A modular test bench for explosion detection systems

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Abstract

Requirements on fire and explosion detection systems continue to rise, especially in safety-sensitive areas. This paper presents a test bench for explosion detection systems. Theoretical computations of the flame temperature as a function of fuel/air ratio and maximum occurring combustion pressure specify the boundary conditions. Additionally, a series of experiments is performed to validate the theoretical results and to characterize the generated deflagrations. Due to its modular construction the test bench is able to create hydrocarbon-based deflagrations of adjustable scale. A high safety standard is guaranteed by filling the fuel and enabling the ignition device in separated steps.

Keywords: Test bench; Deflagration; Explosion; Detection system

1. Introduction

Besides endangering many lives, explosions in mills or refineries generally cause high economical and ecological damage. To limit the extent of such disasters, it is necessary to develop and test novel explosion detection systems. To this end a test bench, which generates hydrocarbon-based deflagrations of adjustable scale, is constructed. This kind of test bench supports the development of new detection technologies and it can help to determine technical limitations of existing systems. In contrast to test benches simulating radiation emission using light emission diodes, the developed test bench supports an analysis of detection systems under realistic conditions.

Previous test benches are constructed essentially to research the fire and explosion hazards [1] or to provide data needed for safety evaluations of hydrogen deflagrations [2]. These experimental analyses use tents and plastic bags of different volumes for field test and tubes to simulate the explosion expansion in tunnels. Furthermore a spherical vessel to verify a flame growth model based on various explosion parameters is described previously [3].

Another set-up simulates the crew compartment of armored vehicles and is used to evaluate the effects of different extinguishing systems [4]. The explosion in the test compartment is generated with a fuel spray using a twin-fluid (fuel and air) nozzle and a hot wire ignition source. All of the extinguishing systems are activated by a fast flame detector.

Analyses of explosion detection systems require reproducible and size-controlled explosions to achieve comparable results. The previously presented test benches for analyzing explosion and deflagration characteristics are either not primarily constructed for detection system testing or cannot ensure a perturbation-free test environment. Additionally, these test benches simulate special cases of explosion hazards, like the behavior of hydrogen-based deflagrations on a large scale, which do not necessarily correspond to the most general explosion hazards. However, with some limitations the presented set-up for evaluating extinguishing systems [4] can be used as a test bench for fast detection systems. Nevertheless the main
focus of this system is on the analysis of different extinguishing systems. Furthermore, the set-up cannot ensure the requirements defined for testing explosion detection systems.

Our test bench is able to create reproducible hydrocarbon-based deflagrations of different scales. The system consists of a deflagration chamber, a fuel-charging device and an igniter. The subsystems are integrated and a closed box allowing defined test conditions.

2. Theoretical analysis of flame temperature and explosion pressure

Information about the process parameters during combustion is necessary for the construction and use of the test bench. The two most important parameters are the combustion temperature as a function of the air/fuel ratio and the maximum explosion pressure. On the one hand the duration and scale of the deflagration is controlled by the air/fuel ratio. On the other hand the explosion chamber’s wall thickness and material has to be chosen according to the combustion temperature and maximum explosion pressure.

A temperature model is used to estimate the maximum temperature in fuel/air-combustion as a function of the air/fuel ratio. The model is based on the balance equation of the combustion process, assuming an adiabatic process and an air composition of 21 vol.% of oxygen and 79 vol.% of nitrogen. A simple temperature model for combustion can hence be described by

\[
\Delta T_{ad} = \frac{H_{\text{fuel}} \cdot n_{\text{fuel}}}{(\lambda - 1) \cdot n_{O_2}^* \cdot C_{p, O_2}^m(T) + \frac{\lambda \cdot n_{O_2, stoich}}{0.21} \cdot C_{p,N_2}^m(T) + \sum_j C_{p,i}^m(T) \cdot n_i}
\]

(1)

The corresponding symbols are defined in Table 1.

| Symbol         | Description                                      |
|----------------|--------------------------------------------------|
| \(H_{\text{fuel}}\) | Lower heating value of fuel                      |
| \(n_{\text{fuel}}\) | Amount of substance of fuel                      |
| \(\lambda\)     | Air/fuel ratio                                   |
| \(n_{O_2}^*\)   | Amount of substance of oxygen for stoichiometric combustion |
| \(C_{p, O_2}^m\) | Mean molar heat capacity of oxygen               |
| \(C_{p,N_2}^m\)  | Mean molar heat capacity of nitrogen              |
| \(C_{p,i}^m\)    | Mean molar heat capacity of other combustion products |
| \(n_i\)          | Amount of substance of other combustion products  |

In a more sophisticated approach the model is currently being extended to describe the influence of the dissociation of combustion products. This completion is especially required, if combustions based on oxygen instead of air are considered.

