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A Small-Scale Study of Fire Whirls and Investigation of the Effects of Near-Ground Height on the Behavior of Fire Whirls

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***Abstract*—**In this work, small-scale experiments of fire whirl were conducted to study the spinning fire phenomenon and to gain comprehensive understandings of fire tornadoes and the factors that affect their behavior. High speed imaging was used to track the flames at both temporal and spatial scales. This allowed us to better understand the role of the near-ground height in creating a boundary layer flow profile that, in turn contributes to formation of vortices around the fire, and consequent fire whirls. Based on the results obtained from these observations, we were able to spot the differences in the fuel burning rate of the fire itself as a function of a newly defined specific non-dimensional near-ground height. Based on our observations, there is a cutoff non-dimensional height, beyond which a normal fire can be turned into a fire whirl. Additionally, the results showed that the fire burning rate decreases by moving the fire to a height higher than the ground level. These effects were justified by the interactions between vortices formed by, the back pressure and the boundary layer velocity profile, and the vortices generated by the fire itself.

***Keywords*—**Boundary layer profile, fire whirls, near-ground height, vortex interactions.

I. Introduction

FIRE whirl (also called fire tornadoes) is one of the most dangerous types of fire that are threatening the lives of millions of people all around the world. They can be formed suddenly and unexpectedly and often draw attention as being the most spectacular and devastating fire events. The recent forest fire incidents in California have caused billions of dollars loss, sever damage to infrastructure, and more importantly dozens of deaths as the results. In addition to the US, Japan has been targeted by these fires many times. For instance, one big fire tornado happened in Great Kanto, Japan as result of an earthquake on September 1, 1923, and as the result, an estimated 38,000 people were reported dead [1]. Another incident was in Hamburg in 1943 during world war II, where more than 30,000 casualties were reported as the result of the fire tornado caused by the widespread bombing [2]-[4]. These fires have also seen many times in different parts of the United States. For example, more 1000 people died in the Chicago and Peshtigo fires on October 8, 1871 [2]. They have usually been seen rotating, spinning and swirling to some height levels and forming a huge cylinder shape made by fire. Some can be extremely devastating, moving and causing the fire to spread quickly and to a large distance ahead of the core of fire whirl itself [5]-[9]. This phenomenon can intensify the fuel burning rate in the normal fire; so as to speed up involved reactions and spread very quickly. This makes it extremely hard, dangerous and sometimes impossible for firefighters to deal with.

For many years, these fire whirls and their physics have been vastly studied theoretically and experimentally by many researchers. The utmost missions in these studies were to find the possible reasons and factors that are contributing in forming these fires and to predict the occurrence. Many researchers have been working on this phenomenon and published many experimental investigations on scaling fire whirls using split cylinders [10], [11] and fixed-frame apparatus [12]-[20] to explain the role of velocity profiles, the burning rates, and flame heights on the fire behavior. As an example, Thomas [21] suggested that the burning rate parameter is essential for the length of a diffusion flame driven by buoyancy. Despite the importance of understanding this phenomenon and finding possible ways to control and manipulate the fire, the root causations are still poorly understood and its mechanism is still left unknown, as acknowledged in the recent literature review [22]. Therefore, in the present work, the authors intend to fully investigate one possible reason for this phenomenon on a small-scale fire whirl setup. The authors study the differences caused in the fire due to this factor and propose non-dimensional near-ground height, which is required for the fire whirls to form. This will help future studies to understand this phenomenon better and study that in more details.

II. Experimental Setup

In this work, a small-scale laboratory setup was used to form and study the stationary fire whirls by implementing scale modelling concepts. Fig. 1 illustrates the setup for the present study. The setup consists of a base, which has a square cross-section of 50.8×50.8 cm and is 16.5 cm in height and the top, which has a cross of square of 30.48×30.48 cm and is 120 cm in height. Note that the top has two slits in two of the edges and slightly rounded edges for the other two for better circulation of air inside the setup, as shown in Fig. 1.

