of turbulence on safety parameters as it makes it more difficult to understand those phenomena.

Nevertheless there are two main reasons giving with this deliverable an insight into the effect of turbulence on the $K_g$-value: there is a huge lack of knowledge on the effect of turbulence on safety parameters and there is a need of knowledge on the influence of turbulence on safety parameters as turbulence is present in several chemical processes. Flows through chemical reactors are influenced by obstacles (e.g. sieve bottoms, packing bodies in a column, grids, measuring heads that stick out, stirrers), which can generate turbulence and can have an influence on safety parameters.

For scientific approach eight fans were installed in an explosion vessel to generate turbulence. With these fans a defined turbulence field can be generated within the vessel. The $K_g$-value has been chosen to be investigated as one of the most important safety parameters. Apparently other safety parameters are also influenced by turbulence but due to the efforts necessary for those experiments only the effect of turbulence on the $K_g$ for some methane-air and hydrogen-air mixtures could be investigated. The deliverable itself gives also only an insight into the dependency of the $K_g$-value on turbulence.
2 Test facility and measurement technique

2.1 Explosion vessel

Fig. 2-1 shows a 3d-view of the used explosion vessel. The vessel has been milled out of a stainless steel cuboid, which makes it resistant to high pressure. A 3d-view of a cut through the explosion vessel along A-A can also be seen in Fig. 2-1. Fig. 2-2 shows a cut through the explosion vessel along B-B.

The vessel possesses the following qualities:

- volume: 2.281 liter
- maximum pressure: 150 bars without windows, 70 bars with windows
- fans for mixing or generating turbulence: 8 fans, which can be used to mix the gas or to generate turbulence during the explosion, the rotational speed of the fans can be controlled up to 16,000 rpm (at atmospheric pressure)
- optical access: the vessel has four round windows with a diameter of 8 cm, the windows are located perpendicular to each other in order to have two optical axes (see Fig. 2-1)

The eight fans are located concentrically within the vessel to generate a homogeneous and isotropic turbulence field without blocking optical access. The fans are driven with DC motors, which are located in special drilling within the vessel. The speed of each fan is measured with an encoder and can be controlled up to a revolution of 16,000 rpm at atmospheric pressure. The revolution of each fan can be controlled individually. However, for this work all fans rotate always with the same speed.

The turbulence field (turbulence intensity and integral length scale) has been measured for different fan speeds and different fan designs. The results are discussed in Chapter 2.4.
Fig. 2-2: 2d-cut through the explosion vessel along B-B
2.2 Flow sheet of the test facility

Fig. 2-3 shows the flow sheet of the test facility.

"V_1" to "V_7" denote magnetic valves, which are used to control the flow of the gases in the pipes. "FIC_1" and "FIC_2" denote mass flow controller, which control the mass flow rate of fuel gas and air during the filling procedure. The pressure sensor "PI_1" measures the pressure in the feed pipe, which is also used to control the filling with the so-called "partial pressure method". The dynamic pressure sensor "PI_2" is located within the vessel and measures the pressure signal during explosion in the vessel. A homogeneous mixture at ignition is guaranteed by mixing the gas with the eight fans "FAN_1" to "FAN_8" before ignition occurs.

2.3 Ignition unit and spark discharge

The ignition of the gas mixture occurs with a high voltage spark. The ignition unit (high voltage ignition unit IPG 1522 of the company HILO-TEST, Karlsruhe, Germany) can produce defined and reproducible spark discharges (see Fig. 2-4). The energy of the spark and the lapse of the discharging current can be changed by modifying electrical components in the discharging circuit of the ignition device. The device consists basically of an electronically controlled high voltage charging unit, energy storage capacitors, discharge resistors, inductances, a discharging switch and a controlling and supervision unit. The charging voltage U can be set stepless between 0 V and the maximum voltage of 15 kV.
Without taking into account the energy losses of the spark due to heat transfer to the electrodes and the pressure wave from the sparks, the energy $E$ of the spark can be estimated by calculating the stored energy of the capacitors of the total capacity $C$:

$$E = \frac{1}{2} \cdot C \cdot U^2.$$  \hspace{1cm} (2-1)

The following capacitors are available: 2 x 100 nF, 2 x 10 nF, 1 nF, 470 pF. By combining the capacitors, several capacity values can be realized. With these capacitors and a charging voltage of 15 kV theoretically energies between 53 mJ and 22.5 J can be realized.

