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Modelling of Explosion Venting Fireballs

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Abstract

The purpose of this study is to compare calculated sizes of explosion venting fireballs to correlations for a range of gas explosions in enclosures fitted with an explosion vent. Explosion vents are commonly used to protect process equipment containing flammable gases. When properly designed, an explosion vent can reduce the peak overpressure inside the enclosure so that the enclosure does not permanently deform or fail catastrophically. The fuel and combustion products that exit the vent, however, create an external fireball hazard. Deflectors can be used to reduce the extent of that external fireball, but their effectiveness has not been rigorously tested for vessels larger than 20 m^3. Recently, there have been questions about the accuracy of correlations to predict fireball dimensions from explosion vents and the effects of deflectors on those dimensions.

The fireball size during venting is crucial in determining the thermal hazard area around the protected enclosure. The National Fire Protection Association standard NFPA 68 and International Standard EN14994 provide correlations for calculating the extent of the expected fireball during explosion venting scenarios. The formulas for gas-explosion fireball-sizes are empirical and based on data from a limited number of experiments.

In this study, explosion-venting scenarios are modelled numerically using FLACS v10. FLACS is a Computational Fluid Dynamics (CFD) software widely used in the oil and gas industry to perform explosion consequence modelling (Gexcon 2015). The CFD model was used to evaluate the fireball extent and temperature. The model results provide the fireball shape and size for different scenarios including scenarios with deflectors. A number of parameters are varied, including:

- Enclosure size
- Type of fuel
- Presence of a deflagration deflector plate

The study elucidates the relative importance of each of these parameters on the explosion fireball size. This can assist in designing future testing programs to examine fireball size and identifying parameters for use in improved fireball size correlations.

Keywords: *venting, fireball, mitigation, industrial explosions, modelling*

1 Introduction

Explosion protection by deflagration venting is a cost-effective and common method to protect equipment and enclosures that contain a flammable gas mixed with an oxidizer (normally air). Without an explosion vent, ignition of hydrocarbon fuel and air mixtures can result in pressures of several atmospheres, potentially causing permanent damage or bursting of the enclosure. Explosion vents are designed to open (or activate) in the case of a deflagration at relatively low pressures. The vent activation pressure, P_{stat}, is designed to be above the operating pressure, but well below the maximum allowable pressure of the vessel or enclosure. If designed properly, the explosion vent area allows sufficient venting of the gases to limit the maximum vented overpressure, P_{red}, below some maximum vessel pressure criteria. The maximum allowable P_{red} will depend on the strength of the enclosure and whether permanent deformation of the enclosure is allowed.

Even when the explosion vent is sized properly, the deflagration still needs to be vented to a safe location to avoid injuries. The maximum temperature of the combusted gases during a hydrocarbon-air deflagration under adiabatic conditions can reach temperatures on the order of 2,500 ˚C (4,500 ˚F). In addition to elevated temperatures, the vented explosion fireballs pose a thermal radiation hazard, due to radiation emitted by high temperature gases and soot.

A deflector plate can be used to reduce the extent of a venting fireball, as outlined in NFPA 68: Standard on Explosion Protection by Deflagration Venting. The use of a deflector reduces the hazard distance calculated under the standard. A deflector is designed as a plate, similar in geometric shape to the explosion vent but larger in scale, placed in front of the vent, at an inclined angle.

In this study, explosion venting scenarios including scenarios utilizing a deflector are modelled numerically using FLACS. A threshold temperature of 1,000 K (727 °C or 1,340 °F) is used to mark the fireball extent. This temperature value is chosen because it is well within the area where soot particles would glow and be visible, signifying the extent of the visible fireball. Other threshold criteria can be used with these simulations to predict the extent of a hazard area. Using a lower threshold temperature extends the calculated fireball length in the simulations. The hazard area may also be larger than the temperature contour boundary identified due to the additional radiative heat transfer from the fireball.

In this paper, the fireball sizes for different gas explosion configurations, including the use of deflector plates, were evaluated using the CFD model and compared to US (NFPA 68) and European (EN 14994) empirical relations. This work is a continuation of the fireball modelling work described in Ibarreta et al. (2018), where combustible dust and flammable gas deflagration fireballs were modelled using FLACS.

