Scaling laws of flow structures around geometrically similar fire whirls

Rikiya YAMADA* and Kazunori KUWANA*
*Department of Chemistry and Chemical Engineering, Yamagata University
4-3-16 Jonan, Yonezawa-shi, Yamagata 992-8510, Japan
E-mail: kuwana@yz.yamagata-u.ac.jp

Received: 8 February 2019; Revised: 6 May 2019; Accepted: 16 May 2019

Abstract
This paper discusses the scaling laws of the flow structures around geometrically similar fire whirls, an insight that will be necessary when applying laboratory-scale data to real-scale fire whirls in urban or wildland fires. A fixed-frame-type fire-whirl generator is used to form geometrically similar fire whirls of three different scales. A particle image velocimetry (PIV) technique is used to measure the tangential (rotational) and the radial velocity components around the fire whirls. Scaling analysis is then conducted to derive two pi numbers, namely, the Reynolds number and the Froude number. Measured tangential velocity distributions are nearly uniform in the vertical direction when the height from the floor is greater than ~1 cm, where the velocity profiles are found to be well correlated using the Froude number, suggesting that viscosity plays only a minor role. Near the floor, on the other hand, the magnitude of tangential velocity is reduced, leading to an enhanced radial inflow toward the flame, a phenomenon similar to the Ekman layer. This inflow layer pushes the flame toward the fuel surface, increasing the heat input from the flame to the fuel and hence the burning rate. It is found that the Froude number can also correlate the radial velocity distributions near the floor.

Keywords: Fire whirl, Tangential velocity, Radial velocity, Scaling law, Dynamic similarity, Froude number

1. Introduction
Devastating damages caused by fire whirls during urban and wildland fires (see, e.g., Emori and Saito, 1982; Soma and Saito, 1991) led to extensive research of them (Forthofer and Goodrick, 2011; Tohidi et al., 2018). Since the increased flame heights of fire whirls are a key factor that caused such damages, a number of studies have been conducted to understand the mechanisms of flame-height increase. It is now established that an increase in flame height is associated with an increase in burning rate (Chuah and Kushida, 2007; Chuah et al., 2009; Kuwana et al., 2011; Lei et al., 2012; Dobashi et al., 2016). A major mechanism that causes the increase in burning rate is the presence of an enhanced radial inflow, which pushes the flame toward the fuel surface, increasing the heat flux from flame to fuel and hence the evaporation rate. Figure 1 compares flame-base structures of an ordinary pool fire and a fire whirl; the flame base of the fire whirl appears to be closer to the fuel surface than that of the pool fire.

Emmons and Ying (1967) pointed out a fluid-mechanic effect that induces a radial inflow; “[t]he ground slows the rotational motion of the air and, therefore, the imposed radial pressure gradient pushes the boundary layer air toward the axis,” a similar phenomenon to the Ekman layer. An enhanced radial inflow near the ground is necessary to generate an intense fire whirl. PIV measurements conducted by Hartl and Smits (2016) and Sasaki et al. (2018) clearly captured the presence of inflow layers. In most previous studies, however, the fire-source sizes were fixed, and the scaling law of the flow structure remains unclear although it is of great importance when applying insights obtained by laboratory-scale experiments to real, large-scale fire scenarios. In this paper, we study scale effects on the flow structure around a fire whirl with an emphasis on whether a dynamic similarity holds satisfied among geometrically similar fire whirls.
Fig. 1 Flame base structures. Left, an ordinary ethanol pool fire of 3 cm in diameter; right, a fire whirl over an ethanol pool of the same size (Kuwana et al., 2011. Copyright © 2010 The Combustion Institute. Published by Elsevier, reprinted with permission).