As it can be seen from Fig. 1, the setup has two narrow slits (shown by red rectangles A and B surrounding the slits) on two sides of it, which are the air entrances. Meanwhile,

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the fuel container was placed in the middle of the setup. Having fire in this specific setup, the fire tornado would appear after a short time after igniting the fuel. A fire whirl consists of a burning core and a rotating pocket of air. Whirling eddies of incoming air from the slits lead to the rotation of the hub for the setup, which subsequently causes fire whirls to form. The small pit of fuel with diameter of 11 cm was placed in the middle of the setup, where it is leveled with the column bottom by creating and placing it into a hole. For each of the experiments, a mix of fuel and water was poured in the pit. Due to its affordability and safety advantages, Hexane was chosen as the fuel for all the experiments. Regardless, it has been proved that the fuel selection has less impact on fire propagation for this setup [15]. A normal aluminum tape was used to tape the slits to the desired heights. To simplify the task of blocking the two air entrances, one of them was totally taped before starting the experiments and the other one was left intact to allow changes in the height over the course of the study.

Fig. 1 Small-scale experimental setup (a) front view, (b) back view

A Phantom Miro Ex4 camera (Vision Research, USA) equipped with an f = 105 mm Sigma (Tokyo, Japan) lens was used to capture images of the fires in all the experiments of this work. The camera was placed in a collapsible camera mount, with a smooth stabilizer in front of the setup to omit all possible errors. With the help of a computer, the video was observed simultaneously with the experiments to assure of the accuracy of the results. It is noteworthy to mention that primary experiments showed that there was no difference between the fire behavior when working with either one open slit or both. Nevertheless, further investigations will be presented here to unfold the physical phenomena behind these observations.

III. Results and Discussion

In this section, effects of near-ground height and the possible vortices associated with that have been investigated in detail. For this purpose, the slit in the back side of the setup was completely covered with a tape during all the experiments and the front side was left open at the beginning. For changing the height of the entrance, the front side slit was taped from the bottom to the certain desirable height each time. Table I shows the different heights (in cm) considered for investigation at each of these experiments. The third column in the table shows the non-dimensional numbers for these heights. The fuel pit is a circular shape container with diameter of 11 cm, which is further used as a characteristic length to obtain the non-dimensional height values. It should be noted that from here all the numbers are presented in non-dimensional format based on the diameter of the fuel pit unless otherwise is stated. Note that the back-side slit was 120 cm, which is equivalent to 10.91, and stayed fully blocked in all experiments of this work. Thus, these two numbers are not presented in the table below. This table presents the data both as dimensional numbers and the associated dimensionless numbers. For each of these experiments, 20 ml of fuel was burned, and it was kept constant to dismiss the impact of fuel on fire behavior. The time for each of these experiments was recorded exactly from the ignition until the fire is extinguished. An extra experiment was carried out with the pit of fuel outside the experimental setup. In this case, we expected a pit fire to happen, as there were no suitable conditions for the fire whirl, and the result was as expected. This experiment served as the benchmark work for the other successive experiments.

TABLE I
The Taped Height in Different Experiments Conducted in This Study

Front Side Blockage (Cm)	Non-Dimensional Front Side Blockage
0	0
5	0.45
7.5	0.68
10	0.91
15	1.36
20	1.82
25	2.27
30	2.73
35	3.18
120	10.91

Figs. 2 (a) and (b) show the fire formed in two different cases. In (a), the fire tornado is formed when one slit was totally open, while (b) presents the type of fire that was formed when both slits were totally taped, which is, as discussed, behaves like a pit fire, however, with some slight differences. In this case, there were marginal pulsing and it is believed that these pulsations are mainly due to non-uniform nature incoming air stream and subsequent flame form.

