Assessing Fire Smoke to Predict Backdraft and Smoke Explosion Potential

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Abstract

The Fire Research Division at the National Institute of Standards and Technology is examining the ability to forecast backdraft or smoke explosions during a fire using a phi meter. Compared to other gas sensors, a phi meter can measure the global equivalence ratio under a broad spectrum of fuel-rich and fuel-lean conditions. Predetermined gas mixtures are fed into the phi meter wherein the equivalence ratio is measured. The measured and expected equivalence ratios for all gas mixtures are observed to be in substantial agreement. Concentration measurements are verified using the carbon to hydrogen ratio. Real-time temperature measurements are made at the inlet and outlet of the phi meter. The estimated enthalpy of the gas mixture from phi meter measurements is observed to increase as the gas mixture approaches stoichiometric conditions. The work demonstrates the potential to relate the estimated enthalpy in the phi meter with its oxygen consumption. The correlation can eventually be expanded to a variety of different fuels and conditions. Once established, the repository of data sets can be correlated to the bounding conditions for actual backdraft and smoke explosions of various strengths.

Keywords: Backdraft, Smoke Explosions, Phi Meter, Combustion Equivalence Ratio Meter, Flammability Limit, Gas Sampling

Introduction

The potential for backdrafts and smoke explosions to occur during fire events present a significant hazard to search and rescue teams, suppression teams, and other personnel in the surrounding area. Accurately assessing the condition of building spaces for potential smoke explosion or backdraft, before and during search and rescue and suppression activities, would improve situational awareness and lead to increased firefighter effectiveness and overall safety.

A backdraft event is preceded by a change in the ventilation of a compartment filled with hot smoke that suddenly mixes with incoming Air through an opened door, broken window, or another venting source. Given the right conditions, the flammable gas mixture produced in the compartment ignites and expands, forcing fire gases out the opening, and subsequently erupting into a fireball or, with wind present, fire flower.

A smoke explosion is an event where a fuel-rich mixture of smoke (i.e., fuel vapors, carbon monoxide, and smoke particulate) located in an enclosed space mixes with oxygen (Air) that infiltrates the space. If a gas mixture is within the flammability limits while an ignition source is present, the mixture may explode with damaging deflagration overpressure. The fire service primarily relies on observations of smoke emanating from enclosures as evidence for the potential of backdraft or smoke explosions, such as puffing of the escaping smoke, color of the smoke, and other clues like darkened soot-covered window panes [1]. The fire service reliance on such indicators is not necessarily well-founded technically and is therefore not entirely reliable.

The full-scale backdraft experiments with No. 2 diesel fuel of Gottuk et al. [2] showed that the nominal fuel mass fraction (estimated from the fuel injection rate) correlated with the occurrence of backdraft and the resultant fireball size. The hypothesis proposed here is that the compartment gas temperature and the amount of fuel, oxygen, and non-combustible gases would allow the classification of the potential hazard. Furthermore, the potential hazard could be rated at varying strengths from no fireball or small overpressure, to large fireball extension or significant overpressure.

A significant hurdle to overcome in classifying backdraft is achieving gas measurements that accurately characterize the extracted sample. Extractive gas measurements with conventional catalytic bead flammable gas sensors are problematic for several reasons, some of which are: 1) the fuel composition is unknown which poses calibration issues; 2) the amount of particulate may play a role in these events and is not accounted for; and 3) these devices are typically limited to a range up to the lower flammability limit, they need sufficient oxygen to work, and poisoning or other loss of sensitivity is possible from the range of smoke exposures.

The idea proposed here is to measure the equivalence ratio, φ, using a phi meter operating under a new set of given conditions. The equivalence ratio is defined as the quotient of fuel to air ratio and the stoichiometric fuel to air ratio of the combustion process where fuel is initially un-combusted. Additional estimations and measurements include calculating the carbon to hydrogen ratio, an approximation of the fuel/oxygen ratio at the entrance of the phi meter, and the enthalpy increase from a combusted gas mixture. The measurements presented here lay the initial groundwork for developing a device that could predict potential backdrafts by quantifying certain conditions.