![Adiabatic combustion temperature as a function of air/fuel ratio for propane-air combustion.](image)
A result of the model when using propane as fuel is shown in Fig. 1. As expected, it can be seen that the adiabatic combustion temperature decreases as the air/fuel ratio increases. However, the curve only displays theoretical results; the real temperature is lower than the computed temperature, because the model does not take into account any heat losses of the combustion gas or incomplete combustion.

The rough estimation of the expected combustion pressure is based on the ideal gas law by assuming an isochoric and complete heat conversion. A further assumption is the use of an average specific gas constant of fuel and air in relation to air/fuel ratio after combustion. Using the presented temperature model for calculating the adiabatic combustion temperature, the maximum combustion pressure can be estimated by

\[ P_{\text{max}} = \frac{(m_{\text{air}} + m_{\text{fuel}}) \cdot R_{\text{fuel,air}} \cdot T_{\text{ad}}}{V} \]  

where the following symbols apply.

| Symbol     | Description                                      |
|------------|--------------------------------------------------|
| \( m_{\text{air}} \) | Air mass                                         |
| \( m_{\text{fuel}} \) | Fuel mass                                        |
| \( R_{\text{fuel,air}} \) | Specific gas constant of fuel and air after combustion |
| \( T_{\text{ad}} \) | Maximum adiabatic combustion temperature          |
| \( V \) | Volume of deflagration chamber                   |

Considering a stoichiometric combustion temperature of 2255 K, the maximum combustion pressure is 8.12 bar. However, due to sealing of the deflagration chamber with a pressure venting foil, the computed maximum pressure will never be reached in reality.

3. Test bench details

The presented test bench for explosion detection systems is set up modularly. It consists of a deflagration chamber, an ignition unit, a fuel-filling device and pressure sensors. The subsystems are integrated and a closed box allowing defined test conditions. Fig. 2(a) shows the entire set-up.

![Fig. 2. (a) Entire set-up while charging the chamber within the open box (dimensions 100 \times 50 \times 50 \text{ cm}^3); (b) deflagration chamber with a volume of 2000 mL.](image)

The deflagration chamber is an air/fuel mixture vessel for generating hydrocarbon-based deflagrations. Fig. 2(b) displays a 2000 mL deflagration chamber, further chambers with a volume of 5000 mL and 10000 mL are realized. Both, the size of the chamber and the controlled air/fuel ratio facilitate the generation of deflagrations of various scales and durations. The fuel-filling is done according to the partial pressure method using feedback control from a high precision digital pressure gauge and a Vögtlin red-y flow controller. The ignition is realized by a pyroelectric igniter, which is integrated in the back
of the chamber. To guarantee high safety standard, the fuel-filling connectors are equipped with quick acting closures with little leakage.

The initiated deflagration is released through two different kinds of bursting foil (aluminum foil with a thickness of 13 μm respectively 25 μm). With this system, the combustion gas can expand as the foil bursts at a defined pressure. Thus the combustion transitions into a deflagration with a certain propagation velocity.

The pressure course within the chamber is measured with a quartz pressure transducer (PCB Piezotronics, model 112A21). Using a PC-based measuring board, pressure data acquisition and a few control commands are run together in a common control computer. Future developments will allow controlling the test bench with a specialized self-developed control program.

The box shown in Fig. 2(a) provides a shielded area for the analysis of detection systems. It guarantees a space which is not influenced by environmental factors. Furthermore other kinds of boxes can simulate true-to-scale environments for testing of novel detection systems before using them in real situations.

4. Experimental tests and results

Propane is used as fuel to acquire measuring data for experimentally testing and analyzing the test bench. Most explosion/fire hazards are based on hydrocarbon fuels. Propane is one of such hydrocarbon fuels, which lends itself to be used in the test bench because of its easy handling. Moreover, it is safe to use due to its small flammable range (1.7 - 9.5 vol.% of propane in air).

The deflagrations are recorded by a Basler pilot piA640 high speed camera (210 frames per second). A sequence of a deflagration with an air/fuel ratio of 1.07 (equal to a propane partial pressure of 40 mbar) is shown in Fig. 3. As displayed, the deflagration expands to its maximum after only 50 ms, which is a short period in comparison to the total duration of 235 ms. This long duration hints at an excess of fuel in the back of the chamber after the deflagration leaves the vessel. In further experiments it is verified that the duration and the propagation of the deflagration increase with increasing fuel ratio.

