Experimental and Numerical Comparison of Small-scale Gaseous Fire Whirls

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ABSTRACT
Fire whirls can occur during urban fires, especially in intense fires in combustible building structures, and more often in forest or wildland fires. They are a special swirling diffusion flame characterized by significant enhancement in burning rates, flame heights and flame temperatures, along with a strong whirling motion of the flame. This whirling motion can pick up large firebrands and scatter them afar leading to spot fires. Many researchers have published experimental work on small- and medium-scale pool fire whirls and gaseous fuel fire whirls using split cylinders and various fixed-frame apparatus to investigate axial and tangential velocity profiles, axial and radial temperature distribution, burning rates, and flame heights. Likewise, several researchers have attempted to predict the experimental results of fire whirls using different modelling approaches and simulation software.

In this paper, experiments were undertaken to study the dynamics of propane gas fire whirls in a small-scale, square-based, fixed-frame apparatus. Measurements of flame height and temperature profiles (both axial centerline and radial) were made for a low initial momentum burner of 76.2 mm internal diameter. The burner was operated at a volumetric flow rate of 6 dm³/min, which gave a heat release rate of 9.12 kW. Simulations using Fire Dynamics Simulator (FDS 6.6.0) and ANSYS Fluent 17.1 were performed to compare with the experimental measurements. Four separate mesh refinements were employed and four different sub-grid-scale (SGS) turbulence models were tested with FDS. The Deardorff, Wall-Adapting Local Eddy-viscosity (WALE), and dynamic Smagorinsky models, formed stable fire whirls for the two largest mesh refinements.

The temperature profiles were overpredicted at the core of the flame with FDS and underpredicted with Fluent. The FDS simulation prematurely predicts the peak temperature for the axial centreline profile, whereas with Fluent the axial temperature profile matches the general trend of the experimental measurements.

The visible flame height, determined through image processing, was approximately 0.88 ± 0.06 m, which corresponds to a measured temperature of ~500°C. The 500°C temperature contour was used as a rough approximation of the flame height in the numerical simulations. It was found that with Fluent the 500°C contour grew until the fire whirl stabilized and reached the top of the hood at 1.6 m, clearly overpredicting the flame height. The height estimates based on the predicted 500°C contours show a strong dependence on the mesh resolution. This is primarily due to increased instability resulting in more mixing and spreading of the temperature for the coarser mesh size. However, the simulated flame heights show less dependence on the SGS turbulence models.

KEYWORDS:
CFD; modelling; fire growth; firenado; fire tornado; fire whirl; swirling fire.
INTRODUCTION

Fire tornado, swirling fire, and firenado are all terms used to define the spiral formation of a fire whirl. Two recent examples have attracted media attention. The first is a video that recorded a fire whirl in April 2016 at St. Albert, AB, Canada [1]. A fire whirl appeared from a small grass fire, which spread so quickly fire fighters had to flee the site and one had to dive into the nearby lake to escape. The second is a video of a mass fire in August 2016 at Phelan, Southern California, USA in which a fire whirl forced 82 000 people to flee the area [2]. By the end of the day it had consumed 73 km² of vegetation and destroyed hundreds of homes. Disasters such as these have occurred throughout the world for many decades and because of the destructive effects of fire whirls have led to increased investigation of fire whirl formation and dynamics. Morton [3] has discussed the mechanisms that lead to both fire whirl formation and what sustains them. However, full-scale experiments on fire whirls are difficult to perform due to safety, costs and resources. A recent comprehensive review paper has summarized the research findings, primarily from laboratory-scale studies of liquid pool fire whirls and gaseous fuel fire whirls [4]. Many researchers have modelled fire whirls with varying degrees of success. Table 1 lists details of some of the modelling efforts to-date and references the experimental data they attempted to simulate with the type of fire whirl generator (FWG).

