Venting of gaseous explosions: influence of flame transmission mechanisms at the vessel exit

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1 Introduction

Evacuation of gases out of a closed vessel during an accidental explosion is a crucial problem to prevent increasing of the internal pressure beyond charges higher than the mechanical resistance of the equipments. One of the most simple and often used method consist in designing relief vents of appropriate size at the vessel walls. Normalized methods exist for dimensioning the surface of vents, eg. NFPA 68 [1] or VDI 3673 [2]. Many works have attempted to improve the accuracy of these methods, particularly Yao [3], Bradley and Mitcheson [4], Moen et al. [5], Cooper et al. [6], Molkov [7-9], Canu et al. [10]. Comparison of their results and domain of validity has been done by Razus and Krause [11]. However, progress toward a more reliable modelling of the venting process is limited by the insufficient knowledge of flame transmission mechanisms from the vessel to the discharge opening. Here, we present results of recent experiments performed to investigate the flame evolution and behaviour at the vessel exit and its influence on the process of pressure discharge.

2 Flame propagation in closed chamber

Experiments were performed in a cylindrical plexiglas transparent vessel (length L_V = 0.385 m, inner diameter $Ø_V$ = 0.1 m), closed at one end and fitted at the other one with an opening of variable diameter simulating the uncovered vent. A stoichiometric propane-air pre-mixture at initial atmospheric temperature and pressure was used in the present series of experiments. Ignition was achieved by a small electrically heated wire, placed on the axis near the closed end of the vessel. Overpressure variations in the vessel were recorded by a Kistler piezoelectric gauge mounted at the vessel wall (opposite to ignition). Flame propagation inside the vessel was visualized by means of high framing rate video camera (Photron) coupled with a laser sheet tomographic method (the chamber was slightly seeded with a micromist of water-glycol droplets). For more details about the experimental details see[12].

Figure 1 displays a typical sequence of flame propagation at the end of the chamber. Bright areas (on the right part of images) and dark areas (on the left part) correspond respectively to fresh and burnt gases. The frontier between the two zones delineates the shape of the flame front. One clearly observes the occurrence of the phenomenon of “tulip flame”. This phenomenon, observed since a long time by Ellis and Wheeler [13], has been the subject of numerous works, see for example (Guenoche [14-15], Leyer and Manson [16], Starke and Roth [17], Dunn-Rankin et al. [18], Clanet and Searby [19], Dunn-

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Rankin et Sawyer [20]). Here, one can see the progressive flattening of the flame front, followed by the curvature inversion. As a result, the edge of the flame along the lateral walls reaches first the opposite side of the chamber, whereas the centre of the chamber is yet occupied by unburnt gases.

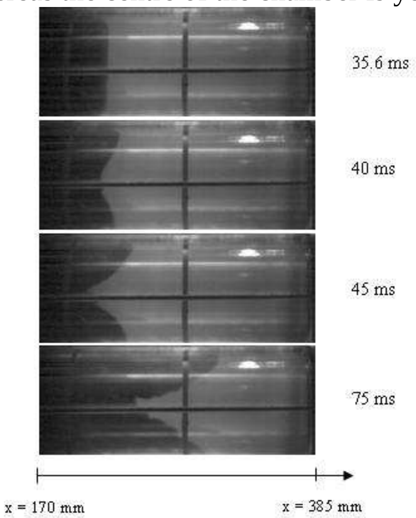

Fig. 1 : Selected frames from tomographic records showing flame propagation in the terminal part of the closed chamber.

3 Different modes of flame transmission through a vent

When a circular hole is fitted at the end of the chamber to simulate a vent, different flame behaviours are observed, following the size of the orifice.

