

EXPLOSION PROCESSES AND DDT OF VARIOUS FLAMMABLE GAS/AIR MIXTURES IN LONG CLOSED PIPES CONTAINING OBSTACLES

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In this work results of experimental investigations towards explosions processes in long pipe systems are presented. The experiments were carried out in pipes with diameters of 0.159 m as well as 0.200 m, and overall lengths of up to 23 m. Three flammable gases mixed in air were used, including propane, ethene, and ethyne. All mixtures were set up to a similar maximum experimental safe gap (MESG) of about 0.94 mm – 0.97 mm (explosion group IIA). It was observed that the maximum pressures as well as the flame speeds differed significantly. The more the mole fraction of the investigated gases in air had to be reduced to achieve a similar MESG (compared to propane/air in stoichiometric composition), the less severe was the explosion.

Turbulence inducing elements enhance the heat and mass transfer in reactive flows. Therefore, the influence of various baffles (blockage ratios of 36%, 51%, 64%, 77%, and 91%) installed into the pipe system on the explosion characteristics was investigated for a stoichiometric propane/air mixture and an industrial mixture consisting of hydrogen, carbon monoxide, carbon dioxide, nitrogen, and air. As a result of the use of baffles, deflagration to detonation transitions (DDT) occurred in the pipe system. Absolute pressures of more than 100 bar joined by supersonic flame speeds of >2000 m/s were determined by piezoelectric sensors and photodiodes.

1 INTRODUCTION

Explosions and fires still cause serious losses in the process industries, followed by accidental releases, [Mannan, 2005], and [Kleiber, 2006]. The industrial principles of protection against gas explosions contain in a first step the avoidance of an explosive atmosphere and effective ignition sources. If neither of these methods nor a combination of both ensures safe handling and processing, constructional explosion protection measures in a second step reduce the impacts of explosions to an acceptable level, [Council Directive 1999/92/EC, 1999], [Bartknecht, 1993], and [Grätz and Förster, 2001].

Within the concept of explosion isolation, flame arresters, if wisely installed into the system, separate the part of the explosion from the tract, which needs to be protected. Therefore, flame arresters must be tested against flame transmission to the specific explosion group of the explosive mixture in accordance with IEC 60079-0 [2004]. The explosion group is determined by the maximum experimental safe gap for an explosive mixture (MESG). It represents the maximum gap of a joint which prevents any transmission of an explosion during multiple tests due to the effects of quenching, [IEC 60079-1, 2002]. The experimental safe gap of a gas mixture is not a constant value, but changes amongst others with the mole fraction of the flammable gas in air. Additionally, the efficiency of flame arresters is influenced by the local transition point from deflagrative to detonative reaction mechanism (DDT). The occurrence of the transition point depends on the length-to-diameter ratio (L/D) and the orientation of the pipe (vertical/horizontal), initial pressure p_0 and temperature T_0, flammable gas concentration X, ignition energy, wall roughness, and occurrence of turbulence inducing elements. According to EN 12874 [2001], EN 13237 [2003], and Grätz and Förster [2001] a deflagration is defined as an explosion propagating at subsonic velocity. The flame speed is smaller than the speed of the shock waves, which propagate at sonic speed. The reaction front at that time is constantly accelerating, and the time to the maximum pressure as well as the time of the pressure drop to the end value is comparatively long. In contrast, a stable detonation is an explosion propagating at supersonic velocity and characterised by a shock wave. Both the flame front and the shock wave are coupled with similar propagation speeds, which remain at a constant value. A stable detonation is furthermore characterised by an almost vertical pressure rise (up to 20 times of the initial pressure), followed by a fast pressure drop to the end value. The transition zone lies between the deflagration and the stable detonation regimes. It includes fast deflagrations, DDT, and overdriven detonations. Latter show pressures of >100 bar (abs.), but the pressure drop to the end value occurs slower than during a stable detonation.

In recent years, many investigations towards explosion processes of flammable gas/air mixtures have been carried out and reported in literature. Bartknecht [1993] reports of experiments with methane/air mixtures in a 1 m^3 vessel with central ignition. He found maximum explosion pressures p_{max} and maximum rates of pressure rise at stoichiometric compositions of the mixtures, with increasing impacts at higher initial turbulence intensities (Tu; ratio of the root-mean-square of the velocity fluctuations and the mean velocity). In addition, it was shown that the p_{max} decreased with an increasing surface-to-volume ratio of the investigated vessels at central ignition. Razus et al. [2007] investigated the influence of the mixture composition and the ignition point on the explosion characteristics of propylene/air mixtures in small spherical and cylindrical vessels. Maximum rates of pressure rise were determined at the stoichiometric composition. Due to the effects of heat loss to the cold vessel walls, the maximum rates of pressure rise at central ignition in the cylindrical vessel exceeded those with ignition at the top of the cylindrical vessel. Lohrer et al. [2007] observed similar dependencies of the p_{max} on the mixture composition for propane/air mixtures in a horizontal pipe system (D = 0.159 m, L = 23 m). Furthermore, a decreasing p_{max} with an increasing pipe length was measured due to the heat transfer of the hot combustion products to the pipe walls.

