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The effect of vent size and congestion in large-scale vented natural gas/air explosions

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A B S T R A C T

A typical building consists of a number of rooms; often with windows of different size and failure pressure and obstructions in the form of furniture and décor, separated by partition walls with interconnecting doorways. Consequently, the maximum pressure developed in a gas explosion would be dependent upon the individual characteristics of the building. In this research, a large-scale experimental programme has been undertaken at the DNV GL Spadeadam Test Site to determine the effects of vent size and congestion on vented gas explosions. Thirty-eight stoichiometric natural gas/air explosions were carried out in a 182 m^3 explosion chamber of $L/D = 2$ and $K_A = 1$, 2, 4 and 9. Congestion was varied by placing a number of 180 mm diameter polyethylene pipes within the explosion chamber, providing a volume congestion between 0 and 5% and cross-sectional area blockages ranging between 0 and 40%. The series of tests produced peak explosion overpressures of between 70 mbar and 3.7 bar with corresponding maximum flame speeds in the range 35–395 m/s at a distance of 7 m from the ignition point. The experiments demonstrated that it is possible to generate overpressures greater than 200 mbar with volume blockages of as little as 0.57%, if there is not sufficient outflow through the inadvertent venting process. The size and failure pressure of potential vent openings, and the degree of congestion within a building, are key factors in whether or not a building will sustain structural damage following a gas explosion. Given that the average volume blockage in a room in a UK inhabited building is in the order of 17%, it is clear that without the use of large windows of low failure pressure, buildings will continue to be susceptible to significant structural damage during an accidental gas explosion.

1. Introduction

When a flammable gas/air mixture is ignited within a confined enclosure, there is an associated pressure rise. The pressure rise is caused by the restriction, that the enclosure places, on the expansion of the hot burnt gases. It is this rapid release of energy with its associated pressure generation and high temperature flame and gases that define a gas explosion. The level of damage a building sustains following a gas explosion is dependent upon the magnitude of the pressure generated and the relationship between the duration of the imposed pressure load and the natural period of vibration of the structure. Overpressures in the region of 30–70 mbar have been shown to be capable of causing significant damage to industrial and residential buildings (Baker et al., 1983). Other studies have shown (Astbury and Vaughan, 1972; Astbury et al., 1970; Harris, 1983; West et al., 1971a, 1971b; Wong and Karamanoglu, 1999) that an overpressure generated by a gas explosion, in the region of 200 mbar, has the potential to cause significant structural damage to buildings typically constructed in the UK.

In accidental vented confined explosions, the building is often vented, when a weak part of the structure fails (e.g. a window), and the pressure is relieved. Up until this point, the event may be considered as a confined explosion (with the potential to develop an overpressure of between 7 and 8 bar), but after venting begins, the rate of pressure rise, and hence the maximum pressure developed, is governed by the balance between the rate at which combustion products are produced and the rate of outflow through the venting process. The rate of outflow is dependent upon the size and location of the vent(s) (Alexiou et al., 1997; Alexiou et al., 1996a; Alexiou et al., 1996b; Bauwens et al., 2010; Eckhoff et al., 1984;

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Fakandu, 2014; Fakandu et al., 2014; Fakandu et al., 2013; Mercx et al., 1993; Pappas, 1983; van Wingerden, 1989; van Wingerden and Zeeuwen, 1983b; Zalosh, 1980), whilst the rate at which hot combustion products are produced is directly related to the burning velocity of the fuel. Consequently, the rate of pressure rise in an accidental explosion is strongly dependent upon the fuels composition and on any turbulence that increases the burning velocity (and hence the flame speed).

Initially, after venting, unburnt gas/air mixture within the building will be expelled from the vent forming a flammable cloud outside the vent opening. When the burned gas reaches the vent opening, a sequence of interdependent events occur very quickly. Firstly, the volumetric flow of gas exiting the chamber increases, by a factor of approximately three, due to the decrease in density of the vented gas. This increase in venting causes a temporary reduction in the pressure within the enclosure as the rate of venting exceeds the volume expansion due to combustion and the inertia of the outflow 'over-vents' the burnt gases. Secondly, the pressure difference across the vent opening triggers a Helmholtz oscillation, which causes the internal chamber pressure to oscillate about the equilibrium pressure (Bauwens et al., 2010; Bauwens et al., 2009). Thirdly, the onset of burnt gas venting initiates Taylor instabilities, where the less dense burned gas is accelerated into the denser unburned gas/air mixture, increasing the mass combustion rate, and amplifying the Helmholtz oscillation. Finally, the venting flame front and the outflow of burnt gases ignite the flammable cloud outside the vent opening resulting in an external explosion. The explosion sends a propagating wave back towards the explosion chamber exacerbating the Taylor instabilities and causing the pressure inside the chamber to increase.