2 Empirical Formulas for Fireball Size

The National Fire Protection Association standard NFPA 68 *Standard on Explosion Protection by Deflagration Venting* provides procedures to calculate explosion vent sizing as well as the extent of the expected fireball resulting from the vent activation. The formulas for gas explosion fireball sizes are empirical and based on data from a limited number of experiments (Mesa & Rockwell 2018).

For gas deflagration venting, NFPA 68 provides the maximum axial fireball distance from the vent (*D*) as

$$D = 3.1\left(\frac{V}{n}\right)^{0.402} \tag{1}$$

where *V* is the volume of the enclosure and *n* is the number of evenly distributed vents. NFPA 68 - 6.6.2.3 provides that the use of a deflector as specified in the standard reduces the calculated maximum axial fireball distance by 50% of the value calculated in Equation 2.

A similar formulation can be found in EN 14994 (2007). According to that standard, the fireball length for gas deflagration venting *(D)* can be estimated as

$$D = 5V^{1/3} \tag{2}$$

where *V* is the volume of the enclosure.

The empirical correlations for fireball sizes outlined above only depend on the protected enclosure volume and number of vents. The equations, therefore, do not take into account the vent geometry, mixture reactivity, peak overpressure or vent performance (*i.e.* activation pressure).

3 The Use of Deflectors for Fireball Reduction

Deflectors are obstructions specifically designed to deflect the explosion fireball generated during venting. They are used to protect occupied areas located in front of an explosion vent by reducing the fireball extent in case of deflagration. NFPA 68 - 6.6.2.4 specifies the design of a deflector for use with a given vent geometry as follows:

> *6.6.2.4 A deflector design shall meet all of the following criteria:*
>
> *(1) The deflector for a rectangular vent shall be geometrically similar to the vent and sized with a linear scale factor of at least 1.75. For a round vent, the deflector shall be square shaped and at least 1.75 times the vent diameter.*
>
> *(2) The deflector shall be inclined 45 degrees to 60 degrees from the vent axis, as shown in Figure 6.6.2.4.*
>
> *(3) The centerline of the deflector shall be coincident with the vent axis.*
>
> *(4) The distance from the vent opening to the deflector on the vent axis shall be 1.5D, where D is the equivalent diameter of the vent.*

(5) The deflector plate shall be mounted so as to withstand the force exerted by the vented explosion, calculated as Pred times the deflector area.

(6) The deflector location shall not interfere with the operation of hinged vent closures.

EN 14994 has identical requirements for the dimensions of deflector plates. In accordance with these guidelines, deflectors were modelled in FLACS as square plates, , with the side length of the plate equal to twice the vent side length (1.75 times the vent equivalent diameter, defined as $2\sqrt{A/\pi}$). The plates were placed at a 45 degree angle, with the upper edge of the deflector angled away from the vent opening, and the center point of the plate placed at a distance of 1.5 times the equivalent diameter of the vent (1.7 times the vent side length).

NFPA 68 allows the use of a deflector plate to limit the hazard distance to 50% of the original length for enclosure volumes ≤ 20 m^3. According to NFPA 68 Section A.6.6.2.5, "[t]he ability of this deflector to limit flame length for [larger] vessels is uncertain." EN 14994 also indicates that the use of a deflector plate limits the hazard distance to 50% of the original value. Likewise, EN 14994 also has a similar limitation, stating "[t]he influence of deflectors has only been investigated for enclosure volumes up to 20 m^3 and shall therefore not be installed when the enclosure volume is greater."

4 Computational Fluid Dynamics (CFD) Model

The FLACS CFD software was used in this paper to model the vented deflagration phenomena and evaluate the maximum extent of the vented fireballs. FLACS is a commercial CFD software that is used in the oil and gas industry to model the behavior of explosions and deflagrations of vapors and gases. The software uses a three-dimensional finite element algorithm to simultaneously solve the combustion, radiation, and fluid equations governing dispersed fuel and air combustion. FLACS models take into account complex geometries that influence combustion behavior, as well as the effects of explosion vents. The FLACS model provides the time-dependent pressure field during an explosion event. The CFD model provides a time-dependent solution to the Navier-Stokes equations. In the model, conservation equations for mass, momentum, energy and gas concentrations are solved on a Cartesian grid using a finite volume method.

4.1 Model Geometries

The model geometries (see example in Figure 1) involve cubic enclosures of varying sizes located above a ground plane. A single rectangular vent is located at one side of the enclosure wall at the center of the wall. All the vents are square in shape and centered on the enclosure surface opposite the ignition location. The vents are set to be solid until the activation pressure, P_{stat}, is reached. At that time, the vents instantaneously open fully.