It has been known for a long time, that turbulence inducing elements enhance the heat and mass transfer in reactive flows, leading to a reduced start-up way of the ongoing detonation. These elements contain amongst others valves and devices for the measurements of mass flows. Pioneering works of Starke and Roth [1989], Andrews et al. [1990] and Phylaktou and Andrews [1991], showed that obstacles induce an acceleration of the combustion process. The deflagration experiments were carried out in comparatively small pipes (maximum lengths of 1.64 m and maximum diameters of 0.1 m) with the mixtures methane/air, propane/air, ethene/air, ethyne/air, and hydrogen/air. Furthermore, experiments in an explosion vessel (20 L; maximum dimension 0.545 m) with Liquefied Petroleum Gas (LPG) have been carried out by Masri et al. [2000] and Ibrahim and Masri [2001]. It was shown, that the flame speeds increased with an increasing blockage ratio BR from 10% to 78% (area percentage; defined as the blocked area divided by the cross-section area of the vessel). Lohrer et al. [2007] quantified the influences of two baffles on the flow velocities and the Tu of air flows through steel pipes (D = 0.159 m) with flange assemblies and baffles (BR = 36% and BR = 91%). The measurements were performed with the 3D constant temperature anemometry (CTA) technique. It was found, that flange assemblies (including gaskets) had no significant effect on the Tu. In contrast, both investigated baffles increased the Tu of the air flows significantly.

This work presents the results of explosion experiments in pipe systems with maximum diameters of 0.2 m and lengths of about 23 m. The investigations were carried out for various flammable gas/air mixtures of a similar MESG and an industrial mixture. In some cases the pipe system was set up with obstacles (BR of 36% to 91%) in order to reduce the start-up way of ongoing detonations.

2 EXPERIMENTS

2.1 MEASUREMENT TECHNIQUE

In the explosion experiments, flame speeds and dynamic explosion pressures were measured. To determine the flame front velocity in a reactive pipe flow, up to 6 photodiodes were mounted along the steel pipe. The pressure was measured with up to 4 piezoelectric sensors (PCB M113A22, 1.5 mV/kPa; PCB-J113A24/061M145, 0.73 mV/kPa). The measuring frequency f was set between 0.18 MHz $< f \leq$ 1 MHz.

2.2 EXPERIMENTAL SETUP

Two horizontal steel pipe systems with different flammable gas/air mixtures were used in the explosion tests:

- A: D = 0.159 m, L = 23 m, p_0 = 1.0 bar (abs.), different flammable gas/air mixtures of a similar MESG (0.94–0.97 mm; explosion group IIA): stoichiometric propane/air (4.2 Vol%), lean ethene/air (4.7 Vol%), and lean ethyne/air (3.6 Vol%),
- B: D = 0.2 m, L = 16 m, p_0 = 1.1 bar (abs.), industrial mixture: air (53.93 Vol%), carbon monoxide (20.33 Vol%), hydrogen (15.68 Vol%), carbon dioxide (9.53 Vol%), and nitrogen (0.53 Vol%).

In preliminary experiments the MESG of the gas/air mixtures for the test setup A had to be determined according to IEC 60079-1 [2002]. The tests were performed with propane/air, ethene/air and ethyne/air at an initial pressure of p_0 = 1.0 bar (abs.). With the assumption of a stoichiometric composition in air, ethene and ethyne belong to the explosion groups IIB and IIC, with a respective MESG of 0.65 mm and 0.37 mm. To achieve an almost

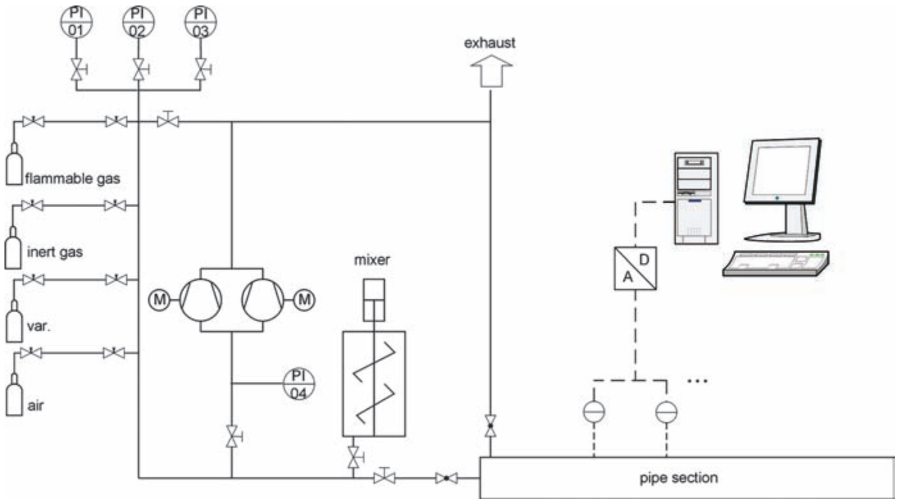

Figure 1. Principle of the experimental setup A, B and signal handling

equal MESG of about 0.94 mm–0.97 mm (compared to stoichiometric propane/air; explosion group IIA), the mole fractions of ethene and ethyne in air had to be reduced from their stoichiometric composition in air (6.5 Vol% and 7.7 Vol%).

