Review of Contributions of Fraunhofer ICT to Gas Explosion Research Illustrated by Film Documents

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Abstract

Fraunhofer Institut für Chemische Technologie (ICT) has been active in the field of gas explosions during the last 25 years. Quite a lot of experiments predominantly on a medium and on a large scale have been performed - some of which with fundamental importance for the understanding of gas explosions. The intention of this paper is to present a review of selected results of our investigations achieved under the management of the late Dr Pförtner. We think that the presentation is especially attractive because we intend to use film material recorded during the tests for measuring the propagation of flames and of detonation fronts. Thus the topic will probably be better understood – apart from the fact that the pictures are very impressive.

1. Introduction

In the seventies the amount of combustable gases and liquids which were produced, stored and transported increased continuously. The increasing hazard potential associated with it and several severe accidents with a lot of damage and casualties were the cause for the beginning of intensified efforts in the investigations of gas explosions. Vast research programs were started to find an understanding of the mechanisms leading to the extreme damages. At that time, one of the most discussed questions has been, if the damages after an accident in a chemical plant for example were the result of a deflagration or a detonation. At ICT the phenomena of deflagration, detonation and deflagration to detonation transition were studied predominantly in the open air on a medium and on a large scale. The fuels were mainly methane, propane, ethylene and hydrogen; these gases have different features, especially with respect to its burning velocities.

2. Detonation of premixed fuel/air mixtures

ICT started into the research of gas explosions with the investigation of spherical gas detonations with volumes of up to 15 m^3 of mainly propane/air and ethylene/air mixtures /1/. The objectives of the tests was the determination of the propagation functions of spherical air blast waves resulting from spherical gas detonations. The comparison of these functions with corresponding functions from the detonation of TNT charges resulted in the so-called „TNT-equivalent“. This served at that time as a means for the evaluation of accidents from vapour cloud explosions. Since the correlations between the degree of damage of structures and overpressures in the case of blast loading from TNT detonations were known, the amounts of gas, which were involved in the explosion, could be derived from this „equivalent“:

Film:
Propagation of spherical detonation front.
Pulsation of combustion products of igniting HE charge in the centre of the sphere.
Pressure/time history at some distance of the detonation origin and correlation with the gas detonation process.
Propagation functions of spherical air blast waves compared with TNT TNT equivalent.

3. Deflagration of premixed fuel/air mixtures

3.1. Deflagration of quiescent, unobstructed fuel/air mixtures

The objective of these experiments was the determination of maximum flame speeds and overpressures in deflagrative reactions of quiescent, unobstructed and unconfined hydrocarbon/air and hydrogen/air mixtures /2/. This is a very idealized situation because in reality there are turbulence and obstacles present within the vapour cloud. Nevertheless the question was to what extent a flame would be accelerated by so called flame induced turbulence alone, i.e. in a quiescent, unobstructed mixture. Flame induced turbulence results from Rayleigh/Taylor instability and leads to an enlargement of the flame surface and thus to an acceleration of the flame. The experiments were performed with hemispherical hydrocarbon/air and hydrogen/air mixtures at different sizes up to a radius of 10 m (hydrogen/air). They showed that there is a dependence of the maximum flame speed on the size of the cloud. The analysis indicated that there exists a limiting value for the flame speed and thus for overpressures. The data fit in different theoretical models /3,4/. In a homogeneous, stoichiometric mixture of H_2/air for example the maximum flame speed is 125 m/s and the corresponding overpressure 130 mbar.

Film:
Deflagration of hydrocarbon/air mixture on a small scale.
Rayleigh/Taylor instability („flame induced turbulence“). Cellular structure of flame front
Deflagration of hydrogen/air mixture on a large scale.

3.2. Deflagration of flat, unquiescent and obstructed hydrocarbon/air clouds

The next step in the investigation of deflagrations was a much more realistic scenario with turbulence and obstacles present within the cloud. ICT was a partner in a project launched by an international consortium of gas suppliers. The ICT task was the performance of 20 tests on a large scale, i.e. volumes of up to 13 000 m^3 (40x40x8 m^3 or R=20 m, H=8 m) with gas mixtures of methane/ethane/air and propane/air. The objective was the simulation of LNG-clouds and the influence of artificially generated turbulence, different obstacle arrangements and of different ignition modes and ignition locations on flame speeds and overpressures /5/. Because of the large number of different parameters investigated, a lot of informations resulted from the analysis of the data. The main results were:

