The Development and Mitigation of Backdrafts: a Full-scale Experimental Study

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ABSTRACT

An experimental study of the development and mitigation of backdrafts shows that the key parameter for backdraft development is the fuel mass fraction. The results reveal that the critical fuel mass fraction, Y_f, required for the development of diesel fuel backdrafts is 0.16 for fully vitiated conditions. Analysis of the data in conjunction with results in the literature has also demonstrated that standard flammability diagrams can be used to predict bounding limits and trends on Y_f with respect to other key variables, such as oxygen concentration.

The injection of water spray was shown to be an effective mitigating tactic that was able to completely suppress backdrafts. The analysis reveals that backdraft suppression occurred primarily by means of diluting the atmosphere and reducing the fuel mass fraction, consistent with the critical Y_f criterion, rather than by a thermal mechanism of cooling.

KEY WORDS: Backdraft, Explosion, Compartment Fire, Water Spray, Fuel Mass Fraction

INTRODUCTION

The occurrence of backdraft explosions continues to be a hazard that threatens the safety of firefighters [1]. A backdraft can develop from fires of either ordinary combustibles or ignitable liquids that become oxygen starved yet continue to generate a fuel-rich environment. If air is allowed to flow into the vitiated space, such as by opening a door, a gravity current of colder air will flow into the compartment while the hot fuel-rich gases flow out the top of the door. The air and fuel-rich gases will mix along the interface of the two flow streams. If a localized flammable mixture is formed, a deflagration can result once the mixture comes in contact with an ignition source. The deflagration will cause the gases to heat and expand within the fire space, thus forcing unburned gases out of the open vent ahead of the flame front. These gases will mix with additional air outside of the fire space. As the flame traverses the compartment and penetrates the doorway, it ignites the gases outside the space resulting in a fire ball and a blast wave. This explosion phenomenon from the gravity current to the blast wave is termed a backdraft.

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This study was part of a larger program aimed at improving Naval firefighting tactics. The general approach was to develop safe, reproducible backdraft scenarios which could be used as a basis to quantitatively study the development and mitigation of backdraft explosions involving combustible fuels onboard Naval ships. This paper discusses the initial series of tests conducted outside in a single compartment that vented directly to the atmosphere. Additional studies of full-scale tests conducted onboard a U.S. Navy research ship are presented in References [2] and [3].

EXPERIMENTAL SETUP AND PROCEDURE

Figure 1 shows the test compartment and layout of instrumentation. The test compartment was a steel structure measuring 2.44 m wide by 4.88 m deep by 2.44 m high (8 ft wide by 16 ft deep by 8 ft high) with a volume of 29 m^3 (1024 ft^3). The only ventilation to the space was through a door on the west end of the compartment. The door was 0.66 m wide by 1.68 m tall (26 in. by 66 in.) and was positioned toward the left side of the west wall. A gasket of ceramic fiber blanket was used to seal the door. As a result, the space was not air tight.
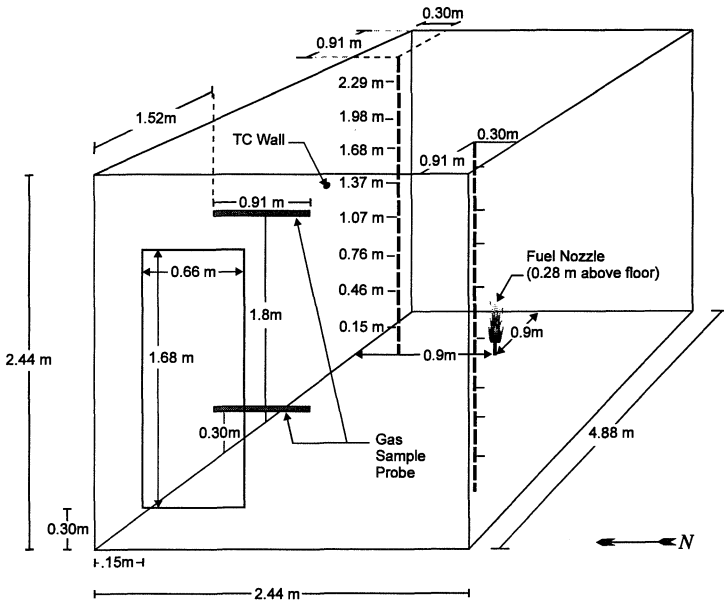

FIGURE 1. Schematic of the steel test compartment with instrumentation

The compartment was instrumented with two thermocouple trees, a bulkhead thermocouple, a pressure transducer, and two gas sampling lines for oxygen concentration measurements. Other data collection consisted of still and video photography. A more detailed description of the experiments can be found in Reference [2].

