A novel PIV seeding method for velocity measurements within a reactive boundary layer

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Abstract

Modelling of flame spread is challenging due to the interactions of the numerous gas and solid-phase processes involved. Models with a high level of complexity incorporate many processes and describe them in great detail. In simpler models, assumptions are utilized to reduce the number of inputs and their associated uncertainties. The use of complex models such as coupled Computational Fluid Dynamic-Pyrolysis as predictive models is not justified in fire engineering practice because it is currently not known which will cause larger prediction errors: the uncertainties of input parameters or applied simplifications and assumptions. Detailed justifications of associated model complexity are not common for model selection of flame spread predictions. Edification of sub-model complexity is currently hampered by the lack of a comprehensive database with measurements related to the main components of flame spread. One of the more challenging data measurements related to flame spread is the flow velocity. Within the research herein, composites were manufactured with seeding particles embedded in the polymer matrix to overcome buoyant flow seeding challenges. The proposed method facilitates the measurement of velocity in the vicinity of the wall and visualizing the velocity field. Two mixing patterns were noticed within the reactive boundary layer. The measurements were found to be in good agreement with values obtained from a coupled Computational Fluid Dynamic-Pyrolysis model in two identified characteristic regions. The proposed seeding method was found to be feasible, and it can be used to gain a greater understanding of the reactive boundary layer, which enables the assessment of wall functions and coefficient of convective heat transfer sub-models for reactive flow.

1 Introduction

During building design, fire engineers execute an analysis using the necessary tools to ensure that the design meets the performance requirements of the legislative body. The suitability and accuracy of the selected tools employed are crucial. The use of inappropriate tools could ultimately lead to fire incidents that expose human life and property to risk such as those that occurred in London’s Grenfell Tower in 2017 (Dixon and Swinford [2017]), or the Lacrosse Tower in Melbourne in 2014 (Koob [2019]), see Figure 1.

Assumptions are inherent in all modelling tools that engineers use, and this also applies to estimates of flame spread (Fukumoto et al. [2013]). The errors that arise in the modelling predictions are a combination of errors due to the uncertainty of input parameters and the lack of inclusion of significant processes (processes are commonly represented by sub-models) or poor descriptions of those processes. As the number of processes required to describe a phenomenon grows, the appropriate level of complexity (i.e., the combination of the errors caused by the uncertainties and lack/poor description of mechanisms is minimum) becomes a major concern (Bal and Ren [2013]). There are numerous processes influencing flame spread in both time and space. Some of the critical processes are related to the gas phase, like radiation and turbulence, while others are related to the solid phase such as pyrolysis and soot formation.
The main components of flame spread were listed by (Wong et al., 2013). They also reported that no comprehensive database is available in the literature with all the measurements needed to assess the modelling of the processes related to each component of flame spread. Typically, the experiments cover one or two components as they are designed to investigate distinct phenomena rather than assess numerical models. (Wong et al., 2013) designed experiments to collect measurements related to all components involved in the modelling of flame spread. They reported significant uncertainties in the measurements of flow velocity. Pressure probes were used in their experiments to measure flow velocity. They reported that the pressure probes failed at high temperatures. Furthermore, pressure differences and velocity values are relatively low in buoyant flow, which lowers the signal-to-noise ratio and thus the reliability of these devices.

Particle Image Velocimetry (PIV) is a more challenging technique to use, especially in a reactive flow environment in which the fluid flows with chemical reactions occurring and combustion species are produced. Introducing of the PIV seeding particles into the reactive buoyant flow without affecting its velocity and structure is difficult. Consequentially, studies that utilized PIV in flame spread experiments are scarce. (Cowlard, 2009) filled a testing room with seeding particles to measure the velocity vectors in the entrainment, pyrolysis, and plume regions. (Morandini et al., 2014) used a bespoke cyclonic seeding device to investigate the effect of the slope of terrain on the spread of wildfires. (Valencia et al., 2017) added the seeding particles to the air of premixed flames to measure the soot concentration and velocity of the flow next to a vertical poly methyl methacrylate (PMMA) burning sample. On larger scales, (Varea et al., 2021) used a similar idea to investigate smoke dynamics at openings of ventilated and under-ventilated compartment fires.