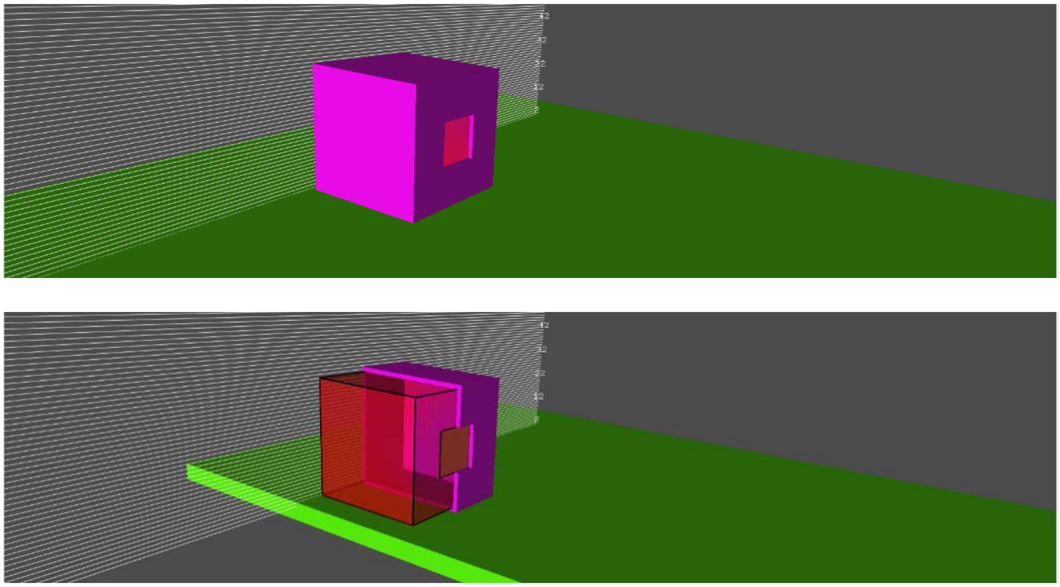

Figure 1. Sample CFD Model geometry without a deflector plate. The top image shows the entire geometry, while the bottom image shows a cut view highlighting the flammable cloud and explosion vent area.

The flammable gas mixture initially uniformly fills the entire volume enclosure, as shown in Figure 1. The ignition of the cloud occurs at time = 0 on the wall opposite to the location of the explosion vent, at the center point on the wall. The flammable gas combustion starts with stagnant conditions (zero velocity and turbulence) inside the enclosure.

In some scenarios, a deflector plate (see Figure 2) was placed in accordance with the description in Section 3.

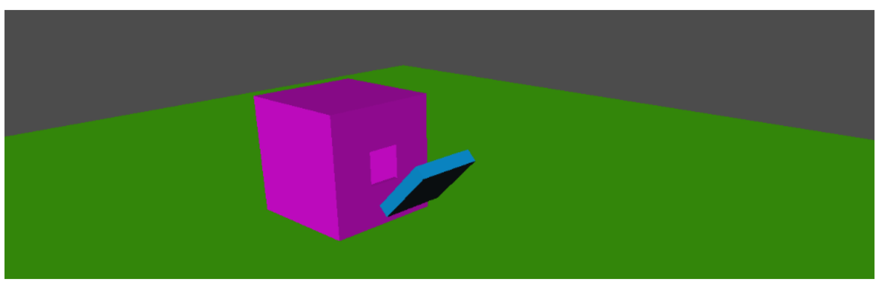

Figure 2. Sample CFD Model geometry with a deflector plate.

4.2 Scenario Conditions

Calculations were performed using methane, propane and ethylene fuels to determine the effect of fuel burning velocity and expansion ratio on fireball extent. The range of scenarios modelled is shown in Table 1. For FLACS calculations, combustion properties are the default values in the software libraries. The NFPA 68 and EN 14994 fireball length correlations do not use fuel specific parameters.

