SUPPORT OF TRAINING IN SAFETY TECHNOLOGY BY USE OF HIGH SPEED FILM MATERIAL FROM REAL EXPERIMENTS

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Preservation and rapid availability of corporate knowledge in the field of safety technology is a necessity against a background of a worldwide increase of competition – especially for the countries of the European Union, where "Know-How" is the main economic resource. Because of the strong development of "New Media" in the past, there is nowadays no problem with the storage and rapid availabilty of data with high information content, like for example photos and film videos, preferably taken from real experiments. These can be used as a support for the training of people, who are involved in safety technology. The way of presentation can be adapted to different levels of knowledge. This method will help for a better and more rapid understanding of problems, and probably for things being better kept in mind. Additionally, learning may become more interesting: especially with safety relevant issues like for example combustion or flow phenomena there is a lot of material which is very attractive from an aesthetical point of view.

In the paper this concept will be demonstrated with examples of gas explosion phenomena, essentially on the basis of flame front and detonation front propagation and resulting overpressure signals. The data used are derived from Fraunhofer Institut Chemische Technologie (Fh-ICT) open air experiments.

INTRODUCTION

Preservation and rapid availability of corporate knowledge in the field of safety technology is a necessity against a background of a worldwide increase of competition – especially for the countries of the European Union, where "Know-How" is the main economic resource. This is also in line with the general call of the European Commission for stronger investments in education and knowledge (CEC, 2003). Because of the latest development of "New Media" with respect to storage capacities and rapid accessibility of data, data with high information content like photos or videos can be handled. Thus these kind of data are now available in the same way as conventional data like texts or diagrams. The idea is, to use photos and videos from real experiments as an additional source of information to illustrate effects and phenomena occurring in safety technology. This visualization technique will help for a better and more rapid understanding of problems, and probably for things being better kept in mind. Additionally, learning will become more interesting: especially with safety relevant issues like for example combustion or flow phenomena there is a lot of material which is very attractive from an aesthetical point of view.

In this paper the above outlined concept will be demonstrated with examples of selected gas explosion phenomena. The data used are derived from Fh-ICT open air experiments (Schneider, 2001). In all the tests described in the text, the fuel air clouds are premixed clouds.

DEFLAGRATION

One of the most important quantities with respect to safety technology is the pressure field p = p(**r**,t) generated during the combustion of a fuel air cloud with appreciable overpressure levels. In case of a deflagration, p(**r**,t) is mainly dependent on the following physical quantities and parameters:

- **Burning velocity**, i.e. by definition the velocity at which the flame propagates with respect to the unburnt mixture in front of the flame.
- **Geometry of the cloud** (spherical, flat) and **location of the ignition** (in the centre or at the edge of the cloud). Dependent on these parameters the flame front may be approximated by a spherical, cylindrical or plane shape. There are two extreme situations conceivable: spherical cloud with central ignition and spherical flame propagation, and for example a flat cloud ignited by a hot surface at one side of the cloud leading to a more or less plane or cylindrical flame front. The main and essential difference between both situations is that in the first case the combustion products are enclosed within the sphere, thus acting like a pushing spherical piston (Taylor, 1946) on the surrounding unburnt mixture, whereas in the second case the combustion products are allowed to expand unhindered and relieve the driving pressure. This makes a clear difference in the pressure field generated.

  Fig. 1 shows for example p(**r**,t) for a spherical flame propagation at constant flame speed: an observer at some distance from the ignition point will record a linear increase of pressure with time until the flame arrives at that point. Then the pressure remains nearly constant until the burn out of the cloud is reached. After burnout the peak overpressure decays inversely proportional to the distance and propagates at the speed of sound. This simple model is valid as long as the flame speed is small compared to the speed of sound. For accelerating flames the pressure increase is more nearly quadratic with time. In case of a cylindrical flame propagation at constant speed the pressure increase is logarithmic with time (Kuhl, 1973).
- **Turbulence.** Turbulence within the unburnt mixture leads to higher mass burning rates with increasing burning velocities and flame speeds. Principally, there are two different sources of turbulence generation: first, turbulence generated by the flame itself because of instabilities in flame propagation resulting in a wrinkled flame front (sometimes called flame induced turbulence). Second, turbulence generated within the unburnt mixture from following sources: atmospheric wind, the release process itself, or the interaction of the flow of the unburnt mixture with obstacles (buildings, pipework, floor) in front of the flame.