The principle setup and signal handling can be seen exemplarily in figure 1, the setup A for the explosion experiments is presented in figure 2. For setup A, the pipe segments had at least 2 drillings every 0.5 m in axial direction for the adjustment of the photodiodes and pressure sensors. Since not all drillings were filled with sensors, plugs were used to close the leftover holes. In order to avoid extra turbulence generation, sensors and plugs closed up flush with the inner wall surface. Before the experiments were carried out, the pipe section was checked for leak tightness. Afterwards, the gas mixer and the pipe section were evacuated. Each flammable gas and air have been mixed with the partial pressure method and the pipe system was filled to the desired initial pressure. The ignition was started at the flange of one side of the pipe by a melting metal wire (ignition energy about 6 J to 12 J). Next to the ignition point, a photodiode triggered the measurement. The pressure signals have been "smoothed" by a low-pass filter to eliminate ground noise.

For setup A, the influence of the parameters flammable gas (without baffles; stoichiometric propane/air (4.2 Vol%), lean ethene/air (4.7 Vol%), and lean ethyne/air (3.6 Vol%) and BR of single hole baffles (for stoichiometric propane/air mixtures; 36%, 64%, and 91%) on the explosion characteristics was investigated. The baffles were installed in 0.6 m axial distance to the ignition point. As long as possible, at least 3 measurements for each parameter variation have been carried out. For the interpretation of the experiments, the values of p_{max} have been averaged over max. 4 sensors and 3 measurements.

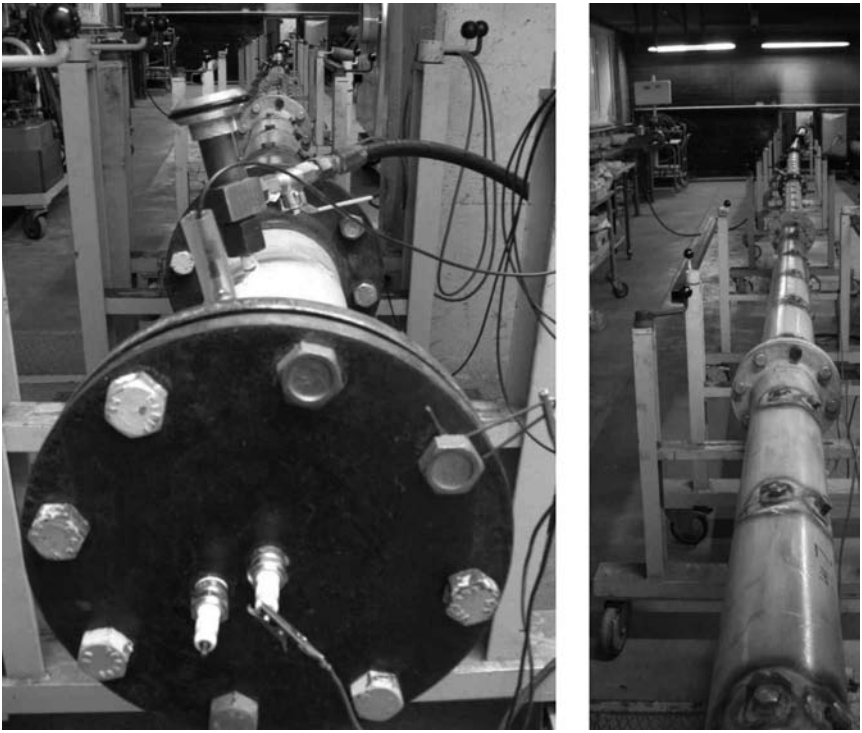

Figure 2. Photograph of setup A to determine the explosion characteristics of various flammable gas/air mixtures in a closed pipe with and without obstacles (L = 23 m, D = 0.159 m)

Experiments in setup B were carried out with the above described industrial mixture, first without and than with two different baffles (BR = 51% [single hole] and BR = 77% [five holes]). Due to the different setup, the 77% BR baffle in these experiments was installed in 6 m axial distance to the ignition point. In addition, one experiment was performed with a pre-volume of 22 L from which the ignition was initiated, followed by a baffle with a BR of 51%. Both were installed in front of the pipe system.

3 RESULTS AND DISCUSSION

3.1 SETUP A

In first test series without baffles, the explosion characteristics of different flammable gas/air mixtures with a similar MESG of about 0.94 mm–0.97 mm were investigated and compared to each other. The results of the explosion experiments are presented in figure 3, figure 4, and figure 5.