The distance of the electrodes has been set to 2 mm for all experiments.

### 2.4 Turbulence field measurement

To characterize the turbulence field within the vessel, LDA (see Chapter 2.4.1) and PIV measurements (see Chapter 2.4.2) were performed. LDA measurements were used to obtain the velocity field and RMS value, PIV measurements were used to obtain the integral length scale of turbulence. Fig. 2-5 shows the location of the measured area in the vessel (red border strip). Within this area LDA measuring points and laser-light sheets were located. In Fig. 2-5 the measured area is magnified in order to illustrate the position of the LDA measuring points and laser-light sheets. Altogether 18 different LDA measuring points and 6 different laser-light sheets were used to investigate the velocity and turbulence field for different fan speeds and fan designs. Due to the symmetry of the vessel, the selected region is sufficient to characterize the velocity field and turbulence of the whole volume.

The coordination system and notation of velocities are also shown in Fig. 2-5.
2.4.1 RMS value measurement with LDA

A 2d LDA (Laser Doppler Anemometry) system has been used to measure velocities within the vessel (Fig. 2-6.). Therefore only two velocity components could be measured simultaneously (uy and uz).

Fig. 2-6: Configuration of the LDA measuring points and recorded laser-light sheets for characterising the velocity and turbulence field within the vessel
In order to measure the 3rd velocity component $u_\kappa$, a second measurement was necessary with the LDA system placed orthogonal to the first position. As the radius of the windows is 4 cm, there is no possibility to measure the velocity component $u_\kappa$ for $x > 3$ cm. Therefore measurements for all three velocity components are only available up to $x = 3$ cm (see Fig. 2-7).

![Fig. 2-7: LDA measuring points](image)

### 2.4.2 Integral length scale measurement with PIV

The integral length scale has been measured by PIV (Particle Imaging Velocimetry). The general procedure is illustrated in Fig. 2-8. A 6 Watt Argon-Ion laser has been used to generate a laser-light sheet through the explosion vessel. MgO$_2$ particles with a diameter of less than 2 µm have been used to trace the motion of the gas. The particles within the laser-light sheet scatter the light and were recorded with a high speed camera, which was located perpendicular to the sheet. As the resolution of the camera was limited to 512*128 pixels at the selected acquisition frequency of 12 kHz and the optical resolution had to be kept high due to the expected small length scale, only small areas could be recorded. Two different optical resolutions were chosen (30.0 µm/pixel and 73.4 µm/pixel) in order to capture the influence of the optical resolution and the post processing procedure on the evaluation of the integral length scale. In order to obtain velocities a special correlation procedure has been used to decrease the interrogation window from initially 32x32 pixels to finally 6x6 pixels. This gave a final resolution of 180 µm/vector and 440 µm/vector. Eventually, a smoothing procedure has been adapted to average 3x3 vectors on each position.
Fig. 2-8: PIV procedure in order to obtain the integral length scale of turbulence

Fig. 2-9 shows the approach to obtain the integral length scale from the vector fields. The spatial correlation of the velocities has been carried out along the x-coordinate. A transversal and longitudinal correlation coefficient has been composed which results in two different length scales. In order to obtain sufficient values for the correlation functions \( g(\Delta x) \) and \( f(\Delta x) \), 6000 images were recorded. Finally, the integral length scales are calculated by integration of the correlation functions \( g \) and \( f \) along \( \Delta x \).

\[
g(\Delta x) = \frac{\sum_{N} u_z'(x) \cdot u_z'(x + \Delta x)}{u_z'(x)^2}
\]

\[
f(\Delta x) = \frac{\sum_{N} u_x'(x) \cdot u_x'(x + \Delta x)}{u_x'(x)^2}
\]

\[
L_z = \int_{0}^{\infty} g(\Delta x) \, d\Delta x
\]

\[
L_x = \int_{0}^{\infty} f(\Delta x) \, d\Delta x
\]

Fig. 2-9: Differentiation of the integral length scale \( L_z \) and \( L_x \) by formation of a transversal and longitudinal correlation coefficient
An influence of the laser-light sheet position on the integral length scale could not be observed, therefore only mean values of all three laser-light sheet positions for each optical resolution are discussed in Chapter 3.