The first two methods are resource expensive and may hinder obtaining measurements near the solid surface as they depend on the proximity between the seeded flow and surface. The third method requires the use of an external source of heat which complicates the Computational Fluid Dynamic-Pyrolysis (CFD-Pyrolysis) model assessment. Herein, the research is focused on investigating the feasibility of adding the seeding particles to the solid material in the manufacturing stage to then obtain velocity measurements in the near-wall region for a reactive flow. It is anticipated that the seeding particles will flow with the pyrolysis gases leaving the solid surface to the gas phase, which will enable records of PIV images and velocity measurements for the near-wall region and minimise the effects of the seeding method on the structure and the velocity of the flow.

2 Methodology

The methodology aims to measure the velocity of flow within the reactive boundary layer next to a vertical burning surface without disturbing the boundary layer. The measurement will be compared with results obtained utilizing a CFD-Pyrolysis model. The methodology section consists of three parts that explain the manufacturing of the materials, the PIV experiments, and the numerical modelling approach.
2.1 Specimen Manufacturing

The specimens were manufactured from PMMA pellets (Plexiglas 8N), obtained from Plastral Pty Ltd, with the seeding material being hollow glass spheres (10 µm in diameter) obtained from Dantec Dynamics. The PMMA was thoroughly mixed with the seeding material in batches of 100 g at weight ratios of 100:1, 100:2, and 100:3 in polypropylene containers, then dried under vacuum at 80°C for 4 hours. The dried mixtures were placed in a desiccator cabinet till they were used. For further mixing and uniform distribution of the seeding material, the mixtures were processed using a Babyplast 6/10 injection moulding machine. The batches were processed at 240°C through the three zones (plastification, chamber and nozzle) to form a continuous extrusion. These extrusions were processed to approximately 3 mm pellets using a Labtech pelletiser, and further dried and stored in a desiccator cabinet till they were moulded. The pellets were injection moulded to 40x30x3 mm³ specimens using the Babyplast. The three heating zones were set to 230°C for plastification, 240°C for the chamber and 250°C for the nozzle. The mould was heated to 60°C. The manufacturing process of the samples is presented in Figure 2(a).

2.2 Experiments

The size of manufactured samples was 40×30×3 mm³. Two samples were mechanically fixed on a vermiculite insulation board with no space in between. The vermiculite insulation board was then placed on the aluminium frame displayed in Figure 2(b). The testing space was painted with black color and black curtains was utilized to cover other sides of the room to avoid noise from ambient lighting. It was noted that the lighting has a marked effect on the image quality. The values used for running the tests were: - 500 milliseconds exposure time, 12 Hz trigger rate, 2000 microseconds time between frames, 95% laser power of 14 MW, and 320 mm distance between laser lens and burning sample. The effects of changes in some of these parameters will be discussed briefly in the result sections.

The flow was lightened by a Nd:YAG Laser with 532 nm provided by Dantec Dynamics. A cylindrical lens was used to produce the Laser sheet. A FlowSense EO-1.3M PIV camera kit with 1280x960 pixels and 39 fps was utilized to collect the images. A 532 nm Narrow-band PIV Camera Filter was used to reduce the noise produced by the fire. The experimental setup is presented in Figure 2(b). Adaptive PIV analysis was performed to match particles in each interrogation area. The correlation measures the displacement of multiple particles within the interrogation area, typically there are no seeding particles inside the wall. Therefore, particles near the wall are generally moving slower than those farther from the wall. A wall windowing method was used to mitigate wall bias. This method was used to avoid the effect of particles moving down with the melting materials on the flow measurements. The minimum signal-to-noise ratio (i.e., S/N-ratio) was set to 4 for validation of correlation peaks.