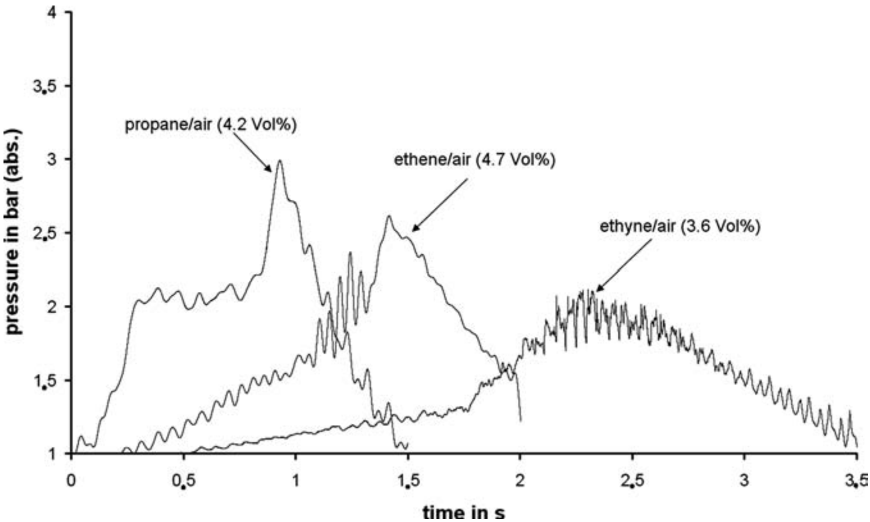

Figure 3. Explosion pressure versus time for three flammable gas/air mixtures of a similar MESG (setup A)

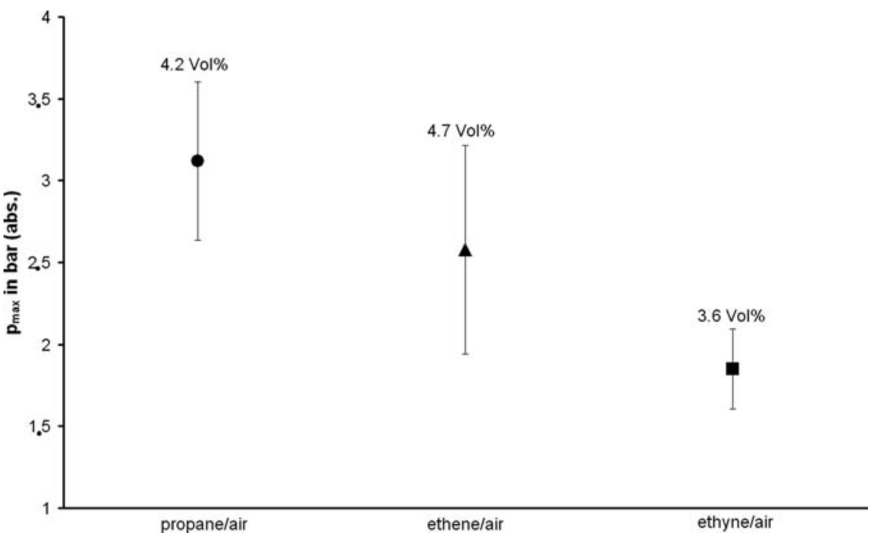

Figure 4. Maximum explosion pressure for three flammable gas/air mixtures of a similar MESG (setup A)

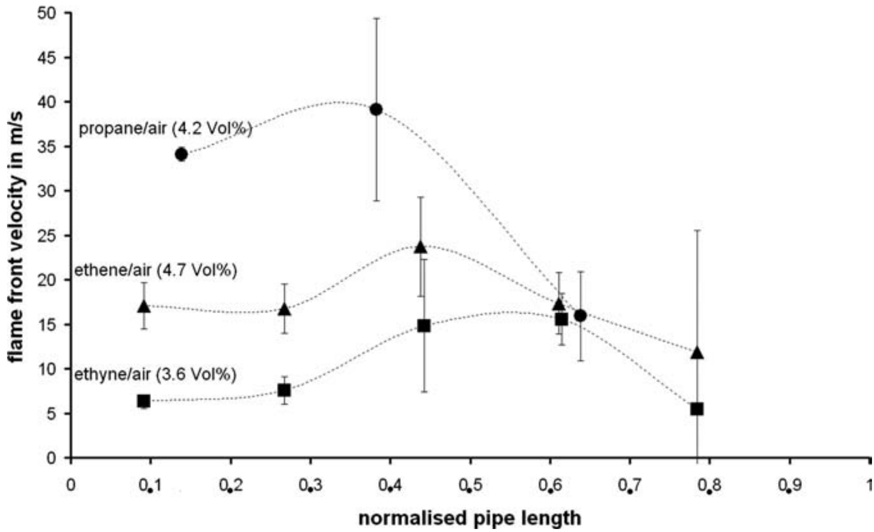

Figure 5. Flame front velocity versus normalised pipe length for three flammable gas/air mixtures of a similar MESG (setup A)

It was observed that the maximum pressures as well as the flame speeds differed significantly. For stoichiometric propane/air mixtures the highest explosion pressures of about 3.2 bar (abs.) were determined, followed by ethene/air and ethyne/air with respective p_{max} of about 2.6 bar (abs.) and 1.9 bar (abs.), figure 3 and figure 4. For ethene/air the mole fraction was reduced from the stoichiometric composition of 6.5 Vol% down to 4.7 Vol% (difference 1.8 Vol%) and for ethyne/air from the stoichiometric composition of 7.7 Vol% down to 3.6 Vol% (difference 4.1 Vol%). As can be seen, the more the mole fraction of the investigated gases in air had to be reduced to achieve an almost equal MESG (compared to propane/air in stoichiometric composition), the less severe was the explosion. Furthermore, the flame speeds of the stoichiometric propane/air mixtures (maximum values of 39 m/s) exceeded the values of the lean ethene/air and ethyne/air mixtures, figure 5. In all cases, flame acceleration was found up to the middle of the 23 m long pipe and deceleration towards the pipe end. Since the pipe system was closed at both sides, the axial propagation was detained, leading to higher radial spread and the flame fronts reached the cold pipe wall earlier and transferred heat to the pipe wall.