2.5 $K_g$ -value measurement

The dependency between the pressure rise $(dp/dt)_\text{ex}$ and the volume of the vessel is known as the cubic law, giving an approximation in scale up of the vessel volume when all other parameters like pressure, temperature, turbulence, etc. are kept constant:

$$K_{g_{\text{ex}}} = \left( \frac{dp}{dt} \right)_{\text{ex}} \cdot V^{1/3}.$$  

Though it is known that the cubic law is not suitable in every case, the $K_g$ -value is used to compare the pressure rise within different vessels and is a measure for explosion severity. A piezoelectric pressure sensor has been used to measure the pressure rise, the specifications are shown in Tab. 2-1.

Tab. 2-1: Specifications of the used pressure sensor

<table>
<thead>
<tr>
<th>manufacturer/model</th>
<th>PCB/113A21</th>
</tr>
</thead>
<tbody>
<tr>
<td>range</td>
<td>1379 kPa</td>
</tr>
<tr>
<td>sensitivity</td>
<td>3.6 mV/kPa</td>
</tr>
<tr>
<td>maximum pressure</td>
<td>6895 kPa</td>
</tr>
<tr>
<td>resolution</td>
<td>0.021 kPa</td>
</tr>
<tr>
<td>resonant frequency</td>
<td>500 kHz</td>
</tr>
<tr>
<td>low frequency response</td>
<td>0.5 Hz</td>
</tr>
</tbody>
</table>
3 Results of the turbulence field measurements for three different fan designs

This Chapter discusses the results of the turbulence field measurements and compares the measurements for different fan designs and different fan speeds. Fig. 3-1 shows the three different fans which were investigated. All fans have a diameter of 45 mm with 6 blades of each 6 mm depth, only the blade angles of the fans are different (0°, 22.5° and 45°).

Fig. 3-1: Fan designs

3.1 RMS values and mean velocities

Fig. 3-2 shows the mean velocities and RMS values for different fan designs at a fan speed of \( U = 5000 \) rpm. The figure shall not give a quantitative analysis of the velocities and RMS values. The length of the bars is proportional to the velocity or RMS value measured at the corresponding position. The figure gives a comparison of the different fan designs and the dependency on the location.

As shown in Fig. 3-2, the blade angle has an influence on the mean velocities. The velocity component in z-direction is influenced significantly. There is a vortex rotation around the x-axis. A smaller blade angle increases the velocity component \( u_z \) and therefore the intensity of the vortex. The velocities in the x-y plane are in general explicitly smaller than the z-component and are influenced less by the blade angle. Nevertheless, there is a slight increase of the velocity at position \( x, y = 3 \) cm towards the vessel centre for a larger blade angle. The velocity field is dominated by a vortex around the x-axis.

The comparison of RMS components at the different LDA measuring points illustrates, that the intensities of all three RMS components are similar at a specific position, validating the assumption of isotropic turbulence within the vessel. There is a dependency of the RMS value on the location. The closer the measuring point is to a fan, the stronger is the RMS value. It has to be highlighted that for the fans with a blade angle of 45° and 22.5° only at the positions \( x = 5 \) cm/\( y = 2 \) cm and \( x = 5 \) cm/\( y = 3 \) cm the mean velocities are larger than the RMS values. The turbulence dominates the flow within the vessel and presumably the mean velocity has no influence on the flame.
The dependency of the RMS value on the fan speed has been investigated at five LDA measuring points along the x-axis. The mean RMS value of the components in y- and z-direction is plotted against the fan speed in Fig. 3-3. The RMS value increases linearly with an increasing fan speed. The dependency of the RMS value on the location which has also been discussed by means of Fig. 3-2 is also recognizable in Fig. 3-3. The measuring point at x = 3 cm is closest to the fans, the positions x = 1 cm and x = 5 cm are most far from the fans. Hence the RMS values at x = 3 cm are largest whereas the RMS values at x = 1 cm and x = 5 cm are smallest.

