Deflagrations in Closed and Vented Pipes - An Experimental Study

Hans Förster[1], Christoph Kersten[2]
[1]Physikalisch-Technische Bundesanstalt (PTB), Braunschweig, Germany
[2]now:RWE-DEA, Wietze, Germany

Introduction

The early stage of incidental explosions in pipes is characterised by subsonic flame propagation (deflagration) /1/. To protect against damage and to prevent the transition to detonation protective measures like explosion venting and explosion decoupling (flame arresters) are used. With a view to the installation of such devices in practice, explosions in closed and vented pipes were investigated experimentally. The provision of detailed explosion data shall support venting rules /2/ and facilitate validation of upcoming CFD prognostics.

Experimental

Steel pipes as well as transparent pipes (polycarbonate, PVC) of different diameter D (69 mm $\leq$ D $\leq$ 300 mm) and length L (2 m $\leq$ L $\leq$ 9 m, both ends closed) were used. Ignition was effected by means of a spark plug at one pipe end. Flame propagation was monitored by photodiodes (steel) or by a high-speed video camera (transparent pipes). Explosion pressures were recorded by pressure sensors mounted to the pipe wall. Venting devices were made of short T-pieces closed by polythene foil of defined static bursting pressure p_V (pressure differential).

Positions x along the pipe are measured from the ignition end (x = 0) and are indicated for the flame front (Index F), the pressure sensors (Index P) and the vents (Index V).

Most experiments were carried out both with propane-air- and ethylene-air-mixtures (stoichiometric, atmospheric conditions) to assess the influence of fuel reactivity.

Results for closed pipes

Fig. 1 shows - as a typical result – the explosion pressure p (absolute pressure) in dependence of the time t after ignition for ethylene and propane mixtures. The ethylene deflagration shows the higher rate of pressure rise due to its higher burning velocity. In any case, the pressures are significantly below maximum values p_{max} tabulated for spherical isochoric explosions with central ignition (ethylene: 9,7 bar; propane 9,4 bar) /3/. This has to be attributed to the early and effective cooling of the burnt gas at the pipe walls.

For a given run the explosion pressures from different positions x_P differ only in the amplitude and phase of the accompanying acoustical oscillations. This indicates flame velocities well below the velocity of sound. In the following, explosion pressure data are given as time-average over about two oscillation periods.

For ethylene deflagrations in most cases the pressure-time curves have a shape similar to that known from spherical explosions. The pressure curves for propane may show an extended plateau (see Fig. 1): Here the production of hot gas in the flame front is balanced by the cooling effect of the pipe walls on the burnt gas behind the flame front. The analysis of the high speed videos reveals that the flame front is decelerated and is propagating rather slowly (some m/s) in this final combustion phase. So the situation is just in contrast to deflagration flames running towards open pipe ends: In the closed system the pushing effect of the burnt gas is decreasing with increasing total pressure and results in a negative feedback on the flame velocity.

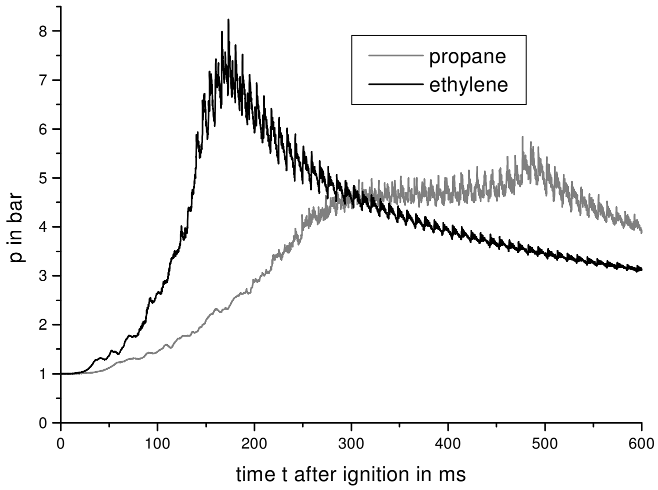

Fig. 1 Explosion pressure in dependence of time t after ignition.
Steel pipe, L = 6 m, D = 0,15 m, x_P = 0,5 L

In the examples of Fig. 1, the occurrence of pressure maxima coincides with the completion of combustion (at the end flange). In cases where the wall cooling outweighs the combustion heating, the maximum pressure occurs at the beginning of the slow propagation phase. Indeed this was observed for propane deflagrations (D < 0,1 m, L > 6 m).