Experimental Method

In this work, the equivalence ratio is evaluated in real-time using a phi meter [3-7]. A phi meter has been constructed per the design of Babrauskas et al. [6] with the addition of thermocouples to measure the incoming and exiting flow temperatures. A flow diagram is provided in Fig.1. The phi meter operates by introducing extracted gas samples into a heated (900°C) plug flow reactor packed with platinum-coated beads as a combustion catalyst. An additional plug flow reactor placed within a furnace is available upstream to allow for the pre-combustion of fuel-air mixtures. Once the fuel/air mixture enters the phi meter, it is introduced to a counterflow of excess oxygen. Enough oxygen is supplied to the reactor such that the gas mixture is completely combusted.

Upon exiting the reactor, water is scrubbed from the gas stream using a chiller, resulting in a mixture primarily consisting of oxygen, carbon dioxide, and nitrogen. Assuming little to no nitrogen or oxygen in the fuel molecules, the known flow rates of the exit flow and added oxygen combined with a downstream measurement of the oxygen concentration allowed for a straightforward calculation of the equivalence ratio.

$$\varphi = \frac{Fuel/_{Air}}{\left(Fuel/_{Air}\right)_{st}} = 1 + \left[\left(\frac{1 - X_{O_2,i}}{X_{O_2,i}\left(1 - X_{O_2,A} - X_{CO_2,A}\right)}\right)\left(\frac{n_{O_2}}{n_A} - X_{O_2,A}\right)\right] \quad \text{(Eq. 1)}$$

Here, n_{O_2} and n_A are the molar flow rates of oxygen introduced in the phi meter and total molar flow introduced into the analyzer, respectively. Additionally, $X_{O_2,i}$, $X_{O_2,A}$, and $X_{CO_2,A}$ are the volume fractions of oxygen in the Air (20.8%), and the dry oxygen and carbon dioxide introduced to the analyzer, respectively. A full derivation can be found in Ref. [6].

The upstream furnace is maintained at approximately 30°C, such that there is an un-combusted gas mixture entering the phi meter. The initial fuels of interest are methane and propane. The gas mixture varies within the flammability limits of the fuel [7] with φ_G ranging from approximately 0.5 to 2. The equivalence ratio is established from the predetermined fuel and air flows feeding into the upstream furnace. This work also has no additional air added to the flow stream past the upstream furnace (i.e., Air, 2=0, per Fig. 1). The fuel, Air, and oxygen volumetric flow rates are maintained using an Alicat Mass Flow Controller[1]. The volumetric flow rate exiting the chiller is measured using an Alicat Mass Flow Meter.

[1] Certain commercial products are identified in this report to specify adequately the equipment used. Such identification does not imply a recommendation by the National Institute of Standards and Technology, nor does it imply that this equipment is the best available for the purpose.

