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Flame acceleration in tube explosions with up to three flat-bar obstacles with variable obstacle separation distance

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ABSTRACT

The effect of obstacle separation distance on the severity of gas explosions has received little methodical study. It was the aim of this work to investigate the influence of obstacle spacing of up to three flat-bar obstacles. The tests were performed using methane-air (10% by vol.), in an elongated vented cylindrical vessel 162 mm internal diameter with an overall length-to-diameter, L/D, of 27.7. The obstacles had either 2 or 4 flat-bars and presenting 20% blockage ratio to the flow path. The different number of flat-bars for the same blockage achieved a change of the obstacle scale which was also part of this investigation. The first two obstacles were kept at the established optimum spacing and only the spacing between the second and third obstacles was varied. The profiles of maximum flame speed and overpressure with separation distance were shown to agree with the cold flow turbulence profile determined in cold flows by other researchers. However, the present results showed that the maximum effect in explosions is experienced at 80 to 100 obstacle scales about 4 times further downstream than the position of maximum turbulence determined in the cold flow studies. Similar trends were observed for the flames speeds. In both cases the optimum spacing between the second and third obstacles corresponded to the same optimum spacing found for the first two obstacles demonstrating that the optimum separation distance does not change with number of obstacles. In planning the layout of new installations, the worst case separation distance needs to be avoided but incorporated when assessing the risk to existing setups. The results clearly demonstrate that high congestion in a given layout does not necessarily imply higher explosion severity as traditionally assumed. Less congested but optimally separated obstructions can lead to higher overpressures.

1. Introduction

Investigators of gas explosions in congested volumes, as typically found in industrial layouts, have identified a number of important obstacle characteristics that affect the severity of explosion (in addition to the combustion chemistry). These include: blockage ratio, size, shape, scale, location of obstacles relative to the ignition and the path of flame propagation, the number of obstacles, and spacing between the obstacles. The separation distance (pitch) between obstacles is one of the areas that has not received adequate attention by the researchers despite general recognition of the important role it plays in determining the explosion severity. According to Lee and Moen (1980), sustained flame acceleration could not be attained for large pitch due to decay of turbulence in between obstacles while for small pitch the pocket of unburned gas between the obstacles would be too small to allow for the flame to accelerate before reaching the next obstacle. In between there has to be a worst case explosion interaction obstacle spacing and there is no previous work that determines this. In compliance with the ATEX directive (ATEX, 1994), the worst case scenarios need to be used in assessing the severity of the hazard posed by gas explosions in process plant or offshore oil and gas platforms. In planning the layout of new installations, it is appropriate to identify the relevant worst case obstacle separation in order to avoid it. In assessing the risk to existing installations and taking appropriate mitigation measures it is important to evaluate such risk on the basis of a clear understanding of the effects of separation distance and congestion.

A number of experimental explosion studies have demonstrated the effect of obstacle separation distance as part of wider

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assessment of the effects of congestion. These include the works of: Moen et al. (1980, 1982); Chan et al. (1983); Harrison and Eyre (1987); Lindstedt and Michels (1989); Teodorczyk et al. (1989); Mercx (1992); Beauvais et al. (1993); Obara et al. (1996); Mol'kov et al. (1997); Yu et al. (2002); Ciccarelli et al. (2005); Teodorczyk et al. (2009); Rudy et al. (2011); Vollmer et al. (2011); Pang et al. (2012); Boeck et al. (2013) and Porowski and Teodorczyk (2013). The bulk of studies was performed with repeat obstacles spaced over a short distance, the spacing between obstacles was small and varied just from 1.3 to 10 characteristic obstacle scales. However, this is not up to the range of 3–20 characteristic obstacle scales downstream of the grid where the maximum combustion rate usually occurs as discussed by Phylaktou and Andrews (1991).

The authors (Na'inna et al., 2013a) reported an experimental study in an elongated tube with two orifice plate obstacles of 30% blockage ratio each, where the obstacle separation distance was varied systematically from 0.5 m to 2.75 m. They reported a direct influence of the obstacle separation distance on flame speed and overpressure. A separation distance of 1.75 m produced close to 3 bar overpressure and a flame speed of about 500 m/s with 10% methane/air explosions. These values were of the order of twice the overpressure and flame speed with a separation pitch of 2.75 m. The profile of effects with separation distance was shown to agree with the turbulence profile determined in cold flows by other researchers. However, the experimental results showed that the maximum effect in explosions was experienced further downstream than the position of maximum turbulence determined in the cold flow studies. Also, the authors (Na'inna et al., 2013b) investigated the influence of mixture reactivity and fuel type on the optimum obstacle separation distance for generation using two induced turbulent generating orifice plates of 30% blockage with variable obstacle spacing.