In general, tests consisted of establishing a hot, vitiated environment inside the compartment by burning a No. 2 diesel spray fire. Once steady-state conditions were achieved, the fuel was shut off, and the door was closed. After a 60 second delay, a known amount of No. 2 diesel fuel was

then injected into the compartment and allowed to vaporize and mix with the combustion gases (typically a 60 second injection). After the secondary fuel was shut off, there was a 120 second delay before the door was remotely opened to induce the backdraft. For the tests aimed at studying backdraft mitigation, water was sprayed into the center of the compartment between the time the secondary fuel was secured and the door was opened. Typically, water was sprayed using a 120 degree, full cone nozzle (Bete TF10FC) for a 60 second period starting 30 seconds after the secondary fuel was shut off.

The fuel was supplied via a 90 degree full cone, fine atomization fuel nozzle (Bete P-series) positioned in the back of the compartment, 0.9 m from the north and east walls, 0.3 m above the floor. The same nozzle and fuel supply system were used for both the pre-burn fire and the secondary fuel injection. Similar to the water flow system, the fuel mass supply rate was calculated based on the pressure at the nozzle and the nozzle flow coefficient. The uncertainty in this measurement was estimated to be 5 percent based on a flow test of the system. The fuel and water nozzles were selected to provide accurate flow control, efficient burning, and fine atomization to assure all secondary fuel and water were vaporized and well mixed in the space.

The initial fire was designed to be a nominally stoichiometric fire so that there was minimal excess air or fuel in the compartment at the time the door was closed. Using the ventilation parameter, $Ah^{1/2}$, to determine the air flow rate into the compartment and a stoichiometric fuel-to-air ratio of 0.068 (assuming the fuel to be $C_{10}H_{19}$), the design fire was calculated to be 2.1 MW (3.6 Lpm (0.96 gpm)).

RESULTS

The test results are presented in terms of the nominal fuel mass fraction, Y_f, which is defined as the ratio of the mass of fuel injected into the fire compartment to the total mass in the compartment. Y_f can be expressed as

$$Y_f \ = \ \frac{m_{fuel}}{m_{mix}} \tag{1a}$$

where

$$m_{mix} \ = \ V_{comp}\,\rho(\,T_{gas}\,) \tag{1b}$$

The mass of the mixture equals the product of the compartment volume and the density of the mixture at the gas temperature in the compartment. The mixture density was calculated with the assumption that the initial gases in the space consist solely of the products of stoichiometric combustion. In the case when water was injected into the compartment, the calculation assumes that any leakage from the compartment occurs as a uniform mixture of steam, fuel, and combustion products.

The test data presented in this paper were averaged over a 10-second interval just prior to the door being opened to induce the backdraft. This period represents the conditions from which the backdraft phenomenon developed.

Series 1

The initial series of 55 scoping tests was aimed at developing a safe, reproducible backdraft test scenario. The tests were conducted at nominal fuel mass fractions ranging from 0.05 to 0.23, with most tests conducted at 0.18. In general, the series was successful in demonstrating that a safe backdraft test was possible. However, backdrafts that resulted in a fire ball (a spherical volume of flame propagating outside and away from the door) were not consistently obtained. Distinct fire balls occurred only about 50 percent of the time for similar test scenarios under repeat conditions.

In some cases, there was a deflagration in the compartment (noted by a peak rise in temperature and pressure) without a fire ball outside of the compartment. These tests were characterized by either the ejection of a large ball of smoke (2 to 5 m in diameter) or a roll out of flame under the soffit. The formation of a smoke ball was very similar to a backdraft explosion (except without flame outside the compartment) in that there was an audibly and visually distinct pressure pulse which thrust the gases out of the compartment to form the ball of smoke. In tests resulting in a backdraft explosion, sometimes the fire ball was preceded by a ball of smoke and/or an extension of flame out the door. Additionally, these tests demonstrated that the hot steel surfaces of the compartment were sufficient to initiate the backdraft explosion. No external ignition sources were used.