Two basic grid geometries were used, depending on the size of the enclosure and domain: (1) a fine grid with 10 cm minimum grid spacing inside the enclosure and downstream of the vent; and (2) a coarser grid, with 20 cm minimum grid spacing inside the enclosure and downstream of the vent. The calculations have 14 to 50 grid cells across the width of the enclosure, meeting the requirements of the FLACS manual to have at least "5-6 grid cells in smallest direction [of] flame acceleration" for a confined vessel (Gexcon 2015). A coarser grid was necessary for the > 30 m^3 enclosure volumes to keep the total grid size manageable. Similarly-sized volumes were run in both the 10 cm and 20 cm grids. The reduced pressure inside of the vented enclosure (P_{red}) was found to be grid size dependent, but the fireball dimensions were found to be relatively independent of the grid size used in calculations.

Table 1. Scenario matrix

Fuel	Methane	Propane	Ethylene
Concentration	Phi = 1.0	Phi = 1.0	Phi = 1.0
Fuel[1] S_u	38 cm/s	45 cm/s	74 cm/s
Enclosure Volume	4 – 1,000 m^3	4 – 1,000 m^3	4 – 1,000 m^3
Vent Size	0.2 – 16 m^2	0.2 – 16 m^2	0.2 – 16 m^2
Vent Activation Pressure	0.1 barg	0.1 – 0.2 barg	0.1 barg
# of scenarios	7	24	7

5 Flammable Gas Explosion Venting Results

FLACS calculated fireball lengths of propane, methane, and ethylene gas mixtures were compared with empirical formulas provided in NFPA 68 and EN 14994 as discussed in Section 2. Figure 3 shows the evolution of a typical gas explosion venting simulation, in this case, for a 3m x 3m x 3m cubic enclosure containing a stoichiometric mixture of propane and air with a 1-m^2 vent that activates at 0.1 barg. At 0.5 seconds after ignition, the jetting fireball has already reached a distance of 17 meters from the vent opening. At 1 second, the fireball has reached 23 meters from the vent opening. At 4.5 seconds, the fireball is nearing its maximum extent of 31.8 meters. Gas explosion fireballs for other sizes of enclosure and other fuel mixtures follow a similar development pattern. The results show how the fireball length is much greater than the height or width of the fireball, in contrast to the correlation in NFPA 68 that assumes all three dimensions are the same.

Figure 4 shows the same case as Figure 3 but with a deflector plate placed directly in front of the vent opening as described as Section 3. At 0.5 seconds after ignition, the jetting fireball has reached a distance of 10 meters from the vent opening, 40% shorter than the case without a deflector. At 1 second, the fireball has reached a distance of 11.5 meters from the vent opening, 50% shorter than

[1] Default values in FLACS library

the case without a deflector. At 2.25 seconds, the fireball has reached its maximum extent of 12.9 meters, 60% shorter than the case without the deflector.