TURBULENCE GENERATED BY FLAME INSTABILITIES

At the beginning of gas explosion research, the question arose if there is some limit in flame acceleration because of flame induced turbulence of the flame assuming that very

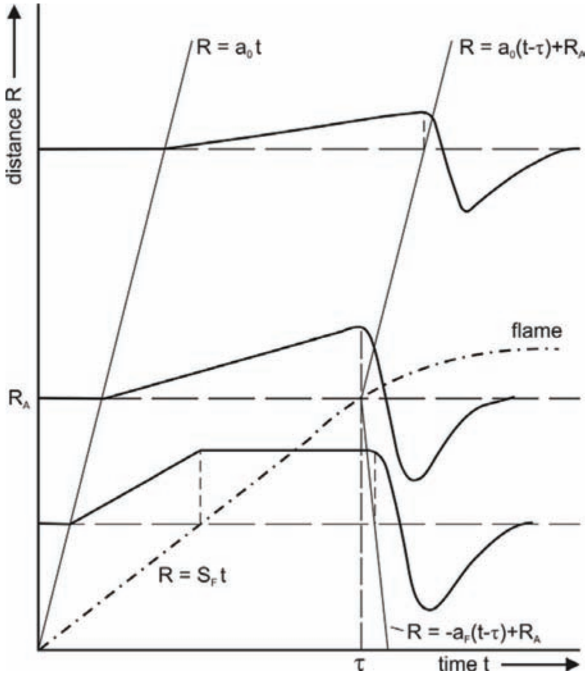

Figure 1. Pressure time histories at different distances from ignition point. Central ignition of spherical cloud with constant flame speed S_F. τ: time of burn out; a_0, a_F: speed of sound in air and combustion products, respectively

large clouds have been accidentially generated. In the past and still at present there are experimental and theoretical investigations with respect to this effect.

In Fig. 2 an example of a spherical, wrinkled flame front with cellular structures is shown, resulting from flame induced turbulence in a premixed hydrocarbon air mixture. For a more detailed investigation of this phenomenon, Fh-ICT performed experiments with hemispherical hydrocarbon air- and hydrogen air mixtures at different sizes up to a radius of 10 m (hydrogen air) with central ignition on the ground. The mixtures were prepared in hemispherical ground-based polyethylene balloons. The balloon envelope was made of several PE foil segments, comparable to the surface of individual orange slices, which were welded together. The test results are shown in Figs. 3 and 4. Fig. 3 is a series of frames taken from a high speed film, where the flame propagation is shown simultaneously from a side view and from a top view. Some time after the ignition the balloon ruptered along the welded seams. Flame propagation as recorded by 4 different high speed cameras from different positions and the resulting pressure time history at a

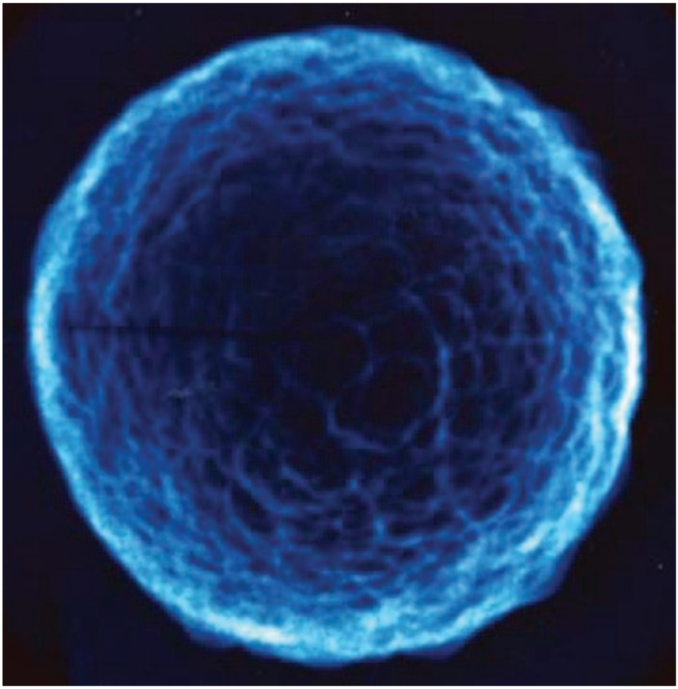

Figure 2. Cellular structure of a spherical flame surface

distance of 5 m from the ignition point are shown in Fig. 4. The flame is accelerating up to a maximum speed of 84 m/s at a time when the overpressure has attained its first maximum. This corresponds to the flame propagation phase where the flame has nearly reached the expanding balloon segments; when the flame approaches the balloon foil the overpressure decreases; the subsequent jetting of the remaining unburnt fuel air mixture between the segments and its turbulent burning beyond the segments results in a final increase in overpressure which marks the burnout of the mixture. Rarefaction waves are responsible for pressure decay and underpressure phase in the pressure time history.