![Sequence of a propane-air deflagration with an air/fuel ratio of 1.07 and 13 μm foil.](image)

A static tearing resistance test of the bursting foils with compressed-air is performed before combustion test starts. The results, presented in Table 3, illustrate that even tiniest damage or inhomogeneous parts of the bursting foil lead to different burst pressure.

|                | Foil 13μm | Foil 25 μm |
|----------------|-----------|------------|
| Mean burst pressure in mbar | 132.15    | 176.08     |
| Standard deviation in mbar   | 11.69     | 23.90      |

The pressure curve measured within the chamber while combusting the propane air-mixture is shown in Fig. 4. The initial pressure value is zero-referenced against the chamber pressure before ignition, so it is equal to the sum of
atmospheric pressure and partial fuel pressure. In the displayed case, the chamber is filled with 40 mbar of propane (a/f ratio of 1.07) and is hermetically sealed by a 13 μm foil.

As displayed, after an ignition delay of 10 ms an exponential pressure rise follows. At a defined pressure, the bursting foil collapses and the pressure within the chamber decreases rapidly. This allows the combustion gases to leave and simultaneously leads to a transition of the combustion into an expanding deflagration. The described pressure loss is followed by a damped oscillation with a computed frequency of 460 Hz, which is presumably caused by alternate reflections of the pressure wave at the box and the chamber.

This oscillating behavior of the pressure, which is also observable in the impulse curve, can most likely be described by a differentiating second order delay (DT2) element. In a next step, the system parameters need to be determined in order to confirm the system behavior.

Finally, the pressure within the chamber converges to a negative value, which results from using the sum of atmospheric pressure and partial fuel pressure as a reference. For computing the impulse curve, the pressure curve is adjusted for the partial fuel pressure after the bursting foil collapses at the maximum pressure. Consequently, the adjusted pressure curve for computing of the impulse starts and ends at zero. This yields the impulse curve displayed in Fig. 5, which is the integral of the said pressure curve.

As displayed in Fig. 6, a series of deflagrations with an air/fuel ratio of 1.07 is performed to verify the deflagration reproducibility. The pressure curves are approximated by exponential functions. The respective time constants of the functions are used as basis for comparison. In a range of 5 mbar to 100 mbar the mean time constant is 3.31 ms with a standard deviation of 0.82 ms. The curves in Fig. 6 show that the test bench is able to generate an acceptably reproducible deflagrations. The outliers presumably result from the non-homogeneity of the mixture. A possible improvement of the homogeneity might be the use of a mixing device within the chamber.

Fig. 4. Pressure course within the explosion chamber during combustion. Fig. 5. Pressure-adjusted impulse curve during combustion deflagration chamber.

Fig. 6. Series of pressure curves of deflagrations with an air/fuel ratio of 1.07 and a foil thickness of 13μm.
The deflagration temperature is measured by recording its spectrometric data. Based on Planck’s law the flame temperature is approximated by fitting a model curve. As show in Fig. 7 the computed temperature $T$ corresponds to the absolute temperature of the observed combustion, but the equivalent emissivity $\varepsilon$ is not comparable to the emissivity of a black or grey body.

![Approximation of the flame temperature of a deflagration with an air/fuel ratio of 1.07 by using Planck’s law.](image)

In comparison to the theoretical temperature model based on Eq. (1), the measured temperature at an air/fuel ratio of 1.07 is considerably lower. The temperature difference results from the assumptions underlying the model and the spectrometric data, which was measured after the deflagration has left the chamber.

5. Conclusions

In this paper a modular test bench for analyzing any kind of explosion detection system is presented. It allows realizing reproducible hydrocarbon-based deflagrations of adjustable scale. Thus an appropriate basis is given to execute scientific trials under defined conditions.

The experiments performed at the HSU show that the test bench is able to create reproducible deflagrations in varying but defined scales by controlling the fuel ration charged into the chamber. However, it is necessary to assure a homogeneous mixture of air and fuel within the chamber in order to improve the repeatability of the deflagrations. For controlling the test bench, a customized PC-based control program is planned to be developed.

In conclusion, the presented test bench provides a good basis for the development of a novel explosion detection method. Additionally, due to its modular construction, any area or space to be monitored can be simulated true-to-scale by using other kinds of boxes.

References

[1] Yang, L. Z., Fan, W. C., Zhou, X. D., Wang, Q. A., 2001. Analysis of Fire and Explosion Hazards of Some Hydrocarbon-air Mixtures, Journal of Hazardous Materials A84, p. 123.
[2] Sato, Y., Iwabuchi, H., Groethe, M., Merilo, E., 2006. Chiba S. Experiments on Hydrogen Deflagration, Journal of Power Sources 159, p. 144.
[3] Jo, Y. D., Crowl, D., 2010. Explosion Characteristics of Hydrogen-air Mixtures in a Spherical Vessel, Process Safety Progress 29, p. 216.
[4] Kim, A., Liu, Z., Crampton, G., 2007. Study of Explosion Protection in a Small Compartment, Fire Technology 43, p. 145