This complex sequence of events is further complicated if turbulence is generated by jet mixing in the gas/air mixture prior to ignition, or by induced flow interaction with obstacles. Both of these turbulence generating mechanisms may be important in accidental gas explosions in buildings; the first, due to flow through interconnected rooms, and the second, due to the interaction of flow with furniture and décor. The enhanced combustion rate, caused by increases in the local transport of mass and energy, and increased flame surface area (Chan et al., 1983) is dependent upon the induced flow velocity ahead of the flame, which itself is dependent upon the reaction rate. Consequently a 'coupling' is created which may manifest as a strong positive feedback mechanism (Schelkin mechanism) which, would result in continuous flame acceleration until the fuel is consumed, or transition to detonation occurs.

Previous studies have shown that reducing the vent size and increasing congestion, in the form of obstacles in the path of the propagating flame front, can affect flame speeds and result in increased overpressures in vented explosions (Alexiou et al., 1996a; Bauwens et al., 2010; Bimson et al., 1993; Chan et al., 1983; Fakandu et al., 2013; Hall et al., 2009; Mercx et al., 1993; Na'inna et al., 2013a, 2013b; Pappas, 1983; Park et al., 2008; Phylaktou and Andrews, 1994; Phylaktou, 1993; Pritchard et al., 2002; Solberg et al., 1980; Taylor and Bimson, 1989; van Wingerden, 1984a, 1984b; van Wingerden, 1989; van Wingerden and Zeeuwen, 1983a, 1983b; Zalosh, 1980, 2008).

Several studies (Harris and Wickens, 1989; Phylaktou et al., 1995; Phylaktou, 1993) have demonstrated that very fast flame speeds, in excess of 600 m/s, may be generated when a flame propagates through a flammable gas/air mixture in the presence of repeated obstacles. To predict the pressure generated during these type of fast flame events, it is necessary to understand the role that the obstacle configuration, blockage ratio, and the parameters that affect the turbulent flow field, play in effecting the strength of the feedback mechanism.

Fig. 1. The explosion chamber.

Whilst the identified studies have demonstrated that reducing the vent size and increasing congestion can affect the flame speed and increase overpressures, the confined and congested situation found in buildings, wherein both adiabatic expansion and turbulent flame acceleration play a role, has received little large-scale attention. Typical industrial buildings or dwellings will have a pathway, for flame propagation, that consists of a number of interconnected rooms, each of which may have significant congestion. For example, in the average UK home a doorway represents an opening with a blockage of approximately 82% and the average room congestion is approximately 17% (Admirals Storage; BBC news, 2011; Drury et al., 2006). Inadvertent individual vent openings, in the form of windows, will provide a minimum area vent coefficient (K_A), defined as the area of the front face of the chamber divided by the area of the vent opening ($K_A = A/A_v$) (Harris, 1983),[1] of 4 where openings are provided on one wall of the room or 8 if windows are provided on more than one wall (Greater London Authority, 2012). To understand the effects of window size and obstacles, in the development of explosions in buildings, a large-scale experimental programme was undertaken at the DNV GL Spadeadam Test Site. Some of the results of this programme are presented in this paper.

2. The experimental programme

In total, thirty-eight large-scale vented confined explosion experiments were carried out at the Spadeadam Test Site using stoichiometric natural gas/air mixtures in a 182 m^3 steel explosion chamber of $L/D = 2$ (Fig. 1). The explosion chamber, of dimensions 9.0 m × 4.5 m × 4.5 m, was constructed of 10 mm thick steel plates supported by regularly spaced I beams. The rear face of the chamber was constructed of two hinged pressure relief panels, with a failure overpressure of 4 bar, to protect the explosion chamber from damage during the experiments. The front face of the chamber accommodated a vent opening of variable size which was covered by a polythene sheet (low failure pressure) to prevent the gas/air mixture escaping during filling. The vent openings were either 20.25 m^2, 10.13 m^2, 5.06 m^2 or 2.25 m^2. Correspondingly, the vent coefficients (K_A), were approximately 1, 2, 4 or 9.

Obstacle supports were attached to the side walls of the

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[1] The vent coefficient may be expressed in other terms (e.g. $K = A_{cs}/A_v$ or $K_v = V^{2/3}/A_v$) but in the context of this work (i.e. adventitious vent openings), K_A was chosen as being most appropriate. However, the experimental data is currently being analysed with reference to explosion relief design standards and this will be the subject of a further paper.