Suppression of a Propane-Air Explosion Using a Powdered Suppressant

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1 Introduction

The use of an explosion-suppression system as a means for explosion protection has become fairly popular in industrial settings, particularly when alternative protection methods such as explosion venting cannot be easily applied. In general, an explosion-suppression system consists of a detector (such as a pressure transducer or an infrared sensor) that detects an accidental explosion at the incipient stage of flame growth and then triggers a high-pressure discharge of suppressant in order to quench the expanding flame ball and inert the remaining explosive mixture. Depending on different factors such as the time of suppressant injection, the amount of suppressant injected, and the distribution of suppressant concentration in the protected enclosure, an explosion-suppression system can potentially reduce damaging overpressures to values within the strength of the protected enclosure.

Experiments and numerical simulations have been conducted at different scales in order to understand the interaction of various suppressants with gas or dust explosions and to evaluate the effectiveness of different suppression systems (e.g., see [1-5]). However, there is still no practical methodology that can be used to evaluate the performance of an explosion suppression system. In particular, it remains unclear how experimental results should be scaled to real applications of explosion suppression systems. In general, the average concentration (mass of suppressant per vessel volume, V) that results in an acceptable reduced overpressure in an experiment should be sufficient at larger scales in a real application. However, this may result in an exorbitant amount of suppressant at large scales, and scaling by $V^{2/3}$ (such that the amount of suppressant is related to the surface area of the flame) is oftentimes preferred.

In the present study, a parametric-experimental study is conducted in an attempt to understand the physical mechanisms that control explosion suppression such that the efficacy of an overall system can be evaluated. A series of suppression experiments using propane-air was performed at two different scales using sodium bicarbonate as an example suppressant. The effects of vessel volume, system-activation pressure, suppressant-injection location, number of injection locations, and suppressant concentration on the reduced overpressure were investigated. In order to synthesize the experimental data that was obtained, a simple model will be developed to describe the suppression of a spherically-expanding premixed flame.

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2 Experimental Details

Suppression experiments were conducted in FM Global's 2.5 and 25 m^3 steel explosion vessels. The smaller vessel is 1.4 m in diameter and 2.0 m in height while the larger vessel is 2.9 m in diameter and 4.2 m in height. The explosion-suppression system that was used consisted of a piezoelectric pressure transducer for detection, a programmable microcontroller, and commercially-available high-rate discharge (HRD) suppressant injectors in four different sizes (2.5, 5, 10 and 50 L). Dispersion nozzles with twelve equidistantly-spaced holes were fabricated for each HRD; the holes were 38.1 mm in diameter for the 50 L HRD and 25.4 mm in diameter for all other HRDs. The HRDs that were required for a given experiment were first filled with a specified amount of sodium bicarbonate (SBC), pressurized with nitrogen to 60 bar, and then mounted onto the vessels at the desired locations (see Figs. 1 and 2 for a sketch of the experimental apparatus).

