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A Study on Positive Pressure Ventilation in Room Fires Using a Small Scale Model

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Abstract

Positive Pressure Ventilation (PPV) is commonly used for blowing out smoke and thus enhancing the visibility inside the fire scene. However, there are different views on operating PPV for firefighting and rescue. Ventilation arrangements, which include the locations of PPV and exhaust openings in a room, should be carefully investigated for better understanding of the efficacy of PPV in firefighting. In this study, scale modelling tests in a 1:10 room model were performed to study different ventilation arrangements in using PPV. Experiments of three fire scenarios were conducted, including (i) a single propanol pool fire, (ii) a centre pool fire surrounded by four propanol pools, and (iii) a single pool fire surrounded by wood cribs. Ventilation arrangement was varied to study the temperature changes and fire spread patterns. It is observed that the ventilation arrangements would determine whether PPV is effective in firefighting of room fires. In using PPV, opening the opposite exhaust opening would give a clear environment without fire spread while operating PPV would give a bigger fire in the room when there is no exhaust opening.

Keywords: Positive Pressure Ventilator; Ventilation arrangement; Modeling, Firefighting

1. Introduction

A big mini-storage fire lasting for 108 hours occurred (Chow, 2016a; Rhodes, 2016; South China Morning Post, 2016) on 21 June 2016 in Hong Kong, killing two firefighters. Positive pressure ventilation (PPV) was employed in the firefighting. It was criticized in some media that operating PPV led to a more hazardous fire environment (Apple Daily, 2016; E Weekly, 2016; Next Magazine 2016; The Standard, 2016) rather than improving the visibility or reducing the temperature inside. Blowing a large amount of air into the fire scene would supply more oxygen to give a bigger ventilation-controlled fire. More combustibles might be ignited, with hot flame and smoke spreading quickly to adjacent areas. Therefore, whether or not to operate PPV in room fires is a very important decision in fighting room fires and should be explored thoroughly. This part was recommended (Chow, 2016b) to study with full-scale burning tests in the fire investigation report.

PPV has been applied to compartment fires for blowing out the smoke or toxic gases in the building but with many different views (Ziesler et al., 1994a, 1994b; Lang and Dixon, 2000; Mowrer, 2001, 2009; Svensson, 2001; Svensson and Weling, 2001; Ingason and Fallberg, 2002; Lougheed et al., 2002; Kerber and Walton, 2005, 2006; Ezekoye et al., 2005, 2007; Prétrel and Such, 2005; Lin et al., 2006; Kerber, 2007; Kerber and Madrzykowski, 2007; Beal et al., 2009; Guigay et al., 2009; Lu et al., 2011; Lamber and Merci, 2014; Kumm and Ingason, 2014; Zevotek and Kerber 2016). In general, the ventilator is operated in front of appropriate inlet opening to blow smoke and heat out through the exhaust opening. Different surveys and experiments came out with different views on using PPV.

In Hong Kong, adverse effects of operating PPV during firefighting have attracted public attention. The fire environment and fire spread pattern in room fires will be different under different ventilation arrangements. Therefore, the changes of fire environment while operating PPV with different ventilation provision in room fire and the resultant fire spread pattern should be judged scientifically by the fire officer-in-charge before giving commands to start PPV. Detailed research projects should be carried out to provide scientific information for professionals in the field. At the preliminary stage, scale models can be used as a first step to observe the possible fire hazard scenario. With further support, more real-scale experiments can then be performed.

Study of the effect of operating PPV using smaller models will be reported in this paper. It should be noted that this is not intended to be a scale-modeling experiment to predict what would happen exactly in real-scale models. This, together with computational tools, would give indication on what further full-scale burning tests should be performed to evaluate the consequence of operating PPV in compartment fires.

2. Overview on Effectiveness of Positive Pressure Ventilator

PPV has been implemented with some success but also with some difficulty (Kerber and Walton, 2005, 2006). The following are questions raised by the fire service based on their experience with PPV, together with some reported (Kerber and Walton, 2005, 2006):

- When should PPV be used?
- Will PPV provide oxygen to the fire and lead to quicker fire growth under some scenarios?

