LARGE SCALE EXPERIMENTS: DEFLAGRATION AND DEFLAGRATION TO DETONATION WITHIN A PARTIAL CONFINEMENT SIMILAR TO A LANE

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ABSTRACT

About 20 years ago Fraunhofer ICT has performed large scale experiments with premixed hydrogen air mixtures [1]. A special feature has been the investigation of the combustion of the mixture within a partial confinement, simulating some sort of a "lane", which may exist in reality within a hydrogen production or storage plant for example. Essentially three different types of tests have been performed: combustion of quiescent mixtures, combustion of mixtures with artificially generated turbulence by means of a fan and combustion of mixtures with high speed flame jet ignition. The observed phenomena will be discussed on the basis of measured turbulence levels, flame speeds, and overpressures. Conditions for DDT concerning critical turbulence levels and flame speeds as well as a scaling rule for DDT related to the detonation cell size of the mixture can be derived from the experiments for this special test setup. The relevance of the results with respect to safety aspects of future hydrogen technology is assessed. Combustion phenomena will be highlighted by the presentation of impressive high speed film videos.

1. INTRODUCTION

At the beginning of a systematic research into gas explosions in mid-seventies one of the main challenges has been the objective to be able to explain the disastrous consequences of gas explosions occurring from time to time in industrial areas where flammable gases or liquids were produced, handled or stored [2]. For a prevention or at least for a reduction of hazards resulting from gas explosions there has been a need for a better understanding of the phenomena leading to destructive pressure loads on buildings and installations. Very soon it became clear that turbulence plays a major role in the acceleration process of the flame which is necessary to achieve effective pressure signals. Principally there are two different types of turbulence generation: first, because of instabilities in the flame propagation process an increase in flame surface and thus an overall rection rate increase is established; this phenomenon is sometimes called flame induced turbulence and it is treated elsewhere [3]. The question to be answered is – thinking of very large clouds - , if there exists any limit in this acceleration process with respect to this special effect. Second, because of the fact that the flow of the unburnt fuel air mixture in front of the flame – generated by the expanding flame – interacts with obstacles like for example buildings, installations or even the ground, turbulence is generated, into which the flame is penetrating and accelerating whereby the flow velocity in front of the flame is increasing again and so on; this positive feedback mechanism may lead to very high flame speeds and overpressures. Finally even a transition to detonation may be triggered.

Since the turbulent flow field of the unburnt gas mixture generated in front of the flame is strongly affected by the obstacle configuration with which the flow interacts, the results obtained in a lab-experiment cannot be easily transferred to real size situations. This has been the main cause for the massive interest of several institutions – especially companies with off-shore operated oil platforms in the north sea - in the development of CFD codes as soon as computer technology allowed it to do so. Meanwhile the simulation of complex scenarios will be able with acceptable accuracy – at least as long as these resemble tested configurations [4].

In case of deflagration to detonation transition (DDT) there is successful modelling [5] of phenomena observed in some well defined experiments [6], where the "gradient mechanism" postulated by Zeldovich [7] and lateron called SWACER effect [8] seems to be confirmed. But there is still no code in a sense that it could be used to predict conditions for DDT in realistic industrial scenarios. This means that for the investgation of DDT and especially for the elaboration of the conditions for DDT large scale tests will be still necessary in the future.

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 already [9] on the basis of more detailed data available in internal reports [10,11]. Here, they are presented and discussed in the light of actual problems of hydrogen industry.

2. EXPERIMENTS

2.1. Explosions of hydrogen air mixtures with point ignition

The simulation of a "lane" was realized by two parallel walls 3 m apart, 3 m high and 10m long. One end of the lane was closed by an additional wall in the center of which the pyrotechnic ignitor was located. The hydrogen air mixture was enclosed in an envelope of PE-foil (thickness .15 mm) within the lane. The hydrogen concentration was between 37 and 41 % by volume in different tests. In each test the homogeneity of the mixture was checked.

The flame front or detonation front was recorded by different high speed cameras (300 up to 6000 frames/s) with view from above and with horizontal view in direction of the main axis of the lane. Overpressures were measured by different types of transducers, located along the main axis on the ground.