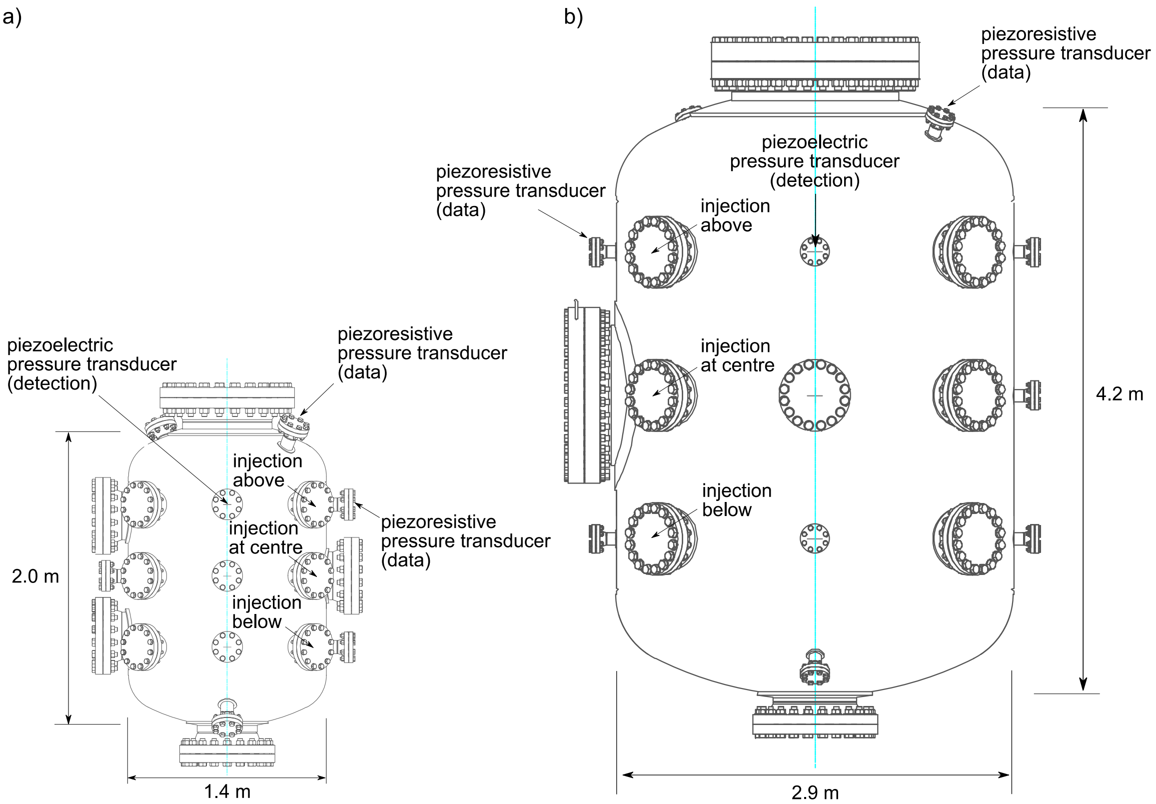

Figure 1. Schematic of FM Global's a) 2.5 m^3 and b) 25 m^3 explosion vessels with pressure-transducer and suppressant-injection locations.

For any given test, the vessel was first evacuated to a near vacuum. A stoichiometric mixture was then prepared in the vessel by the method of partial pressures and recirculated through a pump for at least 15 minutes to ensure a homogenous composition. In some cases, a Cirrus mass spectrometer (PRO100D) was used to verify the mixture composition. The initial pressure of all experiments was 1 atm. Ignition was achieved in the center of the vessel via a weak spark.

In all experiments, a Kistler piezoelectric pressure transducer (211B) was used to detect the incipient explosion (see Fig. 1 for this transducer location). A programmable microcontroller then triggered the HRDs once the activation pressure was achieved in the vessel. Two different nominal activation pressures were used (i.e., Δp_a = 0.1 and 0.2 bar).

The overall pressure development inside the vessel was monitored by two Stellar Technology piezoresistive pressure transducers (GT1600) with a frequency response of 3 kHz. All data were recorded using a high-speed 32-channel data acquisition system with a sampling rate of 25 kHz.

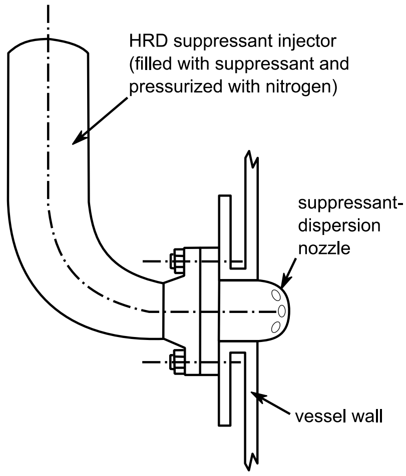

Figure 2. Sketch of an HRD suppressant injector fitted with a dispersion nozzle.

3 Results and Discussion

Examples of typical overpressure histories of propane-air explosions using 2400 and 3600 g/m^3 SBC are shown in Fig. 3. In both of these cases, ignition occurs at $t = 0$ and the subsequent pressure rise in the vessel (before suppressant is injected) is fairly reproducible.