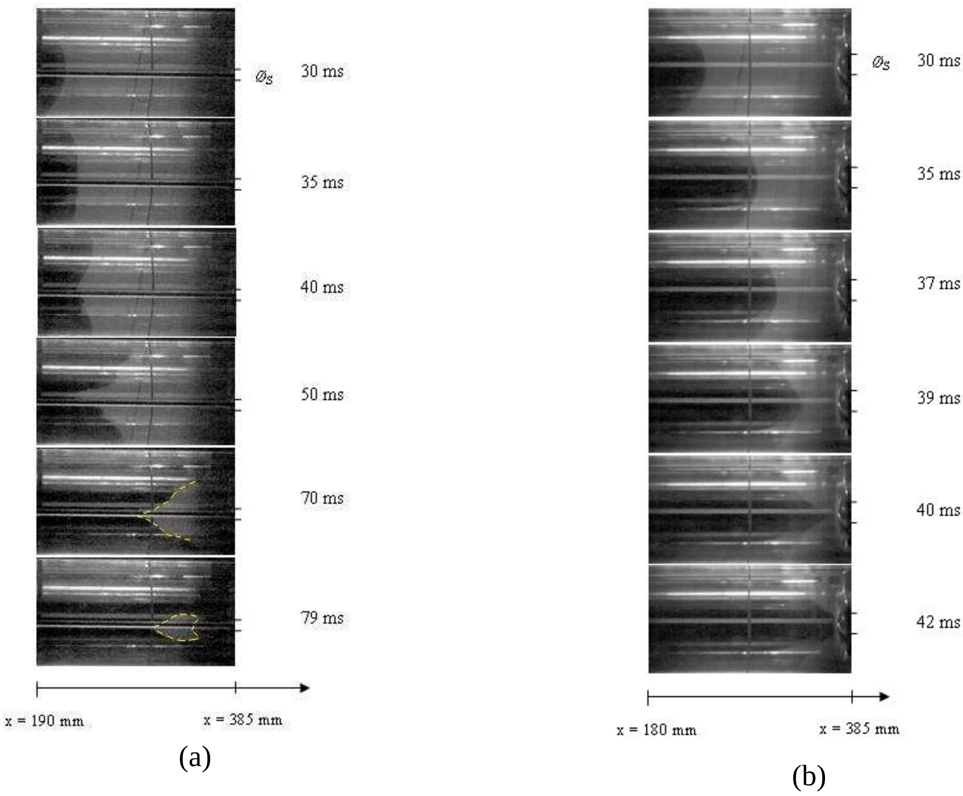

Fig. 2 : Selected frames from tomographic records showing flame propagation in the terminal part of the closed chamber fitted with a venting orifice: (a) hole diameter = 10mm, (b) hole diameter = 21 mm.

The case of an orifice of "small" size is displayed in Fig.2-a (in this example, the hole diameter is 10 mm, which corresponds to a vent area – chamber volume ratio of 0.026 m^{-1}). Evolution of the flame shape during propagation in the chamber is quite similar to the case of the closed chamber, with emergence of the tulip flame and the curvature inversion of the flame front together with its strong deceleration. Then, when the flame approaches the end of the chamber, it penetrates in the central hole by its peripheral sector. As a result, a pocket of unburnt gases is trapped in the centre of the outcoming flow (the boundaries of this pocket are underlined by dotted lines on the two last pictures of Fig.2-a). Locally, the flow velocity lines are opposite to the direction of the mean flow. Existence of this fresh gas pocket has a crucial role in the subsequent pressure evolution in the chamber. It may also take part in the occurrence of a secondary explosion in the gaseous mixture ejected at the exterior of the chamber.

The case of an orifice of "large" size is displayed in Fig.2-b (in this example, the hole diameter is 21 mm, which corresponds to a vent area – chamber volume ratio of 0.115 m^{-1}). Contrarily to the preceding case, the flame front does not encounter an inversion of its curvature because the tulip flame phenomenon formation is prevented by the characteristics of the flowfield in the fresh gases in front of the flame. Due to the larger dimension of the hole, the ejection of fresh gases generates a high longitudinal velocity in the chamber which produces a suction effect on the flame. As a result, the flame is stretched in the direction of propagation, does not decelerate, and its tip penetrates first in the exit hole. Accordingly, dead zones of unburnt gases are observed in the corners of the chamber, which are consumed at subsequent times after the flame had travelled outside of the chamber.

4 Consequences on pressure evolution inside the vessel

These marked differences in the flame front transmission from the chamber to the exterior result in dissimilar evolution of the overpressure inside the chamber, as can be seen in Fig.3. In the closed chamber, the diminishing of the rate of pressure rise corresponds to the beginning of the process of tulip flame formation. For the 10mm diameter orifice, tulip flame formation occurs practically at the

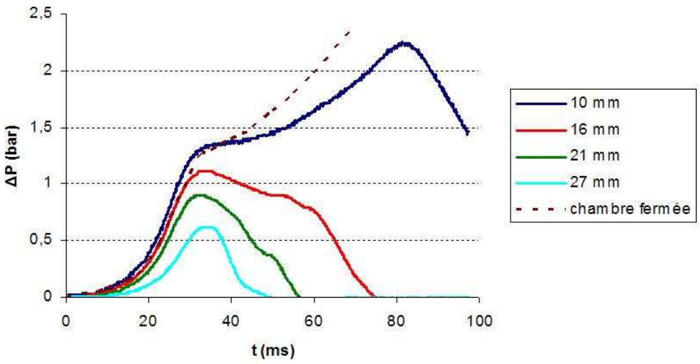

Fig. 3: Pressure evolution inside the chamber for different values of the size of the venting orifice.

same time, but then, the rate of pressure rise becomes smaller due to the evacuation of gases outside of the chamber. The maximum overpressure is reached much later, after the burning of the pocket of fresh gases. On the opposite, for the 21mm diameter orifice, the maximum overpressure is reached at the moment when tulip flame formation was observed in the 10mm diameter hole. Then, it decreases continuously. The combustion of unburnt pockets of gases in the chamber corners is unable to compensate the decrease of pressure caused by rapid evacuation of gases and is achieved noticeably after the flame exited out of the chamber. The separation between the two transmission modes takes place for a hole diameter of about 15mm (vent area – chamber volume ratio of 0.058 m^{-1}). In the case of a chamber with smaller volume (same cross section, but length reduced to 0.14m), only the second mode is observed, even with a small size orifice (10mm) on account of a too large vent area – chamber volume ratio (0.071 m^{-1}). Finally, it is worth to mention that the transmission mechanism is deeply modified by ducting, since addition of a duct at the vent exit to convey gaseous products far away, severely modifies the downstream boundary conditions of flow expansion out of the chamber.

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