Part of the problem of reproducibility may have been the effect of relatively high winds. It was observed that winds of 8-16 km/hr (5-10 mph) had a strong mitigating effect on the formation of a backdraft. For tests with fuel mass fractions of 0.17 or higher and high wind conditions, no backdrafts with fire balls occurred. On the other hand, similar tests conducted under wind conditions of less than 6 km/hr (3.7 mph) produced fire balls 60 percent of the time. The winds blew from the west/northwest straight at the compartment door. Visually, this appeared to retard the flow of hot gases out of the compartment and create a more turbulent bi-directional flow pattern at the door opening.

Series 2

The second series of tests focused on extending the Series 1 work to develop a well-defined, reproducible backdraft test from which the governing parameters could be studied. In addition, the effectiveness of water spray injection as a mitigating tactic was studied. Figure 2 shows a bar graph of the nominal fuel mass fraction for each test along with notes designating pertinent differences between tests. The solid bars indicate tests which resulted in a backdraft with a fire ball, cross hatched bars indicate the formation of a smoke ball only, and clear bars indicate that nothing happened (except, in a few cases, the role out of flame under the soffit). Nominal fuel mass fractions ranged from 0.13 to 0.29. The majority of tests were conducted with nominal fuel mass fractions of about 0.25 (i.e., 4.9 kg (6.1 L) of secondary fuel).

As can be seen in Figure 2 (tests BD74 to BD115), a reproducible test scenario that resulted in a strong backdraft explosion was developed. This was achieved after it was discovered that a build-up of soot on the walls of the compartment had a dramatic effect on creating a backdraft explosion. Prior to test BD74, less than 60 percent of the tests resulted in well-defined explosions with fire balls outside of the compartment. This occurred despite fuel mass fractions as high as 0.29. Prior to test BD74, the compartment walls were covered with soot, up to 1.9 cm (0.75 in.) thick.

It is believed that the soot (carbon) layer on the interior surfaces insulated the walls sufficiently such that it decreased the ignition capability of the metal surfaces. A possible, secondary effect was that the soot layer absorbed some of the fuel injected into the compartment. Therefore, there was a reduction in the amount of vaporized fuel in the space such that the fuel mass fraction was actually lower than calculated.
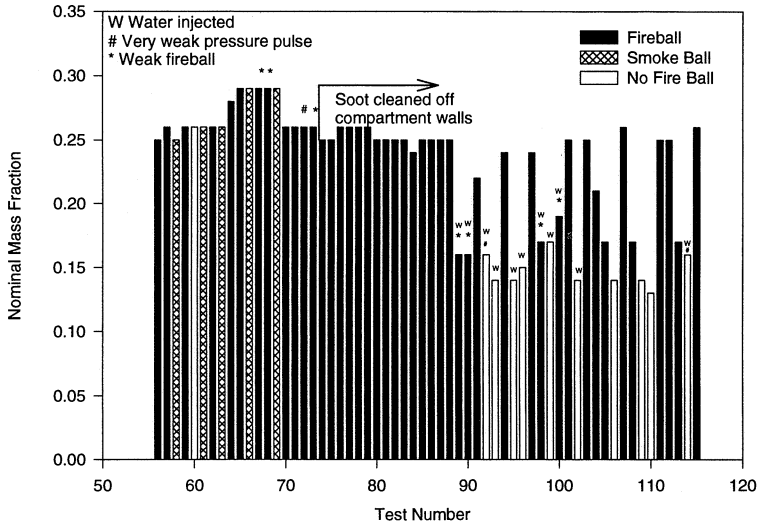
FIGURE 2. Bar graph of nominal fuel mass fractions and resulting outcomes for Series 2 tests

By cleaning the soot from the test compartment walls every 10 tests, the effect of the soot was minimized (soot layers were maintained under 2 mm thick). As a result, the same test conditions resulted in reproducible backdraft explosions with strong, distinct fire balls for all 22 tests. The effect of the soot build-up appeared to be a larger factor than the wind conditions of Series 1; however, this can not be fully substantiated as the same high wind conditions did not occur during Series 2. Weather conditions for Series 2 were very still with wind speeds typically less than 4.8 km/hr (3 mph).