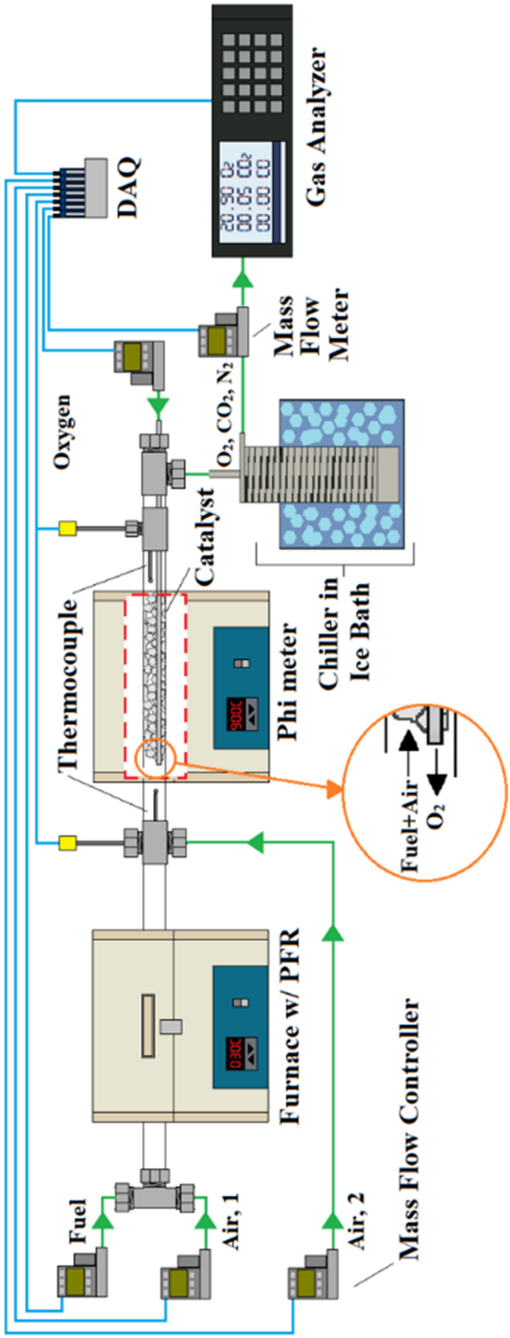

Fig. 1. A schematic of the phi meter experimental setup, including an additional furnace with a plug flow reactor (PFR) located upstream.

Oxygen and carbon dioxide concentrations are determined using a CAI 600 Series Gas Analyzer. Temperature measurements are made using two 20 gauge, 3 mm diameter, bare bead, Type K, low noise thermocouples positioned at the entrance and exit of the phi meter. The dataset is obtained approximately 10 min after the gas mixture composition entering the phi meter has been modified. All measurements are sampled at 2 Hz for approximately 2 min.

As a way to verify the accuracy of the result, the carbon to hydrogen mass ratio (C/H) is calculated for each analyzed sample using the equation below.

$$\frac{\mathrm{C}}{\mathrm{H}} = \frac{\mathrm{MW_C}}{\mathrm{MW_H}} \frac{\left(x_{\mathrm{CO_2}}\right) \frac{Y_{CO_2}}{\mathrm{MW}_{CO_2}}}{\left(y_{H_2O}\right) \frac{Y_{H_2O}}{\mathrm{MW}_{H_2O}}} \quad \text{(Eq. 2)}$$

Here $x_{\mathrm{CO_2}}$ and $y_{\mathrm{H_2O}}$ are the number of carbon (1) and hydrogen (2) in carbon dioxide and water vapor, respectively. The molecular weight of carbon and hydrogen is denoted as MW_C and MW_H, respectively. The mass fraction of species CO_2, denoted as Y_{CO_2} is estimated from its measured volume fraction in the analyzer. The mass fraction of water vapor, Y_{H_2O}, is estimated from the difference between the total mass entering the phi meter and the total mass measured at the mass flow meter located past the chiller.

The uncertainties of all measurements are determined from a combined Type A and B evaluation of uncertainty. The Type A evaluation of uncertainty is estimated as the standard deviation of the measurement made during the sampling period. The Type B evaluation of uncertainty is estimated from the reported bias error in the instrumentation. The uncertainties presented in this work are expressed using a 95% confidence interval. For calculated values, the uncertainty was calculated using the law of propagation of uncertainty.

Results and Discussion

Fig. 2 presents a comparison between the expected and measured equivalence ratio. The expected equivalence ratio is calculated from the predetermined fuel and air flows feeding into the upstream furnace. The measured equivalence ratio is calculated using Eq. 1. As seen in Fig. 2, the measured values are equivalent, with some error, to their respective expected values for both fuel-rich and fuel-lean mixtures. The strong agreement indicates the validity of the phi meter set up, demonstrating a device that can measure the equivalence ratio of a fuel-air mixture.