- What is the best location for the fan and where should the exhaust or vent opening be built?
- What is the consequence if occupants or firefighters are trapped between the fire and the exhaust opening?
- Apart from small houses or apartments, what are the types of buildings that PPV cannot be used?

Opinions supporting or against using PPV technique in firefighting (Ezekoye et al., 2007) are roughly equal in number. PPV (Ziesler et al., 1994a) can remove smoke and toxic gases, and if operated properly, may create a safer environment before firefighters enter the fire site. Advantages of operating PPV are:

- Reducing gas and air temperature for firefighters and people trapped inside.
- Improving air quality for firefighters.
- Removing smoke faster to get better visibility.
- Directing flames away from firefighting location.
- Controlling heat spread damage.

Better conditions in the fire site were observed in small buildings with simple geometry and appropriate openings while applying PPV.

On the other hand, there are concerns on increasing the heat release rate of a ventilation-controlled fire, as additional oxygen is supplied through PPV. The efficacy of PPV should be carefully evaluated (Kerber and Walton, 2005, 2006) in terms of its effects on gas temperatures, gas velocities and mass burning rates to establish specific guidelines for its optimum use in real fire scenarios. The conditions for a victim caught in the fire site may be deteriorated (Ezekoye et al., 2005) because of any changes in the local environment, particularly downwind of the fire, while operating PPV.

As full-scale burning tests require prohibitive resources, water scale-modelling experiments were reported (Ezekoye et al., 2007), with conclusion that it is advantageous to use PPV. However, only one fire source was included in the water modelling tests, though more vigorous burning was simulated by increasing colour dye flow rate through a pump. Additional fire sources due to ignition of unburnt fuel via supplying additional air by PPV cannot be simulated in the water modelling study. In other words, time to flashover and post-flashover fire can only be described by changing the salt water concentration and flow rates in a pre-determined sequence matching with those observed in burning additional objects in a real fire. The applicability of such water modelling results to fires in mini-storages storing high amounts of combustibles needs justification. Consequently, whether the PPV technique can reduce temperature, reduce toxic gas levels, and improve visibility during a big ventilation-controlled fire in buildings with complicated geometry and high fire load density should be further investigated.

Applying PPV might be able to achieve those advantages and reduce the potential to flashover if the fire is still at the growth stage, not yet progressing to flashover. The fan might prevent heat damage spread for small fires. Therefore, results (Ziesler et al., 1994a) match better in houses with simple geometry, such as a corridor with several rooms at the early stage of fire. Using PPV for post-flashover big fires such as the mini-storage fire with hundreds of cubicles storing high amounts of combustibles should be considered carefully as the fire scenario is totally different.

Effects of PPV on a room fire were studied with full-scale burning tests (Kerber and Walton, 2005, 2006). Gas temperatures, gas velocities and total heat release rates in a series of fires in a furnished room were examined with and without operating PPV. The door was opened in the study.

Although some experimental data have been collected and analyzed to support benefits in using PPV, a number of effects and aspects of PPV still need careful investigation as suggested (Kerber and Walton, 2005, 2006). Scientific foundation on real fire scenarios should be explored for optimum use of PPV in firefighting. To improve the effectiveness of using PPV, numerous studies had been conducted and introduced to the public. Several factors should be considered when using PPV. Research focused on search of effective techniques while using PPV for controlling smoke and fire was presented at the National Fire Protection Association (NFPA) meeting (Kerber 2007). Results of the NFPA presentations are summarized below.

