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Experiments on vented hydrogen-air deflagrations: The influence of hydrogen concentration

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ABSTRACT

The explosion venting of hydrogen-air mixtures with equivalence ratios ranging from 0.4 to 6.0 was investigated in a small vented cylindrical vessel. The experimental results show that the maximum internal overpressure initially increases with an increase in hydrogen equivalence ratio up to approximately 1.6 and subsequently decreases. The discrepancy between the maximum internal overpressure and the vent burst pressure is significantly high for equivalence ratios ranging from 1.0 to 2.0 but low for very lean or very rich mixtures. Buoyancy has a significant effect on the evolution of the internal flame bubble for very lean hydrogen-air mixtures only. The speed of the external flame oscillates violently and its maximum value is achieved at a distance downstream from the vent. The maximum length of the flame ejected from the vent, which depends on the hydrogen equivalence ratio, may be underestimated by engineering models.

1. Introduction

Hydrogen is widely used in refining, fertilizers, chemical synthesis of materials etc., but it has a reputation of being dangerous owing to its extensive flammable range, low ignition energy, and high burning rate. Explosions might occur when hydrogen-air mixture is introduced in confined spaces; accordingly, an explosion vent may be installed to protect equipment or buildings against accidental internal deflagrations by means of quick pressure relief.

It has been established that hydrogen concentration has a significant effect on the reactivity of hydrogen-air mixtures and furthermore, on the overpressure of vented explosions (Kumar et al., 1989; Bauwens et al., 2012; Kasmani, 2008; Lowesmith et al., 2011; Schiavetti et al., 2014; Bauwens and Dorofeev, 2014; Daubech et al., 2013). The experiments performed by Kumar et al. (1989) with lean hydrogen-air mixtures in a vented spherical vessel demonstrated that the maximum pressure for central ignition increases with an increase in hydrogen concentration from 6% to 20% by volume. Bauwens et al. (2012) also determined that the peak pressure and burning velocity of the flame increase when hydrogen concentration increases from 12% to 19%. However, no significant increase in the maximum pressure for central ignition was observed with the increase of concentration of lean hydrogen-air mixtures (Kasmani, 2008). Lowesmith et al. (2011) investigated the effect of hydrogen concentration on explosion overpressures of methane/hydrogen mixtures. It was discovered that adding up to 20% hydrogen to methane resulted in a small increase in overpressure and a significant increase was observed when 50% hydrogen was added. Molkov et al. (1999, 2000) numerically investigated the explosion venting of hydrogen-air mixtures and the theoretical correlation they proposed predicted the deflagration pressures reasonably well.

On the other hand, when unburned hydrogen-gas mixtures are ejected out of a vented vessel, violent external combustion may occur. The formation and combustion of the external combustible cloud in front of the vent were studied by seeding the gas mixtures in a vented vessel (Daubech et al., 2013; Proust and Leprette, 2010). It was observed that the expelled gas velocity is linked to the internal pressure, and the maximum velocity of the external flame occurs when the flame reaches the stagnation point of the leading edge of the cloud (Proust and Leprette, 2010).

Apart from the aforementioned research, some aspects of the

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effect of hydrogen concentration on the process of explosion venting have not been studied yet. For example, only lean (Kumar et al., 1989; Bauwens et al., 2012; Kasmani, 2008) and stoichiometric (Rocourt et al., 2014) hydrogen-air mixtures were investigated, but the extent of the effect of hydrogen concentration on pressure history and flame behaviors of hydrogen-rich mixtures still remains unclear, which also deserves detailed investigation because any concentration of hydrogen-air mixtures between the lower and upper explosion limits can be attained in real life—for example, when hydrogen is accidentally leaked in a confined space.

In this paper, experiments were conducted using hydrogen-air mixtures with equivalence ratios ranging from 0.4 to 6.0 in a small vented vessel for the following reasons: first, to clarify the effect of the equivalence ratio on the maximum internal overpressure, and second, to investigate the behavior of internal and external flames before and after vent failure, especially the flame structure, flame speed, and length.

2. Experimental details

The experimental setup and procedures are similar to those adopted in our earlier work (Guo et al., 2015) and will be briefly described in this section. The setup consisted of a cylindrical vented vessel, flame image recording systems, pressure measuring system, and ignition unit. Both the inner diameter and length of the cylindrical vessel were 250 mm (volume $V = 12266$ cm^3). A 10-cm-long vent duct with a cross section of 7 cm × 7 cm was connected to the waist of the vessel. A diaphragm was used as a vent cover to seal the exit of the short duct before the experiment. The moment of vent failure was obtained from the electrical circuit interruption owing to the breakage of a thin metal strip fixed to the diaphragm (Guo et al., 2016). The flame images inside and outside the vented vessel were captured by means of high-speed photography. Two piezoelectric pressure transducers (PCB 102B16) were used to record pressure history during the venting process—one (PT_1) was installed on the vessel wall opposite to the vent and the other one (PT_2) was installed on the duct wall 2 cm away from the vent cover. The hydrogen-air mixtures with equivalence ratios (ϕ) ranging from 0.4 to 6.0 were ignited at the center of the vessel with ignition energy of approximately 500 mJ. The initial pressure and temperature of the hydrogen-air mixture in all the experiments were 1 atm. and 300 K, respectively.

