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Capturing the Fire Whirls Heights and Rotational Speed by High Speed Camera

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Abstract

Fire whirls are destructive, natural occurring phenomena in urban and wild land fires, where the prediction of their erratic behaviour is of great interest to firefighters. To predict the fires, a visual-based investigation of laboratory-scale fire whirls has been conducted to demonstrate that precise flame data from a high speed camera can also give additional information, such as the fluctuation frequencies and the rotational speed, by numerically processing the data from the high speed camera. The numerical process consists of GIMP, an image manipulation software, Visual Basic for Applications (VBA) codes, and Fast Fourier Transform (FFT). In running the experiments, independent parameters considered are the position of the split cylinders and the pan size. Through the analyses, the following characteristics have been observed: Fire whirls in the experiments rotate between 22 and 126 radian per second, which have no correlation with the flame height. Whenever pool fires transform to fire whirls, there is a large increase in flame height. FFT frequency analysis shows that pool fires have a dominant frequency at 11 Hz, while fire whirls have no dominant frequency. The multi-frequencies nature of fire whirls is due to the vortex flow, which breaks the flame into multiple ribbons and peaks.

Keywords

Fire whirls, Scale Modelling, High Speed Imaging, Numerical Processing

Introduction

This paper outlines a relatively simple approach in using the high speed camera to measure the flame height and rotational speed of fire whirls. The approach has the potential of being developed into a digital application for fire research.

Fire whirls are destructive natural occurring phenomena in urban and wild land fires. They occur when intense rising heat and favourable wind conditions combine to form a whirling eddy of fire and air. The eddy tightens into a tornado like structure, absorbing gust, burning debris and combustible gases while burning them all. In a review paper, Forthofer and Goodrick (2011) examined the vortex-driven phenomenon in great details.

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The research aims to develop a safe and effective method for fire whirl prediction and containment, and the objective of this paper is to obtain the transient dynamics of fire whirls using scale modelling and high speed imaging, with the goal of developing a dynamic model. Previous models of fire whirls (Snegirev et al., 2004, Zhou and Wu, 2007, Chuah and Kushida, 2007, Lei et al, 2011, and other Chuah et al., 2011 derived models) are limited in explaining the transient effects of fire whirls, as the models assume that the fire whirl phenomenon is steady or quasi-steady.

To capture transient data, both high speed imaging and intelligent software processing are necessary. This paper presents a visual-based data analysis based on the available laboratory test data to derive the flame height and rotational speed of fire whirls.

Theory and Methodology

In order to measure the fire whirls height and rotational speed, experiments have been conducted at the laboratory scale using a standard CCD high speed camera and a data acquisition system. Laboratory-scale fire whirls are representative models of real fire whirls, scaled down in size for cost and safety consideration as well as for the ease of controlling the experiments.

In scaling down the experiments, it is important to consider the physics in terms of dimensionless numbers. First, the chemical reaction rates are not affected by the scale as they are much faster than the transport phenomena. The slower transport phenomena however is a balance between the inertial force and the diffusion force (or the equivalent turbulent mixing force). The ratio of these two forces is the Peclet number (Pe).

Based on Burke-Schumann flame theory, combustion occurs at the flame front between the fuel zone and the oxidation zone (1928). The rate of diffusion of gases from the two zone determines the burning rate, which in turn determines the flame length.

With the introduction of whirl to the fire whirls, a new dimensionless parameter, named the vortex strength (α) becomes important as well in controlling the burning rate.

Overall, the fire whirl theory, as derived by Klimenko and Williams (2013), states that: for a flame with a characteristic area of diameter (d), the flame length (L) is linear proportional to Pe, while inversely proportional to α and the fuel strength (Z), where Z, given in terms of stoichiometric fuel-air ratio (f) is:

$$Z = \frac{f}{1+f}$$

The equation can be written as:

$$\frac{L}{d} = \frac{Pe}{8\alpha Z}$$

Figure 1 shows the experimental setup of the system. The experiment apparatus consists of a fire whirls generator, a high speed camera, a number of fuel pans, and alcohol fuels. The fire whirls generator is a fixed-frame type generator (Satoh and Yang, 1997) with two semi-cylindrical walls placed around the fuel pan, where the walls' centre of curvature are offset by a small distance from the centre of fuel pan to form two air gaps between the two walls. Ethanol prepared in the fuel pan represents the source of fire. The high-speed camera captures the flame from the side, measuring the height fluctuation and in directly the rotational speed.