Applying PPV created slightly lower gas temperatures in the fire room and significantly lower gas temperatures in the adjacent corridor. The gas velocities at the window plane were much higher in the PPV case than in the naturally ventilated scenario, though giving much better visibility. Additional oxygen supplied to the fire would increase the heat release rate compared with the case of natural ventilation. PPV caused an increase in heat release rate for an initial period of 200 s after operating PPV. The maximum heat release rate was 14 MW for the PPV ventilated fire, which was slightly higher than 12 MW for the naturally ventilated fire. Peak heat release rates of both fires were reached approximately 40 s with a spike to their respective maximum. The peak of the PPV tests was reached 5 s after that of the natural ventilation test, corresponding to the 5-s period before the PPV was started. However, the heat release rate decreased at a faster rate than that in the naturally ventilated experiment. After this transition, the fire remained at a steady burning rate until the fuel was completely consumed. This observation indicated that under the conditions in this experiment, firefighters should wait for 60 s to 120 s after starting PPV, before moving into the fire site. This would allow the flows to stabilize, temperatures to decrease and visibility to improve. The heat release rate of the fire could become steady, as determined by the modified air flow, and rather unlikely to rapidly change as the firefighters approach. The time to reach this new steady condition could vary with the building layout, fire size and fan capacity. As a conclusion, the full-scale burning tests presented at NFPA indicated a maximum heat release rate of 14 MW for operating PPV and 12 MW for natural ventilation in the first 200 s in that set of experiments with the door opened. The situation would be different when all doors and windows are closed to give an under-ventilated fire. An additional amount of heat 400 MJ (2 MW $\times$ 200 s) would be liberated. This indicated that PPV caused higher fire room temperatures, increased window gas flows and higher pressure differentials than the natural ventilation conditions in the tests.

Other experiments have also shown that operating PPV would increase the rate of heat release. Experiments showed (Svensson, 2001) that PPV increased the temperature in rooms on the leeward side of the fire and reduced temperatures on the windward side of the fire. Therefore, exit openings were suggested to be built as close to the seat of the fire as possible. The following were observed (Svensson, 2001) in that particular room geometry:

- Flow rate through an exhaust increases with increasing distance between the fan and inlet up to some maximum value and a decreasing flow rate after this point.

- Flow rate through an exhaust decreases as volume of the structure increases. A larger volume might have more leakage, and so lower efficiency of PPV.
- Increasing the exhaust area decreases the flow loss, thus increasing the efficiency of PPV.

However, the results are different with different geometries, say applying PPV (Lamber and Merci, 2014) in front of a staircase, and single houses and apartments (Lougheed et al., 2002). Experiments on firefighting tactics clearly showed that PPV is a useful procedure, if used correctly with caution (Svensson and Werling, 2001). The use of PPV must be coordinated with the presence of exit openings in attacking the fire, fire suppression and removal of victims.

Full-scale burning tests in a hall for studying fire ventilation actions were performed (Svensson and Werling, 2001). However, fires were small compared to the size of the room. A larger fire would create more turbulence, more smoke and hotter air, making it harder to ventilate the smoke and hot gases by using PPV. To ventilate such a scenario using PPV, it would have been necessary to use a larger fan, thus creating more turbulence in the hall. Increasing turbulence would induce more hazardous conditions for trapped victims and firefighters. In view of such considerations, tests with small fires would not match with real-scale big mini-storage fire.

There are very few researches on assessing the effectiveness of PPV technique for firefighters under different real fire scenarios, particularly on the big mini-storage fires as experienced in 2016. Without thorough understanding of the impacts or effects caused by PPV on the fire sites, the controversy associated with the use of PPV in fighting fires in compartments or similar building structures remains. It is the aim of the present study to fill up this gap.

3. Experimental Details

Air flow pattern generated by PPV at the fire site depends on the positions of the fan inlet and exhaust openings. The pressure inside the room can be higher than that outside while operating PPV. If air inflow of PPV through the door is not strong enough, backflow might occur and affect the performance of PPV (Zevotek and Kerber, 2016).

The exhaust to inlet opening area ratio was suggested to be greater than 1:1 (Zevotek and Kerber, 2016). As it is hard to get a window that has similar size as the door, two normal-sized windows were selected. Therefore, one door opening and two window openings were provided in the model (Fig. 1(a)). The door had dimensions of 90 mm (W) x 200 mm (H) and the window had dimensions of 90 mm (W) x 120 mm (H). The actual room size was scaled down to a model in a scale of 1:10.5, as shown in Fig. 1(b).

