# A binary logistic regression model to evaluate backdraft phenomenon

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## Abstract

A technique to predict backdraft phenomenon using a binary logistic regression model is presented. The model is established from time-averaged temperature, global and local equivalence ratios, and oxygen concentration measurements obtained in a series of backdraft experiments conducted at the National Fire Research Laboratory at the National Institute of Standards and Technology. The experiments utilized methane and propane fires of different sizes in a reduced-scale enclosure to create conditions conducive to a backdraft phenomenon. Time-averaged measurements estimated immediately before an anticipated backdraft were observed to vary with the duration of the total fuel flow time into the compartment. The established model's accuracy was found to improve with the inclusion of all time-averaged measurements as opposed to fewer components.

**Keywords:** Backdraft; binary logistic regression model; time-averaged measurements; Reduced-scale enclosure

## Introduction

Backdrafts are an extreme fire phenomenon that poses a life-threatening risk to anyone who may encounter them. A backdraft occurs in an isolated heated enclosure starved of oxygen with a substantial concentration of unburned fuel. When an opening is suddenly introduced into the enclosure, a gravity current of colder air is driven inward, mixing with the residing heated fuel. In the presence of an ignition source, a localized flammable mixture can ignite, deflagrate, and generate an extending flame and pressure wave through the enclosure's opening.

Firefighters rely on visual cues such as dark sooty smoke 'puffing' out from an interior around vents and door creases. Some works [1-8] have conducted extensive research to establish the physical mechanisms of the backdraft. Most backdraft research, however, is limited in its output in that there is no systematic approach to evaluate the potential risk.

This work describes a binary logistic regression model that utilizes time-averaged temperature and gas species composition measurements to predict the likelihood of a backdraft. Time-averaged measurements include the global and local equivalence ratios and the temperature and oxygen concentration of the sampled gas. The significance of each measurement to the model is tested, providing a more comprehensive understanding of their impact on the backdraft phenomenon.

## Experimental Method

All backdraft experiments are conducted in a reduced-scale enclosure (1.0 m x 1.0 m x 1.5 m) 2/5$^{th}$ the ASTM fire test room dimensions. Ref. [9] details the design and construction of the enclosure. The enclosure's front has a centered, pneumatically operated door on a short wall with an approximately 43.0 cm wide and 80.0 cm high opening. A nominally 17.8 cm square sand burner's center is positioned approximately 1.25 m from the front opening of the compartment. Two spark igniters were used, either in the low or middle spark position, approximately 25.4 cm or 50.7 cm from the compartment floor.

Gas mixture composition measurements were examined at two locations within each experiment's compartment. Three sets of different locations were selected as positions of interest: one in the center of the upper (90.0 cm) and middle (49.5 cm) vertical layer of the compartment, another approximately 5 cm above (56.0 cm) and below (46.0 cm) the middle spark igniter, and another above (32.0 cm) and below (22.0 cm) the low spark igniter.

Extracted gas samples were portioned into a gas analyzer and phi meter. The gas analyzer includes a paramagnetic sensor to provide real-time $O_2$ concentration measurements. A chiller was positioned upstream of the gas analyzer to remove water vapor, indicating that all oxygen concentration measurements were obtained on a dry basis. A phi meter [10] was implemented to evaluate the extracted gas sample’s global and local equivalence ratios.

Temperature measurements were obtained across the various heights of the compartment opening using four 24.8 cm long Type K thermocouples positioned approximately 62.0 cm from the compartment opening. The heights of thermocouples span 19.7 cm to 79.4 cm from the compartment floor and are spaced approximately 19.9 cm apart. The temperature measurements are utilized to determine the temperature of an extracted gas sample via a linear regression fit at the corresponding height.

Backdraft experiments were initiated when the sand burner, fed fuel via mass flow controller, was ignited using a propane wand (t=0). Initially, the fire burns while the compartment doorway remains open for 60 s (t=60). After the front doorway was closed, fuel continued to be fed into the sand burner until a predetermined fuel flow time (FFT) was achieved (t=FFT). The flame was observed via borescope to extinguish at approximately

200 s from the ignition time, most likely due to limited ventilation. After the fuel flow time was achieved, the doorway remained closed for an additional 30 s, after which the doorway opened (t=FFT+30), and a backdraft was potentially observed.

Backdraft measurements generated from gaseous fuels were obtained from three controlled methane fires and three propane fires. A list of fuel flow times for each fire configuration is provided in Table 1. The uncertainty for all fire sizes was approximately 1.0 kW.