2.3 Numerical modelling

Fire dynamic simulator (FDS) is an open-source modelling software developed by the National Institute of Standards and Technology (NIST) (McGrattan et al., 2013). The software solves the temporal profile of velocity, temperature, and concentration of species of a thermally driven flow, with emphasis on heat and smoke released by fires. It offers the use of the Large Eddy Simulation (LES) method in which the time-dependent Navier-Stokes equations are filtered by a space filter. Large eddies, which pass the space filter, are computed by unsteady Navier-Stokes equations while properties of small eddies are filtered out. These small eddies and their interactions are solved by a sub-grid scale (SGS) model. The governing equations and involved sub-models are presented in the software technical guides (McGrattan et al., 2013). In the absence of clear literature guidelines on sub-model selection for flame spread, the simulation herein was run on the default sub-models of FDS 6.7.9 except that the turbulence model was set to LES instead of very LES. The use of LES lowers the value of the space filtering length and enabled the capture of more flow features.

The experiment was represented by three main components in the coupled model, namely: the insulation board, the burning sample, and the ignition source. The density, specific heat, conductivity, emissivity, absorption coefficient, and thickness of the vermiculite insulation board were 375 kg/m³, 0.94 kJ/(kg.K), 0.12 to 0.19 W/ (m.K), 0.67 W/m², 5 x104 l/m, and 0.055 m, respectively. The properties of the PMMA sample were added from FDS’s library which originate from the SFPE Handbook of Fire Protection Engineering (Hurley et al., 2015). The size of the PMMA sample was 40x90x3 mm³. The first 20 mm were assumed ignited and to have released a constant amount of heat. The heat release rate per unit area of PMMA was
set to 600 kW/m² (Lyon, 1996). The distance between the edges of the sample and the edges of the insulation board was three times the characteristic burning length to negate the effect of model boundaries on the flow. The vertical and horizontal (i.e., normal) velocities were computed at four different heights (i.e., 10 mm, 30 mm, 50 mm, and 70 mm from the sample lower edge). The mesh size was selected to be 1 mm to allow multiple measurements with 1 mm spacing from the fuel surface (i.e., in the normal direction). The numerical model is displayed in Figure 2 (c).

![Figure 2: a) The manufacturing process, b) the experimental setup, and c) the numerical model.](image)

### 3 Results and Discussion

In this section, firstly, the effect of different test settings is discussed briefly. Secondly, the reasoning for selecting the analysis regions and some notes on the flow field are provided. Thirdly, the effect of varying the type of adaptive PIV algorithm along with a convergence study is presented. Lastly, the results of the vertical and horizontal flow velocities, which were obtained by using different amounts of seeding particles, are presented and compared to the modelling results.

#### 3.1 The effect of the testing conditions

Two consecutive frames with a known temporal difference are needed to run the PIV algorithm. Two PIV photos that were collected are shown in Figure 3 (a-b). Increasing the exposure time allowed the collection of more light, which increased the level of noise produced by fire in the image. On the other hand, it was found that decreasing it beyond 250 milliseconds limits the ability of collecting the scattered laser, see Figure 3 (c). In addition, it was found that the distance between the laser lens and the burning sample had an important effect on the image quality, while increasing this distance caused the laser sheet to spread beyond the upper and lower edges of the burning samples because of the cylindrical lens. Decreasing it beyond 320 mm caused significant glare in the photos as illustrated in Figure 3 (d), which prevented the PIV algorithm from identifying the seeding particles. Ultimately, some glare was still presented in the second frame images, (Morandini et al., 2014) reported a similar issue. They explained that standard PIV cameras were unable to shoot two consecutive images with the same short exposure time. The storage time is typically not short enough to allow the camera to set the exposure time before imaging the second frame. The time between two consecutive frames was set to 2000 microseconds as in (Morandini et al., 2014).

