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Pressure characteristics during vented explosion of ethylene-air mixtures in a square vessel

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ABSTRACT

The vented explosion in a 2 m × 1.1 m × 0.5 m stainless cylindrical vessel with the ethylene-air mixture is investigated as the function of the ethylene concentration, vent area and vent burst pressure. The internal pressure histories measured by two piezoelectric transducers with the vented door of different thickness are used to analyze the effect of vent burst pressure on the whole explosion. It is shown that the peak overpressures are the highest just at the ethylene concentration is 8 vol%. The internal overpressure is grown with the concentration and in turn decreases after internal pressure reached the peak. As the vent burst pressure increases, the same trend that internal peak overpressure is increasing accordingly is found. The dominant peak overpressure will be change with different vent areas. Not only that, it is apparent that venting is more effective on the account of the low ethylene concentrations. The high-speed images demonstrate that the flame is strongly distorted and the unburned mixture is ignited by the external flame. The comparison between experimental results and calculation values has been discussed in consideration of the influences of vent area and vent burst pressure. The predicted overpressures of different theoretical models are relatively conservative than measured peak overpressures.

1. Introduction

The ethylene industry has an important status in chemical industry, since it is a reactive fuel as the typical decomposition product of hydrocarbon fuels for applying to the high-speed propulsion, such as pulse detonation engines. And it also plays a key role in the combustion process of most gaseous fuels [1,2]. The yield of ethylene also represents the level of the petrochemical industry in a country. However, a potential explosion risk still exists in the ethylene operating system due to the lower explosive limit and the wider explosive range. Practically, the leaking of the ethylene can easily occur in the vessel and pipeline caused by facility failure, design deficiency and operator error. Accident gaseous explosion of storage, transportation and production is a serious problem. The most convenient method to prevent disastrous consequences is explosion venting. For the design of venting, many scholars have advanced some guidelines based on the empirical observation and theoretical calculation [3–5]. Bradley [6] present a detailed model containing adjustable parameters to estimate the reduced explosion pressure. Solberg [7] found that the flame front is sudden enhanced due to the opening of the vent and formed Taylor instability during the venting process. Chippett [8] considered initial turbulence by introducing some empirical parameters, the flame acceleration and the increase in burning rate generated by hydrodynamic instabilities ahead of vent opening had been taken into account in the vented deflagration models. The method of computational fluid dynamics was employed extensively for vented deflagration modeling [9–12]. Nevertheless, the numerical computation approach is not an effective prediction tool for vented explosion because the influence of complicated combustion mechanism can not be estimated for arbitrary working condition. Molkov [13] proposed the computing models of hydrocarbon-air deflagrations based on the advanced lumped parameter in vented large vessels. The experiment result showed the accurate prediction of numerical simulation is unachievable without proper modeling in many practical cases. Epstein [14] summarized that the best way to gain a realistic prediction is adopting a constant correction factor rather than employing the elaborate equations through a series of numerical computations whose accuracy is limited to the exacting experimental conditions. The more experimental investigation of vented gaseous explosions to improve understanding of the phenomena is essential.

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Vent burst pressure is one of the important vent parameters on the process of vented gaseous explosion [15–19]. Chow [20] studied the vented explosion in a 3: 1 length: diameter ratio, cylinder tube for ethylene-air mixtures. The effect of ignition location, vent area and vent burst pressure on the flame speed and was systematical investigated. The different vent burst pressures have a significant influence on the development of internal pressure. At the high vent burst pressure, the first peak pressure plays an important role for internal pressure while the second peak pressure was always dominant at the low vent burst pressure. The influence of vent burst pressure (P_V) from 3.5 to 45 kPa on the overpressure in a cylindrical vessel for ethylene-air and methane-air was investigated by Fakandu et al. [21]. The experimental results derived from the assumption that the peak overpressure in the vessel is higher than the P_V in EU and US vented standards (NFPA 68 [22] and EN 14994 [23]).

When an explosion of fuel-air mixtures occurs, the concentration always plays a significant role on the development of internal overpressure [24–28]. The impact of vent burst pressure is also investigated by the Amyotte [29] for stoichiometric ethylene-air explosion tests in a 26 L spherical vessel. A linear relationship between vent bursting pressure and internal overpressure is not observed on account of the different initial pressure. Ponizy [30] have been tested the explosion for stoichiometric ethylene-air and propane-air mixtures in the duct, the burning velocity of ethylene-air is higher than the case of propane-air. The steel wire-net placed at the entrance of tube can effectively reduce the pressure rise during the explosion venting. In the presence of steel wire-net, the highest values of peak pressure have been observed for ethylene-air. Especially in a lean concentration of fuel-air mixtures, the contribution of flame instabilities must be included. The role of fuel concentration in the explosion venting for lean hydrogen-air mixtures was discussed with Bauwens [31]. The results present that the maximum pressure of main pressure transient can significantly below the predicted overpressure due to the thermal-diffusive instability. Movileanu [32] tested the explosion of ethylene–air mixtures with various concentrations between 3.0 vol % and 14.0 vol %. The explosion overpressure increase with the concentration rises from 3.0 vol % to 8.0 vol %. And the relation between explosion overpressure and concentration is contrary when the concentration of ethylene is higher than 8.0 vol %.