The application of turbulence models (Karlovitz, 1954; Abdel-Gayed, 1981) to the data of a series of tests of this type resulted in a limit with respect to flame speed and overpressure; for a stoichiometric hydrogen air mixture for example these limits should be 125 m/s and 13 kPa, respectively. Recently a large eddy simulation model (LES) (Molkov, 2005) has also been successfully applied to the large experiment described above.

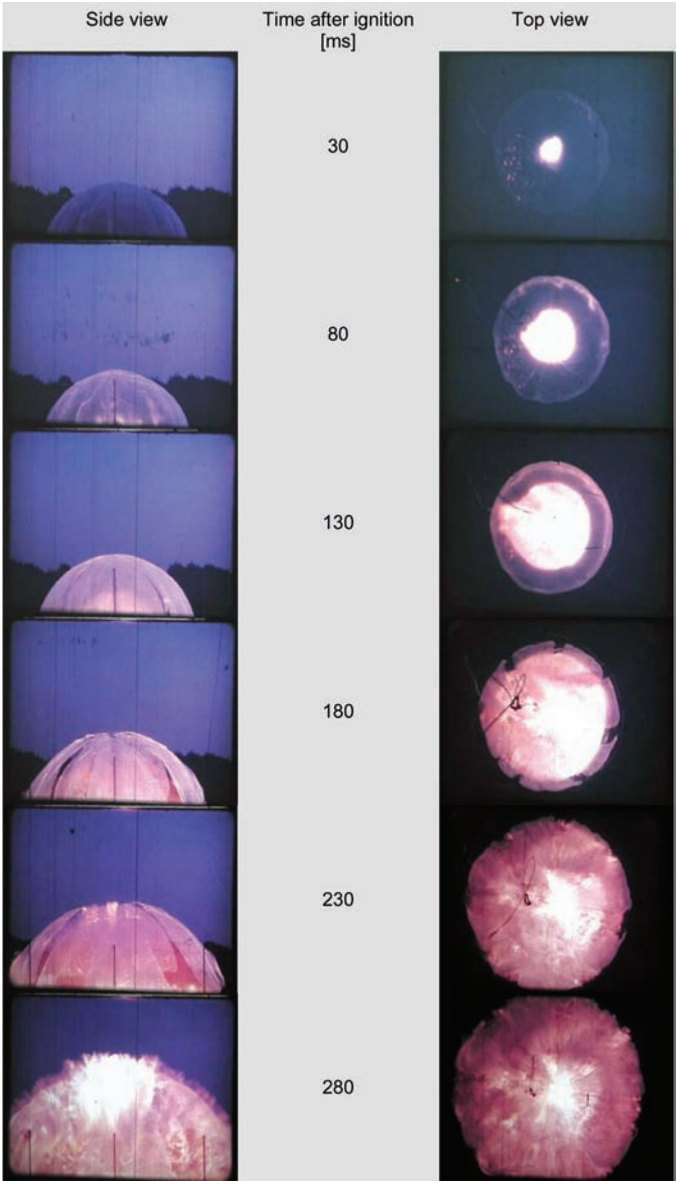

Figure 3. Deflagration of a hemispherical hydrogen air cloud; cloud radius 10 m

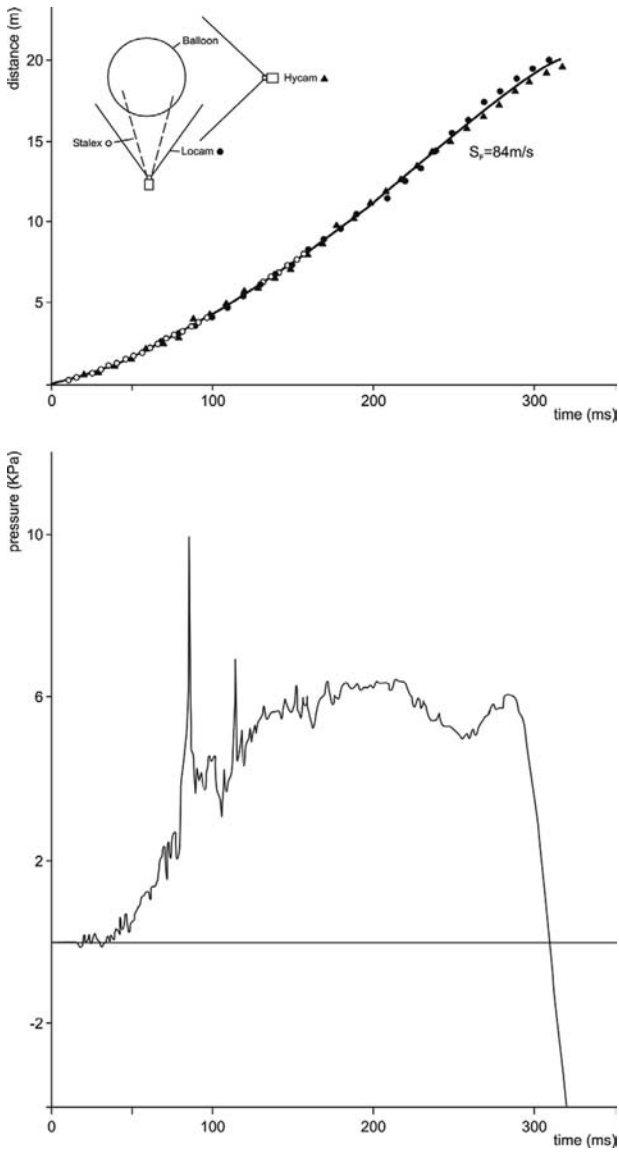

Figure 4. Flame propagation of hemispherical hydrogen air cloud with radius 10 m and pressure time history at a distance of 5 m from ignition point

FAN GENERATED TURBULENCE WITH OBSTACLES

The interaction of the flow of the unburnt mixture in front of the flame with obstacles like for example buildings, installations or even with the ground generates turbulence in the unburnt mixture; when the flame is penetrating into this region flame acceleration takes place because of higher mass burning rates, which in turn may lead to higher flow rates increasing the turbulence and so on. Finally even the deflagration may transit into a detonation. A precondition for this to occur is a high burning velocity of the mixture and a high blockage ratio of the obstacle arrangement as for example pipeworks (EU-project EMERGE, 1997).

In a series of tests with flat clouds containing stoichiometric methane air mixtures, Fh-ICT investigated the influence of artificially, fan-generated turbulence and obstacles on flame propagation. In a reference test without turbulence and without any obstacles, the hemispherical flame front – resulting from central ignition on the ground – looks undistorted and rather smooth (Fig. 5). Fh-ICT tested the influence of different arrangements of obstacles on the flame propagation. In Figs. 6 and 7 examples of such obstacle arrangements are shown. Cylindrical and cube shaped obstacles were used. In some tests these obstacles were arranged in such a way as to simulate some sort of a lane or street (Fig. 7) with a turbulence generating fan in the centre near the ignition point on the ground. Fig. 8 shows the flame propagation in a sequence of frames taken from a high speed camera with this type of arrangement. It can be clearly seen that the flame speed is markedly enhanced between the obstacles forming a lane compared to the situation outside of the obstacles, in the horizontal as well as in the vertical direction. In this

Figure 5. Hemispherical flame propagation in a flat, quiescent hydrocarbon air cloud