| Authors [Ref] (Year) | Experimental [Ref], FWG | Transport model or software | Combustion model | Turbulence model |
|----------------------|-------------------------|-----------------------------|------------------|------------------|
| Satoh & Yang [5] (1997) | Satoh & Yang [6], 4 corner gaps | UNDSAFE-I | None, 20 kW non-uniformly distributed volumetric heat source, no radiation | - |
| Barouk et al. [7] (2000) | Analogous to Satoh & Yang [6], 4 corner gaps | Low Ma form of Navier-Stokes | None, Thermal Element Model (TEM) based on mixture-fraction theory | LES, Smagorinsky with $C_s = 0.14$ |
| Battaglia et al. [8] (2000) | Emmons & Ying [9], Chagier et al. [10], Satoh & Yang [6], imposed circulation | NIST Fire Dynamics Simulator (FDS) | TEM | LES, Smagorinsky with $C_s = 0.14$ |
| Meroney [10] (2003) | Bryant & Martin [11], 2 tangential slits; Satoh & Yang [6], 4 corner gaps | Fluent 6.0 | None, 11.6 kW heat source at base for [11], 20 kW square-based vertical volume for [6] | LES, Smagorinsky-Lilly |
| Matsuyama et al. [12] (2004) | Full-scale Fire Lab at the Building Research Inst., Japan, 4 corner gaps | FDS 3.1 | None, 10, 15 & 20 kW propane burner, mixture-fraction model | LES, Smagorinsky |
| Snojigre et al. [13] (2004) | Room enclosure at Training Centre of the Greater Manchester County Fire Service with 1 door and a ceiling vent | 3D CFD model and code Fire3D, density averaged, low Ma, thermal radiation (Monte Carlo) | Single-step global reaction, reaction rate determined by eddy break-up model | Modified k-ε model |
| Forthofen et al. [14] (2009) | Soma & Sato [15], L-shaped fire in a cross wind (wind tunnel experiment) | FDS 5.0 | None, specified heat-release-rate-per-unit-area | LES, SGS model not listed |
| Hartl et al. [16] (2014) | Di-methyl-ether burner, offset split cylinders | Spectral element–Fourier method [17] | None, heat input using flux boundary conditions | DNS |
| Satoh et al. [18] (2014) | Ilaver & Kyudyakov [19], Hamins et al. [20], Satoh et al. [21–24, and Zhou et al. [25], 4 corner gaps | FDS 6.0 | Mixture-fraction method | LES, SGS model not listed |
| Yuen et al. [26] (2016) | Chow & Han [27] | FDS 6.1.2 | Mixture-fraction method | LES, SGS model not listed |

A successful model should capture both the qualitative and quantitative aspects of a fire whirl. Qualitative observations should include the transition from a buoyant diffusion gas flame to a stable fire whirl, and the stability of the fire whirl. If the qualitative properties of the simulation match experimental observations, then the quantitative properties (flame height, temperature and velocity profiles) should reasonably match the experimental data. The objectives of this study were to compare simulation results from FDS 6.6.0 and ANSYS Fluent 17.1 with data from gaseous fire whirl experiments, to identify limitations of and areas for improvement in the adopted modeling approaches, and to identify limitations in the experimental measurement techniques. The primary focus of this study was on fire whirl formation, stability, temperature profiles, and flame height.

EXPERIMENTAL

The dynamics of propane fire whirls was studied in a small-scale, square-based, fixed-frame apparatus, as shown in Fig. 1(a). The front and rear walls were tempered glass and the two sides were aluminum, all supported in tracks, which enabled them to slide to allow adjustment of the corner air gaps. For the experiments presented in this study, the air gap was set to 457 mm high × 64 mm wide. The base plate had an opening to accommodate gas burners of different diameters. Four low initial-momentum gas burners, each with a burner tube made of
aluminum pipe (50.8, 76.2, 101.6, or 152.4 mm ID) packed with wire wool at the base and then filled with sand to just below the burner rim, were constructed. However, only the 76.2 mm ID burner was used in this study. The mass flow rate, and hence the heat release rate (HRR), was set by a mass flow meter at 6 dm$^3$/min, corresponding to a HRR of 9.12 kW. Temperatures were measured with type K thermocouples, centered in the frame. Eight thermocouples (T1–T8) were positioned at heights of 50, 100, 300, 500, 700, 900, 1000, and 1100 mm above the burner rim. Measurements were made at radial distances of 0 (centre of the burner), 20, 40, and 60 mm. A GoPro HERO4 Silver Camera was used to record the flame shape and height.