In order to give only one RMS value for a specific fan speed, a mean value of the three locations shown in Fig. 3-3 is formed. This value is used in Chapter 4 to compare the influence of turbulence on the $K_g$-value.
### 3.2 Integral length scales

The integral length scales have been measured with two different optical resolutions. Additionally, a longitudinal and transversal correlation coefficient has been formed, giving two length scales: $L_x$ and $L_y$ respectively.

The results are presented in Fig. 3-4. Three diagrams show integral length scale plotted against fan speed for the three fan designs. The closed blue symbols denote the measurements of the worse optical resolution (0.44 mm/vector), the opened green symbols denote the results of the better optical resolution (0.18 mm/vector). As one can see, the integral length scale is independent of the fan speed and also independent of the fan design. The length scales of the measurements with the worse optical resolution are about 1 mm larger than the length scale of the better optical resolution. An optical resolution superior to the one used here could technically not be realized.

It should be noted, that the longitudinal length scale is on an average 30% larger than the transversal length scale. This can be explained with the theory of turbulence and confirms the accuracy of the measurements but is not further discussed here.

As a result of the length scale measurements, the results of the measurements of the better optical resolution are used to characterize the turbulence. The integral length scales in the explosion vessel are therefore 4.2 mm +/- 0.1 mm and 3.3 mm +/- 0.1 mm for the longitudinal and transversal length scale respectively, they are independent of fan design and fan speed.
Fig. 3-4: Measured integral length scales at different fan speeds; blue/closed symbols: optical resolution 73.4 µm/pixel, green/open symbols: optical resolution 30.0 µm/pixel; squares: longitudinal length scale, triangles: transversal length scale.
4 Results

For the following results the fans with a blade angle of 22.5° have been selected to generate turbulence. The influence of turbulence on the $K_g$-value has been investigated for three methane-air mixtures and for two hydrogen-air mixtures at atmospheric conditions ($p = 1$ atm, $T = 20$ °C). Altogether 68 measurements were accomplished.

4.1 Effect of turbulence on $K_g$-value for methane-air mixtures at 1 atm and 20 °C

The effect of turbulence on $K_g$-value for methane-air mixtures at 1 atm and 20 °C is illustrated in Fig. 4-1. The $K_g$-values for a lean (6.4 vol.-% methane), a rich (12.8 vol.-% methane) and the stoichiometric (9.3 vol.-% methane) methane-air mixture is plotted against the fan speed. For all mixtures the $K_g$-value increases linearly with the fan speed. The $K_g$-value for the stoichiometric methane-air mixture increases from 170 bar m/s without turbulence to 2000 bar m/s at a fan speed of 16,000 rpm. The $K_g$-values for the lean and rich mixtures increase from 35 and 65 bar m/s at $U = 0$ rpm to 1500 bar m/s at $U = 13,000$ rpm and 500 bar m/s at $U = 3,500$ rpm respectively. The lean mixture couldn't be ignited for fan speeds larger than 13,000 rpm, the rich mixture couldn't be ignited for fan speeds larger than 3,500 rpm.

In Fig. 4-2 the $K_g$-values obtained for this deliverable are compared to other $K_g$-values from several vessels without turbulence generators measured for the EU-project SAFEKINEX. The diagram reveals that turbulence has a tremendous influence on the $K_g$-value. The $K_g$ values from all other vessels are below 100 bar m/s, whereas the $K_g$-values for the here measured lean, stoichiometric and rich mixtures increases to 1500 bar m/s, 2000 bar m/s and 500 bar m/s respectively. This means that for the given turbulence conditions the $K_g$-values increase by a factor of 42.8, 11.7 and 7.7 for the lean, stoichiometric and rich mixture respectively. The
stochiometric mixture has not quenched at the maximum fan speed of 16,000 rpm, therefore even higher $K_g$-values have to be expected for the stochiometric methane-air mixture.