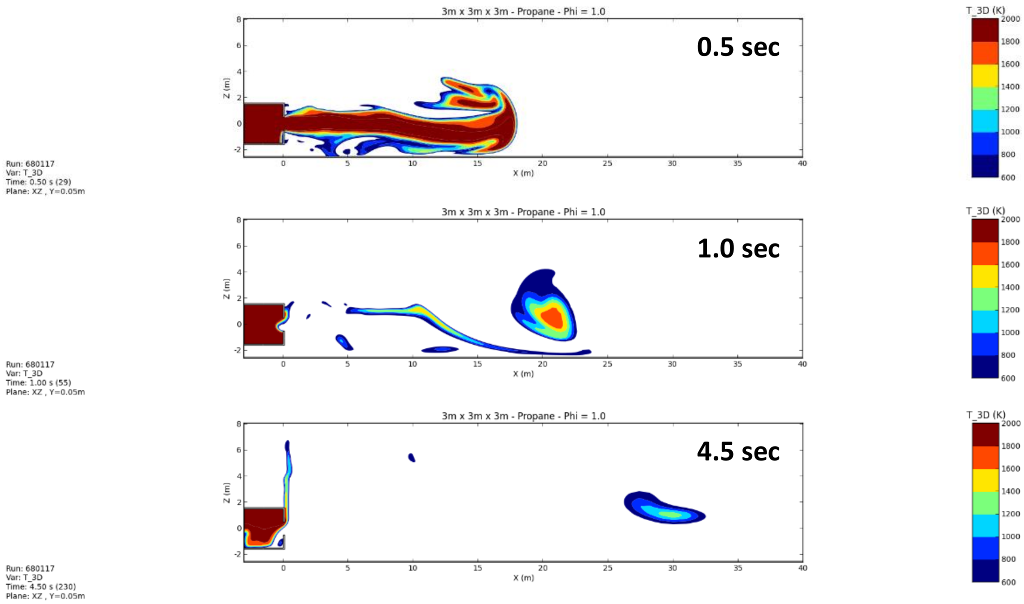

Figure 3. Time sequence of fireball temperature contours showing FLACS simulation of a propane/air (Phi = 1) vented explosion for a 3m x 3m x 3m enclosure with a 1 m^2 vent that activates at 0.1 barg. The maximum overpressure (P_{red}) for this scenario is 0.33 barg; and the maximum fireball extent is calculated to be 31.8 meters, based on the 1,000 K contour.

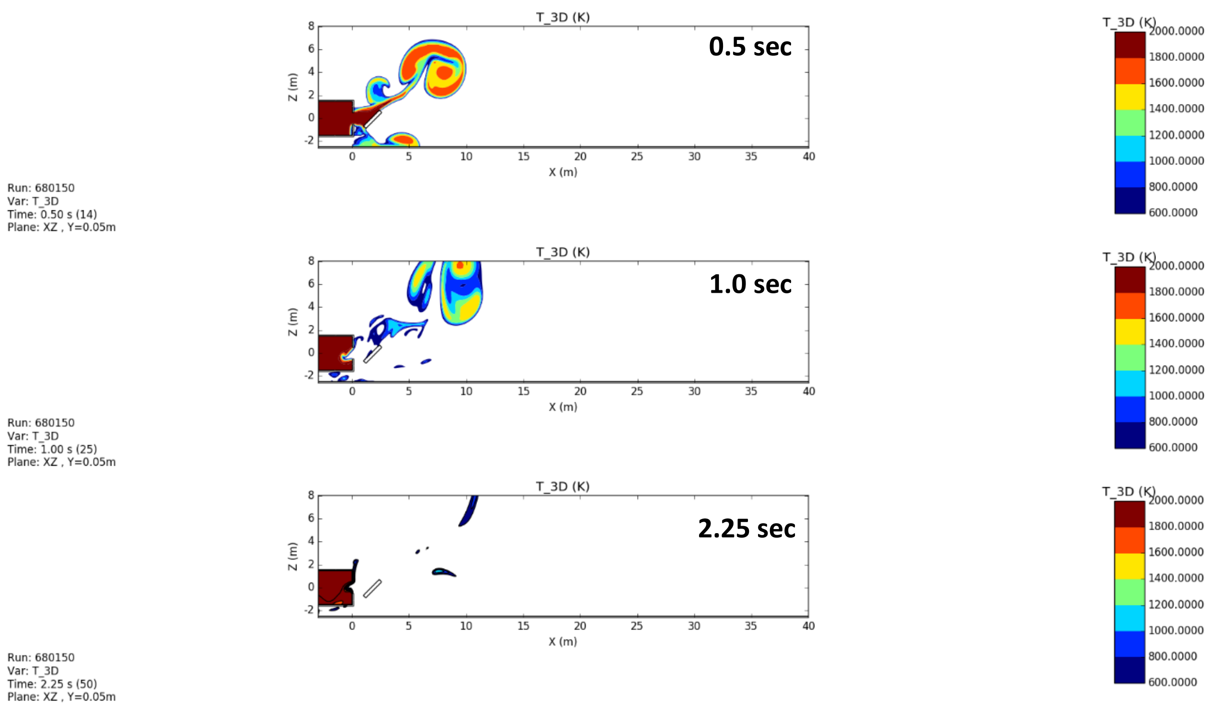

Figure 4. Time sequence of fireball temperature contours showing FLACS simulation of a propane/air (Phi = 1) vented explosion for a 3m x 3m x 3m enclosure with a 1 m^2 vent that

activates at 0.1 barg with a 45degree deflector that has the center surface located 1.7 m away from the vent opening

To calculate the fireball extent, output data from FLACS simulations were analyzed to determine the furthest distance from the vent opening that reached the threshold temperature, taken as 1,000 K (727 °C or 1,340 °F).Figure 5 shows the calculated fireball lengths for stoichiometric mixtures of propane, methane, and ethylene in air as a function of enclosure volume. The calculated fireball lengths are compared to the fireball extent correlations from NFPA 68 and EN 14994, as discussed in Section 2. The fireball lengths calculated from the FLACS simulations are significantly larger than both correlations. The fireball length for methane deflagrations is smaller than that of propane for a given enclosure volume, while the fireball length for ethylene is similar to that of propane for lower enclosure volumes but longer at some larger enclosure volumes.