3. Results and discussion

3.1. Pressure profile in vessel

Typical pressure profiles of the current experiments are shown in Fig. 1. As expected, ϕ has a critical effect on the pressure-time histories both in the vessel (PT_1) and at the duct exit (PT_2). Contrary to the pressure profiles with multi-peaks in existing research (Schiavetti et al., 2014; Rocourt et al., 2014; Bauwens et al., 2011), only one dominant internal pressure peak was observed for all the equivalence ratios tested. As shown in Fig. 1, PT_1 increases monotonically to its maximum value p_{max} after vent failure and subsequently decreases to a negative peak owing to over-discharge (Molkov et al., 2006; Ferrara et al., 2006). Subsequently, a pressure peak with low amplitude can be distinguished for $\phi \geq 0.8$, which is due to the "residual" combustion in the vessel (Molkov et al., 2006).

Compared to PT_1, more pressure peaks form at the duct exit (PT_2). As shown in Fig. 1, the first pressure peak p_1, which can always be observed, results from the burst of the vent cover (Rocourt

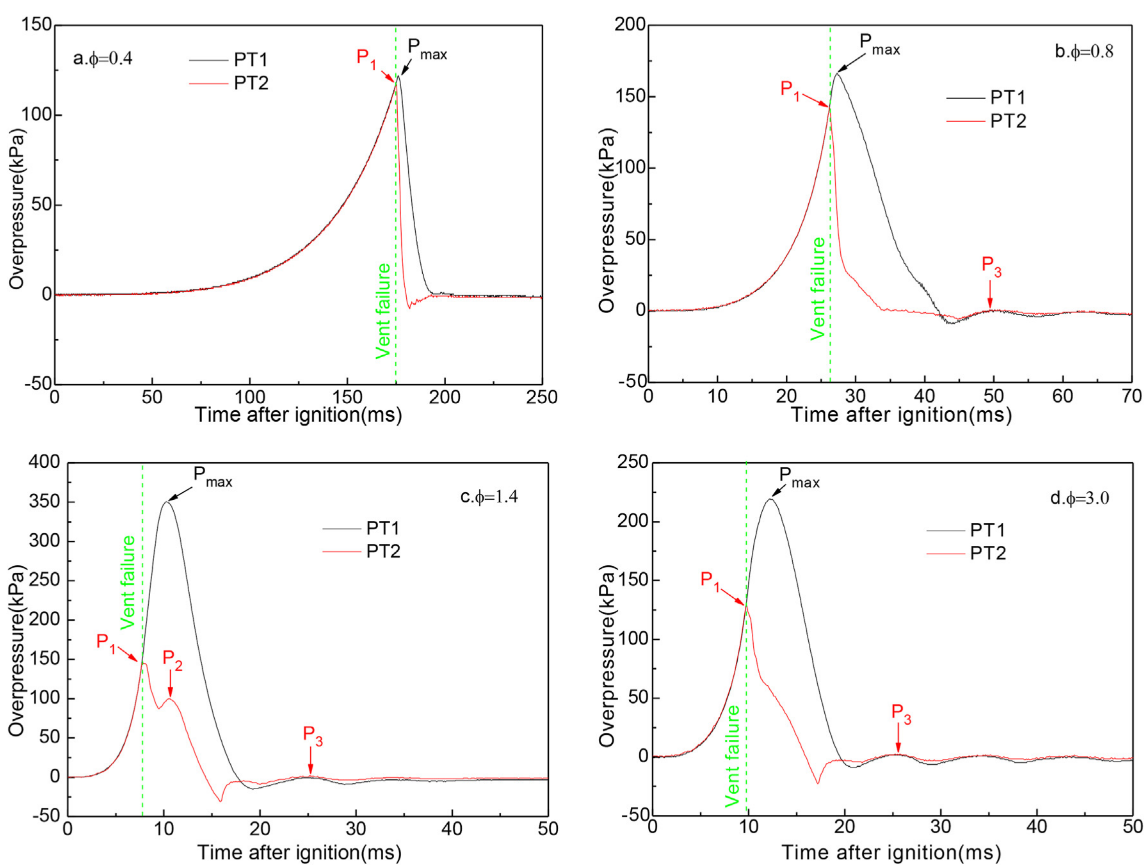

Fig. 1. Typical pressure profiles for various ϕ.