Fig. 2 Fire which was formed, (a) when one slit was totally left open, (b) when both slits were totally taped

The significant effects of the covered slit height, however, can be seen more clearly in Fig. 3, where the fire tornado formed in two different cases are compared. This figure shows the difference between the maximum height achieved by the fire in two different cases of height factor of 1.36 and 3.18. Fig. 3 (a) shows that in case of $\hat{H} = 1.36$, there is still a strong fire tornado formed in the setup. In the 3.18 case, presented in (b), however, the fire whirl has some features of wandering fire as well instead of being a strong fire tornado. The pulses in fire tornado of case 3.18, were more frequent than the ones with 1.36, which is believed to be behind the fire being weaker. In general, this behavior was observed in for cases with higher heights. Additionally, the maximum height achieved by the fire whirl, which is considered to be one of the factors of the fire strength, has changed significantly in different investigated cases. For instance, the fire height was recorded to be 81.3 cm, 72.5 cm, 49.8 cm and 18.1 cm for cases of 0, 1.36, 3.18 and 10.91, respectively. By taking a closer look, for instance, blocking the slit height from fully open to case 3.18 (about 29% of the setup height), the maximum fire height was changed about 39%.

Fig. 3 Fire which was formed for cases with height factor of 1.36, (a) and, 3.18, (b)

Fig. 4 presents the results for time that the fire takes to burn all the fuel as a function of height factor for different study cases. The experiments have been repeated 10 times and, these data are averaged out of 10 different sets of experiments for the same cases. The dots show the times for different cases, while the solid line is the time for a normal pit fire when putting the pit outside of the whole setup. As it can be seen in the figure, the time was increased as the blockage height was increased. However, the burning time was less than the time for a pit fire in all of the cases. This could originate from the pulsations in the fire with fully closed setup, as discussed in the above section, which makes the fire slightly similar to a fire tornado. From this figure, the slope of the graph was increased dramatically at $\hat{H} = 2.73$. This shows that beyond this height, the fire was weakened considerably. In addition, by incorporating the high-speed imaging videos captured from the experiments, it was further concluded that beyond this height, fire behavior manifests some characteristics of wandering fire, combined with some with fire tornados. The most significant difference is the pulsing in the fire after this height.

Fig. 5 clarifies the conclusions from Fig. 4, by presenting the fuel burning rates for all different cases in these experiments. Again, the dots show the data for different experiments and the solid line shows the fuel burning rate of a normal pit fire, while the fuel container was placed outside the whole setup. As it can be seen from this figure, the fuel burning rate was decreased gradually as the blockage height was increased for all the cases. In all these cases, the fuel burning rates were greater than the fuel burning rate of a normal pit fire, thus the fire was always burning more fuel than the normal pit fire. Fig. 5 emphasizes that the fuel burning rate of the fire decreased more significantly after $\hat{H}$ = 2.73, as the graph's slope has changed dramatically, which confirms the theory of new features exhibition from the fire proposed in this work. Note that in Fig. 4 and Fig. 5, the data were not shown after $\hat{H}$=3.18, as the fire showed almost the same burning rate and burning time.