For the material of the model, as there was fire inside the model, materials with high ignition point such as steel and glass were used. To observe and record the burning process clearly, a side of the scale model was covered by glass.

From scale modelling, the relationship (Quintiere, 1989) of ventilator velocity V and a characteristic dimension of the room scale L is related to that of full-scale room by the following equation:

$$\left(\frac{V_{model}}{V_{full-scale}}\right)^2 = \frac{L_{model}}{L_{full-scale}}$$

A small fan (diameter 6 cm, fan velocity 11.32 ms^{-1}) as in Fig. 1(c) was used in the experiment with size matching with the scale of the room model. The ratio of fan velocity of the actual PPV (commercial catalogue (Positive Pressure Ventilator Catalog, 2016), diameter 45.7 cm, fan velocity 35.32 ms^{-1}) as in Fig. 1(c) to that of the small fan was 1.32. It should be pointed out that scaling laws are very complicated due to the confined buoyancy induced flow.

Three scenarios with different fire sources were conducted as shown in Fig. 2(a), 2(b) and (c):

- Scenario S1: the propanol pool fire P1 was located at room centre (Fig. 2(a));
- Scenario S2: P1 was surrounded by 4 propanol pool fires P2 (Fig. 2(b)); and
- Scenario S3: the centred propanol pool fire P1 was surrounded by 4 wood cribs W (Fig. 2(c)).

P1 was a 25-ml propanol pool fire of diameter 40 mm, P2 was a 10-ml propanol pool fire of diameter 25 mm. Note that for liquid pool fire, pool surface areas would determine the heat release rate, amount of fuel heat would determine the burning duration. W was wood crib made of small wood sticks of size 3 cm x 3 cm x 8 cm of 18 layers (Fig. 2(d)).

A high revolution camera was used to record the burning process in the experimental study. Transient gas temperatures were recorded inside the room model by a K-type thermocouple tree at positions shown in Fig. 2(e).

For each set of scenario, three tests with different ventilation arrangements as shown in Fig. 3 were conducted:

- Ventilation V1: without exhaust opening (window closed).

  The middle pool was ignited at 0 s with the fan operated at 120 s.
- Ventilation V2: with exhaust opening (opposite window open).

  The middle pool fire was ignited at 0 s, window opened at 110 s and ventilator operated at 120 s.
- Ventilation V3: with adjacent exhaust opening (adjacent window open).

  The middle pool fire was ignited at 0 s, window opened at 110 s and ventilator operated at 120 s.

A summary of the three scenarios is shown in Table 1.

A reference scenario V0 was carried out without operating the fan. Results were used for comparing fire environments among the different ventilation provisions.

In the experiments, the following were recorded while operating PPV under different ventilation conditions:

- Flame spread pattern
- Ignition of adjacent combustibles
- Merging of flame for different objects, if any
- Gas temperatures

The shape of flaming region was observed for the single pool fire test. For other tests, flame spread among propanol pools and wood cribs in the model were also recorded.

4. Results I: Observation of Burning Process and Flame Pattern

4.1 S1: One Burning Pool P1

The flame patterns observed under different ventilation for Scenario 1 are shown in Fig. 4. In V0, the flame was steady as shown in Fig. 4(a). Although the flame sometimes tilted to a side, at most of the time, the flame kept straight. In test V1, the flame was steady with straight flame before the fan started operating. When the fan was operating, the flame kept fluctuating as shown in Fig. 4(b). In test V2, the flame was steady with straight flame before the fan started operating. When the opposite window was opened, the flame tilted to the opened window. When the fan was operating, the flame kept fluctuating as shown in Fig. 4(c). In test V3, the flame was steady with straight flame before the fan started operating. When the adjacent window was opened, the flame tilted to the opened window. When the fan was operating, the flame kept fluctuating as shown in Fig. 4(d).

4.2 S2: One Burning Pool Surrounded by Four Pools

In Scenario S2, the propanol pool fire P1 was surrounded by 4 propanol pools P2 as shown in Fig. 2(b).The flame patterns observed together with the ignition sequence of the adjacent fire sources P2 are shown in Fig. 5.