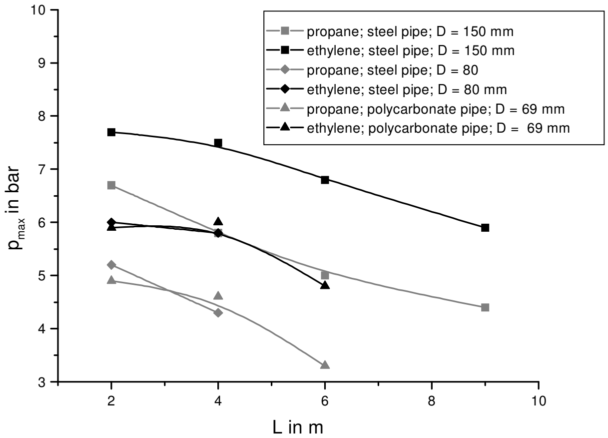

Fig. 2 Maximum explosion pressure in dependence on pipe length L, pipe diameter D and pipe material

For practical safety considerations the "maximum explosion pressure" is a crucial feature. So this characteristic is given for the present set of experiments in Fig. 2. The lines group pipe diameter, pipe material and fuel, respectively. Fig. 2 indicates the following trends within the investigated parameter ranges:

- Increasing the span of time for combustion increases the span of time for cooling and therefore lowers maximum explosion pressures. The span of time for combustion is affected by the reactivity of the fuel (propane/ethylene) and the total pipe length L.

- Decreasing the pipe diameter (given pipe length) increases the surface/volume ratio of the pipe and leads to a more effective cooling and to lower maximum explosion pressures.
- The material of the pipe wall (polycarbonate/steel) seems to have no significant effect on the maximum explosion pressure.

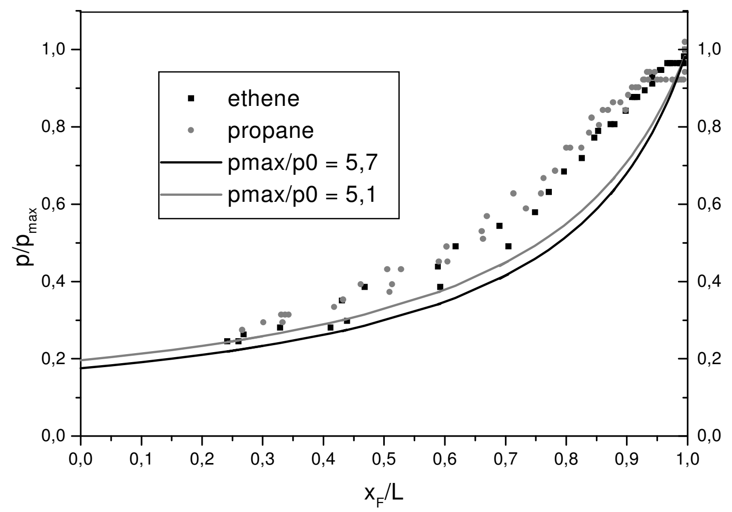

Fig. 3 Explosion pressure p in dependence on the relative flame front progress x_F/L. Dots: experimental data, L = 2 m, D = 0,69 mm, $x_P = 0{,}5L$. Lines: Semi-empirical, see text.