These results show that for flammable gas/air mixtures of a similar MESG the most conservative estimations towards the impacts of possible explosions will be achieved for stoichiometric compositions.

The experiments with stoichiometric propane/air mixtures were extended to the use of three different single hole baffles with BR of 36%, 64%, and 91% in the setup A. Figure 6

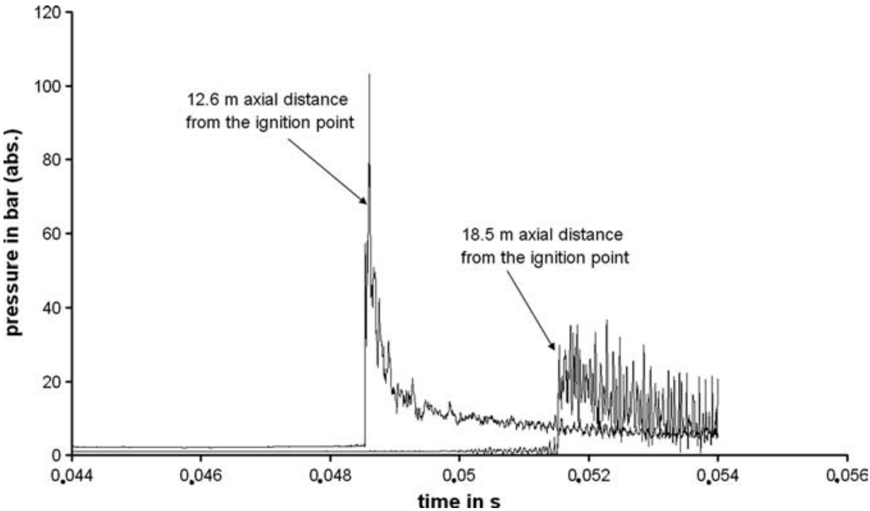

Figure 6. Pressure-time histories in 12.6 m and 18.5 m axial distance from the ignition point during a stoichiometric propane/air explosion with the use of a baffle (BR = 91%, setup A)

illustrates two pressure-time histories in 12.6 m and 18.5 m axial distance from the ignition point during a stoichiometric propane/air explosion with the use of a baffle (BR = 91%). Both pressure peaks describe different explosion regimes. In the first part of the pipe, the explosion starts as a deflagration (not visible with the chosen setup of the sensors) and finally accelerates to a detonation. The first peak in 12.6 m distance represents an overdriven detonation, characterised by a high pressure of 103 bar (abs.). Towards the end of the pipe at 18.5 m the local pressures decreased to 35 bar (abs.).

The influence of the BR on the p_{max} for explosions of stoichiometric propane/air mixtures in the setup A is presented in figure 7. The blank circles represent the pressure measurements in 12.5 m axial distance and the black points represent the pressure measurements in 18.5 m axial distance to the ignition point. Figure 8 gives the flame speeds versus the normalised pipe length (middle of the distance between the measuring points divided by the total pipe length) for the three investigated baffles with different blockage ratios. The flame speeds in these experiments were detected with 6 optical sensors along the pipe length.

For the baffle with a BR of 36% 5 out of 6 explosions occurred as deflagrations. Only in one experiment a DDT was observed, which is presented in figure 7 and figure 8. As can be seen for this case, the pressure in the rear part of the pipe system (53 bar (abs.)) exceeded the one in 12.6 m distance (5.2 bar (abs.)). Furthermore, the flame front accelerated to a maximum value of 480 m/s towards the end of the pipe. Both the pressure distribution in the pipe and the flame speed point to an ongoing detonation in the experiment

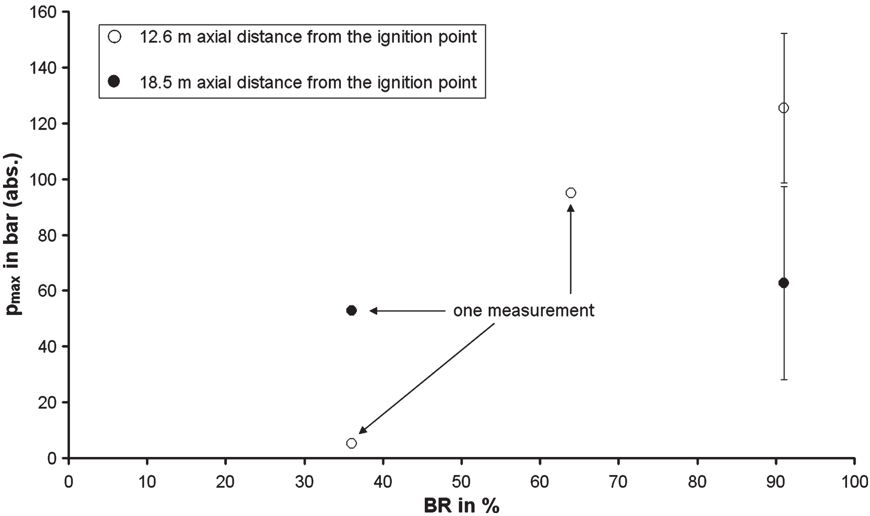

Figure 7. Maximum pressure versus blockage ratio of the baffles for stoichiometric propane/air explosions (setup A)