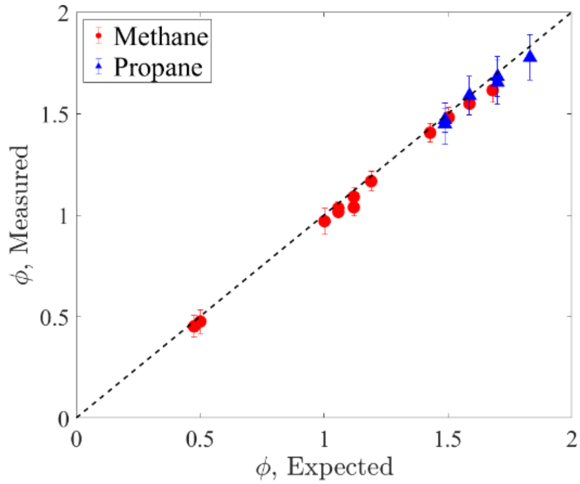

Fig. 2. A comparison between the expected and measured equivalence ratio. Note that the dotted line represents equivalency between the expected and measured values. The vertical bars are the estimated uncertainties of the measured equivalence ratio, calculated from the methods described in the previous section.

The limited propane data demonstrate a limitation of the phi meter design as conceived by the research engineer used in this work. The propane data presented here is limited by the flow capacity of the mass flow meter positioned downstream of the chiller. In this work, the maximum reading of the mass flow meter was 2 SLPM. In comparison to methane, propane requires a higher amount of Air to achieve stoichiometric combustion, which limited the investigation of propane to fuel-rich mixtures, given the mass flow meter constraint.

As previously stated, the carbon to hydrogen ratio is used to validate the accuracy of the measured volume fractions. As shown in Fig. 3, the estimated carbon to hydrogen ratio for each gas mixture is in strong agreement with the theoretical values of their respective fuels. This agreement validated the accuracy of the concentration measurements and the approximation of water concentration. These validation results suggest an additional feature of the phi meter; the calculated carbon to hydrogen ratio could be used to predict the composition of incoming fuels.

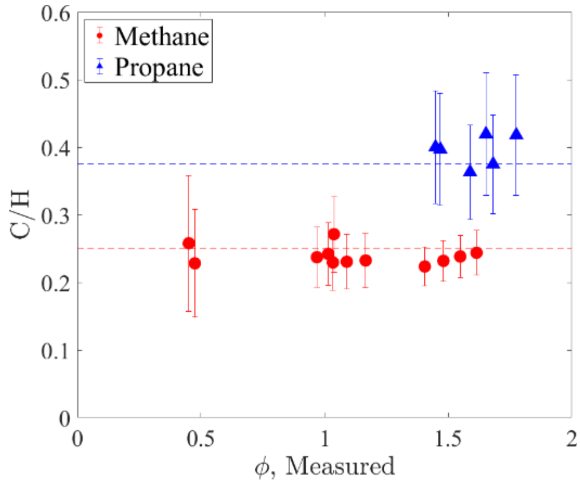

Fig. 3. Carbon to hydrogen ratio calculated from the product of all gas mixtures compared to the theoretical values at different equivalence ratios. The vertical bars on each data point represent the estimated uncertainty of the carbon to hydrogen ratio, calculated from the methods described in the previous section.

Fig. 4 presents the temperature difference across the phi meter for methane gas mixtures, maintained at a constant volumetric flow rate (2 SLPM), as a function of the total fuel to total oxygen ratio in the entire phi meter, $(Fuel/O_2)_{Tot}$. The temperature difference profile, as a function of the fuel/oxygen ratio, is not provided for propane since that obtained data is limited. The fuel/oxygen ratio is calculated from the un-combusted fuel and Air and the additional oxygen introduced to the mixture at the entrance of the phi meter. Since the objective of the phi meter is to completely combust the incoming fuel/air mixture, with the aid of additional oxygen, the combined gas mixture must always be lean such that $n_{\mathrm{Fuel}} < (n_{\mathrm{O_2}} + 0.21 \cdot n_{\mathrm{Air,1}})$. Based on that requirement, the fuel/oxygen ratio acts as an indicator of the operation of the phi meter. The fuel/oxygen ratio is calculated from the Eq.3, where $n_{\mathrm{Air,1}}$ is the molar flow rate of un-combusted Air flowing into the phi meter.