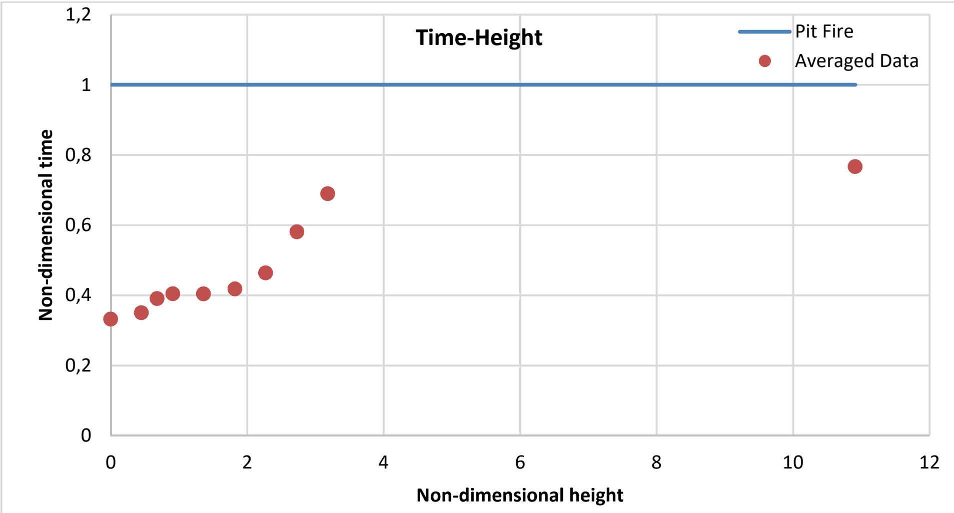

Fig. 4 Non-dimensional fire burning time versus blockage height factor

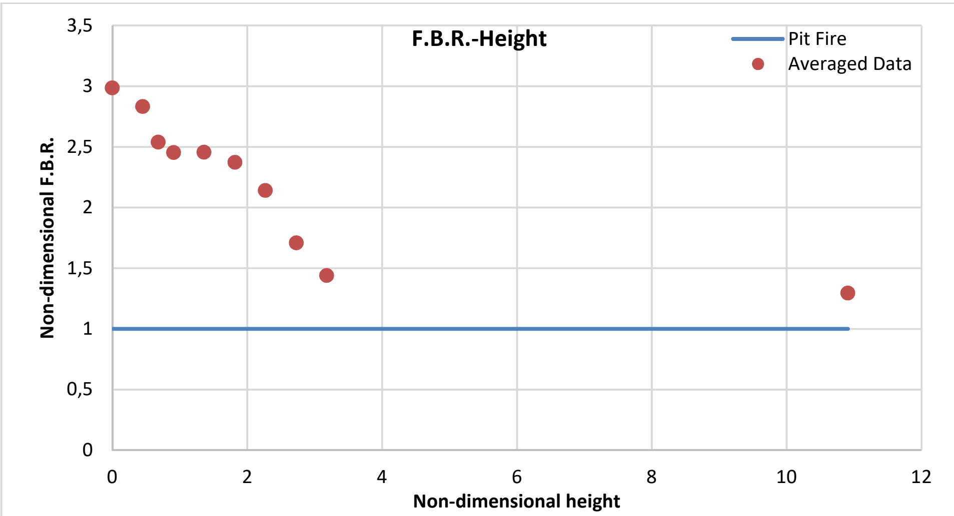

Fig. 5. Non-dimensional fuel burning rate versus blockage height factor

Note that in Fig. 5, the fuel burning rate was calculated by dividing the amount of fuel in the pit by the time that the fire was burning the fuel and then was non-dimensionalized by the pit fire fuel burning rate.

Using the diameter of the fuel pit, one can compute the non-dimensional value $\hat{H}$=H/D with D, the pit diameter and H, the blocked near-ground height), which is believed to be one of the crucial factors in controlling the type of fire. This value defines a critical height from the ground to the first place where the boundary layer forms and drives a normal fire to form a fire tornado, if all other conditions are met. In addition, it is firmly believed that by employing this non-dimensional parameter, the results of this study can be extended to any other case of fire in the real world, where fire whirls are created in forests and expended through urban areas. As the result of this study, cutoff height factor $\hat{H}_c$ was concluded to be 2.73, and for values higher than that, no fire whirl can be formed; instead, wandering fire with less fuel burning rate can be anticipated. For even greater values of the height factor, the fire may act like a pit fire with slight pulsations.

IV. Conclusions

Small-scale experiments on stationary fire whirls were conducted to investigate effects of near-ground height as a possible factor causing and controlling the physical attributes and fuel rate consumption of fire whirls, and in turn, fire extinguishing time. In agreement with the offered hypothesis, it is concluded that as the near-ground slit was blocked and height factor ramped up, the fire whirls formation time increased and the fuel burning rate of the fire decreased. Thus, the time for the fire to burn the given amount of fuel was, thus, increased. This confirmed that the vortices formed due to ground boundary layer are really important factors in forming these fire whirls. In addition, by increasing the height factor beyond a certain point, the fire whirl started to show some characteristics of a wandering fire, while on the other hand appeared to show some attributes of a fire tornado. This again confirmed that without those vortices, there cannot be a fire whirl and, thus this factor plays an important role in forming and controlling fire tornadoes. Further studies need to be done to understand this phenomenon with more details and other possible factors contributing to the fire tornado formations and behaviors. It is strongly expected that these conclusions can be easily extended to a real-world and with bigger size fire tornado in light of scale modelling analysis.

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