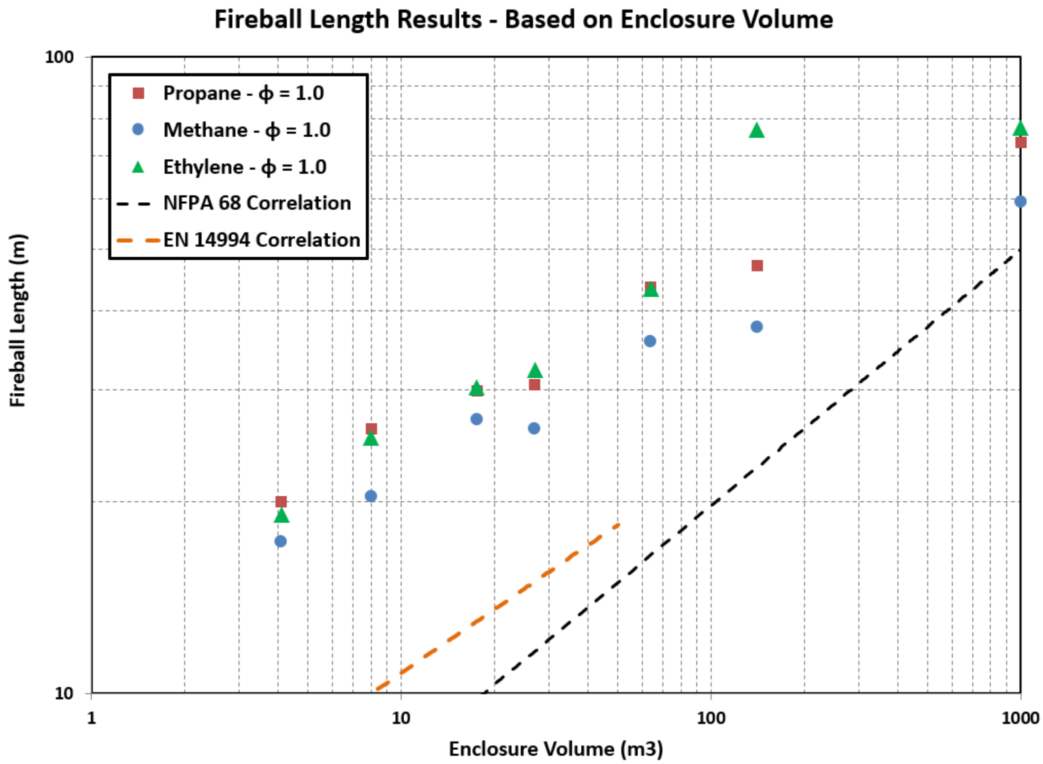

Figure 5: FLACS calculated fireball length for propane/air, methane/air, and ethylene/air mixtures at an equivalence ratio of 1 compared to the NFPA 68 and EN 14994 predicted values.

Both the maximum overpressure or expansion ratio and flame speed of the fuels increases from methane to propane to ethylene. It is likely that the differences in fireball dimensions are due to differences in the expansion ratios of the fuel, however, further analysis is required to separate the effect of expansion ratio and flame speed.

The effect of a deflector plate as a function of enclosure is shown in Figure 6. The fireball length of the FLACS simulations with and without the deflector plate are plotted against the given enclosure volume. The data show how the presence of a deflector plate has a very large impact on the fireball length, especially for smaller enclosures. The reduction in flame length is diminished for larger enclosures but is still sizeable. Correlations of fireball length with enclosure volume by EN 14993 and NFPA 68 with and without deflectors are also shown. What is not clear in Figure 6 is that the deflector plate not only reduces the downstream extent of the fireball, but also angles it upward, so that the longest flame extent occurs at an elevated location, further protecting potentially occupied areas near ground level. The fact that the FLACS calculations with a deflector plate agree with the NFPA 68 correlation for fireballs without a deflector plate is merely coincidental. The deflector plate shortened the fireball extent by at least 50% in all cases except for the case with a 1000 m^3 enclosure volume which had a fireball extent that was shortened by 30%. Cases where the enclosure volume was less than 20 m^3, the flame extent was shortened by at least 60%. The presence of an inclined deflector plate is therefore shown to decrease the length of the fireball by a factor of 1.5 to 3.6, with larger decreases for smaller enclosures.