Figure 2 also shows the effect of water injection into the fire space using the same backdraft test scenario used in Tests 74-88. The fuel mass fractions are decreased due to the water vapor in the space. If water was not injected, the fuel mass fraction would be the same (0.25) as in tests without water. Depending on the amount of water used, the tests with water injection resulted in either the elimination of the explosion (i.e., the fire ball) or in backdraft explosions of reduced intensity. This subject is addressed in more detail in the Discussion section.

At the time the door was opened, average compartment temperatures were typically 340 to 400° C, steel surface temperatures were 390 to 420° C and average oxygen concentrations were 0.5 to 1.5 percent (i.e., average of both sample locations). These temperatures are within 20° C of those at the time of the backdraft explosion. Similar to the Series 1 tests, there was usually a 15 to 20 second delay between the time the door was opened and the sudden formation of a fire ball outside of the doorway. Reference [2] includes detailed results and time histories of all tests. The largest fire balls observed were about 7 m (23 ft) in diameter and extended over 9 m (30 ft) from the compartment. The maximum measured over-pressure for tests in which a backdraft explosion occurred ranged from 100 to over 280 Pa. In most instances, dense smoke obscured any view of the deflagration until it suddenly penetrated the door way. However, in some tests, the deflagration could be seen originating in the upper back (south-east) corner of the compartment and traveling as a flame across the overhead of the compartment. Contradictorily, for a few tests, the flame/fire ball appeared to originate low in the doorway.

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DISCUSSION

The results of these tests show that there is a very well defined correlation between the nominal fuel mass fraction and the occurrence of No. 2 diesel backdraft explosions. Simply stated, fuel mass fractions of 0.16 or higher are needed for the creation of a diesel backdraft explosion in highly vitiated environments. Figure 3 shows the frequency with which backdraft explosions occurred as a function of the nominal fuel mass fraction, Y_f, in the fire space. This figure includes results from 42 tests from Series 2 (Tests BD73-BD115). Tests BD1-BD73 have not been included since the problems of wind and soot build-up introduce secondary variables that artificially skew the results. For the tests with water injection, Y_f represents the mass fraction after the water was injected. As can be seen in Figure 3, no backdraft explosions occurred for tests with fuel mass fractions of 0.15 or less. Fuel mass fractions between 0.15 and 0.18 represent a transition region from fuel loading conditions unable to create an explosion to fuel loadings that do. All tests with fuel mass fractions of greater than 0.17 resulted in an explosion with a fire ball. The tests that did not result in fire balls had average gas temperatures equal to or greater than the tests that did and similar oxygen concentrations. Therefore, these results indicate that the fuel mass fraction was the determining factor for creating an explosion, and a value of 0.16 can be considered as the critical Y_f needed to potentially create a backdraft.

The concept of a critical fuel mass fraction can be illustrated using a flammability diagram as shown in Figure 4. To the authors' knowledge, a specific diagram for diesel fuel or similar molecular weight hydrocarbons does not exist. Therefore, for illustration a diagram for hexane fuel (C_6H_{14}) mixed with oxygen and nitrogen is used. This flammability diagram is presented in units of percent mass concentration and has been developed from data in Reference 4.

As can be seen in Figure 4, all mixtures within the designated envelope are flammable (explosive). The dashed line originating from point A is a line of constant proportionality between oxygen and nitrogen corresponding to air. Any mixture of hexane and air will fall along this line.
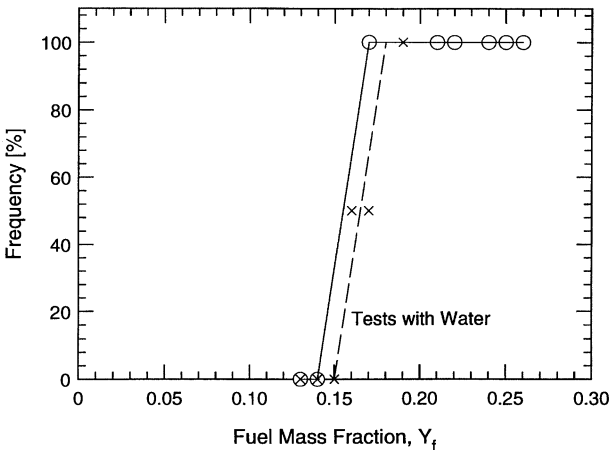