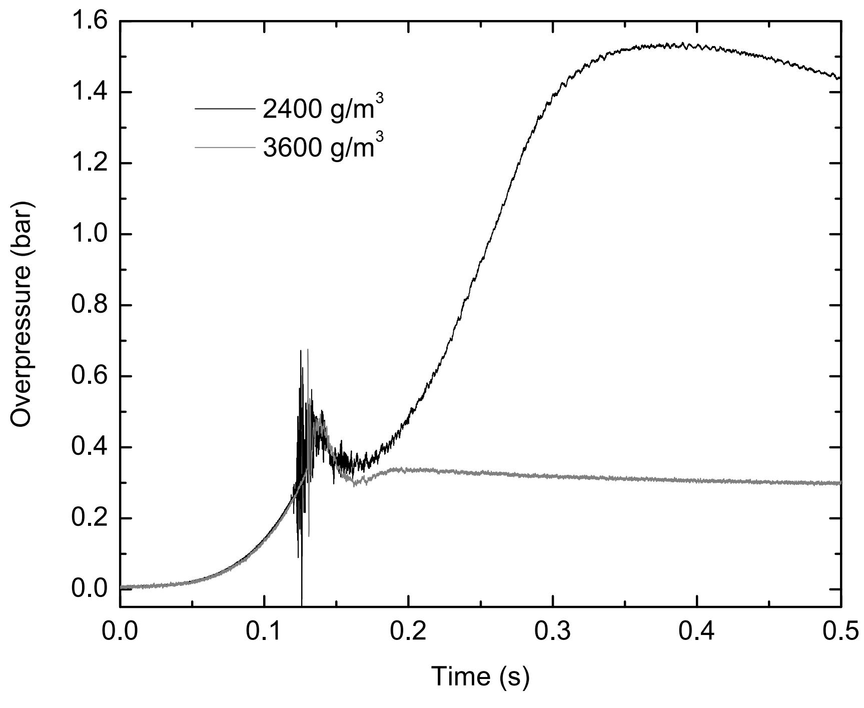

Figure 3. Overpressure histories of stoichiometric propane-air injected with different SBC concentrations (V_{vessel} = 2.5 m^3; Δp_a = 0.2 bar; injection above ignition).

At the detection pressure of Δp_a = 0.2 bar, the suppression system was triggered and SBC was injected into the vessel following a short time delay, which is manifested as a sudden onset of noise in the pressure histories. For the case where 2400 g/m^3 of SBC was used, the growth of the flame ball appears to be momentarily inhibited following suppressant injection at Δp_{inj} = 0.28 bar; however, after a short duration, the overpressure inside the vessel begins to increase again until $\Delta p_{red} \approx$ 1.53 bar.

For the case where 3600 g/m^3 of SBC was used, the suppressant was injected at a slightly later time (and thus at a slightly higher overpressure of Δp_{inj} = 0.34 bar). Subsequent to suppressant injection, the flame appears to be completely quenched, and a reduced overpressure of $\Delta p_{red} \approx$ 0.34 bar is observed. It should be noted, however, that the maximum overpressure that is achieved in this case ($\Delta p_{max} \approx$ 0.47) is greater than the final reduced overpressure and is associated with the high-pressure injection of the suppressant. This is observed in many cases and should be considered as a performance limit of an explosion suppression system.

The maximum reduced overpressures as a function of SBC concentration for the tests conducted in the 2.5 and 25 m^3 vessels are shown in Fig. 4. In general, it can be seen that a small amount of SBC (500 g/m^3 or less) is sufficient to reduce the overpressure from its maximum unsuppressed value (8.5 bar) by about 1 bar (in both vessels). As the SBC concentration increases, the resulting reduced overpressure decreases. It is also found that reduced overpressures are lower when detection of the incipient explosion occurs sooner (i.e., the system is triggered at a lower Δp_a). It should be noted, however, that the actual pressure at which SBC is injected into the vessel (Δp_{inj}) is greater than the detection pressure (Δp_a) and varies from test to test. The actual value of Δp_{inj} can have an effect on the reduced overpressure, which can not be discerned from Fig. 4. As well, for a single injection location, lower reduced pressures are found when the SBC is directly injected into the growing flame ball (as compared to when the SBC is injected above the ignition location). However, it appears that a similar effect can be achieved by distributing the same amount of SBC over multiple injection locations (without direct injection onto the growing flame ball).