Fig. 2 Experimental setup. (a), configuration and a PIV image ($d = 10$ cm, $z = 25$ cm) for measuring the tangential velocity component; (c) and (d), definition of the $r$ and $z$ directions, respectively, along which velocity was measured.
2. Experimental method

A similar experimental setup to our previous study (Kuwana et al., 2011) was used (Fig. 2). A pair of half-cut cylinders with axisymmetrically-placed slits was used to create a spinning flow by entrainment due to the buoyant, upward flow from a fire source. The inner and the outer diameters of the cylinder are 39 and 40 cm, respectively, while its height is 100 cm. At the center of the cylinder, a methanol pool fire was embedded in such a manner that the top rim of the container was flush with the floor. Methanol was used because its weak emission of light was expected to improve the accuracy of particle image velocimetry (PIV) measurement. Three different pool sizes (inner diameters, \( d \), of 6, 10, and 20 cm) were tested with the scale ratio of 3:5:10. The slit distance, \( s \), was adjusted such that geometrically similar fire whirls were generated, specifically \( s = 14 \) cm for \( d = 6 \) cm, \( s = 8 \) cm for \( d = 10 \) cm, and \( s = 5 \) cm for \( d = 20 \) cm. The average visible flame heights were then about 30, 50 and 100 cm, respectively. It is ideal to use geometrically similar half-cut cylinders of three different sizes for the scale-model experiment. Nevertheless, this similarity requirement is not imposed in this study because the flow far outside the flame is nearly a free vortex, and therefore the cylinder diameter does not cause significant influences on the flow structure as long as it is large enough. The cylinder height, on the other hand, should be greater than the flame height to maintain a uniform spinning flow up to the flame tip. The cylinder size was determined based on these considerations.

The tangential velocity component, \( v_\theta \), at various heights, \( z \), from the floor was measured along the \( r \) direction shown in Fig. 2(b) using a similar PIV method to that described in Sasaki et al. (2018). The \( r \) direction was chosen because it is least affected by the presence of the slits. A smoke generator was used to provide fine smoke particles (average diameter, 10 \( \mu m \)) by vaporizing a glycol solution. The particles were generated into a tank placed approximately 2 m away from the slit at the same level as the floor, and they were entrained into the measurement area by the pressure difference through a pipe connecting between the tank and the slit. The particles were then illuminated by a 450 mW Nd:YVO4 laser sheet. A highspeed camera with a bandpass filter recorded images of illuminated particles at 400 frames per second for a period of 10 seconds. A distribution of the tangential velocity component along the \( r \) direction was obtained from each pair of consecutive frames, and then the average distribution over the 10 seconds was computed. The radial component, \( v_r \), near the floor was similarly measured along the \( z \) direction (with its origin at the edge of the pool) defined in Fig. 2(c). Note that the tangential velocity component was measured only for pool diameters \( d = 6 \) and 10 cm because the hot plume from the fire whirl of \( d = 20 \) cm interfered the highspeed camera. On the other hand, the radial velocity component was measured for \( d = 6 \), 10, and 20 cm. For measuring the tangential velocity component, smoke particles need to stay within the laser sheet during the time period of 1/400 s of each frame. Based on the velocity data measured by Hassan et al. (2005), the upward velocity is estimated to be mostly less than 0.4 m/s with the maximum value about 0.5 m/s. The thickness of the laser sheet was 1 mm, which is in most part enough for smoke particles to stay within the sheet, although a relatively large error may be caused near the flame where the upward velocity is large. It should be noted that experimental errors tend to be large inside the flame because of the difficulty in supplying particles there due to the evaporation of particles and also because of the light emission from the flame.

3. Results and discussion

3.1 Tangential and radial velocity distributions

Figure 3 shows the average tangential velocity distributions of five different tests for \( d = 10 \) cm at \( z = 25 \) cm. Each profile has a Rankine-type, combined-vortex structure, i.e., a forced vortex in its central core and an outer free vortex. In this study, measured tangential velocity distributions were fitted by the Burgers vortex, an exact solution to the Navier-Stokes equation,

\[
v_\theta = \frac{\Gamma}{r} \left(1 - e^{-r^2/c^2}\right)
\]

where \( \Gamma \) is the circulation, and \( c \) the core radius, both of which were treated as fitting parameters. The values of \( \Gamma \) and \( c \) were obtained by the method of least squares. It was found that most data points were within ±10% of the best fitting curve except near the central axis (\( r \approx 2 \) cm). Experimental errors tended to be large in the near-axis region.
because of the difficulties mentioned above. Nevertheless, the experimental errors there do not cause significant influences on the discussion below because the peak of tangential velocity was captured outside the flame, enabling fitting by Eq. (1). A similar observation was reported by Hassan et al. (2005).