1.With point ignition on the ground, and without any obstacles and turbulence in the cloud, the highest overpressures are generated during the hemispherical flame propagation phase. The highest overpressure is generated behind the flame in the product gas and will be constant in the case of constant flame speed. Outside of the hemispherical flame zone overpressures increase with time until the flame reaches the nearest boundary of the fuel cloud to the ignition point. The overpressure at the flame increases as the square of the flame speed. The peak overpressure decays with the inverse of distance outside of the hemispherical combustion zone.
2. Cylindrical and planar flames generate smaller overpressures than hemispherical ones for the same flame area and speed. Additionally, flame speeds achieved in these phases are smaller because the product gases can escape from behind the flame, relieving the driving pressure.
3. Turbulence generated by means of fans or by interaction of the flow ahead of the flame with obstacles enhances burning rates and thus flame acceleration occurs with a significantly increase of overpressures. At high flame speeds high local overpressures are generated which cause a separate pressure pulse each time the flame interacts with an obstacle.
4. The magnitude of the overpressure due to each separate event depends on the volume of gas consumed and the average flame speed during it. Its decay is inversely proportional to distance from where the event occurred. If the volume is equated to a hemisphere then the peak overpressure is proportional to the product of the radius of the hemisphere and the square of the flame speed. The dominant overpressure of the whole explosion, therefore, could arise through rapid combustion of a small volume of gas or else through slower combustion of a larger volume.

Film: From the film material those film passages will be presented, which are able to highlight the above listed main results.

4. Deflagration of non-premixed fuel/air mixtures

The accidental release of combustable substances normally takes place under pressures higher than the ambient pressure and the resulting vapour cloud will not be perfectly and homogeneously mixed with air. An example of such an event is the bursting of a container filled with heated liquified gas, flash evaporation of the liquid and mixing with air. In a series of tests the bursting of a real railway wagon, which has been overfilled and heated up in the sun, was simulated by different sized containers /6,7/.

Film: Bursting of different sized containers (up to 1 m^3), evaporation, ignition and deflagration of vapour cloud.

5. DDT in hydrogen/air mixtures under the influence of high turbulence and partial confinement.

Another phenomenon – although with a lower level of probability in industrial plants – is the transition of a deflagation to a detonation. The objective is to find out the conditions under which DDT occurs; only if the mechanisms are known, which lead to DDT, measures can be taken to prevent it. What are the scaling laws – if there are any? ICT simulated the combustion of hydrogen/air mixtures under high turbulence within structures like lanes /8/. The „lane" consisted of two parallel walls at a distance of 3 m, 3m high, 12 m long, and closed at one end. Turbulence was generated at the closed end by means of a fan with a capacity of 24 000 m^3/h, which was in operation during the combustion process. Ignition was at the closed end. Some meters after the flame had passed the fan, attaining a speed of ca 220 m/s, detonation was triggered near the wall. As the flame velocity was well below the sound velocity of the unburnt mixture, it was assumed that the high flow velocity induced by the high flame velocity interacted with the boundary layer producing still higher turbulence. This was the first time that such a transition was observed in a more or less free cloud only confined by two parallel walls. In a similar test set up the fan was replaced by a chamber with a small opening at its front side, which was filled with the same mixture as in the lane and ignited at its rear side - thus producing a flame jet penetrating into the lane /9,10/. A transition to detonation occurred only in mixtures with a H_2 concentration higher than 20.8 vol%. This corresponds to a cell size of 4.5 cm in the well-known diagram cell size vs equivalence ratio. In similar experiments on a smaller scale (factor 1/3) only in stoichiometric mixtures (λ =1,5 cm) DDT took place. Therefore it looks as if for this special situation DDT can be scaled with 3λ.

Film: The events are shown in real time and in extreme slow motion.

6. Additional and future work

Another research topic was the investigation of the thermal radiation associated with gas explosions, which may be a potential hazard, too: the radiation which was emitted from small sized gas explosions was detected with very fast spectrometers /11/. Recently ICT was a participant in a EC- sponsored project (EMERGE), which aimed at the validation and improvement of existing CFD- codes /12/. With these codes now the quality of predictions of the results of gas deflagrations in different scenarios has reached a rather high level. However, one field - and a very interesting one -, which still needs research efforts — is DDT.

7. Literature

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