Figure 6. Arrangement of cylindrical obstacles

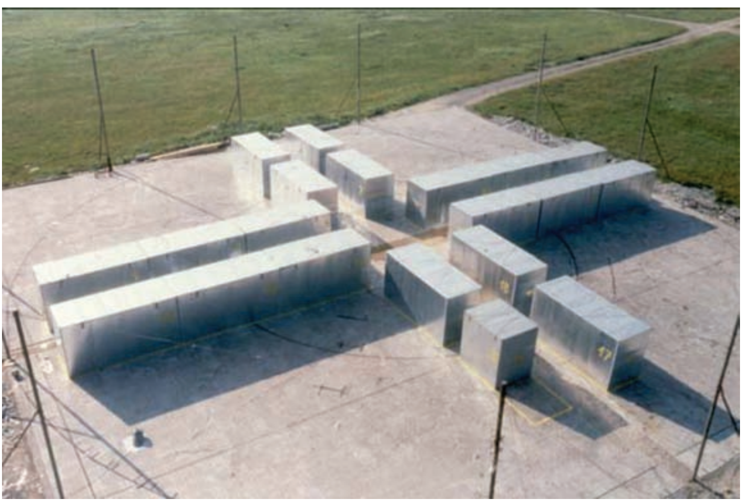

Figure 7. Arrangement of cube shaped obstacles

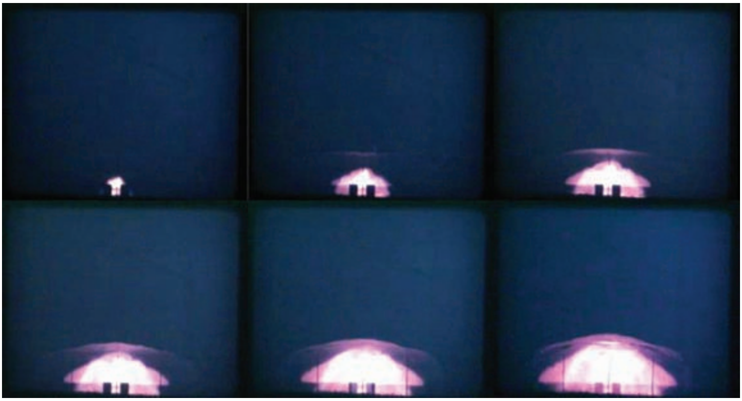

Figure 8. Deflagration of a flat hydrocarbon air cloud with turbulence and cube shaped obstacles

special case a shear layer next to the obstacles may be mainly responsible for additional turbulence generation and flame acceleration. Pressure time history (Fig. 9) reflects the influence of obstacles: several short-time overpressure signals are the result of the interaction of the flame front with the obstacles; the final pressure increase is due to the combustion of the whole cloud.

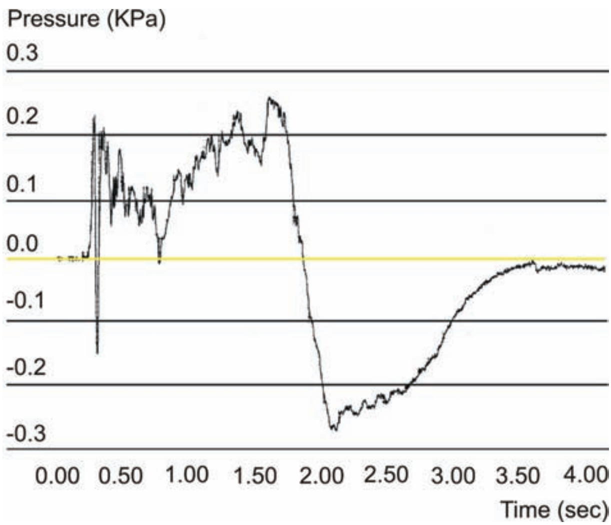

Figure 9. Pressure/time history resulting from a gas deflagration with turbulence and obstacles

DEFLAGRATION TO DETONATION TRANSITION

The phenomenon of the transition of a deflagration into a detonation is still a matter of basic research, even though there has been a progress in successful modelling (Khokhlov, 1999) of phenomena observed in some well defined experiments (Scarini, 1993), where the "gradient mechanism" postulated by Zeldovich (Zeldovich, 1970) – later on called SWACER effect (Lee, 1978) – seems to be confirmed. But there is still a lack in the identification of criteria for DDT to occur in realistic industrial scenarios.

The experiments described in the following have been performed in relation to safety aspects of nuclear plant development in combination with an adjacent facility for the gasification of coal. Partly the results have been published (Pförtner, 1985) on the basis of more detailed data available in internal reports (Pförtner, 1984; Schneider, 1984).

HIGH FLAME SPEED AND PARTIAL CONFINEMENT

As follows from section 2, the transition to detonation of a completely unconfined fuel air cloud is very unlikely, but in scenarios where the flame is interacting with obstacles the positive feedback mechanism mentioned in 2.2. may lead to very high flame speeds resulting in a transition to detonation. In the test described below, it was intended to generate high flame speeds by means of a fan (max. capacity 24 000 m^3/h), which has been installed at one end of some sort of a "lane", consisting of two parallel walls 3 m apart, 3 m high and 10 m long (Fig. 10). One end of the lane was closed by an additional wall in the centre of which the pyrotechnic ignitor was located. A hydrogen air mixture (41 vol%) was enclosed in an envelope of PE-foil (thickness .15 mm) within the lane. When the fan was operated below its maximum capacity, a fast deflagration occurred. In a test performed with maximum capacity, corresponding to a turbulence intensity of about 1.6 m/s, the deflagration with maximum flame speed of 220 m/s after the flame passage through the fan transits to a detonation, originating at a distance of

