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Characterization of backdrafts generated from methane fires

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Abstract: An analysis of oxygen concentration measurements is conducted to investigate compartment ventilation before a potential backdraft phenomenon. Experiments are performed in a 2/5th scale compartment of varying configurations such as fuel flow time, spark igniter location, and compartment opening size. A 25.0 kW methane fire and 37.5 kW methane fire are chosen as the fires of interest. Ignition is prompted via a spark igniter positioned at either 50.7 cm or 25.4 cm from the compartment floor. Compartment opening size is modified to either a door or window configuration. Oxygen concentrations are measured at two different heights within the compartment using paramagnetic sensors. Total heat release of experiments with backdraft events are reported. Time-averaged oxygen concentrations are calculated from measurements obtained 5 s before the compartment opening and are observed to correlate with experimental parameters such as fire size and fuel flow time.
Keywords: Backdraft, Equivalence Ratio, Reduced-Scale Enclosure Experiments, Total Heat Release

1. Introduction

Backdrafts are hazardous events for anyone who may encounter them. A backdraft occurs when a gravity current of air is introduced into an isolated, heated enclosure previously starved of oxygen with a substantial concentration of unburned fuel. If a localized flammable mixture is formed around an ignition source, a deflagration occurs, generating a fireball and pressure wave outside the enclosure. Fleishmann et al. [1] demonstrated how certain physical mechanisms, such as the gravity current generated at the opening, turbulent mixing within the enclosure, and ignition are all conducive to a backdraft phenomenon. Other works [2–12] have expanded upon these physical mechanisms using other parameters such as fuel type and enclosure configuration.

In this study, a series of backdraft experiments are conducted using a $2/5^{\text{th}}$ scale compartment. Methane fires of 25.0 kW and 37.5 kW fire size are selected as enclosure conditions to potentially generate a backdraft. Oxygen concentration measurements are recorded at various heights within the compartment. In experiments where a backdraft occurs, the heat release rate is estimated. Using an analysis of the oxygen concentration preceding a backdraft, this study aims to establish the relationship between an enclosure's configuration and backdraft characteristics.

2. Methods/Experimental

2.1 Compartment configuration

All backdraft experiments are conducted in a reduced-scale enclosure (1.0 m x 1.0 m x 1.5 m)[1], $2/5^{th}$ the dimensions of the ASTM fire test room. Figure 1 provides a schematic of the compartment with spark igniters and gas sampling probes. The enclosure's front has a pneumatically operated door located along a short wall with a 43.0 cm wide and 80.0 cm high opening. The door opening is transformed into a window configuration by adding a 15.2 cm high lip to the front entryway, forming a sill covering the lower half of the opening. In experiments where a window configuration is used, the opening size is reduced by approximately 20%. In this experimental series, either a middle or low spark igniter position is used, 25.4 cm or 50.7 cm from the compartment floor, respectively. Oxygen concentration measurements are obtained at two locations in the center of the compartment (nominally 50.0 cm from the sidewall), 37.5 cm from the opening using a stainless steel gas sampling line. A detailed description of the compartment is available in Ref. [13].