$$\left(\frac{\mathrm{Fuel}}{\mathrm{O_2}}\right)_{\mathrm{Tot.}} = \frac{n_{\mathrm{Fuel}}}{\left(n_{\mathrm{O_2}} + 0.21 \cdot n_{\mathrm{Air,1}}\right)} \qquad \text{(Eq. 3)}$$

The temperature difference across the phi meter as a function of the fuel/oxygen ratio is consistent for the methane fuel. The temperature is observed to increase as the fuel-lean gas mixture approaches stoichiometric conditions. For comparison to the calculated adiabatic flame temperatures, the temperature difference for each gas mixture is considerably less, indicating substantial heat loss within the reactor. Regardless, measuring the enthalpy increase of the reactor stream provides additional insight into the characteristics of the extracted gas mixture. The enthalpy measurement could be used to estimate the oxygen consumed internally based on the principle of oxygen consumption calorimetry.

The significance of the temperature measurement across the reactor is the additional information it can provide regarding the incoming fuel. As previously stated, the phi meter operation is based on the assumption that there is little to no oxygen and nitrogen in the fuel molecule. If the phi meter were to be used to investigate a fuel with a significant portion of oxygen or nitrogen in its composition, it could cause a significant error in the equivalence ratio measurement. The temperature measurements provide additional insight into the gas mixture introduced into the phi meter, which may prove useful when investigating unknown fuels.

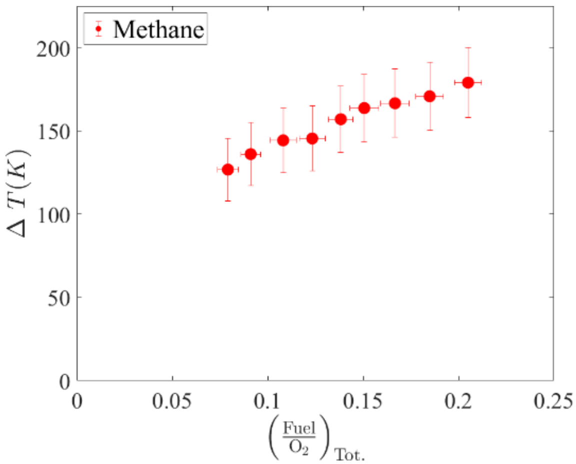

Fig. 4. The measured temperature difference across the phi meter as a function of the estimated fuel/oxygen ratio. It should be noted that the error of the temperature difference is determined from the measurement uncertainty derived from the uncertainty provided by the thermocouple manufacturer ($\pm 2\%$ of the reading). The horizontal bars on each data point represent the uncertainty of the fuel to oxygen ratio within the phi meter and is calculated from the methods described in the previous section.

Conclusion and Future Work

This work highlights the application of a phi meter for measuring the equivalence ratio of methane and propane for fuel-rich and fuel-lean gas mixtures. This work demonstrates the phi meter's ability to measure the temperature rise across the reactor, which can be used if the future to infer the oxygen consumption within the phi meter and possibly provide additional information when dealing with fuels containing significant portions of oxygen and nitrogen. Future work will focus on expanding the library of fuels and gas mixtures to include gaseous fuels, with and without combustion gas diluents, and solid fuels like wood, plastics, and polyurethane foam combusted in low oxygen environments. Once an extensive library has been established, the phi meter will be applied to a 2/5 scale compartment, designed based on similar research [5,7,9], where backdraft and smoke explosions of various strengths can occur. The phi meter measurements can then be correlated to the bounding conditions for actual backdraft and smoke explosions of various strengths.

Acknowledgments

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