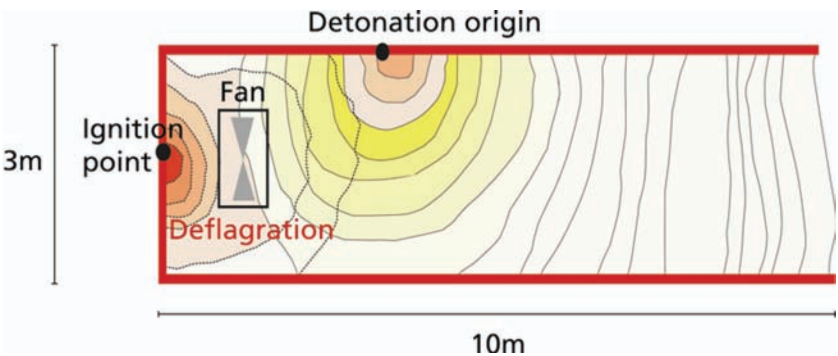

Figure 10. DDT of a hydrogen/air mixture within a "lane", simulated by two parallel walls (top view)

3.5 m from the ignition point in the corner between the ground and the wall. A detonation front propagated at a constant speed of about 2000 m/s through the unburnt mixture associated with an overpressure of 2.5 MPa. Fig. 11 shows the event in a sequence of frames.

FLAME JET IGNITION AND PARTIAL CONFINEMENT

In another series of tests, Fh-ICT investigated the action of a flame jet on a hydrogen air mixture enclosed in a lane similar to that described above (Fig. 12). The side walls of the lane were extended from 10 to 12 m and at one side of the lane a container was installed in such a way that its front side coincided with the front side of the lane. A square shaped

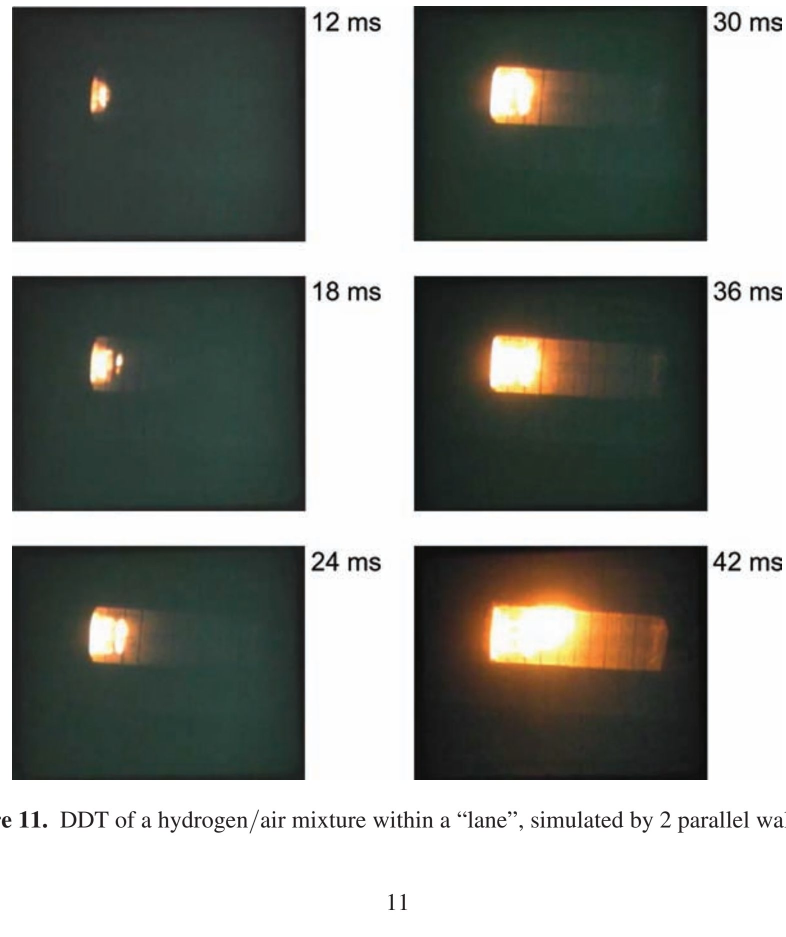

Figure 11. DDT of a hydrogen/air mixture within a "lane", simulated by 2 parallel walls (top view)