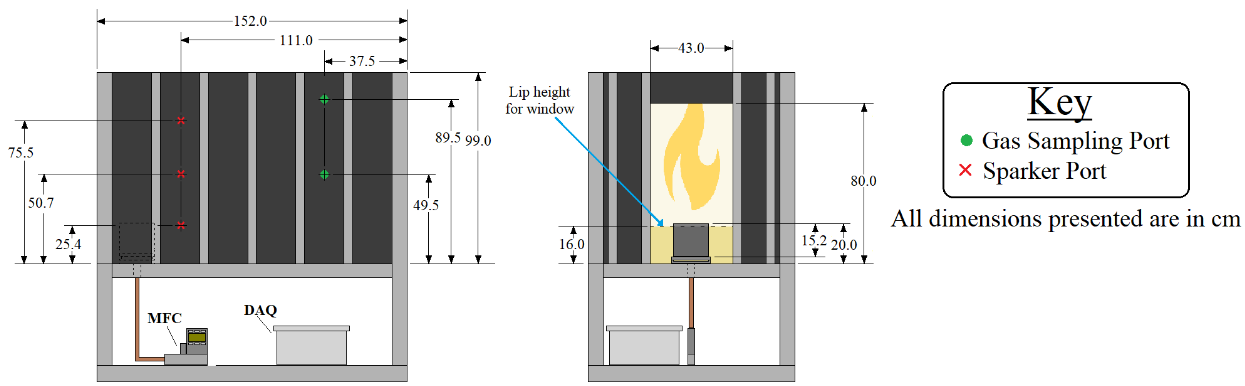

Figure 1: Schematic of the $2/5^{th}$ scale compartment utilized for backdraft experiments. All dimensions are presented in cm.

Backdraft experiments are initiated when a small sand burner, fed fuel via mass flow controller (MFC), is ignited using a propane wand (t=0). Gaseous fuels are fed into a 17.8 cm square sand burner whose center is approximately 1.25 m from the front opening of the compartment. Initially, the fire burns while the compartment doorway remains open for 60 s (t=60). After the front doorway is closed, fuel continues to feed into the sand burner until a predetermined fuel flow time is achieved. A list of fuel flow times for each fire size is provided in Table 1. The doorway remains closed for an additional 30 s, after which the doorway opens and a potential backdraft is observed. Backdraft measurements reported here are obtained from two controlled methane fires of sizes 25.0 kW and 37.5 kW whose uncertainties[2] range $\pm$ 1%. Compartment configurations are modified by varying door and window opening configurations.

[1] All dimensions reported in this manuscript have a relative uncertainty of 2%.

[2] Unless otherwise stated, all uncertainties expressed in this work are combined relative uncertainty with an coverage factor of 2, representing a 95% confidence level.

Table 1: List of fuel flow times for each fire configuration

Fire size (kW)	Fuel flow time (s)	Fuel flow (SLPM)
25.0	360, 390, 420, 450	26.4±1.2
37.5	240, 270, 285, 300	42.5±1.2

2.2 Oxygen concentration measurements

Measurements of compartment oxygen concentrations are examined in the upper (y=89.5 cm) and middle (y=49.5 cm) layer of the compartment for each backdraft experiment. Gas samples are extracted into the gas analyzer via vacuum pump. The gas analyzer includes a paramagnetic sensor to provide real-time O_2 concentration measurements. Oxygen concentrations in the paramagnetic sensor data is recorded at 1 Hz throughout the experiment using a data aquistion system (DAQ). A chiller is positioned upstream of the gas analyzer to remove water vapor. Therefore, all oxygen concentration measurements are obtained on a dry basis.

Time-averaged oxygen concentration measurements, $\bar{X}_{O_2}$, are measured to examine the compartment ventilation immediately prior to a potential backdraft. Time-averaged oxygen concentrations are calculated from the average measurements of both positions made 5 s prior to the doorway opening. The uncertainty of time-averaged concentration measurements are estimated from a combination of the Type A and B evaluation of uncertainty. The variance between the averaged measurements is the dominant contributor to their respective uncertainties for time-averaged measurements.

2.3 Total heat release measurements

The compartment is positioned under a 3 MW calorimeter (6 m canopy hood) [14]. In instances where a backdraft event is observed, the total heat release is calculated. Since large volumes of unburned hydrocarbon fuel can be present in the exhaust, the total heat release is corrected for by utilizing carbon dioxide generation calorimetry with a correction for carbon monoxide generation. The calculation for the corrected total heat release, $THR_{corr.}$, is presented in Eq. 1 .

$$THR_{corr.} = \sum_{t=0}^{\infty} \left[\dot{m}_{\mathrm{CO_2}}(t) \left(\frac{\mathrm{LHV_F\ MW_F}}{\mathrm{x\ MW_{CO_2}}} \right) + \dot{m}_{\mathrm{CO}}(t) \left(\frac{\mathrm{LHV_F\ MW_F}}{\mathrm{x\ MW_{CO}}} - \Delta \mathrm{H^o_{C,CO}} \right) \right] \Delta t \qquad (1)$$