with the 36% BR baffle. Though, the overdriven detonation regime was not achieved in 18.5 m distance to the ignition point due to an insufficient turbulence generation in the main body of the flow. Lohrer et al. [2007] measured the turbulence intensities in 0.2 m distance behind a similar baffle across the pipe diameter for different air flows with the CTA technique. Due to the influence of the baffle on the flow characteristics, the Tu, in regions close to the wall, increased to a 5 times higher value (about 50%) compared to an empty pipe (about 10%). On the pipe axis the Tu dropped to a minimum value of about 3%.

As expected, the maximum pressures increased with an increasing BR due to an enhanced turbulence generation in the reactive flows. For the baffle with a BR of 91% the maximum Tu (55%) of various air flows was determined somewhere in the middle between the wall and the baffle opening. In the pipe axis Tu of about 10% were measured, [Lohrer et al., 2007]. The use of a baffle with a BR of 91% led to detonation processes in all three experiments. Figure 8 illustrates the acceleration process along the pipe. In the rear part of the pipe, flame speeds of >1500 m/s were determined. As can be seen in figure 7, the pressure values in 12.6 m distance (average p_{max} of about 125 bar (abs.)) exceeded the ones in 18.5 m distance (average p_{max} of about 62 bar (abs.)) to the ignition point. This observation confirms the assumption, that the deflagration was accelerated behind the baffle to an overdriven detonation.

An experiment with the medium baffle (BR = 64%) led to serious damages to the last two pipe segments and was therefore not repeated. The damages included a tear off of the pipe at the weld seam of the flange connecting the last two pipe segments, a crack in

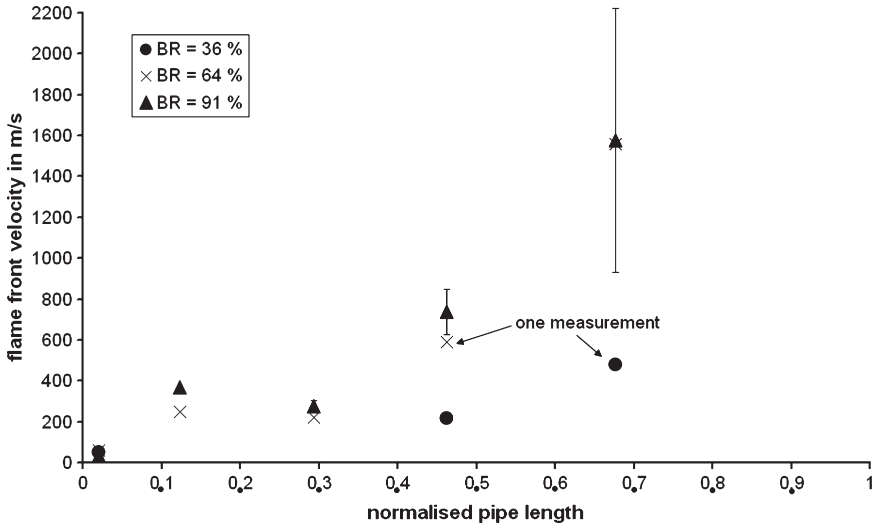

Figure 8. Flame front velocity versus the normalised pipe length during stoichiometric propane/air explosions with three baffles (setup A)

the weld seam at the end flange, and a 2 mm deformation in the middle of the blind flange (22 mm of thickness) which closed the pipe. Only one piezoelectric sensor (in 12.6 m distance) was able to measure the pressure time history. At this point a p_{max} of 95 bar (abs.) was determined (figure 7). Nevertheless, all photodiodes were able to measure the flame speeds along the pipe. The values are slightly smaller than those of the experiments with the 91% BR baffle (figure 8).

3.2 SETUP B

In contrast to setup A, setup B consisted of connected pipe segments with a diameter of 0.2 m and a total length of 16 m filled with a flammable industrial mixture. Both pressures and flame speeds were detected each with 4 piezoelectric sensors and photodiodes along the pipe axis.

Five preliminary experiments without turbulence inducing elements led to deflagrative reaction mechanism in the setup B. An exemplary pressure time history for this case is presented in figure 9. For these experiments a mean value of p_{max} = 3.56 bar (abs.) and maximum flame speeds of 72 m/s in the middle of the pipe were determined. As expected, the flame fronts decelerated towards the end of the closed pipe, which is characteristic for deflagration processes.