It was the aim of this work to extend the investigation into the experimental assessment of the influence of obstacle spacing using three obstacles of variable number of flat-bars (obstacle scale, b) with fixed 20% blockage ratio.

2. Experimental set-up

A long cylindrical vessel 162 mm internal diameter made from nine flanged sections, 8 of them of 0.5 m length each and one section 0.25 m in length (total nominal length of 4.25 m). The test vessel was rated to withstand an overpressure of 35 bar. It was mounted horizontally and closed at the ignition end, with its open end connected to a large cylindrical dump-vessel with a volume of 50 m^3. This arrangement enabled the simulation of open-to-atmosphere explosions with accurate control of both test and dump vessels pre-ignition conditions.

Up to three obstacles (flat-bar types) with different number of bars as shown in Fig. 1 made from stainless steel of 3.2 mm thick, and 20% blockage were used in the test vessel. The different number of flat-bars for the same blockage achieved a variation of the obstacle scale, b (width of the bar), which was also part of this investigation.

The obstacles were mounted between the section flanges. For the double obstacle tests, the first obstacle was positioned 1 m downstream of the spark (for all tests) while the second obstacle's position was varied from 0.25 m to 1.75 m downstream of the first obstacle in order to obtain the worst case obstacle spacing. For the triple obstacle tests, the first two obstacles were kept at the established worst case spacing and only the spacing between second and third obstacles was changed.

A pneumatically actuated gate valve isolated the test vessel prior to mixture preparation. A vacuum pump was used to evacuate the test vessel before a 10% (by vol.) methane-air mixture was formed using partial pressures, to a total mixture pressure of 1 atm. The dump vessel was filled with air to a pressure of 1 atm as well. After mixture circulation, allowing for at least 4 volume changes, the gate valve to the dump vessel was opened and a 16 J spark plug ignition was effected at the centre of the test vessel closed-end flange. The test vessel had an overall length-to-diameter ratio, L/D of 27.7. The set-up is shown in Fig. 2.

An array of 24 type-K mineral insulated exposed junction thermocouples positioned along the axial centre line of the test vessel was used to record the time of flame arrival. Average flame speeds allocated to the midway position between two thermocouples were obtained by dividing the distance between two thermocouples by the difference in time of flame arrival at each thermocouple position. A smoothing algorithm was applied to the flame arrival data, as described by Gardner (1998), to avoid either high or negative flame speeds where the flame brush appears to arrive at downstream centreline locations earlier than upstream ones, particularly in the regions of strong acceleration downstream of the obstacles.

The test vessel and dump vessel pressure histories were recorded using an array of 8 Keller-type pressure transducers – 7 gauge pressure transducers (PT1to PT7) and 1 differential (DPT), as shown in Fig. 2. Wall static pressure tapping measured by a differential pressure transducer (DPT) were located at 0.5D upstream and 1D downstream of the first obstacle as specified by BS5167-2 (2003). Pressure transducers, PT3 and PT4 were positioned 0.5D upstream and 1D downstream of the second obstacle and they were used to obtain the pressure differential across these obstacles. For the third obstacle tests, PT2 and PT5 (0.5D and 1D upstream and downstream respectively) were used to measure the pressure drop across such obstacles and these were used in calculating the induced gas flow velocities and other flow turbulence characteristics (but these are not reported in this paper). Pressure transducers PT1 and PT6 were positioned permanently at the ignition position-end flange and end of the test vessel (25D from the spark) respectively. The pressure history in the dump vessel was measured using PT7 positioned as shown in Fig. 2.

A 32-channel (maximum sampling frequency of 200 KHz per channel) transient data recorder (Data Logger and FAMOS) was used to record and process the explosion data.

Each test was repeated at least three times. In presenting the results of the experimental tests in this research, all the repeat tests were shown on the graph where possible. However, for clarity purposes average results are shown in some cases for the analysis of flame speed, S_f and overpressure, P. In total, over 50 tests were carried out demonstrating 16 different test conditions.

Table 1 shows a list of the tests carried out as part of this work and an overview of the results.

Fig. 1. Turbulence generation obstacles: two and four flat-bar obstacles of 20% blockage each.