FIGURE 3. Frequency of occurrence of backdraft explosions with fire balls with respect to the nominal fuel mass fraction (X indicates tests with water addition)

Consider a fire compartment that has been depleted of oxygen, and thus, the fire has extinguished. The vitiated compartment is now fuel rich. The flammability diagram will be used to illustrate the two primary conditions that can be created in the fire space depending on the amount of unburned fuel that is volatilized in the space. For this illustration, the combustion products are represented by nitrogen. Point B designates a mixture of 5 percent fuel, 95 percent nitrogen, and no oxygen. Line B-A shows the varying mixture compositions that will be created if a door to the space is opened allowing fresh air to flow into the compartment and mix with the composition designated by point B. Since this line does not intersect the flammability envelope, a flammable mixture will never be created, and thus, an explosion cannot occur.

Point C represents an initial mixture of about 11 percent fuel and 89 percent nitrogen. Again, line C-A shows the varying mixture compositions that will be created if a door to the space was opened allowing fresh air to flow into the compartment and mix with the composition designated by point C. Since line C-A is tangent to the flammability envelope, it represents the minimum fuel mass fraction necessary to obtain a flammable mixture once mixed with air. Therefore, for an initial mixture of fuel and nitrogen only, the critical fuel mass fraction corresponds to that at point C. As can be seen from the diagram, any mixture with a fuel concentration greater than 11 percent (e.g., point D) will result in a flammable mixture after it is mixed with sufficient air. This is illustrated by the intersection of line D-A with the flammability envelope.

The above example demonstrates the concept of a critical fuel mass fraction for an initial mixture containing fuel and combustion products with no oxygen. This scenario is closely representative of the backdraft work performed in this study. However, it is reasonable to expect that conditions may arise in which oxygen concentrations are not zero. This case is also illustrated in Figure 4.

Similar to the discussion above, point F is the mixture corresponding to the critical fuel mass fraction for mixtures with 10 percent oxygen. For this case, a mixture with about 6.5 percent hexane is the minimum fuel concentration necessary to develop an explosive mixture once it is mixed with air. Initial mixtures with fuel concentrations less than 6.5 percent (e.g., Point E) will never produce an explosive mixture. Initial mixtures with fuel concentrations greater than 6.5 percent, point G for example, can produce flammable mixtures since the addition of air is represented by the line G-A which intersects the flammability envelope. This illustration shows how the critical fuel mass fraction decreases with increasing oxygen concentration. In terms of backdraft development, the critical fuel mass fractions at oxygen concentrations of 0 and 12 percent by volume (typical lower oxygen limit for most hydrocarbon fuels) represent bounding values.