2.1.1. Explosions of quiescent hydrogen air mixtures

In Fig. 1 the main result of this type of experiment is shown: in the initial phase after ignition the flame is propagating hemisperically and flame speed as well as peak overpressure (50 mbars) are the same as in tests with unconfined hemispherical balloons [12], i.e. there is no influence of partial confinement. Then the flame front changes into a more or less plane shape; this and the fact that the combustion products are allowed to freely expand means a reduction in overpressure. Finally at the end of the lane a stronger acceleration of the flame is recorded due to the jet-like expansion of the gas mixture ahead of the flame. Thus in this region flame speeds of up to 170 m/s are reached corresponding to overpressures of about 150 mbars.

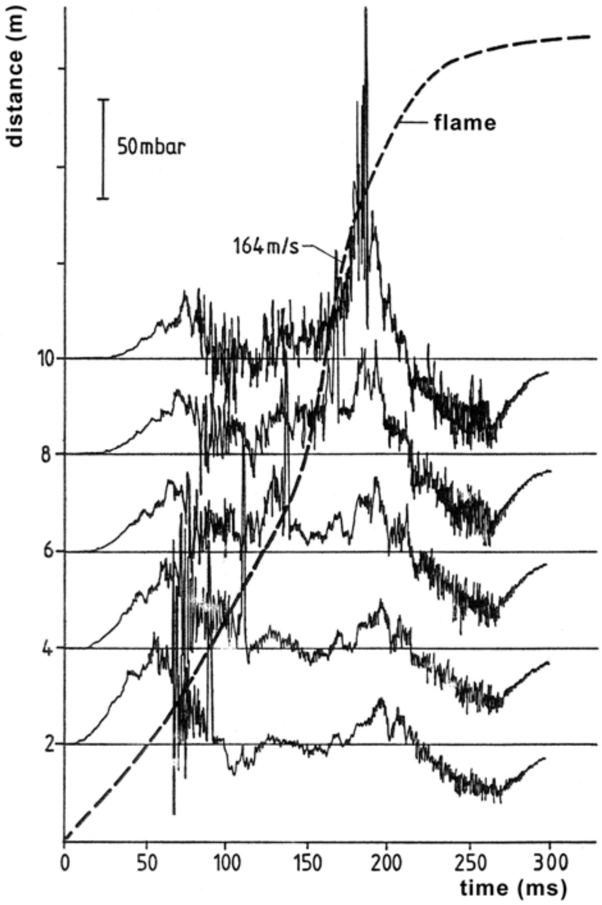

Figure 1. Flame propagation and pressure time histories for a quiescent hydrogen air mixture (37% H_2) in a lane

2.1.2. Explosions of turbulent hydrogen air mixtures

Since the combustion process is strongly dependent on the turbulence of the unburnt mixture, it is interesting to know the relation between flame speed or turbulent burning velocity and the data characterizing the turbulence field in front of the flame, i.e. essentially turbulence intensity. Therefore in a series of 6 tests flame speeds and overpressures were measured for different turbulence levels generated by means of a fan. The fan (dia 1.25 m) was located near the ignitor at the closed end of the lane and operated at 50, 75, 90 and 100 % of its full capacity of 24 000 m^3/h with the main flow direction towards the open end of the lane. In Fig. 2 the main result of tests without DDT is shown in a distance vs. time diagram (90%-test): during the passage of the flame through the fan the flame was accelerated up to 200 m/s and at a distance of about 3.5 m from the ignition point the flame was slowing down to 106 m/s. The first strong pressure increase was recorded at that time when the flame was accelerated in the fan region. The overpressure signal then propagated at the speed of sound with decaying amplitude. The last overpressure peak (just before the subsequent pressure decay) was recorded roughly at that time when the flame was hitting on the side walls of the lane. Maximum peak overpressure was about 500 mbars.