In V0, the flame was steady. Although the flame sometimes tilted to a side, at most of the time, the flame kept straight. In the whole process, the surrounding pools of propanol did not ignite (Fig. 5(a)).

In test V1, the flame was steady with straight flame before the fan started operating. When the fan was operating, the flame kept fluctuating and all the surrounding propanol pools were ignited in succession as shown in Fig. 5(b). First, the flame tilted in the direction of the draught produced by the fan, and the first P2 pool along the draught direction became ignited. The second and third P2 pools were ignited later due to the big fire caused by the central P1 pool and the first P2 pool. Around one and a half minutes later, the flame started to tilt to the door and the fourth P2 pool was ignited. Smoke and flame extended out of the door during the experiment. The sequence of igniting adjacent P2 pool fires is numbered as shown in Fig. 5(b).

In test V2, the centre pool burnt steadily with straight flame before the fan started operating (Fig. 5(c)). When the opposite window was opened, the flame tilted to the opened window. At this moment, one propanol pool (numbered as "1" in Fig. 5(c)) became ignited. When the fan was operating, the flame kept fluctuating. The flame tilted in the direction of the draught blown out by fan. Part of the flame extended out the opposite window during the experiment. The sequence of igniting adjacent pools is shown in Fig. 5(c).

In test V3, before the adjacent window was opened, the flame tilted towards the opposite window side and ignited the first and second propanol pools as shown in Fig. 5(d). The fire was fierce due to the burning of three pools. When the adjacent window was opened, the flame tilted towards the opened window. At this moment, the third propanol pool was ignited. When the fan was operating, the flame kept fluctuating. Around two minutes later, the fourth pool became ignited. However, due to the strong draught by the fan, the fourth propanol pool kept ignited and died out until the centre pool fire went out. The sequence of igniting adjacent pools is shown in Fig. 5(d).

4.3 S3: Pool Fire Surrounded by Wood Cribs

Scenario S3 with 1 propanol pool fire P1 and 4 wood cribs is shown in Fig. 2(c). Flame patterns and ignition sequence of adjacent cribs are shown in Fig. 6.

In test V0 (Fig. 6(a)), during the ignition, the flame tilted towards the opposite window side and ignited one wood crib first and then the other cribs also became ignited. In the whole process, the flame was steady. Although the flame sometimes tilted to a side, at most of the time, the flame kept straight. The sequence of igniting adjacent cribs is shown in Fig. 6(a).

In test V1, the flame was steady and straight before the fan started operating (Fig. 6(b)). When the fan was operating, the flame kept fluctuating. In the experiment, the flame reached all wood cribs placed around the propanol pool. However, only one wood crib was ignited. The sequence of igniting adjacent cribs is shown in Fig. 6(b).

In test V2, the flame was steady and straight before the fan started operating (Fig. 6(c)). When the opposite window was opened, the flame tilted towards the opened window. The flame reached the wood crib near to the opposite window but did not ignite it. When the fan was started, the flame kept fluctuating. The flame tilted towards the door side and ignited one wood crib. In the experiment, the flame reached all wood cribs. However, only one wood crib was ignited.

In test V3, the flame was steady and straight before the fan started operating (Fig. 6(d)). When the adjacent window was opened, the flame tilted to the opened window. The flame reached the wood crib near to the adjacent window but did not ignite it. When the fan was started, the flame kept fluctuating. The flame tilted towards the door side and ignited the first wood crib. Some small wood chips emitted from the burning crib were carried by the air flow to move inside the room. It reached and ignited the second wood crib. The sequence of igniting adjacent cribs is shown in Fig. 6(d).

4.4 Comparison of Flame Patterns

The initial flame patterns before opening any window and starting the fan are shown in Fig. 7.