On a mass basis, most hydrocarbons, particularly above C_4, have the same lower explosive limit [4]. As such, the critical fuel mass fraction is expected to be nearly the same for higher molecular weight hydrocarbons, such as hexane and diesel fuel. If there is a variation, then the critical fuel mass fraction will be greater for fuels with higher molecular weights. This would suggest that the critical fuel mass fraction for hexane backdrafts should be equal to or less than that of diesel. Consistent with this, the data for zero percent oxygen conditions show that the calculated critical Y_f for hexane (0.11) is less than the experimentally determined value for diesel (0.16).
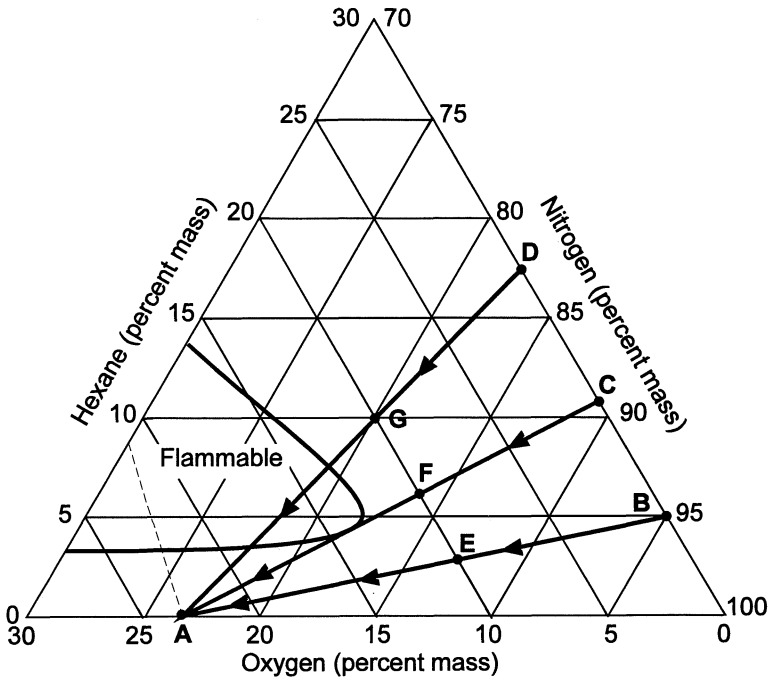
FIGURE 4. A typical flammability diagram illustrating the possible mixture compositions that can result from mixing air with an initial fuel-rich mixture

The actual critical fuel mass fractions for both of these fuels are not expected to differ by this much. As shown below for methane-fueled backdrafts, the standard flammability diagram underestimates the actual critical Y_f. The discrepancy is attributed to the fact that the calculated critical Y_f is based on a flammability diagram for mixtures of fuel, oxygen, and nitrogen. Where as the actual backdraft scenario consists of fuel, oxygen, nitrogen, and other combustion products, such as carbon dioxide and water. The heat capacities of CO_2 and H_2O are significant. If these combustion products were accounted for in the flammability diagram, then the flammability envelope would be smaller, resulting in significantly higher critical fuel mass fractions. Therefore, the actual critical fuel mass fraction for hexane backdrafts would be expected to be greater than 0.11 and nearly equal to 0.16.

As indicated earlier, the purpose of the flammability diagram in Figure 4 is to illustrate the concept of a critical Y_f and particular trends. In order to perform a quantitative study, several parameters, such as other mixture constituents and temperature, would need to be considered. The above analysis has been done with flammability data for hexane mixtures at 25 C. Corrections for elevated temperatures, which are more representative of the backdraft conditions, will tend to result in slightly lower predictions for critical fuel mass fractions. However, the thermal effect on flammability limits is minor compared to the effect of accounting for other combustion products [4].

Within the published literature, there is only one other significant quantitative experimental study of backdraft explosions. This work was performed by Fleischmann for excess methane in a reduced-scale enclosure [5,6]. The 3.6 m^3 (128 ft^3) enclosure measured 1.2 m by 2.4 m by

1.2 m high (4 by 8 by 4 ft) and corresponds to about 12 percent of the size (by volume) of the space studied in this work. A methane burner was ignited within the closed compartment and allowed to burn until the fire extinguished as the oxygen concentration decreased below the lower oxygen index. The fuel was allowed to flow for a set period after extinguishment, at which time a hatch was opened at one end of the enclosure. An electric spark positioned near the burner was used as an ignition source. Two vent configurations were studied: 1) a horizontal opening and 2) a window-style opening, both centered on the short wall at the opposite end from the burner.

The backdraft tests of Fleischmann were conducted with fuel mass fractions up to 0.29. Typically, average compartment oxygen concentrations were about 11 percent by mass and gas temperatures were 60 to 100 C. Fleischmann reported that the fuel mass fraction must be greater than 0.10 in order for a methane backdraft to occur. Based on the flammability diagram for methane [4], the critical fuel mass fraction at 11 percent oxygen (by mass) is 0.06, which is approximately 60 percent of the actual experimental value. Consistent with the discussion above, these data further illustrate the need to fully represent the combustion products in the flammability diagram in order to correctly determine the critical fuel mass fraction.