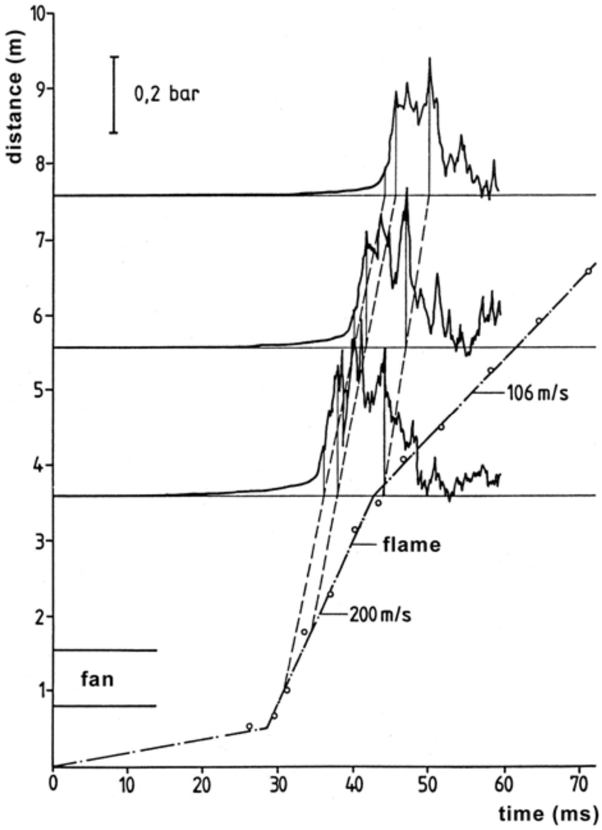

Figure 2. Flame propagation and pressure time histories for a turbulent hydrogen air mixture (41% H_2) in a lane

A test done with the full capacity of the fan resulted in a maximum flame speed of 220 m/s and at a distance of 3.5 m from the ignition point transition from deflagration to detonation occurred close to the wall (Fig. 3). A detonation front propagated at a constant speed of 2 100 m/s through the unburnt mixture associated with an overpressure of 25 bars. Turbulence intensity in front of the fan in this case was 1.6 m/s. This value has been measured by hot wire anemometry without combustion.

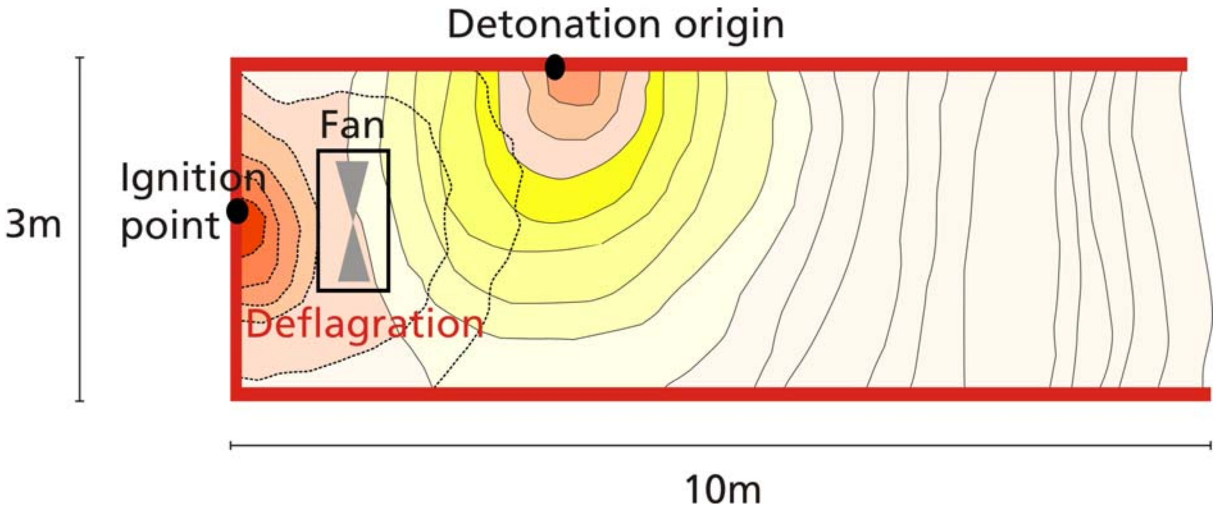

Figure 3. Propagation of flame front and detonation front in DDT experiment in a lane (turbulent hydrogen air mixture with 37% H_2)

2.2. High speed flame jet ignition of hydrogen air mixtures

At the moment there is no physical model available for the quantitative description of the DDT phenomenon in gas explosions. The question then is how to derive empirical laws giving information on the conditions for DDT from experiments. A powerful method for practical applications are scaling laws as for example d = 13 λ, with d=tube dia. and λ=detonation cell size, as a criterion for the propagation of a detonation from a tube to an adjacent unconfined cloud [13]. In the tests described below the derivation of such a scaling law with respect to DDT has been tried to establish for a test set up with flame jet ignition of a hydrogen air mixture contained within a lane.