A totally different behaviour occurred with the use of baffles and a pre-volume. Figure 10 and figure 11 give pressure-time histories at 4 axial distances to the ignition

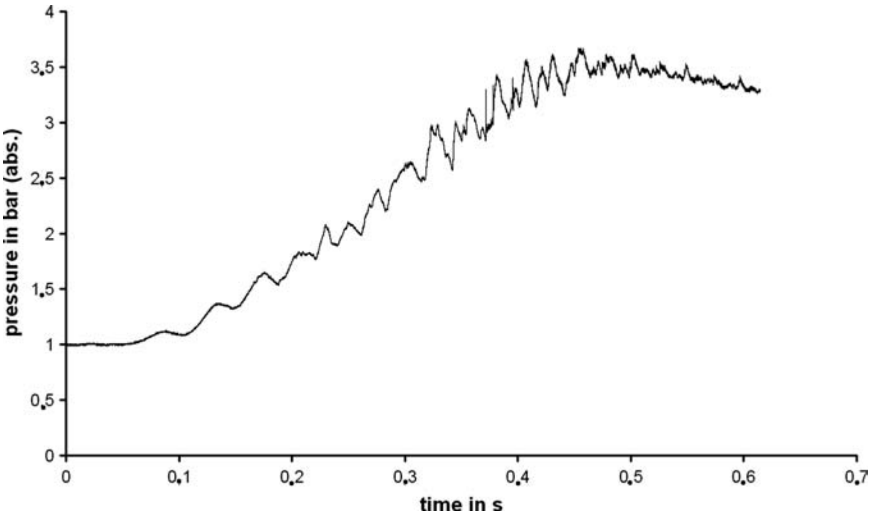

Figure 9. Deflagration pressure versus time for an industrial mixture (setup B; see "Experimental setup")

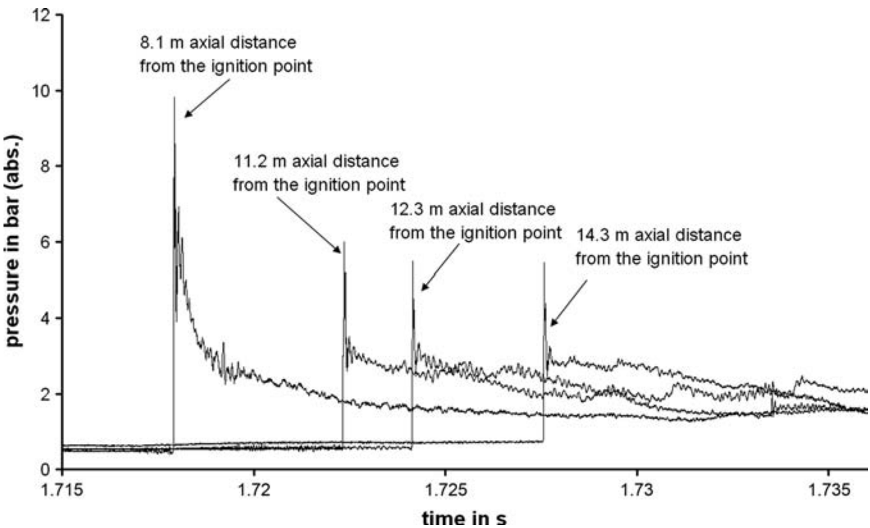

Figure 10. Pressure-time histories at 4 axial distances to the ignition point during an explosion of an industrial mixture with the use of a baffle (BR = 77%, setup B)

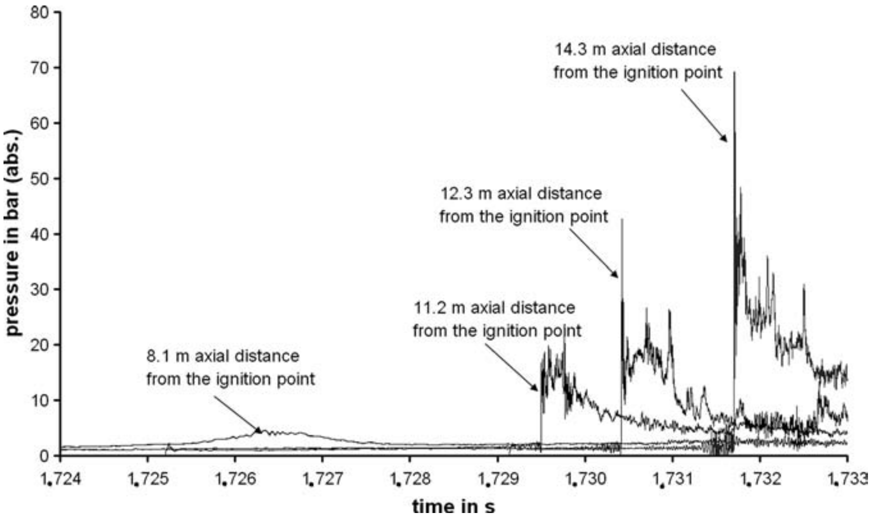

Figure 11. Pressure-time histories at 4 axial distances to the ignition point during an explosion of an industrial mixture with the use of a baffle (BR = 51%) and a 22 L pre-volume (setup B)

point with the use of baffles (BR = 77% as well as BR = 51% and a pre-volume). The velocities of the shock waves and the flame fronts in both experiments are merged in figure 12.