In all experiments, after igniting the centre pool, the fuel was allowed to burn freely without operating the fan and ventilation for 2 minutes to let the fire come to its maximum temperature. In these two minutes of burning, although the flame fluctuated, it always tilted towards the door side. This abnormal flame pattern was due to the smoke movement. When the fire was ignited, smoke started accumulating on the ceiling of the room model. On the door side, the accumulated smoke could leave the room through the door. However, on the other side, the smoke was trapped and kept on accumulating. In this case, some smoke particles collided the wall and were reflected to the door side. Due to the direction of the smoke particles, the flame changed its straight shape and tilted towards the door side.

5. Results II: Gas Temperature Inside Model

The measured transient temperatures would give some indication of the changes of flame pattern. Also, a high temperature in the room model corresponds to a more severe fire and vice versa. Gas temperatures were recorded by the thermocouples at top of the model during experiments. Six thermocouples were used with a data logger to monitor the temperature change inside the model. The positions of thermocouples are shown in Fig. 8.

From Fig. 8(a) for Scenario S1, the temperature changes of the reference test and the three tests with different ventilations before fan operation were similar except S2. That was because V2 and V3 behaved differently from V0 and V1 with more pool fires ignited after starting the fan. In the reference experiment V0, in which no fan was operating, the temperature in the room model became steady. The temperature increased slowly with time until the fire died out.

For the three tests, at the time the fan started operating, the temperatures in the three tests dropped suddenly as some relatively low-temperature air was blown in by the fan. The temperature in Test V1 dropped less compared with those in test V2 and V3. In test V1, although there was low-temperature air added, the hot smoke was trapped in the model. Therefore, the temperature in test V1 had smaller drop after fan operation. After the fall, the temperature rose again before it finally declined. In test V2 and V3, after the sudden drop, the temperature became steady as shown in Fig. 8(b).

From Fig. 8(b) for Scenario S2, the temperature changes of the control and the three tests before fan operation were similar. In the reference experiment V0, the temperature became steady. The temperature increased slowly with time until the fire eventually died out.

For test V1, the temperature decreased slightly after fan operation due to the introduction of lower-temperature air. Then, it increased rapidly and reached a peak. The temperature fluctuated but kept higher than other ventilation arrangements.

In tests V2 and V3, the temperature dropped suddenly due to the introduction of lower-temperature air when the fan was turned on. After the sudden drop, the temperature of test V2 decreased slowly before the fire died out. For test V3, the temperature fluctuated after the sudden drop. After 2 minutes of fluctuation, it became steady and decreased slowly.

From Fig. 8(c) for Scenario S3, the temperature changes of the control and the three tests before fan operation were similar. In the reference experiment V0, without forced ventilation, the temperature rose to about 200 °C, remained steady, and eventually the fire died out.

For test V1, the temperature decreased slightly after operating the fan, due to the introduction of lower-temperature air. Then, it increased because of increased oxygen supply and reached its peak. After the peak, the temperature declined slowly until the fire died out. For tests V2 and V3, the temperature dropped suddenly when the fan was turned on, due to the introduction of lower-temperature air. After the sudden drop, the temperature became steady.

6. Discussion on Effectiveness of PPV

The main criticism on PPV reported in firefighting in Sweden is that, blowing fresh air by a fan into the fire will increase the intensity of the fire and spread it throughout the building.

Any increase in burning rate could not be observed in the tests with small pool fire. Operating a larger fan would generate higher flow rate of air into a room that may very well contribute to an increased rate of heat release and an increased risk of fire spread. Opening a door or a window by firefighting access to the fire site will change the ventilation conditions to the fire in any case. Driving air to the room model by a fan would change the ventilation condition to drive smoke and heat out under appropriate room geometry. But if the firefighting operation is delayed for some reason, the fire will eventually spread, causing a number of problems to the firefighters. Therefore, training of personnel and co-ordination of different measures at the fire site are important to capture the optimum time for executing the appropriate firefighting measures.

The fire patterns in different cases are summarized in Table 1.