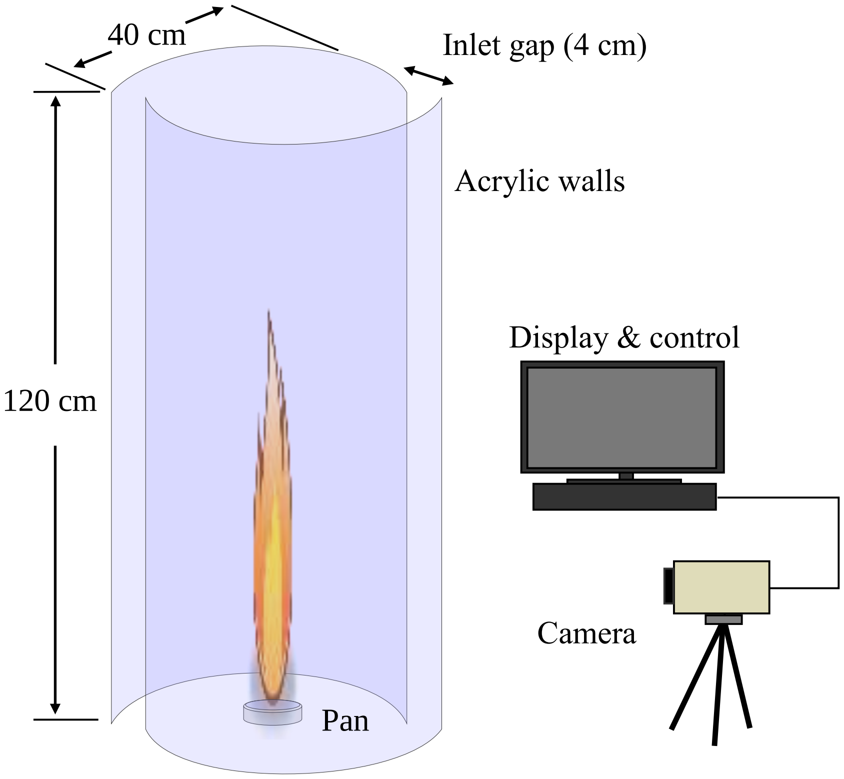

Figure 1. Experimental setup

The visual data obtained from the experiments is a time series of images. The images depict the light intensity from the fire when the rays hit the camera's sensor array. GIMP, an image manipulation software extracts the images from a video, and a plug-in named 'Batch Image Manipulation' performs an RGB to binary black & white colour conversion for each image.

Figure 2 shows the before and after of a sample image conversion. The conversion process involves a weighted averaging of the three channels of light captured, respectively the red, green, and blue channels, followed by a threshold filter at a fixed cut-off value to produce the binary colour output. The converted image are exported to an Excel spreadsheet for further analysis.

Figure 2. Sample fire image conversion (top: original, bottom: processed)

In Excel, the image data is arranged as a series of pixels with a respective (x, y) position for each pixel. The flame height detection algorithm is a line-by-line checking algorithm that finds the first pixel with a value of one (from left to right) for each line, and subsequently, finds the left most pixel of all lines. The distance from the left most pixel to the fuel surface pixel is therefore the flame height in pixel unit, which is convertible to the standard length unit based on the pixel size measured in the experiments. Using Excel's built-in Fast Fourier Transform (FFT), or Fourier analysis, the frequencies of the flame height over time can be obtained.

The process to obtain the rotational speeds is by tracking the fire images frame-by-frame and counting the time intervals. The fire step is to determine the number of frames required for the fire to make one 360 degree turn. From the sequence of images in Figure 3, each recognizable feature of the flame structure is identified and tracked. Some features only last for a few frames before they move behind the flame. Nevertheless, an effective tracking is possible with a combination of several features. With the number of frames Δf determined, and the camera frame rate *f*, the rotational speed is:

$$\omega = \frac{2\pi f}{\Delta f}$$

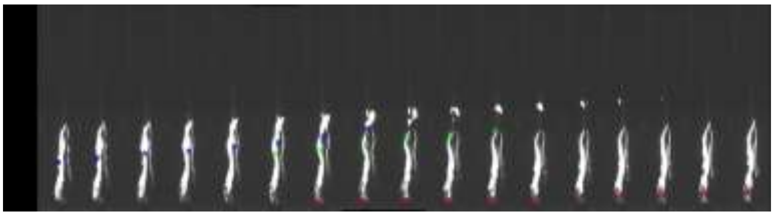

Figure 3. A time series of images from the high speed camera

Results and Discussion

Table 1 is a list of experiments reported in this paper. The fuel is Ethanol, which produces yellow flames with shades of blue slightly above the pan. Experiment 1 performed without the acrylic walls is a pool fire. Experiment 2 and 3 are fire whirls, generated with the acrylic walls placed around the pan and with inlet gap size of 4 cm equally on both side of the walls.