The almost vertical pressure rises in figure 10 (baffle; BR = 77%) suggest an overdriven detonation at the first sensor and a stable detonation at the following points since the pressure dropped from 9.8 bar (abs.) and remained constant at about 5.4 bar (abs.). Though, the pressure values seem too low for a fully developed detonation and the velocities of the shock wave and the flame front differed significantly from another (figure 12). The shock wave propagated at considerably higher velocities (688 m/s to 580 m/s) through the pipe than the flame front (507 m/s to 177 m/s). With regards to the comparably low pressures and the different velocities of shock wave and flame front, a fast deflagration seems more likely in this case. The steep pressure rise in this case could be explained by a jet ignition and vigorous combustion behind the baffle due to an instantaneously enhanced combustion area.

An ongoing overdriven detonation was observed with the use of a baffle (BR = 51%) and ignition from a pre-volume. As can be seen in figure 11, the maximum pressures along the pipe increased from 4 bar (abs.) at 8.1 m distance to 70 bar (abs.) at 14.3 m distance to the ignition point. The combustion process started as a deflagration and developed to an overdriven detonation. This process is illustrated in figure 12. The coupling of the shock wave and the flame front (which is characteristic for a detonation) occurred at the end of the pipe system. In this case, velocities of >1600 m/s were detected.

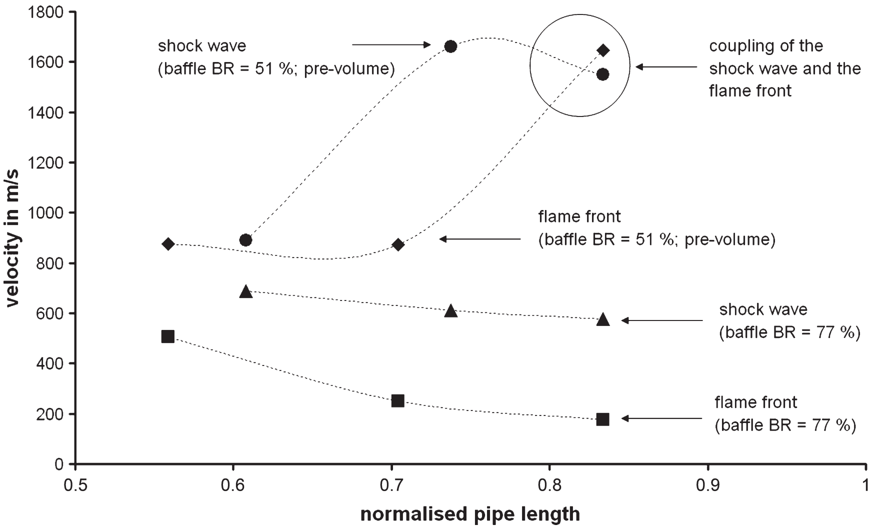

Figure 12. Shock wave and flame front velocities at 4 axial distances to the ignition point during explosions of an industrial mixture with the use of a baffle (BR = 51% and 77%) and a 22 L pre-volume (setup B)

4 CONCLUSIONS

Explosion experiments were performed in pipe systems with diameters of 0.159 m and 0.2 m and lengths of about 23 m and 16 m. The investigations were carried out for various flammable gas/air mixtures of a similar MESG and an industrial mixture. In some cases the pipe system was set up with obstacles (blockage ratios of 36% to 91%) in order to reduce the start-up way of ongoing detonations. It was found that the explosion characteristics of different flammable gas/air mixtures with a similar MESG differed significantly from another. The more the mole fraction of the investigated gases in air had to be reduced to achieve a similar MESG (compared to propane/air in stoichiometric composition), the less severe was the explosion. These results show that for classification of flame arresters (EN 12874, 2001) to be used in systems with various flammable gas mixtures of the same MESG, the most conservative estimations will be achieved for stoichiometric mixture compositions.

Furthermore, the experiments showed that baffles with blockage ratios of 36% – 91% increased the turbulence intensity of reactive flows tremendously, leading to DDT in the steel pipe systems. Absolute pressures of more than 100 bar (abs.) joined by supersonic flame speeds of >2000 m/s were determined by piezoelectric sensors and photodiodes. In consequence, technical equipments with comparable blockage ratios such as valves and devices for the measurements of mass flows, pipe elbows, bifurcations, in- and outlets as well as pipe cross section changes will reduce the start-up way of detonations. These conclusions have to be considered when designing constructional explosion protection measures in pipe systems in which flammable gas mixtures are transported.

5 NOMENCLATURE

A_d	m^2	area of the baffle opening
A_D	m^2	cross-section area of the pipe
BR	%	blockage ratio of the baffle; $BR = (1 - A_d/A_D) \cdot 100$
d	m	inner diameter of the baffle opening
D	m	inner diameter of the pipe
f	Hz	frequency
L	m	length of the pipe
p_0	bar (abs.)	absolute initial pressure
p_{max}	bar (abs.)	absolute maximum explosion pressure
T_0	K	initial temperature
Tu	%	turbulence intensity
X	Vol%	propane mole fraction in air

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