**Table 1.** List of fuel flow times for each fire configuration

| Fuel | Fire size (kW) | Fuel flow time (s) |
|---|---|---|
| Methane | 25.0 ± 1.0 | 360, 390, 420, 450 |
| | 31.3 ± 1.0 | 300, 360 |
| | 37.5 ± 1.0 | 240, 270, 285, 300 |
| Propane | 16.7 ± 1.0 | 270, 300, 315, 330 |
| | 20.9 ± 1.0 | 210, 225, 240, 285 |
| | 25.0 ± 1.0 | 240, 270, 285, 300 |

All temperature and gas mixture composition measurements are sampled at 1 Hz using a data acquisition system during an experiment. Measurements were averaged over a 10 s interval before the compartment doorway opening. The time-averaged measurement's combined uncertainty is estimated from a combination of the Type A and B evaluations of standard uncertainty. Uncertainty analysis of the time-averaged measurements is provided in Ref. [11].

As shown in Eq. 1, the binary logistic regression model [12] uses time-averaged temperature, $\overline{T}$, global equivalence ratio, $\bar{\varphi}_G$, local equivalence ratio, $\bar{\varphi}_L$ , and oxygen concentration, $\overline{X}_{\mathrm{O}_2}$, measurements of the extracted gas to output the likelihood of a backdraft, using a probability of 0.5 as the threshold.

$$p\left(\bar{T},\bar{\varphi}_G,\bar{\varphi}_L,\bar{X}_{\mathrm{O}_2}\right)=\left[1+e^{-\left(\beta_o+\beta_1\bar{T}+\beta_2\bar{\varphi}_G+\beta_3\bar{\varphi}_L+\beta_4\bar{X}_{\mathrm{O}_2}\right)}\right]^{-1};\ p\left(\bar{T},\bar{\varphi}_G,\bar{\varphi}_L,\bar{X}_{\mathrm{O}_2}\right)\geq 0.5\ \text{Backdraft} \qquad (1)$$

The model was established using a machine learning software package using R software [13]. Compartment configurations (i.e., fuel, fire size, spark igniter location, etc.) are neglected since the model's purpose is to demonstrate an ability to predict backdraft without anticipating uncontrollable factors contributing to the phenomenon.

## Results and Discussion

Figures 1 and 2 display the time-averaged temperature, global and local equivalence ratios, and oxygen concentration measurements for various sizes of methane and propane fires. When plotted as a function of fuel flow time for each fuel, the time-averaged temperature measurements are shown to decline. The decrease in temperature is most likely due to the increased duration between the flame extinguishing and door opening.

The time-averaged global and local equivalence ratios increase with fuel flow time in instances where the parent fuel is methane. The local equivalence ratio is fairly constant in the middle region of the compartment (approximately 50.0 cm from the compartment floor) for most methane fire configurations. Time-averaged oxygen concentration measurements are also nominally constant at different heights within the compartment for different fuel flow times, with the highest concentration observed at the lowest sampling position.

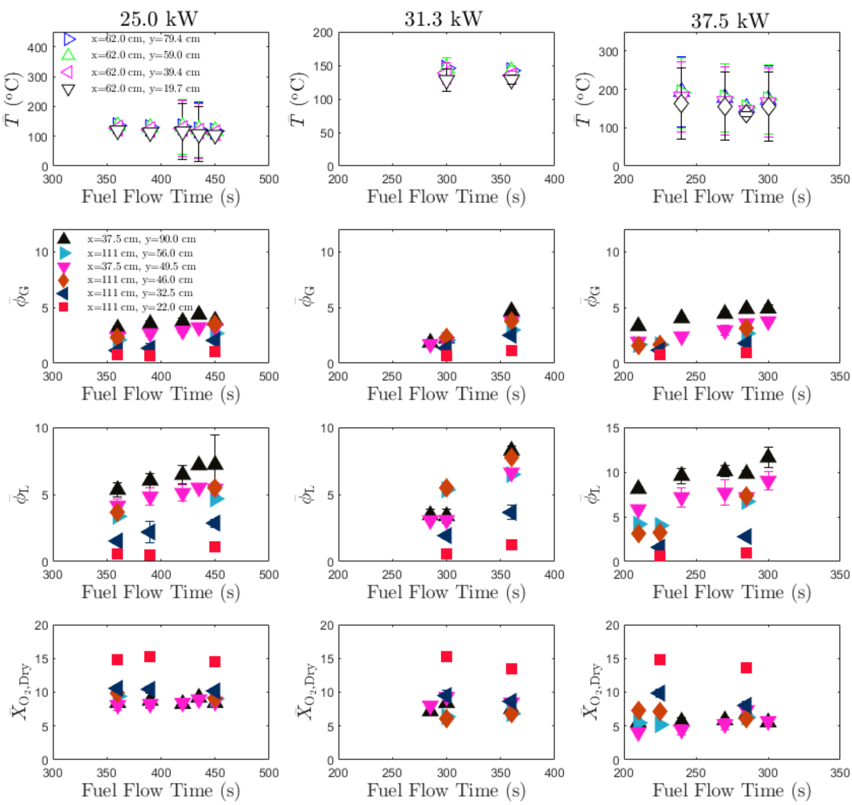


**Figure 1** Time-averaged temperature and gas mixture composition measurements of the 25.0 kW, 31.3 kW, and 37.5 kW methane fires as a function of fuel flow times at different positions within the compartment.