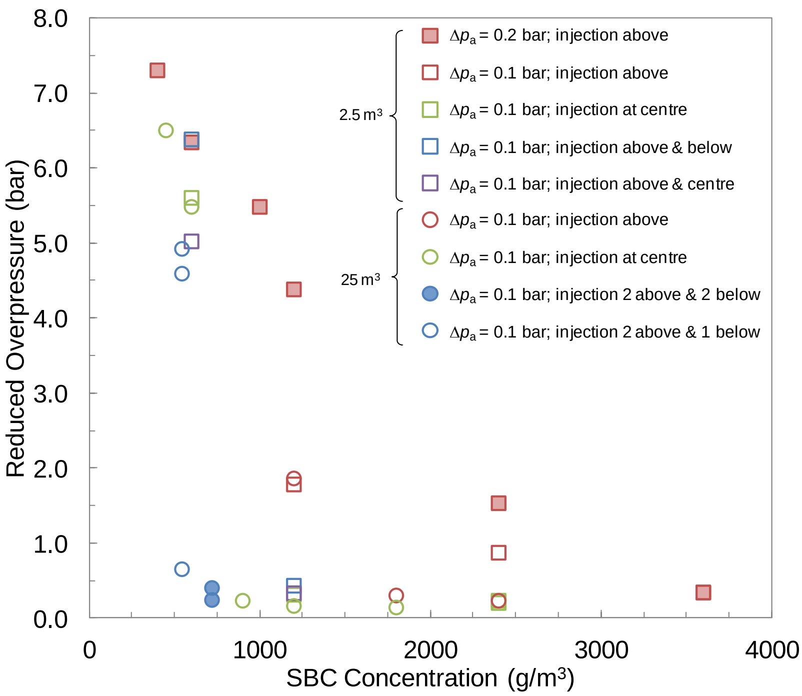

Figure 4. Reduced overpressures as a function of SBC concentration for stoichiometric propane-air in the 2.5 and 25 m^3 vessels.

It can be seen in Fig. 4 that scaling by volume is appropriate for some cases; i.e., Δp_a = 0.1 bar with injection at the center (green symbols) or with injection above and below the ignition location (blue symbols). However, for the case where suppressant injection occurred above the ignition location and

Δp_a = 0.1 bar (red symbols), it appears that volume scaling is overly conservative as less suppressant is required in the 25 m^3 vessel compared to the 2.5 m^3 vessel (in order to achieve comparable reduced overpressures).

When the same results are shown as a function of the SBC mass normalized by the 2/3 power of the vessel volume (see Fig. 5), it can be argued that surface-area scaling may be appropriate for the experimental conditions denoted by the red symbols. This is perhaps not a surprising result as the rate of pressure rise (*dp*/*dt*) is generally slower in a larger vessel. However, the present results indicate that there is no consistency between which scaling methodology is universally applicable. Other factors such as the actual injection pressure and *dp*/*dt* at the time of suppressant injection should be taken into consideration.