As for as the vented cover study, a great mount of researches concentrates on the gas accidental explosions in the vessels and pipelines, in this case, the vented exits are always closed by the relatively thin vented membranes like as aluminum film, paper film or plastic film. Few studies have examined the vented door used to the large confined space. In this work, the vented deflagration characteristic of ethylene in a small-scale model of actual square building was investigated in consideration of the influence of the self-produced vented door. The mechanism of pressure transition and external phenomenon is still necessary to make clear in this respect. The objective of this paper is to figure out the mechanisms of the internal pressure under a variety of experimental conditions. Therefore, the explosion venting of ethylene-air mixtures is conducted with different concentrations, vent areas and vent burst pressures in this work. The results of these experiments are of great significance to security design of explosion prevention and protection of industry construction and civil building. And it also provides theoretical basis to the research of the destructive effects on gas explosion accidents and supported technical supports to explosion resistant structure.

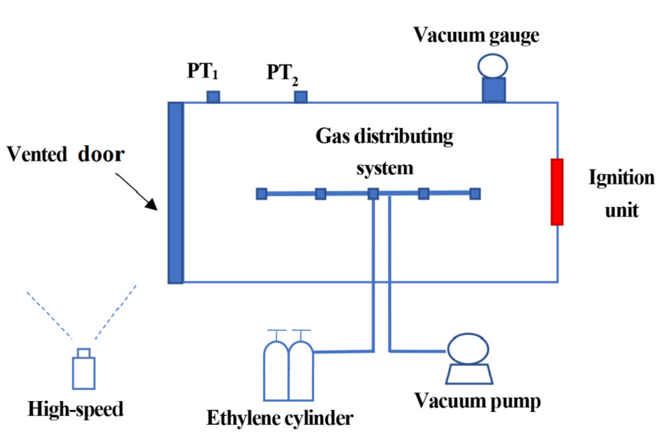

Fig. 1. Schematic of experimental layout.

2. Experiment setup

2.1. Apparatus

Experiments at ambient initial temperature and atmospheric pressure were performed in a 2 m × 1.1 m × 0.5 m stainless vessel, as shown in Fig. 1. The angle iron was welded to the stress raiser to strengthen the intensity of the square vessel. Two piezoelectric pressure transducers (PT_1 and PT_2) were mounted in the horizontal direction on the top of vessel. The distances of PT_1 and PT_2 from the vent were 0.1 m and 0.3 m, respectively. A vented door designed as hinge joint structure was fixed on the front wall of the vessel; the ignition end was connected by bolts to welded cylindrical flanges, ignition was performed by electric resistance wire connected with the DC power source mounted at the opposite wall to the vent. The pressure history during explosion was recorded with two piezoelectric pressure transducers (PCB 113B) connected to the Charge Amplifier. The piezoelectric pressure sensors have a linear characteristic over the entire pressure range 0–500 kPa (with a sensitivity of 5 mV/psi and a linearity error below 1%). The response time of transducers was smaller than 1 μs The frequency range of Charge Amplifier (with standard filter) is 0–20 MHz and the error below 3%. A high-speed camera (Photron UX 100) with a frame rate of 4000 fps was placed at 5 m away from the explosion vessel.

2.2. Procedures

In each test, the explosion vessel was evacuated by a vacuum pump in the first place. The ethylene of different concentrations (c = 4 vol %, 5 vol %, 6 vol %, 7 vol %, 8 vol %, 9 vol % and 10 vol %) was calculated by Dalton's law and the ethylene and air was separately filled in the vessel sealed by the door with different thicknesses (δ=10 mm, 8 + 10 mm, 10 + 10 mm) of two areas (A_V = 0.18 m^2 and 0.55 m^2). Then the mixture was ignited by resistance wire with the ignition energy of 200 mJ; the high-speed camera was triggered by the electrical signal through the transistor-transistor logic simultaneously. Signals from the pressure transducers were recorded by the data acquisition instrument with a recording rate of 10000 samples per second at the same time. The moment of door rupture was obtained from the electrical signal produced by the strain gage fixed on the vented door. The initial pressure and temperature of all experiments were maintained at 1 atm and 298 K. Table 1 present the characteristic parameters of vented explosion for different vent burst pressures. The experimental data recorded in Table 1 referred to the internal overpressure than atmospheric pressure. The thicknesses (δ) of vented door corresponding to different vent burst pressures (P_V) were used as vent covers prior to ignition as summarized in Table 1, it also included the maximum rate of pressure rise ($(dP/dt)_{max}$) and the highest peak internal pressures (P_{ves}).