#### 3.2 The adaptive PIV algorithm convergence study

In the standard PIV algorithm, a cross-correlation is applied between two consecutive images with a known temporal difference in each interrogation area. The two correlated images are represented by two arrays. The entities related to the interrogation areas are compared to all entities related to the interrogation areas within the search length. Once the correlation peak table is created, the table is searched for the maximum correlation value (Hart, 1997).
In the analysis conducted in this study, the correlations were calculated using a two-dimensional Fast Fourier transformation with Gaussian windowing function. The Gaussian windowing function assigns value to the sub-pixels to smooth the correlation peaks. The peaks near the centre of the interrogation area were multiplied by a factor of one. The peak values near the edges of the interrogation area were multiplied by a small fraction but did not reach zero (i.e., removed completely). Gaussian in the spatial domain becomes a Gaussian in the frequency domain, therefore it did not produce ringing artefacts expected for edges. Therefore, the use of the Gaussian fitting windowing function was preferable over other windowing functions like Top Hat and Bartlett (DantecDynamics, 2021).

In recent years, adaptive PIV methods have been attracting considerable research interest (Novara et al., 2012). The adaptive PIV algorithm has a similar working method to that of the standard PIV algorithm, but it modifies the shape and/or the size of the interrogation areas. It was decided to use the adaptive PIV algorithm since the density and amount of seeding particles were hard to control in the reactive gas phase. The utilized adaptive PIV algorithms are included for users in the Dynamic Studio software. The algorithms are modified versions of (Sciacchitano et al., 2013) algorithm. The idea of deforming the interrogation areas was also presented by (Kitzhofer et al., 2012).

The first adaptive PIV algorithm adapts the size of the interrogation area based on parameters related to the seeding density. The parameters include lower particle detection limit and a desired number of particles inside the interrogation areas; these were set to 5 and 10, respectively. The second adaptive PIV algorithm adapts the shape of the interrogation areas to the velocity gradients. The velocity gradients were limited to 0.1, and the combined effect of the four gradients was limited to 0.2 to limit the change in the shape of the interrogation shape.

The effect of adapting the interrogation area to the density of the particles and the density of the particles along with the velocity gradient on the vertical velocity values is presented in Figure 4. The velocities were measured at various distances measured normally from the burning surface. The velocity values converged after 15 iterations; thus, the number of iterations was set to 15 in the following parts of the study. The second algorithm, which is based on particle density and velocity gradients, appeared to have less impact on the results, thus it was used for the rest of this study. It should be noted that the seeding density at a distance of 6.99 mm from the burning surface was low, which could cause the significant change in the velocity value using the second algorithm. The results were validated using the signal-to-noise ratio, based on the method proposed by Charonko et al. (Charonko and Vlachos, 2013).
3.3 The flow patterns

The measurements that were collected at a specific time (i.e., 40 s and 110 s), and height (i.e., 10 mm, 30 mm, 50 mm, and 70 mm) were not in good agreement with the CFD-Pyrolysis results or even repeatable. This was likely caused by the unsteady and dynamic nature of the flame spread problem. Therefore, it was decided to focus the analysis on characteristic locations, namely the flame tip and the pyrolysis region. Figure 5 shows an exemplary image of the collected PIV images with the analysed regions. As mentioned above, a mask that covers the sample was defined to mitigate the influence of the seeding particles flowing down with the material on the measurement. Furthermore, the analysis was restricted to the area within the green box.

As expected, the seeding particles flowed with the pyrolysis gases leaving the burning solid surface and, mixed with air in the near-wall region. The seeding particles leaving the solid sample from the burning region below the imaging region are expected to diffuse into the air incoming towards the boundary layer and the reaction zone. Thus, the seeding particles were distributed within the reactive boundary layer. However, the flow of oxygen towards the boundary layer prevented the seeding particles to flow past the external edge of the boundary layer. The localized analysis (i.e., analyzing a restricted area) allowed the exclusion of the non-seeded region (i.e., the black region in the PIV image). As the seeding particles are assumed to be massless (i.e., to move with the flow without being influenced by their inertia), they were utilized to represent the flow velocity and structure. The flow leaving the sample surface was assumed to represent the flow of pyrolysis gases, while the flow coming towards the solid sample was assumed to represent the flow of oxygen. Techniques to identify the gas species were not used in the current study.