Figure 4 shows best fitting curves obtained at various heights from the floor. Tangential velocity is nearly uniform in the $z$ direction except near the floor ($z \lesssim 1$ cm), where the rotational motion is slowed as Emmons and Ying (1967) stated (quoted in Section 1). According to them, the imposed radial pressure gradient then pushes the boundary layer air toward the axis. Figure 5 shows the measured radial velocity distributions along the line of $z$ defined in Fig. 2(c) for four different tests, together with the average and the standard deviation. The data for each test is the time average over a period of 10 seconds as mentioned above. Note that a negative value of $v_r$ corresponds to a flow toward the axis. The data accuracy was found to be about ±5 cm/s although errors tend to be large near the floor ($z = 0$) where it was difficult to steadily provide seeding particles. Nevertheless, it was clearly observed that there is a boundary layer in which $v_r < 0$, in other words, there exists a flow toward the axis. The layer thickness was less than about 5 mm, and capturing this thin layer requires special attention to it. Experimental data presented thus far confirm the presence of a thin inflow layer near the floor that was induced by the reduction in tangential velocity.
3.2 Dynamic similarity

There must be a balance among inertial, buoyancy, and viscous forces. If the balance between the inertial and the viscous forces is important, then the distributions of tangential and radial velocity can be written in the following dimensionless form,

\[
\frac{v_\theta d}{\nu} = f_{Re,\theta} \left( \frac{T}{d} \right), \quad \frac{v_r d}{\nu} = f_{Re,r} \left( \frac{Z}{d} \right)
\]

which is Reynolds-number scaling. Here, \( \nu \) is the kinematic viscosity, and \( f_{Re,\theta} \) and \( f_{Re,r} \) denote certain functions. If, on the other hand, the balance between the inertial and the buoyancy forces is important, the following Froude-number scaling law is obtained.

\[
\frac{v_\theta}{(gd)^{1/2}} = f_{Fr,\theta} \left( \frac{T}{d} \right), \quad \frac{v_r}{(gd)^{1/2}} = f_{Fr,r} \left( \frac{Z}{d} \right)
\]

where \( g \) is the acceleration of gravity.

Figure 6 compares the Reynolds-number and Froude-number scaling laws using tangential velocity distributions along the \( r \) direction defined in Fig. 2(b) for two different pool diameters, \( d = 6 \) and 10 cm. The tangential velocity distributions are compared at the height of \( z/d = 1.5 \), where tangential velocity was found to be uniform in the \( z \) direction (see Fig. 4). It appears that the Froude-number scaling law can better correlate the tangential velocity distributions, suggesting that the buoyancy force is more important than the viscous force. It should be noted that the maximum value of scaled tangential velocity, \( v_\theta/(gd)^{1/2} \), is close to unity, indicating a balance between the inertial and the buoyancy forces.

Finally, Fig. 7 plots radial velocity distributions along the line of \( z \) defined in Fig. 2(c) for three different pool diameters, \( d = 6, 10, \) and 20 cm, to test the Reynolds-number and Froude-number scaling laws. It is apparent that Froude-number scaling can better correlate the radial velocity distributions of different scales than Reynolds-number scaling. The data for \( d = 6 \) and 10 cm appear to be somewhat close in the left figure because the difference in the scaling factor of the Froude number, \( d^{1/2} \), for the two configurations are less than 30%. On the other hand, the scaling factor of \( d = 20 \) cm is more than 80% greater than that of \( d = 6 \) cm. The data for \( d = 20 \) cm thus enabled to clearly capture the difference in the left figure. It is again noted that the maximum of the absolute value of scaled radial velocity, \( v_r/(gd)^{1/2} \), is close to unity. Figures 6 and 7 thus suggest that Froude-number scaling be used to estimate the flow structures around real-scale fire whirls. In other words, this study offers a guideline as to how a scale-model
experiment can be designed to simulate a large-scale fire whirl.