Fig. 1. Fixed-frame fire whirl apparatus and simulation geometries

NUMERICAL SIMULATIONS

The most common numerical approaches to fire modelling are RANS (Reynolds-Averaged Navier-Stokes), URANS (Unsteady RANS) and LES (Large-Eddy Simulation). In this study, a LES turbulence model was employed. In LES, the large-scale unsteady energy-carrying geometry-dependent anisotropic eddies are resolved, but the effect of the smallest scales in the flow are included through the sub-grid scale (SGS) model.

The two geometries shown in Fig. 1(b) and (c) were used for simulations with FDS 6.6.0. The geometry in Fig. 1(b) included an open region above the real outlet of the experimental apparatus to prevent boundary effects from impacting the simulation results. The geometry in Fig. 1(c) provided a simplified representation of the actual outlet, but is therefore also more sensitive to the boundary condition at the open face. The aluminum (black) and glass (blue) panels were 0.6 × 0.6 × 1.2 m, which corresponds to the size of the experimental apparatus [Fig. 1(a)]. An opening of 460 × 60 mm at the bottom right corner of each panel simulated the actual air gaps. A refinement study using four uniform computational meshes, containing 192 000 (M1), 648 000 (M2), 1 536 000 (M3), and 5 184 000 (M4) cells, was performed for geometry 1 to analyse the impact of mesh resolution on the numerical temperature predictions. Two meshes, which contained 1 280 000 and 4 320 000 cells, were tested for geometry 2. These meshes provide Plume Resolution Index values (as defined in the FDS User’s Guide) between 8 and 25 for the simulations in this study. This is a similar range to many of the validation cases provided in the FDS Validation Guide. Thermocouple probes with the same properties as those in the experiments were used to record temperatures. Four different SGS turbulence models were tested using geometry 1 to study their impact on the simulation: Deardorff model ($C_D = 0.1$), Wall-Adapting Local Eddy- viscosity (WALE) model ($C_W = 0.6$), constant coefficient Smagorinsky model ($C_S = 0.2$), and dynamic Smagorinsky model. Van Driest damping was used for the Deardorff, and constant and dynamic Smagorinsky models to adjust the eddy viscosity in the cell layer immediately adjacent to walls. Only the Deardorff model was tested for geometry 2. The default combustion rate model in FDS 6.6.0 is a mixing-controlled, mixture-fraction model based on the Eddy Dissipation Concept (EDC). The default FDS combustion model settings were used in this study, and propane was specified as the fuel. The default FDS settings were retained for solving the Radiative Transport Equation (RTE). The burner was modelled as a square inlet having an equivalent cross-sectional area to the burner. All FDS simulations were run for at least 120 s. Data was averaged after the simulations has reached a pseudo-steady-state over at least 60 s.

The geometry used for ANSYS Fluent 17.1 simulations is shown in Fig. 1(d). The computational mesh was refined towards the center and contained a total of 351 581 grid cells. The hood dimensions on top of the main section are 1.22 × 1.22 × 0.2 m, and the connection to the exhaust is 0.2 × 0.2 × 0.2 m. As in the experimental apparatus, the bottom surface of the hood is not covered, rather there is an air gap opening as shown in Fig. 1(d). The Algebraic Wall-Modeled LES model (WMLES) was used as the turbulence model for this study. A non-premixed combustion model was applied using the Probability Density Function (PDF) approach to include the effect of turbulence-chemistry interaction. Radiation heat transfer was included using the P-1 model. The
turbulent Schmidt and Prandtl numbers were set to 0.7. The fire whirl stabilized relatively fast in the Fluent simulations, and therefore data was averaged between 10 and 60 s.