![Graph](image)

Fig. 4-2: $K_g$-values influenced by turbulence for three methane-air mixtures at $p = 1$ atm and $T = 300$ K compared to $K_g$-values from other explosion vessels without turbulence generators. The turbulence level dots at the vertical lines in the graph are in reverse order to the legend at the right.

### 4.2 Effect of turbulence on $K_g$-value for two lean hydrogen-air mixtures at 1 atm and 20 °C

The effect of turbulence on $K_g$-value for hydrogen-air mixtures at 1 atm and 20 °C is illustrated in Fig. 4-3. The $K_g$-values for two lean hydrogen-air mixtures are plotted against the fan speed. The $K_g$-value for the mixture with 12.0 vol.-% hydrogen increases linearly with the fan speed, whereas the $K_g$-value for the mixture with 7.6 vol.-% hydrogen first increases linearly before it become constant at $U = 6000$ rpm. The $K_g$-values of the 7.6 vol.-% and 12.0 vol.-% hydrogen-air mixtures increases from 15 bar m/s and 100 bar m/s without turbulence to 200 bar m/s and 1200 bar m/s at a fan speed of 10,000 rpm respectively.

Due to technical problems the fan speed could not be increases further for the hydrogen experiments, which means that even higher $K_g$-values for the 12.0 vol.-% hydrogen-air mixture have to be expected, the $K_g$-value for the 7.6 vol.-% hydrogen-air mixture reaches a constant value and presumably won't increase further.
In Fig. 4-3 the $K_g$-values for the two lean hydrogen-air mixtures obtained for this deliverable are compared to other $K_g$-values from several vessels without turbulence generators measured for the EU-project SAFEKINEX. The diagram reveals that also for hydrogen-air mixtures turbulence has a tremendous influence on the $K_g$-value. The $K_g$-values increase by a factor of 13.3 and 12.1 for the 7.6 vol.-% and 12.0 vol.-% hydrogen-air mixtures respectively by increasing the turbulence up to a RMS value of 3.5 m/s.

Fig. 4-4: $K_g$-values influenced by turbulence for two hydrogen-air mixtures at $p = 1$ atm and $T = 300$ K compared to $K_g$-values from other explosion vessels without turbulence generators.
5 Conclusion

Eight fans were installed within an explosion vessel to investigate the effect of turbulence on the $K_g$-value. Comprehensive measurements were necessary to characterise the turbulence in the explosion vessel. LDA (Laser Doppler Anemometry) and PIV (Particle Imaging Velocimetry) measurements yield that the flow within the vessel is dominated by turbulence as the RMS values are larger than the mean velocities. Additionally, the turbulence is almost isotropic and therefore appropriate to investigate the effect of turbulence on combustion phenomena. The turbulence intensity characterised by the RMS (Root Means Square) value increases linearly with fan speed, whereas the integral length scale is not influence by fan speed. There is an influence of the location on the RMS value, which means that the turbulence intensity is not absolutely homogeneous. Nevertheless, this influence is acceptable.

The effect of turbulence on the $K_g$-value has been investigated for three methane-air and two hydrogen-air mixtures. The results show, that turbulence has a tremendous influence on the $K_g$-value. The $K_g$-value increases with an increasing turbulence intensity. The strongest rising has been observed for the lean methane-air mixture, where it increases by a factor of 42.8 by increasing the turbulence intensity up to a RMS value of 4.0 m/s. A general dependency of the $K_g$-value on the RMS value can't be given, as the mixture composition has an unknown influence too.

Due to the tremendous influence of turbulence on the $K_g$-value the present results clarify that the influence of turbulence has to be taken into account for risk analysis. Therefore the geometry of a vessel and potential turbulence generators (e.g. sieve bottoms, packing bodies in a column, grids, measuring heads that stick out, stirrers) have to be assessed concerning there capability to generate turbulence by shaping an obstacle for a flow.

Presumably other safety parameters are influence by turbulence likewise. Therefore further investigations are necessary to assess the risks of turbulence and clarify the effect of it on safety parameters.
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