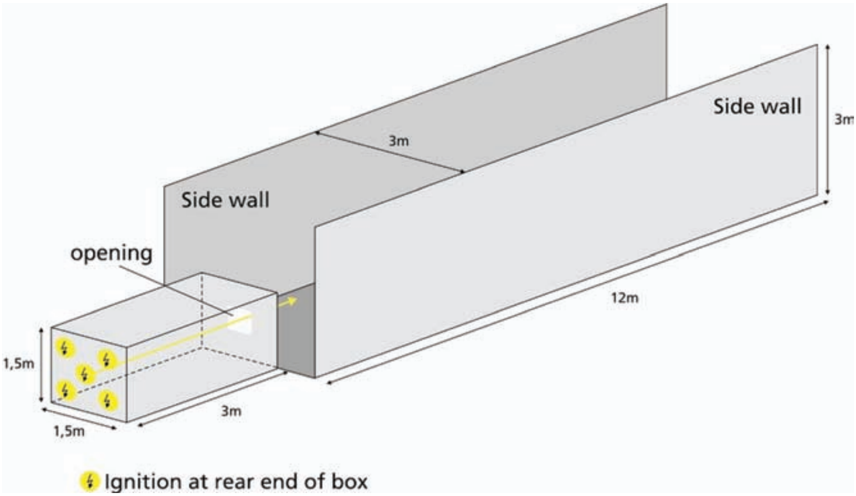

Figure 12. Test set up for igniting a hydrogen/air mixture by means of a flame jet within a "lane", simulated by two parallel walls

opening was in front of the container with 1/10 of the total front side area of the container. Hydrogen concentration (20 vol%) was exactly the same within the container and within the lane. Ignition of the quiescent mixture was at the rear side of the container. In the tests DDT occurred either in the corner between the ground and the wall at some distance from the container opening or at the ground. Some frames from the test with DDT near the ground are shown in Fig. 13. The conclusion from this type of experiments is that whenever very high flame speeds are generated – either by a positive feedback mechanism or flame jets for example – the additional presence of obstacles like a wall or even the ground can trigger a self sustained detonation.

DETONATION

Finally the phenomenon of a gas detonation ignited by means of a high explosive charge is addressed. Originally, the test set up with 2 hemispherical balloons – connected by an opening with a dia of 20 cm in the region where the balloons are touching each other – has been intended for checking if a gas detonation initiated in the upper balloon will be transmitted to the lower one. This was not the case. More interesting here is what happened within the upper balloon after the detonative reaction of the fuel air mixture. The series of frames (Fig. 14) show that the combustion products resulting from the high explosive charge are repeatedly light and dark. The gas detonation of the upper balloon gives rise, in addition to an outward facing shock wave, to an inward facing shock: the latter implodes

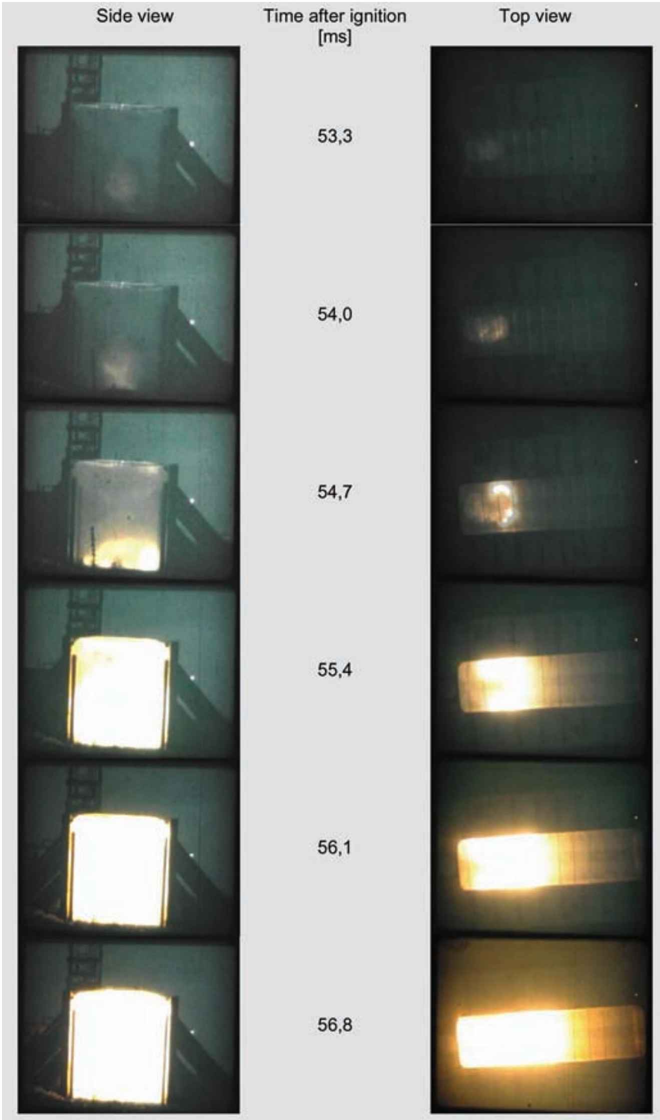

Figure 13. Flame jet ignition of hydrogen air cloud within a “lane” with subsequent transition to detonation near the ground