The velocity vectors obtained utilizing the adaptive PIV algorithm (Sciacchitano et al., 2013) for the whole analyzed region along with the resultant scalar map are shown within the green box in Figure 5. The velocity values were found to vary between 0 to 1 m/s, and to have a non-unified direction (e.g., parallel, normal). However, the flow movement was found to be parallel to the surface at the flame tip shown within the dark blue box in Figure 5. There was no horizontal component in the velocity at this region as the sample was being heated, but not pyrolyzing yet.

In some areas of the pyrolysis regions, the pyrolysis gases seemed to leave the surface of the solid fuel to the boundary layer outer edge where they mix with the ambient oxygen. In these regions, the velocity is mostly horizontal as shown in Figure 5 inside the light blue box. These regions are surrounded by two
vortices. The described pattern was found in many of the collected images. A second pattern that was noticed in the measurements is shown within the dotted light blue box in Figure 5. The pyrolysis gases and oxygen were moving towards the mixing line shown in red, they mixed and transformed in the buoyancy direction. The reasons that caused the change between the two noticed flow patterns are hard to predict or explain. Furthermore, the existence of other flow patterns that were not identified is possible. A much faster PIV system is needed to enable the monitoring of the formation and dissipation of vortices and mixing processes.

Figure 5: Exemplary PIV image, and the scalar velocity map with the velocity vectors: – for the analysed area shown within the green box (scale is 0 to 0.6 m/s), – at the flame tip region shown within the dark blue box (scale is 0 to 0.9 m/s), – at the pyrolysis region shown within the light blue box (scale 0 to 0.25 m/s), and – at the pyrolysis region shown within the dotted light blue box at another time incidence with the mixing line shown in red (scale is 0 to 3 m/s).

Identifying all patterns in the reactive boundary layer is outside the scope of this study, as the study is focused on investigating the feasibility of the proposed seeding method. However, it is evident that the flow patterns in the reactive boundary layer are different from that in nonreactive flow. As reported by (Goller et al., 2017), all correlations used in CFD models to describe the wall functions and convective heat transfer depend on correlations developed for non-reactive flow. It was proven recently that convective heat transfer coefficient models have a significant effect on flame spread predictions (Maragkos et al., 2021). Furthermore, it can be concluded by reviewing the flame spread modelling literature that reducing the cell size to a level in which wall functions are not needed, lead to better predictions of flame spread quantities (Fukumoto et al., 2013). Therefore, the proposed method of adding seeding particles directly into a combustible solid could enable measurements that are critical to assess wall functions and convective heat transfer correlations. The proposed technique can also provide measurements that form a significant component from a comprehensive database to assess the CFD-Pyrolysis models and enhance the understanding of their performance.
3.4 The velocity measurements

After examining the rest of the results, it was decided to perform the comparative analysis in two locations: the flame tip, and the location at which the majority of the flow is horizontal within the pyrolysis region, as shown in Figure 5. While the vertical velocity was compared at the flame tip region, the horizontal velocity was compared at the pyrolysis region. The vertical velocity in the pyrolysis region varied in value and direction. Thus, it was not possible to find a characteristic region to conduct the comparative analysis within the pyrolysis region for the vertical velocity.

The measurements of vertical velocity at the flame tip using PMMA-Glass spheres samples with 1 wt.%, 2 wt.%, and 3 wt.% at the flame tip are shown in Figure 6(a-c), respectively. The velocity peaked at a normal distance of 3 mm from the burning sample at 0.9 m/s. The presented average and standard deviation were obtained from 3-5 PIV images. The CFD-Pyrolysis modelling results are displayed in Figure 6(a-c). The experimental values obtained from the 2 wt.% PMMA-Glass spheres composites are in good agreement with those obtained from the numerical model. The thickness of the reactive boundary layer in the experimental measurements was found to be around 6 mm, which is less than that in the numerical model (i.e., 10 mm). This could be due to two possible reasons the true value of the velocity is not zero, but the oxygen flow prevented the seeding particles from reaching the outer edge of the boundary layer, or that the PMMA-Glass spheres composites melted in the experiments which caused a significant reduction in the burning mass. The mass loss due to melting is not accounted for in the numerical model. The fluctuations observed in the experimental results produced utilizing the 1 wt.% PMMA-Glass spheres sample could be due to the insufficient amount of seeding in localized areas within the boundary layer. Therefore, it is advised to use seeding content of more than 2 wt.%. A detailed analysis of the seeding destiny is needed to accurately explain the effect of varying the seeding content on the collected measurements.