Based on a previous study (Chen et al., 2011) about the crossflow ventilation in compartment fires, there could be two possible flow patterns as shown in Fig. 9. If the incoming draught speed exceeds a critical value, unidirectional flow will occur. If the draught speed is below this critical value, bidirectional flow, where hot air escapes through the upper part of the openings and cold air enters through the lower parts, will take place. However, in this research, bidirectional flow occurred in opposite openings under strong draught. In the experiment, the flame tilted to the door side against the draught. If unidirectional flow occurs in both openings, the flame should tilt towards the window side. Hence, further studies should be conducted to find out the critical air flow speed for unidirectional flow.

The high temperature in a fire scene is a severe threat to firefighters. A study revealed that PPV can reduce the temperature inside the fire scenario and ease the firefighting process

(Panindre et al., 2017). In this research, while the PPV was in operation under proper ventilation arrangement, the temperature inside the model dropped. The experiments suggested that employing PPV would only be able to reduce the room temperature under appropriate geometry. It would be interesting to calculate the heat transfer to the adjacent objects in the different scenarios. This is particularly relevant since the heat transfer will determine if the secondary objects will ignite or not. The above experiments show that the secondary objects would not ignite in some cases. This could point towards a ventilation-controlled fire. On the other hand, if the distance of the objects from the fire source is too long compared to reality, the above experiments have only shown that the geometry of the fuel packages is important. If this would be the case, the above experiments only indicated the possibility of employing PPV to reduce the temperature in the scale model studied with the fuel composition that was used. More information has to be compiled from further physical scale modelling experiments and justified by several key full-scale burning tests.

Further studies should be conducted to further understand the relationship of operation of PPV and the temperature change. Based on the understanding, better firefighting strategy could be formulated to make a safer environment for firefighters or other occupants.

It is recommended that the following should be carefully considered by further detailed investigations while deciding to apply PPV in firefighting of room fires:

- PPV pushes fresh air into a room through an inlet and increases the flow rate of hot smoke out through an outlet, if applied properly. Such results have been demonstrated for small houses with simple geometry through water modelling tests. However, there are not much research data on ventilation-controlled fire in buildings with complicated structure and with high combustible content.

- Applying PPV in a large hall creates turbulence, which would disrupt the stratification of an upper hot smoke layer and a lower clean air layer. Consequently, the working conditions for firefighters become more dangerous.

- Burning rate as well as the risk of fire spread may be increased when applying PPV. The conditions to any trapped occupants would be more hazardous. This risk becomes higher when a larger fan with a higher flow rate of air is used.

- The importance of command and control during firefighting operations with support from knowledge of fire science is of paramount importance.

As a summary, there are concerns on applying PPV (Svensson, 2001; Svensson and Werling, 2001). Literature results (Kerber and Walton 2005, 2006; Ezekoye et al., 2007) suggested that PPV is effective when used with careful judgement, though the heat release rate would increase for some time due to increased air supply. Based on the results of water model tests, there is strong support to use PPV in small houses with simple geometry. However, scale water model tests cannot simulate ignition of the second combustible item. Therefore, these tests would work only for studying smoke movement at the early stage of fire. These diversified conclusions suggest that further research on the effectiveness of PPV in big fires in complicated structures, such as the mini-storage fire, is needed.

A clear knowledge of the fire site should be obtained before using PPV. More importantly, there must be appropriate openings at the other end. A careful scientific judgement must be carried out before operating the PPV in fire attacks. Otherwise, there might be more vigorous burning with increase in heat release rate and emission of higher concentration of toxic gases including carbon monoxide and carbon dioxide as suspected by the media (South China Morning Post, 2016; E Weekly, 2016; Next Magazine, 2016; The Standard, 2016) in the big mini-storage fire. The issue of the appropriateness of operating PPV in that big fire (South China Morning Post, 2016; E Weekly, 2016; Next Magazine, 2016; The Standard, 2016) must be investigated thoroughly.

7. Conclusions

Ventilation arrangements determine whether PPV is beneficial or harmful to a fire scenario. PPV is able to perform well in room fires with appropriate geometry without contributing to fire growth if proper ventilation is provided. In the present study, the opposite vent resulted in a relatively small fire size and lesser fire spreading. Therefore, when using PPV in a fire, a similar ventilation arrangement is advised. On the other hand, operating PPV without ventilating would lead to severe results. The firemen should never apply PPV to fire if there is no ventilation. Other ventilation arrangements for PPV in different room geometries should be further investigated to determine the advantages and disadvantages.

