Journal of Loss Prevention in the Process Industries 50 (2017) 121–130

Contents lists available at ScienceDirect

Journal of Loss Prevention in the Process Industries

journal homepage: www.elsevier.com/locate/jlp

Large-scale vented deflagration tests

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ARTICLE INFO

Article history:
Received 2 April 2017
Received in revised form
17 September 2017
Accepted 18 September 2017
Available online 21 September 2017

ABSTRACT

This paper presents results from a test program carried out to determine the peak deflagration pressure achieved within a congested enclosure vented through one wall of the enclosure. The industry standard in the United States for predicting the peak pressure developed in a vented deflagration is the National Fire Protection Association's Standard on Explosion Protection by Deflagration Venting (NFPA 68). The NFPA Explosion Protection Committee has compiled a database of published and unpublished explosion venting test data. This data was summarized in a 2008 report (Zalosh) that served as the foundation of the development for the vented deflagration correlations in the latest (2013) edition of NFPA 68. In this latest edition, NFPA 68 (2013), the vent area correlation accounts for varying degrees of congestion if the ratio of the obstacle surface area (A_{obs}) to that of the enclosure internal surface area (A_s) is greater than 0.4 (i.e., $A_r = A_{obs}/A_s > 0.4$). Congestion is accounted for within the correlation at all values of A_r, however when A_r is < 0.4, variations in the level of congestion are not accounted for. The tests described in this paper were performed using an obstacle array with an A_r ratio of less than 0.4.

These tests were conducted in a rig with a 48-foot width, 24-foot depth, and 12-foot height. The rig is enclosed with solid walls, roof, and floor, allowing for venting through one of the long walls (i.e., 48-foot by 12-foot). The venting face of the rig was sealed with a 6 mil (0.15 mm) thick plastic vapor barrier to allow for the formation of a near-stoichiometric propane-air mixture. The flammable gas cloud was ignited near the center of the rear wall. Steel vent panels (20-gauge, 2 lb_m/ft^2) were installed over the plastic vapor barrier using explosion relief fasteners. The vent panels were configured to release at 0.3 psig; vent panel restraint devices were not utilized. The congestion inside the rig was provided by a regular array of vertical cylinders (2-inch schedule 40 pipe and 2-inch outer diameter cylinders) giving area and volume blockage ratios (ABR and VBR) within the congestion array of 4.9% and 0.5%, respectively. The obstacle-to-enclosure surface area ratio (A_r) is 0.3 with the array extended throughout the rig and vent panels installed, which is less than the critical value to account for congestion in the NFPA 68 correlation.

Four series of tests were conducted with varying vent parameters, flammable gas cloud sizes, and congestion levels. Baseline tests were performed with the congestion array and flammable gas cloud extending throughout the entire rig without vent panels present (i.e., vapor barrier only). The second test series included the addition of vent panels for the same congestion pattern as that employed for the baseline tests. The third test series utilized a flammable gas cloud that filled only the back half of the rig. For the fourth test series, the congestion array occupied only ¼ of the rig. The peak pressures and impulses for each test series are provided, along with pressure histories internal and external to the rig for selected tests. The steel vent panel throw distance is also provided as a function of internal peak pressure.

The test data were compared with the predictions of the vent area correlations provided in NFPA 68. For all but the fourth test series (i.e., congestion array occupying ¼ of the rig), the average internal peak pressures were approximately a factor of 2 larger than those predicted by NFPA 68. Adjustments to the NFPA 68 correlation were investigated to improve the agreement with the current test data.

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https://doi.org/10.1016/j.jlp.2017.09.012

1. Introduction

The primary objective of these tests was to measure the blast loads produced by a vapor cloud explosion (VCE) within a vented congested enclosure and compare the measured peak pressures to those based on the industry standard for predicting vented deflagration peak pressure (i.e., NFPA 68, 2013 Edition). In a VCE, if the flame propagates through the unburned fuel-air mixture at a burning velocity less than the speed of sound, it is termed a deflagration. The overpressure generated in a deflagration is a function of the flame speed achieved: minimal overpressure is produced at very low flame speeds (e.g., in a flash fire), and higher overpressures are produced at higher flame speeds. The level of confinement and congestion associated with the area encompassed by a flammable cloud affect the flame speed achieved in a VCE. Confinement refers to solid surfaces that prevent free expansion of the expanding gas in one or more dimensions (e.g., solid walls, roof, etc.). Congestion refers to obstacles in the path of the flame that generate turbulence (e.g., the vertical cylinders in the rig used in these tests); turbulence increases both the combustion rate per unit surface area as well as the flame surface area. Increasing confinement and/or congestion increases flame speed and therefore increases the resulting VCE blast overpressure.