Here, $\dot{m}_{\mathrm{CO_2}}(t)$ and $\dot{m}_{\mathrm{CO}}(t)$ represent the mass flow rate of carbon dioxide and carbon monoxide measured in the duct, respectively. The number of carbon atoms and lower heating value of the parent fuel is represented by x and $\mathrm{LHV_F}$, respectively. Molecular weight of the parent fuel, carbon dioxide, and carbon monoxide is denoted as $\mathrm{MW_F}$, $\mathrm{MW_{CO_2}}$, and $\mathrm{MW_{CO}}$, respectively. The heat of combustion for carbon monoxide, $\Delta \mathrm{H^o_{C,CO}}$ used in Eq. 1 is 10.10 kJ/g as reported by Ref. [15]. Since data was collected at 1 Hz, $\Delta t = 1$.

While a typical backdraft exhaust only persists for approximately 2 s, the combustion gases captured by the hood exhaust mixes within the duct and sampling lines for a longer time. The increased mixing time is beneficial to gas analyzers with response times longer than the backdraft event, which better resolves the total heat release measurement. For the NIST 3 MW calorimeter, it is estimated that the total heat release is resolved for 5 s gaseous fuel pulses to within 10 % [14].

3. Results and Discussion

3.1 Oxygen concentration measurements

Figure 2 shows the time-averaged oxygen concentration measurements calculated from both positions, 5 s prior to the door opening as a function of the total fuel volume fed into the compartment for both opening configurations. The total fuel volume is estimated from the product of the fuel flow time and fuel flow provided in Table 1. The uncertainty of the total fuel volume is estimated via the Type B evaluation of uncertainty of the mass flow controller.

The time-averaged oxygen concentration for both opening configurations are similar since the gas mixtures within the compartment are independent of its configuration prior to the door opening. The 25.0 kW methane fire is observed to cluster at a higher oxygen concentration (approx. $10\% \pm 3\%$) compared to the 37.5 kW methane fire, which may be attributed to the a significant volume of unburned fuel and combustion products (i.e., carbon dioxide, water vapor, and carbon monoxide) present in the enclosure. No discernible distinction between backdraft and non-backdraft events is observed in each cluster, suggesting that other factors such as fuel concentration relative to ventilation or compartment configuration (i.e., spark igniter position) are likely predictors for a backdraft event.