For designing practical venting installations, the transient explosion pressure p(t) during the combustion process is decisive. Run-time effects may be eliminated when x_F is used instead of t from the relation $x_F(t)$, which is available from the high-speed videos. Fig. 3 shows two such examples for measured explosion pressures p/p_{max}. As expected, the different flame velocities have a minor effect on the dependence of p on the flame path x_F. Assuming a definite (measured) expansion ratio $\varepsilon = p_{max}/p_0$ (p_0 = initial pressure) and assuming an adiabatic course of the explosion, the following semi-empirical relation between pressure p and flame path x_F can be deduced:

$$p/p_{max} = 1/(\varepsilon - x_F/L*(\varepsilon - 1))$$

In Fig. 3 these semi-empirical relations are also shown as lines. The match with the measured data is acceptable for $0 < p/p_{max} < 0{,}3$ ($p/p_0 < 1{,}5$); this range is most important for practical venting applications.

Results for vented pipes

Explosion venting devices like bursting diaphragms are to be characterised by their bursting pressure differential p_V and their position in the pipe x_V. For any given vent, these data may be marked in a p-x-diagram as in Figure 3. The above semi-empirical p-x_F-relation may then be taken as a conservative borderline for design and installation of vents: If the vent “point” (p_0+p_V;x_V) lies above that borderline, the flame passes the vent before opening and burnt gas is vented immediately. For vent "points" below that curve the vent opens before flame arrival and remaining unburnt mixture is decompressed first.
The vented explosion pressures for the one or the other case may differ significantly as is shown in Fig. 4 for three exemplary tests: Keeping the vent position unchanged (x_V = 0,5 L),

the venting pressure differential p_V was chosen to provide vent points below ($p_V = 70$ mbar and $p_V = 200$ mbar) and above ($p_V = 700$ mbar) that borderline. In the first two cases, the venting acts as intended by limiting the vented explosion pressure p(t) to values essentially below p_0+p_V. In the last case, the venting leads to sharp pressure peaks with maximum values far above p_0+p_V.

The inspection of the corresponding high-speed videos helped to explain this undesired effect: Immediately before venting, the remaining unburnt mixture upstream of the flame front is

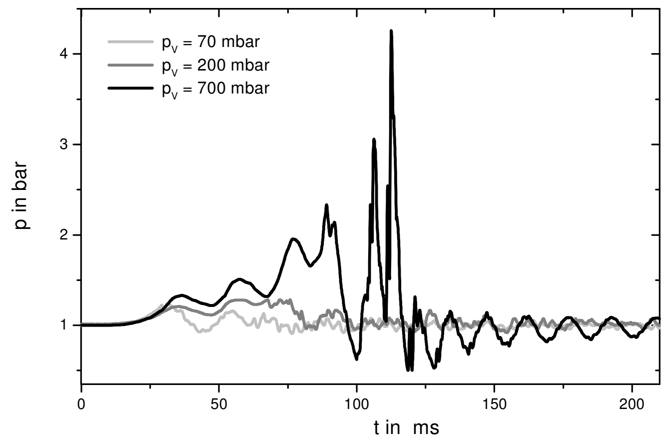

Fig. 4 Effect of venting pressure p_V on the transient explosion pressure.
PVC pipe; D = 0,08 m; L = 3,2 m; $x_V = 0{,}5L$; $x_P = 0{,}8L$; propane.

considerably compressed. Venting then initiates a backflow of that mixture, pushing the flame front far back into the first half of the pipe and eventually resulting in a highly turbulent pressure-combustion-complex which causes the high pressure peaks.

Conclusions

- In closed pipes deflagration flames decelerate in the later phase of combustion; explosion pressures may even decline then due to effective cooling of the burnt gas by the pipe wall.
- The “maximum explosion pressure” is significantly influenced by this cooling; the effect of cooling depends on the reactivity of the fuel and the length and diameter of the pipe.
- A semi-empirical model for the relation between explosion pressure and flame-path can help to design effective venting systems.
- Venting at pressure differentials above 0,5 bar and/or inadequate positioning of the venting device may result in adverse piling up of explosion pressures.

References

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