Data was also collected regarding external blast wave propagation and panel throw distance. Twelve tests (three tests for each of four test series) were performed in this test program. The test matrix is provided as Table 1.

2. Test rig configuration

The test rig was an enclosure with three solid walls, roof and floor with dimensions of 48 feet wide, 24 feet deep, and 12 feet tall. Venting was allowed through one of the long walls (i.e., 48-foot by 12-foot). The venting face of the rig was sealed with a 6 mil thick plastic vapor barrier, which released (i.e., tore open) at approximately 0.1 psig. For test series C, the plastic vapor barrier was installed halfway between the rear of the test rig and the venting surface. This allowed for the formation of a fuel-air mixture only in the rear half of the enclosure. For all other test series (A, B, and D), the vapor barrier was installed on the external venting face of the rig, resulting in a flammable cloud filling the entire enclosure volume.

A near-stoichiometric (slightly fuel-rich) propane-air mixture was produced inside the test rig for all tests and was ignited in the center of the rear wall, opposite the venting surface. For test series B and C, steel vent panels (20 gauge) were installed over the plastic vapor barrier using Fabco® Vent-All explosion relief fasteners to provide a 0.3 psig vent release pressure (P_{stat}). The vent panels weighed 2 lb_m/ft^2. Vent panel restraint devices were not utilized. Fig. 1 shows photos of the test rig configured for test series A, B, and C, respectively. The photo of the rig configured for series C is prior to installation of the steel panels in order to show the vapor barrier location.

The congestion inside the rig was provided by a regular array of vertical cylinders (2.375-inch and 2-inch outer diameter cylinders) giving area and volume blockage ratios (ABR and VBR) of 4.9% and 0.5%, respectively, within the congestion array. The 2.375-inch outer diameter cylinders are located at the front of the rig in order to minimize plastic deformation resulting from repeated blast and drag loading.

For test series A, B and C, the congestion extended throughout the entire enclosure. For test series D, the same congestion array was located in the center rear of the test rig (i.e., surrounding the location of ignition); however, it only extended over 25% of the enclosure.

Fig. 2 shows the congestion array for test series A, B, and C (top half of figure) and test series D (bottom half of figure). The obstacle-to-enclosure surface area ratio (A_r) for the congestion array used in test series A was 0.33. The congestion array A_r for test series B and C was 0.3, and test series D used a congestion array with an A_r equal to 0.07.

Six pressure transducers were fielded within the test rig, and twenty-four transducers were fielded external to the rig directly in front of the venting surface. Internal to the rig, two transducers were located at the rear of the enclosure (east/west rear) at a height of 7 feet, two were located on the side walls (east/west wall) at a height of 4 feet, and two were located at grade level on the floor (east/west floor). External to the rig, three parallel transducer lanes were deployed, each containing eight transducers and aligned in the direction of blast wave propagation. High speed (3000 fps) and high definition (30 fps) cameras were deployed to record panel release. The layout of the interior and exterior pressure transducers and location of the video cameras is shown in Fig. 3.

3. Results and discussion

3.1. Internal pressure measurements

Pressure measurements for the six internal pressure transducers were recorded for all tests. Exemplar pressure traces from test series B02 (fully congested/vent panels/100% flammable cloud volume) are provided in Fig. 4. The peak pressures measured by the six internal transducers were used to determine an average internal peak pressure for each test, and subsequently for each test series. The maximum impulse (integration of pressure with respect to time) for each pressure transducer was calculated based on the positive phase of the measured pressure history. The average internal impulse was then determined for each test and series. The average internal peak pressure and impulse for the exemplar test shown in Fig. 4 (B02) was 7.5 psig and 330 psi-ms, respectively, while the average internal peak pressure and impulse for the entire test series B (three tests total) was 7.0 psig and 320 psi-ms, respectively. The resulting average internal peak pressure and impulse are provided in Table 2. Exemplar pressure traces from the west rear gauge location for each test series are provided in Fig. 5, to allow for direct comparison between test series.

3.2. Comparison to NFPA 68

The NFPA 68 correlation for venting deflagrations of gas mixtures was used to predict the internal peak pressure and duration for each test series. The internal peak pressure and duration were

Table 1
Large scale vented deflagration test matrix.

Test Series	Description	Flammable Volume	Congested Volume	Vent Parameters
A	Baseline	100%	100%	6 mil plastic
B	Vent Panels	100%	100%	20 gauge steel panels
C	50% Cloud	50%	100%	20 gauge steel panels
D	25% Congested	100%	25%	6 mil plastic