A comparison of the critical fuel mass fraction for methane backdrafts (0.10) and that observed in this study for diesel fuel (0.16) shows a significant difference. The difference is attributed primarily to the oxygen concentrations within the compartments. Average compartment oxygen concentrations for this study were approximately 1 percent by volume whereas the average oxygen concentrations in Fleischmann's tests were estimated to be about 10 to 12 percent by volume. As illustrated above with Figure 4, this difference in oxygen concentration can result in a factor of 1.5 to 2 in the critical Y_f. Adjusting Fleischmann's results to be at the same oxygen concentration as the diesel fuel backdrafts yields a critical Y_f of about 0.15 to 0.2 which is consistent with the diesel fuel test results.

As discussed for the Series 1 diesel backdraft tests, wind was observed to have a significant mitigating effect on backdraft development. Fleischmann's results also indicate that the compartment/vent geometry and, thus, the fluid dynamics have an effect on backdraft development. Backdrafts were much more difficult to create for the smaller window opening tests, despite fuel mass fractions of 0.15 to 0.18. The gas temperatures and oxygen mass fractions for the window opening tests were essentially the same as those of the horizontal slot tests. It is uncertain whether the mitigating effect from the window style vent is due to a reduction in size or due to the different geometry. The smaller size vent decreases the mass flow rate into the enclosure. This is reflected in the longer ignition delay times (15 to 25 sec vs 6 sec) for the window vent. The reduced flow may limit the size of the mixing region which reaches a flammable level at the point of ignition, thus causing a weak deflagration that is unable to form an explosive fire ball. It is unclear how the change in geometry compared to the change in size effects the large-scale vortices (i.e., the entrainment process) compared to the small-scale vortices that impact the localized mixing of the fluid streams. The authors are currently studying this process with the Computational Fluid Dynamics code STAR*CD.

Water Spray

The effect of water injection on mitigating the backdraft phenomenon was clearly established. Table 1 shows the comparison of Series 2 water spray injection tests with the same initial conditions. That is each test consisted of 4.92 kg (1.58 gal) of secondary fuel injection corresponding to a pre-water injection fuel mass fraction of about 0.25. Table 1 shows that the strength and size of the backdraft explosions/fire balls decreased with increasing amounts of water injection. As the amount of water was increased from 5.5 kg to 13.7 kg (1.5-3.6 gal), the severity of the backdraft phenomenon changed from the creation of an explosion with a fire ball to full prevention of an ignition. At the highest injection level of 13.7 kg (3.6 gal) of water, no ignition or fire occurred at all.

The trend of mitigating and eliminating explosions with increasing water injection into the fire space correlates very well with the resulting fuel mass fraction in the fire space. Injection of water into the fire space results in a decrease in the fuel mass fraction due to dilution. There was very good agreement with the criterion that fuel mass fractions greater than 0.15 are needed to produce a backdraft explosion. This result can be seen in Figure 3, which includes the outcome of all backdraft tests with water spray injection. Similar to the results for tests without water injection, there are three principle regimes denoted by fuel mass fractions. For tests with fuel mass fractions after water injection of less than 0.16, no explosions or even flames out of the door occurred. Whereas, tests with fuel mass fractions of 0.16 or 0.17 represent a transitional range with outcomes of only flames out of the door to small fire balls. The third regime shows that backdraft scenarios with fuel mass fractions greater than 0.17 result in explosions with a distinct fire ball out of the door.

Overall, the results indicate that the use of water spray in these tests suppressed the diesel explosions, primarily by means of diluting the atmosphere and reducing the fuel mass fraction rather than by a thermal mechanism of cooling. Further evidence for this conclusion can be found in the flammability diagram of Figure 4. The initial gas mixture (without water) in the fire compartment is represented by point D. The fuel concentration is greater than the critical fuel mass fraction; therefore, as air is introduced into the fire compartment (line D-A), an explosive mixture will be created. Due to the high temperatures in the fire space (>300EC), it is reasonable to assume that all water injected is turned to steam; thus, it can be treated as an inert gas. For the purpose of illustration, the steam can be treated as though it were nitrogen (i.e., the right axis could be any inert gas). The injection of water into the compartment is equivalent to moving down the right axis from point D toward point B. Any mixture which is below point C (i.e., the critical fuel mass fraction) will not result in an explosion as air mixes with the fuel-rich fire compartment gases (e.g., line B-A).