Contrary to methane experiments, the time-averaged global equivalence ratio measurements obtained in experiments with propane fires are lower and are observed to converge to an approximate value as the fuel flow time increases. The time-averaged local equivalence ratio measurements vary, suggesting that the fuel disperses throughout the compartment. The variation in the local equivalence ratio is further supported by the oxygen concentration measurements, which are also shown to vary at different heights within the compartment.

The time-averaged measurements were implemented in a binary logistic regression model, as shown in Eq. 1. When compared to the backdraft outcomes of the experimental dataset using a single-point reading, the model's accuracy was observed to correctly predict the potential for a backdraft in 70.8% of the total experiments. The model's accuracy is the sum of all true positive and negative predictions over the total number of experiments. Calculated probabilities in the model greater than 50% were designated backdraft events.

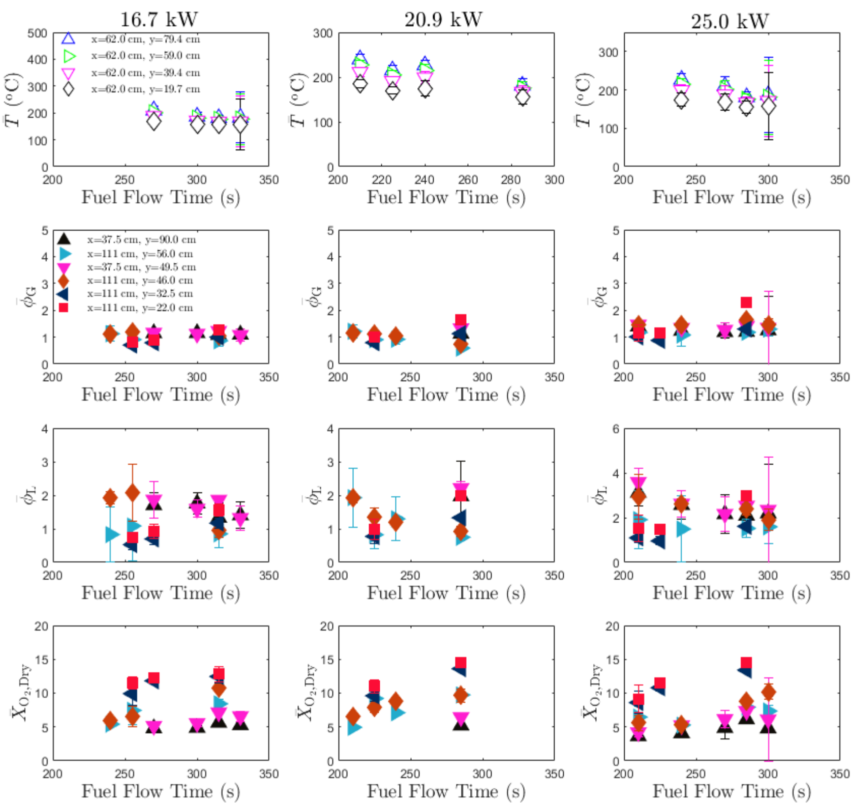


**Figure 2** Time-averaged temperature and gas mixture composition measurements of the 16.7 kW, 20.9 kW, and 25.0 kW propane fires as a function of fuel flow times at different positions within the compartment.

The model's accuracy was tested using a combination of measurements. Table 2 displays the model's accuracy as more measurements are included. Measurements selected for removal correspond to the absence of specific instrumentation. For example, the local equivalence ratio cannot be measured without knowing the oxygen concentration at the phi meter's inlet, which is obtained using an external gas analyzer. As fewer measurements are incorporated into the model, its accuracy decreases.

**Table 2** Logistic regression model's accuracy incorporating varying measurements

| Global Equiv. Ratio | Inlet Temperature | Inlet $O_2$ Concentration | Local Equiv. Ratio | Accuracy |
|---|---|---|---|---|
| X | X | X | X | 70.8% |
| X | X | X | | 70.5% |
| X | X | | | 29.4% |
| X | | | | 29.4% |

The model with all components was re-evaluated by incorporating two measurements obtained at different positions. When compared to the backdraft outcomes of the experimental dataset, the two-point model's accuracy was observed to correctly predict the potential for a backdraft in 82.4% of all cases. The greater accuracy of the two-point model indicates that the backdraft evaluation system is improved by increasing the number of sampling positions at various heights within the enclosed structure.

## Conclusion

This work presents a binary logistic regression model that utilizes temperature and gas mixture composition measurements to predict the likelihood of backdraft. The approach described here is implemented using a phi meter that evaluates global and local equivalence ratios with oxygen concentration and temperature measurements of the extracted gas. The developed model demonstrated 70.8% accuracy with all measurements incorporated from a single sampling position. The model's accuracy was observed to decline with the absence of measurements. The method described herein demonstrates a quantifiable technique that predicts backdraft and provides firefighters with a way to reduce the risk.

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