Table 1. Design of Experiments

Experiments	Pan diameter (cm)	Inlet gap size (cm)	Analysis
1	5.8	Pool fire	FFT
2	5.8	4	FFT
3	5.8	4	Rotational speed

Using the method described, fire whirls in the experiments rotate between 22 and 126 radian per second. From Experiment 3, the rotational speed reaches an average speed of 39 rad/s at the beginning before eventually peaks at 126 rad/s. At the peak, the fire whirl is stable, and the average flame height is 40 cm. After the peak, the speed starts to decay.

It is worth noting that at the stage when the fire whirl is forming, the rotational speed fluctuates heavily with a minimum rotational speed of 22 rad/s, a maximum of 59 rad/s, and a standard deviation of 13 rad/s. This is accompanied by a large increase in flame height.

It is also worth noting that at the peak when the fire whirl is stable, the correlation between flame height and rotational speed is -0.141. This suggests that flame height is independent of the rotational speed of the flame.

In Figure 4, FFT frequency analysis shows that pool fires have a dominant frequency at 11 Hz and fire whirls have no dominant frequency. The multi-frequencies of fire whirls are due to the rotational flow, which forms an invisible vortex around the flame. The vortex is sufficiently strong that in the current configuration of the fire whirl generator it breaks the flame into ribbons of smaller flame. Each ribbon moves upward and disappears at various points in height. The ribbon peaks are highlighted in Figure 5.

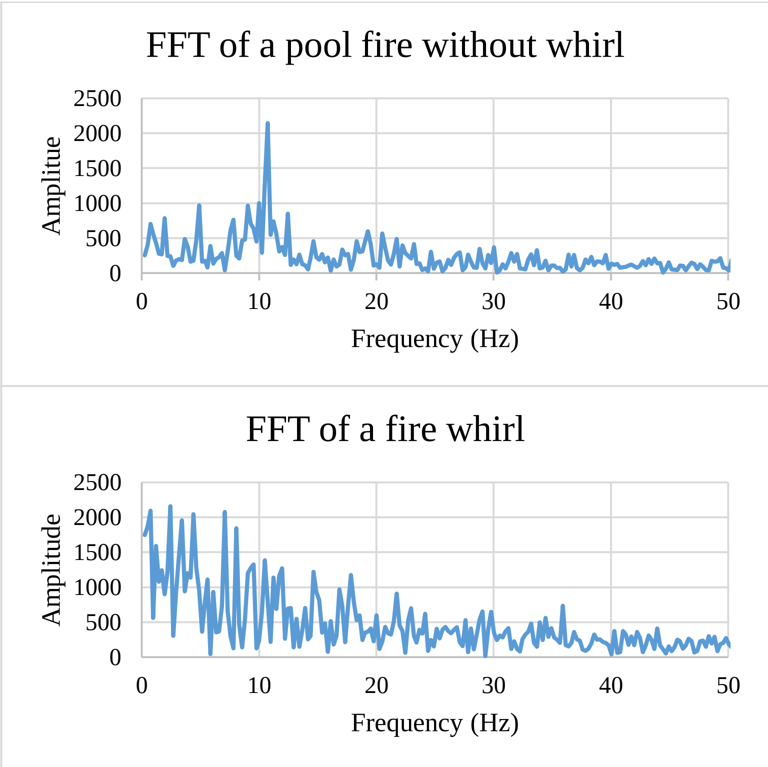

Figure 4. Frequencies of a small-pan fire (top) and a fire whirl (bottom); Fuel: Ethanol

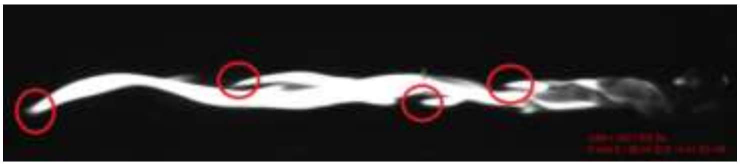

Figure 5. Multiple peaks of fire whirls (Top is on the left; gravity to the right)

Conclusions

It is clear that precise data of the flame structures and the position changes with respect to time can be obtained from a high speed camera. In addition, by numerically processing the data from the high speed camera, the fluctuation frequencies and the rotational speeds can also be obtained. Through the analyses, the following characteristics have been observed: Fire whirls in the experiments rotate between 22 and 126 radian per second, which have no correlation with the flame height. Whenever pool fires transform to fire whirls, there is a large increase in flame height. FFT frequency analysis shows that pool fires have a dominant frequency at 11 Hz, while fire whirls have no dominant frequency. The multi-frequencies nature of fire whirls is due to the vortex flow, which breaks the flame into multiple ribbons and peaks.

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