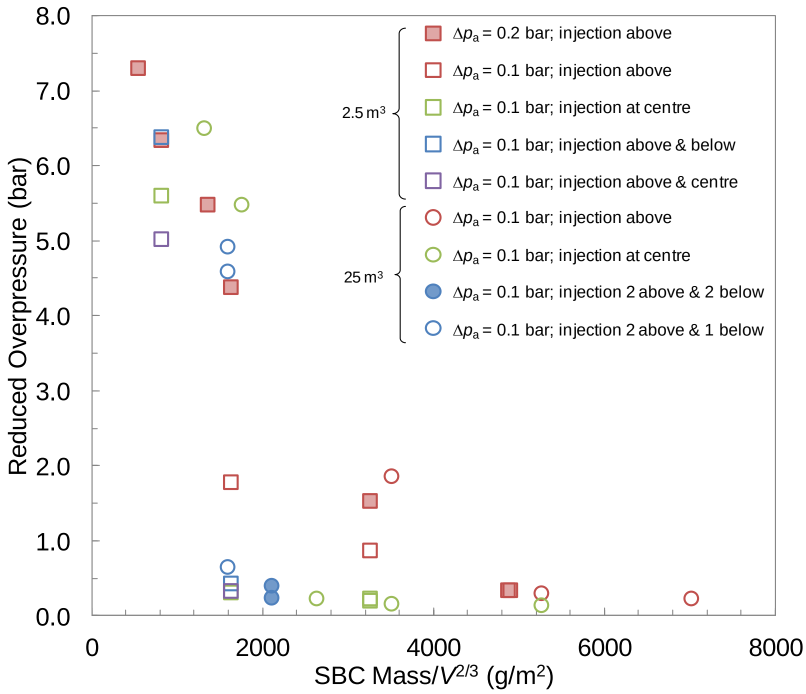

Figure 5. Reduced overpressures as a function of SBC mass normalized with $V^{2/3}$ for stoichiometric propane-air in the 2.5 and 25 m^3 vessel.

4 Concluding Remarks and Further Steps

In general, it was found that lower system-activation pressures resulted in lower reduced overpressures. As well, multiple injection locations were more effective in reducing the overpressure compared to a single injection location (for the same total amount of suppressant); however, direct suppressant injection from a single location onto the growing flame ball was shown to be just as effective. From the experimental results, there was no clear indication how the results should be scaled to full-volume systems.

In order to help synthesize the experimental data that was obtained, a simple model will be developed to describe the suppression of a spherically-expanding premixed flame. In this model, the pressure inside a vessel increases due to a spherically-expanding flame. As suppressant (approximated as a hemispherical cloud that grows with time) interacts with the flame, the pressure rise decreases as the flame surface area becomes quenched. (See Fig. 6 for a sketch of the model.)

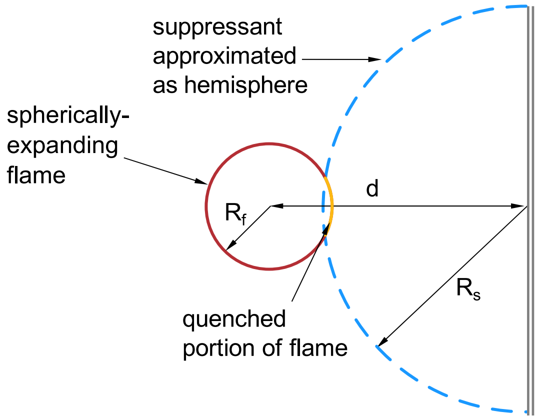

Figure 6. Sketch of a simple model describing the suppression of a spherically-expanding flame via the interaction with a hemispherical suppressant cloud.

From the conservation of mass, assuming isentropic compression, the following expression can be used to characterize the pressure development in the vessel due to flame propagation and suppressant injection:

$$\frac{V_0}{\rho p_0}\left(\frac{p}{p_0}\right)^{\frac{1-\gamma}{\gamma}}\frac{dp}{dt} = (\sigma - 1)A_{\mathrm{f}}S_{\mathrm{u}} + \frac{1}{\rho_{\mathrm{s},0}}\frac{dm_{\mathrm{s}}}{dt}$$

where the subscript “0” denotes initial conditions in the protected enclosure and V, p, and ρ are volume, pressure, and density, respectively. Because the injected suppressant is approximated as a hemisphere, the flame surface area, A_{f}, is given by $4\pi R_{\mathrm{f}}^2$ - A_{cap} where A_{cap} is the surface area of the spherical cap resulting from the intersection of a hemispherical suppressant cloud with a spherical flame; this represents the portion of the flame quenched by the suppressant. The mass flow rate of the suppressant injected into the protected volume is dm_{s}/dt and can be determined from isentropic choked flow from a finite volume where stagnation conditions do not remain constant.

References

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