Fig. 4 shows the test set up used at ICT. 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. Two different sized square shaped openings in front of the container were used in the tests: 0.1 and 0.3 of the total front side area of the container. Hydrogen concentrations were exactly the same within the container and within the lane: between 19.9 % and 22.5 % by volume (±0.3%) in a series of 5 tests. Ignition of the quiescent mixture was done at the rear side of the container with 5 over this plane equally distributed pyrotechnic ignitors. Again, flame fronts were recorded with high speed cameras and overpressures measured within the lane as in the former tests.

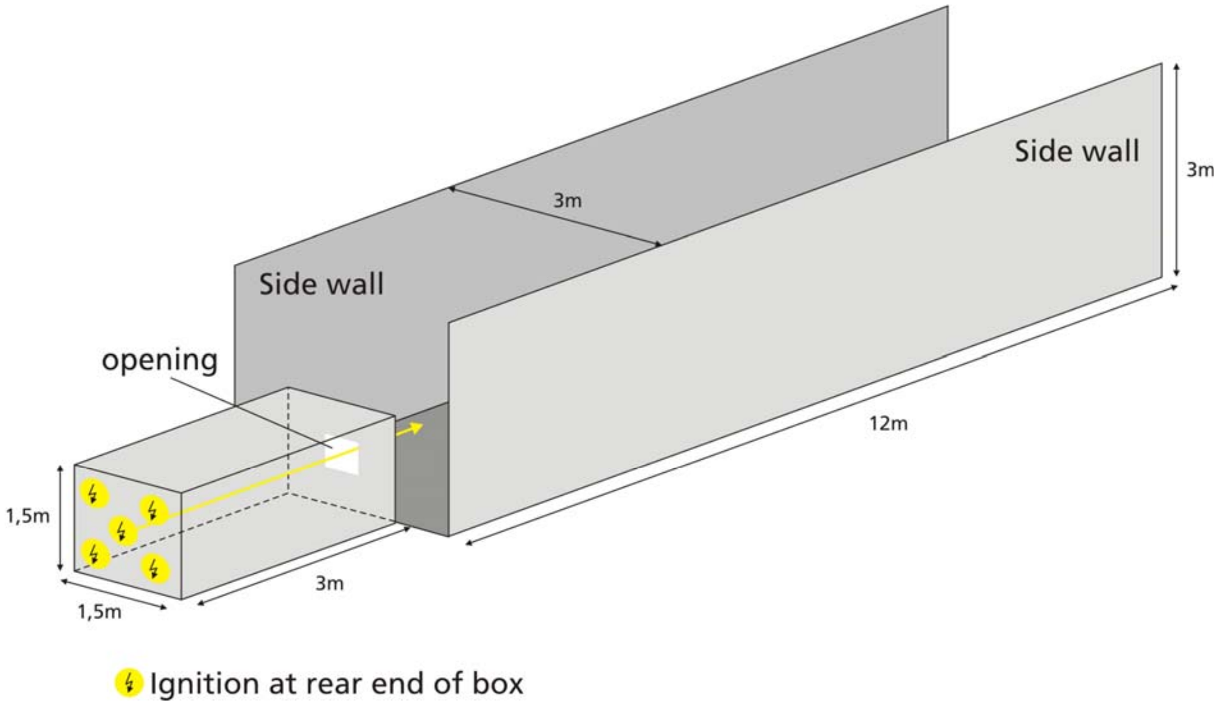

Figure 4. Test set up for the ignition of a hydrogen air mixture within a lane with a flame jet