4. Conclusions

Geometrically similar fire whirls of three different scales were created using a fixed-frame-type fire-whirl generator, and tangential and radial velocity distributions have been measured using a PIV method to establish the scaling law of the flow structures around fire whirls.

It was first confirmed, in agreement with previous studies, that the rotational motion is slowed near the floor, and therefore, the imposed radial pressure gradient pushes the boundary layer air toward the axis. This inflow boundary layer is believed to be an important mechanism to generate and maintain an intense fire whirl.

Measured velocity distributions of two (for tangential velocity) or three (for radial velocity) different scales were then compared in dimensionless forms to test the validity of the Reynolds-number and Froude-number scaling laws, Eqs. (2) and (3), respectively. It was found that the Froude-number scaling can better correlate both tangential velocity and radial velocity. The balance between the inertial and the buoyancy forces is therefore more important than that between the inertial and the viscous forces. This study offers methodology to apply laboratory-scale data to predicting the flow structures around real, large-scale fire whirls.

Fig. 6 Scaling of tangential velocity at the height of $z/d = 1.5$. Left, Reynolds-number scaling; right, Froude-number scaling. The ±10% ranges of the best fitting curves are compared.

Fig. 7 Scaling of radial velocity along the line of $z$ defined in Fig. 2(c). Left, Reynolds-number scaling; right, Froude-number scaling. The ranges of the average ± standard deviation are compared.
Acknowledgments

This study was supported in part by Center for Fire Safety Science and Technology, Tokyo University of Science, and in part by JSPS KAKENHI Grant Number 18H01665.

References

Chuah, K.H. and Kushida, G., The prediction of flame heights and flame shapes of small fire whirls, Proceedings of the Combustion Institute, Vol.31 (2007), pp.2599–2606.

Chuah, K.H., Kuwana, K. and Saito, K., Modeling a fire whirl generated over a 5-cm-diameter methanol pool fire, Combustion and Flame, Vol.156 (2009), pp.1828–1833.

Dobashi R., Okura, T., Nagaoka, R., Hayashi, Y. and Mogi, T., Experimental study on flame height and radiant heat of fire whirls, Fire Technology, Vol.52 (2016), pp.1069–1080.

Emmons, H.W. and Ying, S.J., The fire whirl, Proceedings of the Combustion Institute, Vol.11 (1967), pp.475–488.

Emori, R.I. and Saito, K., Model experiment of hazardous forest fire whirl, Fire Technology, Vol.18 (1982), pp.319–327.

Forthofer, J.M. and Goodrick, S.L., Review of vortices in wildland fire, Journal of Combustion, Vol.2011 (2011), Article ID 984363.

Hartl, K.A. and Smits, A.J., Scaling of a small scale burner fire whirl, Combustion and Flame, Vol.163 (2016), pp.202–208.

Hassan, M.I., Kuwana, K., Saito, K. and Wang, F., Flow structure of a fixed-frame type fire whirl, Fire Safety Science, Vol.8 (2005), pp.951–962.

Hayashi, Y., Kuwana, K., Mogi, T. and Dobashi, R., Influence of vortex parameters on the flame height of a weak fire whirl via heat feedback mechanism, Journal of Chemical Engineering Japan, Vol.46 (2013), pp.689–694.

Kuwana, K., Morishita, S., Dobashi, R., Chuah, K.H. and Saito, K., The burning rate’s effect on the flame length of weak fire whirls, Proceedings of the Combustion Institute, Vol.33 (2011), pp.2425–2432.

Lei, J., Liu, N., Zhang, L., Deng, Z., Akafuah, N.K., Li, T., Saito, K. and Satoh, K., Burning rates of liquid fuels in fire whirls, Combustion and Flame, Vol.159 (2012), pp.2104–2114.

Sasaki, T., Igari, M. and Kuwana, K., Fire whirls behind an L-shaped wall in a crossflow, Combustion and Flame, Vol.197 (2018), pp.197–203.

Soma, S. and Saito, K., Reconstruction of fire whirls using scale models, Combustion and Flame, Vol.86 (1991), pp.269–284.

Tohidi, A., Gollner, M.J. and Xiao, H., Fire whirls, Annual Review of Fluid Mechanics, Vol.50 (2018), pp.187–213.