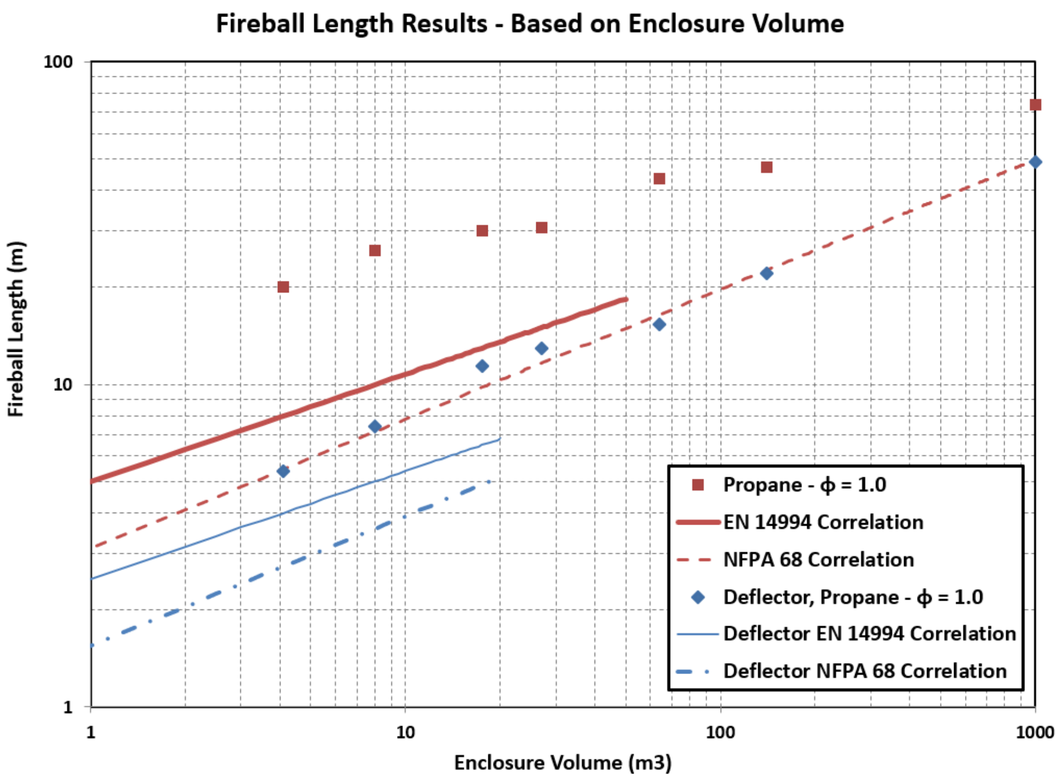

Figure 6. FLACS calculated fireball length for propane/air mixtures with and without a deflector plate as a function of enclosure volume compared to the NFPA 68 and EN 14994 predicted values.

6 Conclusions

This paper describes the results of CFD simulations of gas deflagration events in vented enclosures. The models were used to estimate the fireball extent, as well as the reduced enclosure overpressure resulting from the deflagration events. The paper presents a comparison between the numerical results and the empirical correlations in internationally recognized standards on deflagration venting, such as NFPA 68 and BS EN 14994.

Relatively-poor agreement was obtained between gas deflagration venting simulation fireball length data and the empirical correlations presented in the standards. In particular, the fireball size calculated using the FLACS CFD model is up to 2 to 3 times larger than the estimates obtained using the standard correlations. The simulations also show that the length of the fireball is much longer than the width or height of the fireball, whereas NFPA 68 assumes that all three dimensions are identical. Furthermore, a dependency of the fireball size on flammable gas species has been identified with propane and ethylene leading to larger fireballs.

The presence of an inclined deflector plate is shown to decrease the length of the fireball by a factor of 1.5 to 3.6, with larger decreases for smaller enclosures. The presence of a deflector plate not only reduces the downstream extent, but can also deflect the flame upward, further protecting locations near ground level.

Further analysis is required to determine the relative role of the expansion ratio and flame speed on the fireball dimensions. Intermediate and large-scale testing is recommended to better understand and characterize fireball sizes involving gas deflagration venting.

7 References

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