Schildknecht [14] started with this type of experiment in a completely identical test set up with dimensions which were reduced by a factor of 3. He succeeded in getting DDT only in the case of a stoichiometric hydrogen air mixture. The idea now was, that if there is a scaling law based on the detonation cell size λ, it might be that for larger scales there is a broader range of hydrogen concentrations where DDT is possible. In Fig. 5 the well known U-shaped relation between cell size and hydrogen concentration is given [15]. From this curve results, that for a test set up with 3 times the dimension of the Schildknecht test, the GO/NO GO - limit with respect to DDT should be at 3 times λ_{min}, with λ_{min}=1.54 cm (corresponding to the stoichiometric mixture), that is at 20.8% by volume of hydrogen. In 2 tests with concentrations higher than 20.8 % DDT occurred and in 3 tests with lower values it did not. This result was obtained for both sizes of the front opening of the container. The highest peak overpressures were recorded at a distance of between 3-4 m downstream from the container opening for all the tests. In one test DDT occurred in this region near the ground simulaneously at severel locations and in the other test at a distance of 6 m at one distinct point at the corner between ground and wall.

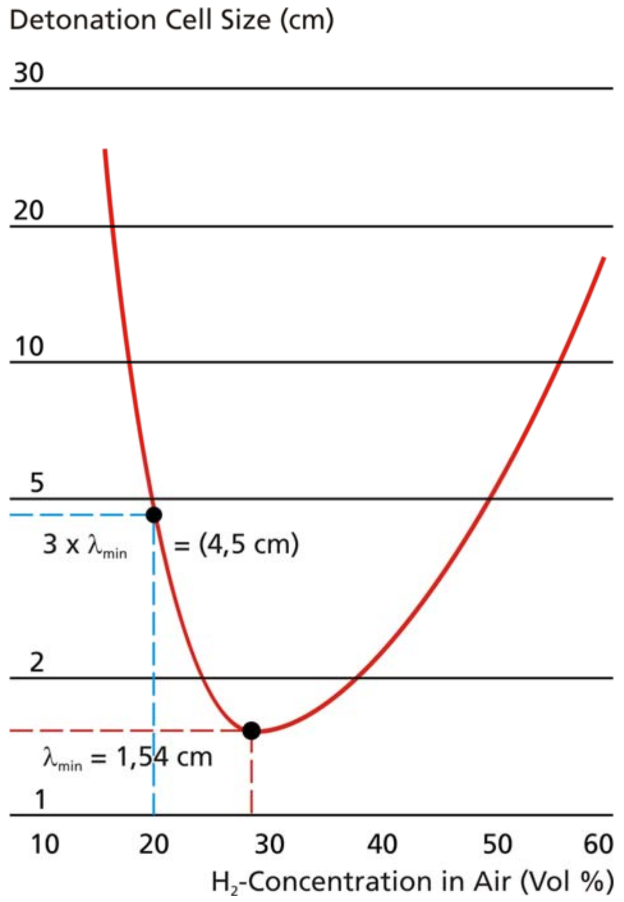

Figure 5. Scaling of DDT experiments with detonation cell λ

3. DISCUSSION

One of the main aspects of this paper with respect to hydrogen industry is the question, if there are realistic scenarios, where these types of experiments will have relevance. A precondition should be a very rapid release of an appreciable amount of hydrogen like for example with a catastrophic failure of a storage tank, otherwise a large amount of fuel will escape in the atmosphere before ignition occurs. Turbulence intensities with an order of magnitude of 1.5 m/s which are at least necessary for DDT in combination with partial confinement may be achieved by the release process itself or by the interaction with turbulence generating obstacles. The ignition of a hydrogen air mixture by a high speed flame jet may be conceivable, if by an accidental release hydrogen is penetrating through an opening into a building for example, where it will be ignited and an outgoing flame jet will ignite the hydrogen outside of the building. Thus it seems realistic to assume that in principle there are scenarios, where the results of the tests presented in this paper are relevant. A final clarification will be achieved only by experiment.

4. CONCLUSION

Situations where the combustion of quiescent hydrogen air mixtures occurs within partial confinements like for example a lane only minor damages will be produced resulting from overpressures. As soon as turbulent mixtures are involved, dangerous levels of overpressures may be generated and in combination with obstacles like walls or even the ground turbulence will be enhanced so that DDT can not be excluded. Relatively low values of turbulence intensity of about 1.6 m/s are sufficient. Therefore each scenario where a large amount of hydrogen is released within a short time period in surroundings with partial confinement should be strictly avoided.

As long as there exists no theoretical access for the DDT phenomenon which would be useful for practical applications, scaling laws derived from experiments may be helpful for the design of facilities.

5. REFERENCES

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