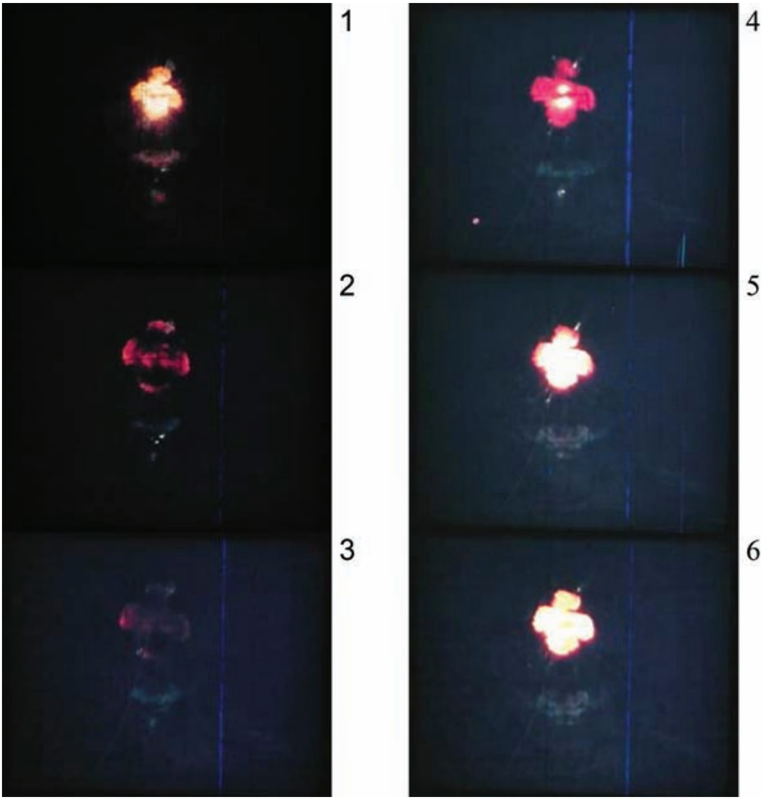

Figure 14. Detonation of spherical hydrocarbon air cloud, initiated by high explosive charge: Light emitting combustion products of HE charge after gas detonation

on the centre, and subsequently is reflected, after outward movement, at the interface of the expanding combustion products of the gas detonation with the surrounding air. The reflected shock wave again implodes in the centre of the balloon and so on. As a result there is an infinite number of pulsations or secondary shocks of decreasing amplitude. The remaining high explosive combustion products are repeatedly heated by this event, which initiates light emission (Freiwald, 1963; Brode, 1959). This behaviour is also documented in the pressure time history, recorded by a pressure transducer located at some distance from the original gas detonation (Fig. 15), where the second shock signal indicates the arrival of the propagating shock wave after the first "implosion" in the detonation origin.

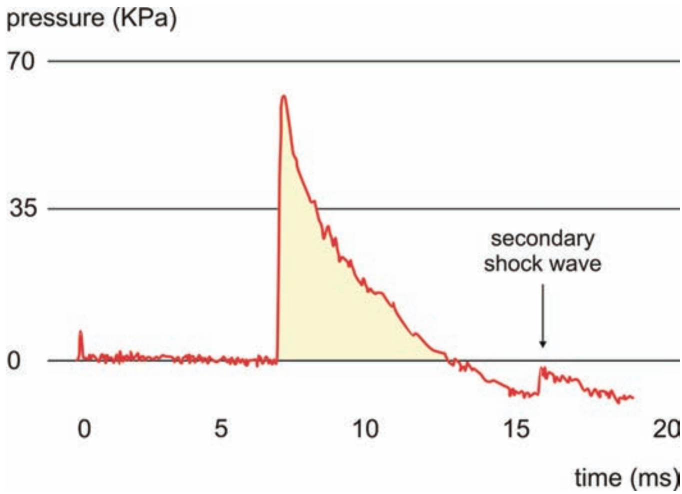

Figure 15. Pressure/time history of a shock wave in air resulting from the detonation of a premixed, spherical hydrocarbon air cloud

CONCLUSION

It can be shown, that a better and much more rapid understanding of phenomena occurring in gas explosion research is possible by means of photos and film videos taken from selected real experiments, where special phenomena are addressed. This can be still improved if the data are presented in a more co-ordinated manner, as for example a synchronization of flame propagation and pressure signals; thus the correlation becomes more obvious. For a more refined mode of presentation clearly more effort is required. Additionally, as a next step, the results of numerical simulation of phenomena with CFD-codes could be presented in parallel. In future developments even interactive software may be used.

NOMENCLATURE

p	pressure
r	radius vector with **r = 0**: location of ignition source
t	time with t = 0: time of ignition

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