TABLE 1. The effect of increasing amounts of water injection on the development of backdrafts for tests with 4.92 kg of secondary fuel

Y_f	Y_f before water injection	Test	Volume of Water		Outcome of Backdraft Test
			(L)	(gal)	
0.14	0.24	BD93	13.7	3.6	No flame, no fire ball
0.14	0.24	BD95	13.7	3.6	No flame, no fire ball
0.14	0.25	BD102	13.7	3.6	No flame, no fire ball
0.15	0.24	BD96	10.9	2.9	No flame, no fire ball
0.16	0.25	BD114	10.9	2.9	Very weak pressure pulse, roll out of flame
0.16	0.22	BD90	10.9	2.9	Small fire ball (4 m extension from compartment)
0.17	0.25	BD98	8.2	2.2	Small fire ball
0.17	0.25	BD99	8.2	2.2	Small fire ball
0.19	0.25	BD100	5.5	1.5	Fire ball (larger than BD98 and BD99)

A comparison of the fire compartment temperatures for similar tests with and without water injection shows that the thermal effect of water injection was insignificant with respect to backdraft development. In general, the temperature decreased marginally by about 35° C due to water addition. Of more importance is the fact that even with water injection, the fire space gas temperatures were typically 310 to 360° C and the steel compartment temperatures were 390 to 410°C. The minimum auto-ignition temperature for diesel fuel can be taken to be less than 250° C based on similar high molecular weight hydrocarbon fuels [4,7]. Therefore, all the tests with water injection had average compartment temperatures greater than the auto-ignition temperature (AIT) for the fuel.

The fact that all tests had temperatures greater than the AIT and only tests with fuel mass fractions of 0.15 or less resulted in no explosion, indicate that the use of water injection suppressed the backdraft explosions primarily by means of diluting the atmosphere, thus reducing the fuel mass fraction rather than by cooling the space i.e., by mitigating the ignition source or by condensing fuel. The small decrease in gas temperature with water injection is attributed to the large thermal capacity of the steel compartment. The energy required to vaporize the injected water is only a fraction of that stored in the steel structure.

In a typical compartment with gypsum board, the use of water spray will reduce the gas temperature significantly (several hundred degrees Celsius is possible) since the boundary is more of an insulator and not a thermal reservoir. Additionally (even for steel structures), it is expected that gas temperatures will decrease more as the fire compartment volume-to-surface area ratio increases, thus reducing the contact between water and hot surfaces. As gas temperatures are decreased toward or below 100 C, some water may not become steam and will remain as droplets. As a result of these different conditions, mechanisms other than dilution may enhance the mitigation of backdrafts: 1) fuel vapor may condense for Class B fuel scenarios, 2) thermal cooling may impact the flammability marginally but may significantly impact the ignition source, and 3) water may physically scrub Class B fuels from the gas phase.

SUMMARY AND CONCLUSIONS

This study has shown that the key parameter for backdraft development is the fuel mass fraction. The results show that the critical fuel mass fraction, Y_f, required for the development of diesel fuel backdraft explosions is 0.16 for fully vitiated conditions. Since most hydrocarbons have the same lower flammability limit on a mass basis, this value of 0.16 is expected to be representative of most fuels.

This study has also demonstrated that standard flammability diagrams can be used to predict bounding limits and trends with respect to other key variables on Y_f. Analysis of the data in combination with the results of Fleischmann's methane backdraft tests has shown that the critical fuel mass fraction is dependent on the oxygen concentration in the compartment and, to some extent, the fluid dynamics of the mixing fuel and air streams. In order to obtain a better quantitative understanding, the Computational Fluid Dynamics code STAR*CD is currently being used to study the effect of compartment geometry and the resulting fluid dynamics on the development of a backdraft.

The injection of water spray was shown to be an effective mitigating tactic that was able to completely suppress explosions. The analysis reveals that backdraft suppression occurred primarily by means of diluting the atmosphere and reducing the fuel mass fraction rather than by a thermal mechanism of cooling. In addition, there was excellent agreement of correlations between backdraft occurrence and Y_f for tests with and without water spray.

ACKNOWLEDGEMENTS

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