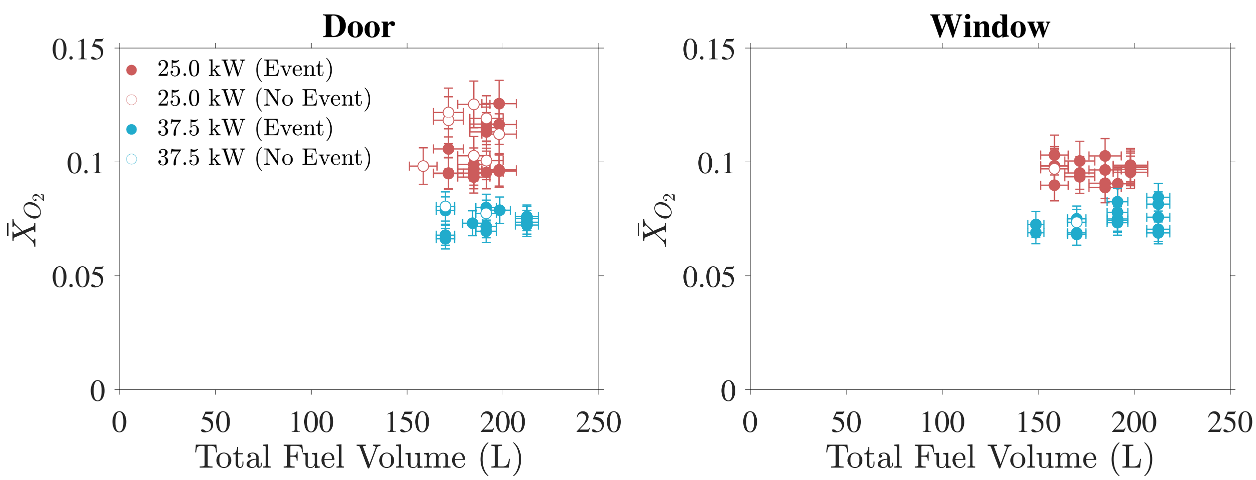

Figure 2: Oxygen concentrations as a function of the total fuel volume for a 25.0 kW and 37.5 kW methane fire with a door (left) and window (right) opening configuration. The oxygen concentration uncertainty represent a combined Type A and B evaluation of uncertainty. The total fuel volume represents the Type B evaluation of uncertainty.

3.2 Total heat release measurements

For both opening configurations, the total heat release of each backdraft event is plotted as a function of the total fuel volume fed into the compartment and displayed in Fig. 3. The total heat release is observed to increase with total fuel volume for both fire sizes and opening configurations with measurements observed to follow a trendline within experimental uncertainty. For experiments with a window configuration, the total heat release gave a wider range of values compared to experiments with a door configuration. The wider span of total heat release measurements of experiments with window configuration may suggest that the turbulent mixing of the gravity current is influenced more from the presence of the lip.

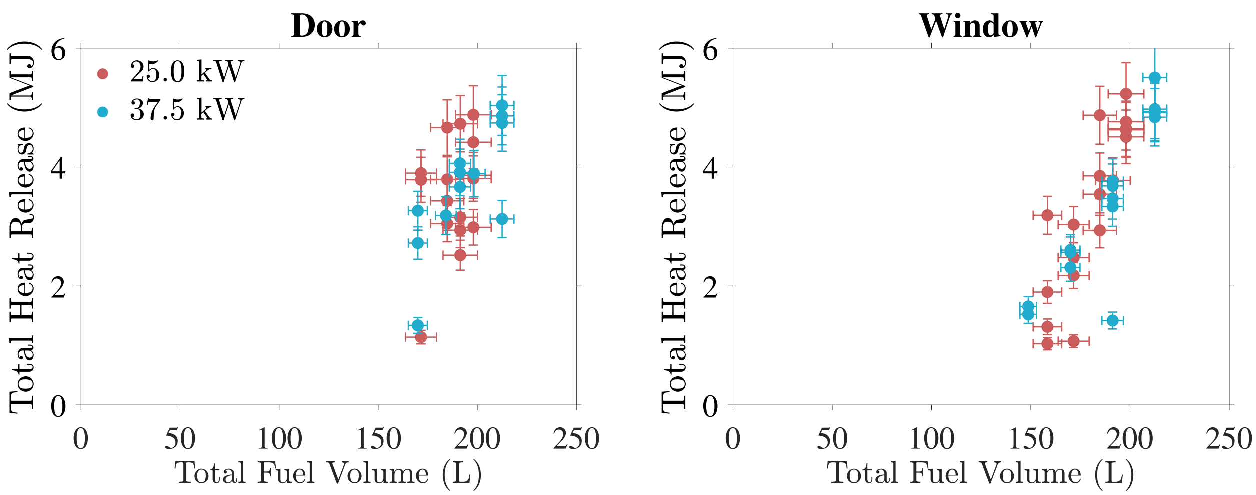

Figure 3: Total heat release of experiments where a backdraft occurs as a function of the total fuel volume for a 25.0 kW and 37.5 kW methane fire with a door (left) and window (right) opening configuration. The relative uncertainty for all total heat release measurements is estimated to be 10%. The total fuel volume represents the Type B evaluation of uncertainty.

4. Conclusions

This study characterizes gas species concentrations and resulting total heat release of experiments where a backdraft potentially occurs. Time-averaged oxygen concentration and total heat release measurements are reported for two methane fires of sizes 25.0 kW and 37.5 kW. No significant difference was observed for oxygen measurements in the two specified configurations. Therefore, further investigation is warranted to investigate additional factors/variables responsible for a backdraft event. The total heat release is observed to increase with total fuel volume for every fire and compartment configuration. Future work will aim to better establish conditions conducive to backdraft by modifying compartment configurations and other parameters.

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