Similarly, the horizontal component of the velocity was obtained using PMMA-Glass spheres samples with 1 wt.%, 2 wt.%, and 3 wt.%, and reported in Figure 7(a-c), respectively. These measurements were obtained from 3-5 PIV images but for the pyrolysis region. The values of the velocities were found to vary between 0.62 m/s to 0.21 m/s. The results of the numerical model were not added as they were found to vary between 0.04 m/s to 0.06 m/s. The effect of the horizontal velocity on the boundary layer seems to be neglected in the numerical model. As mentioned, generally, the numerical models apply corrections and empirical functions that were developed for non-reactive flows. It is expected that the variations in the experimental measurements for both vertical and horizontal velocities are related to the change in the flow conditions, rather than the repeatability of the results. Another important point is that the measurements are related to specific characteristic regions and cannot be thought of as average of velocity values within the reactive boundary layer.
Figure 7: PIV measurements of horizontal velocity vs. normal distance from the burning sample using a) 1%, b) 2%, and c) 3% PMMA-Glass spheres composites.

4 Conclusions

The feasibility of incorporating the seeding particles within the solid fuel in the manufacturing stage was investigated. Poly methyl methacrylate-glass sphere composites were manufactured with various glass spheres content. Concurrent upward flame spread experiments were conducted to investigate the effectiveness of the proposed seeding method in measuring velocity with the reactive boundary layer. The results obtained utilizing the proposed seeding method were found to be promising when compared to those obtained from a coupled numerical model. The lighting condition had a significant effect on the quality of the collected PIV images. It is suggested that experimentalists run multiple experiments to find a balance in which enough lighting is allowed to locate the seeding particles, but an excessive amount of light is prevented to avoid causing glare and noise.

Two adaptive PIV algorithms with a mask and a windowing function were used to enhance the quality of the collected measurements. Furthermore, the cross-correlation peaks were validated with a signal-to-noise ratio method. The adaptive algorithm, which varies the size and the shape of the interrogation area, was found to have a lower impact on the results that the adaptive algorithm which varies the size of the interrogation area only. Furthermore, fifteen iterations were found sufficient to reach convergence of the velocity measurements for the studied case.

The mixing of pyrolysis gases and oxygen was found to have two patterns within the reactive boundary layer. In the first pattern, the pyrolysis gases were found to flow horizontally through the full boundary layer towards oxygen, and two vortices were formed above and below the horizontal flow region. In the second pattern, the oxygen and the pyrolysis gases collided at an inclined vertical mixing line located within the reactive boundary layer, and then the mixture flowed in the buoyancy direction. A faster PIV system is needed to investigate the reason behind the change in mixing patterns, and if there are any unidentified patterns.

The velocity measurements at the flame tip were in good agreement with the values obtained from the pyrolysis-computational fluid dynamic model. However, it was not possible to compare the velocity values within the pyrolysis region to the numerical model as the horizontal flow of the pyrolysis gases was not considered in the numerical model. Nevertheless, the measurements from various experiments at specific characteristic regions were found to be similar. Overall, the results are promising, and the technique could be optimized by using higher concentration, or other types of seeding materials to enhance the quality of the measurements. Furthermore, the use of a faster PIV system could lead to a greater understanding of the reactive boundary layer, which in turn leads to better predictive models. The described testing setup needs to be upgraded to allow controlling the air velocity in order to assess the similarity in correlations and empirical function of reactive and non-reactive flows.
Acknowledgements

This work was supported by the Australian Government Research Training Program (RTP). The authors would like to thank SFPE foundation for funding the experimental programme of research through Student Research Grant Award, 2022. The authors would like to thank the Centre for Advanced Materials Processing and Manufacturing (AMPAM) at the University of Queensland for the use of laboratory equipment and facilities.

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