RESULTS AND DISCUSSION

Fire Whirl Formation and Stability

In all experiments, a stable fire whirl was established within approximately 10 s following ignition of the propane. Once formed, the flame experienced small oscillations in its visible height and precessed somewhat irregularly around the burner. The Fluent simulation predicted fire whirl formation after approximately 3 s, followed by a small amount of precession around the burner. The FDS simulations using geometry 2 did not yield stable fire whirls. For geometry 1, the FDS simulations using meshes M1 and M2 did not provide stable fire whirl predictions for any of the SGS models. The constant Smagorinsky model did not predict a stable fire whirl for mesh M3, and only a partially stable whirl was predicted for mesh M4. The Deardorff, WALE and dynamic Smagorinsky models with meshes M3 and M4 predicted stable fire whirl formation within 10 s. Following formation, these models predicted irregular precession around the burner, providing qualitative agreement with the experimental results. Therefore, only these three SGS models and two meshes were analyzed further.

Temperature Comparison

Figure 2 shows measured temperatures and simulation results from FDS and Fluent. The experimental data were averaged over the pseudo-steady-state period. The error bars in Fig. 2 indicate the root-mean-square error (RMSE) and provide a measure of the variability in the data due to flame oscillation and precession. The average axial centreline temperatures from the experiments, Fluent simulations, and FDS simulations using the Deardorff model with mesh M4 are compared in Fig. 2(a). Close to the burner, (below 10 cm) the FDS model overpredicted the temperature and as the height increased from 30 to 90 cm it underpredicted the temperature until the plume region. The simulation predicts the peak temperature (i.e. the temperature hump) prematurely. The likely reason for this is an overprediction of turbulence close to the burner outlet, resulting in unrealistically high combustion rate predictions. In reality, the first section of the flame should be relatively unmixed with low initial combustion rates, but properly resolving this rate would likely require a combination of higher mesh resolution, a better approximation of turbulence at the wall, and maybe also a better representation of the burner. However, Fluent simulations underpredicted temperatures below 10 cm and overpredicted them above 30 cm. Nevertheless, the axial profile predicted by Fluent matches the general trend of the experimental profile more
closely. The delayed onset of combustion is likely due to the use of the PDF, but it is apparent that the model would require further tuning to provide a closer prediction for the experiment. Figures 2(b–d) show the radial temperature profiles of the measured and numerical predictions. As expected from the axial profile, there are significant differences between the measured and predicted profiles. Although FDS and Fluent both over and underpredict temperatures in the flame at various positions, the shapes of the profiles generally follow the same trends as observed in the experiments. The combustion and/or turbulence modelling approaches would need further refinement to provide a better quantitative prediction of the data.

**Height Comparison**

Figure 3(a) shows the stable experimental fire whirl at 30 and 60 s. The visible flame height, as obtained by image processing through MATLAB, is approximately 0.88 ± 0.06 m. From the experimental data, the edge of the visible flame height corresponds to an average centreline temperature of approximately 500°C [Fig. 3(b)]. Since it is difficult to quantify the flame height in the numerical simulations, the 500°C contour was assumed to provide a representation of the flame height. Of course, this is only a crude approximation and should therefore not be interpreted as providing a definitive measure of the flame height. In the Fluent simulations, the 500°C contour grows until the fire whirl has stabilized and reaches the top of the hood at 1.6 m, which is an overprediction of the actual flame height. Again, this prediction could likely be improved through changes to the combustion model; however, more accurate radiation modelling may also improve predictions of the temperature. The predicted 500°C contours (height estimates) for the Deardorff and WALE SGS models for meshes M3 and M4 are provided in Fig. 3(c). Clearly there is strong link between the mesh resolution and the predicted height of the contour. As expected based on the temperature profiles presented in the last section, there is a much weaker dependence on the SGS model. The differences in the predictions between the two mesh resolutions is primarily due to increased instability, which leads to more mixing and spreading of the temperature for the coarser mesh. The surprising aspect is how much difference this makes in the time-averaged temperature contour. Considering that the finer mesh already contains over 5 million cells on the order of 5 mm in dimension, it will be necessary to explore model modifications (e.g. changes to the combustion model) that lead to better predictions without increasing computational requirements much further.

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