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Declaration of Originality

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List of Table:

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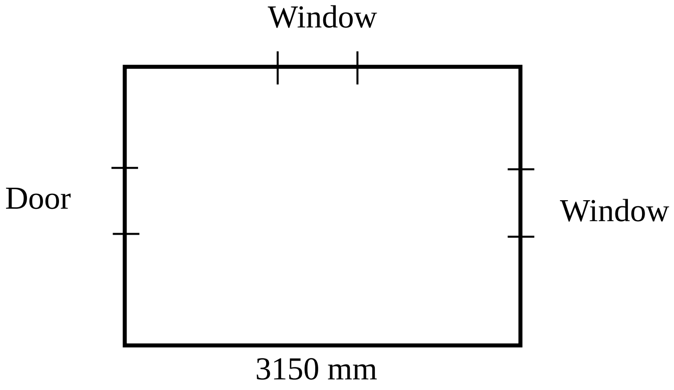
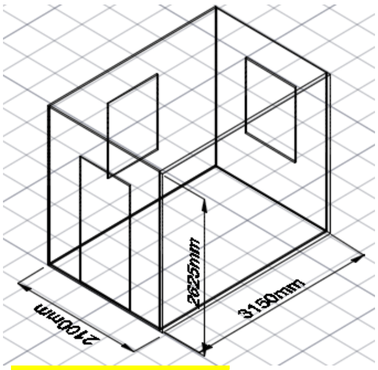
Table 1: Summary of test scenarios and results

	S1: One pool propanol		**S2: Centre pool surrounded by 4 pools**			**S3: Pool fire surrounded by wood cribs**		
	Fire	Maximum temperature/^{o}C	Fire	Maximum temperature/^{o}C	Fire spread	Fire	Maximum temperature/^{o}C	Fire spread
V0	Reference fire	182	Reference fire	196	No	Reference fire	205	🔥
V1: PPV without window	Slightly reduced	96	Bigger fire	313	🔥🔥🔥	Fire slightly reduced	138	🔥
V2: PPV with opposite window	Smaller fire	52	Smaller fire	56	🔥	Smaller fire	63	🔥
V3: PPV with adjacent window	Small fire	47	Smaller fire	73	🔥🔥🔥	Smaller fire	58	🔥🔥

🔥 refers to the fire spread vigorous or not.

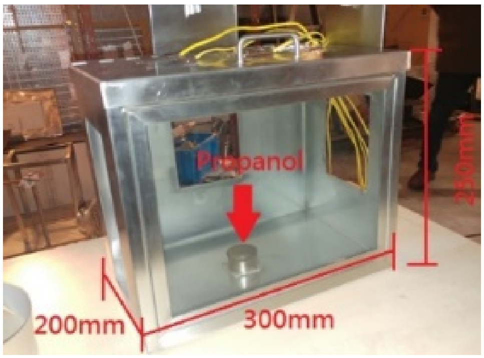


(a) Plan view of model room



Actual room size =
2,100 mm x 3,150 mm x 2,625 mm (H)

(i) Actual size



Model size =
200 mm x 300 mm x 250 mm (H)

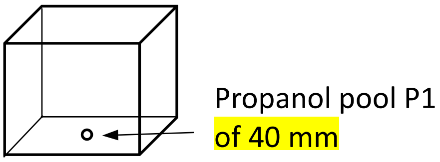
(ii) Scaled size: 1/10.5

(b) Room models

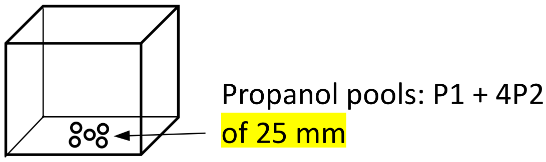
Actual fan	Small fan used
Fan velocity = 35.32 ms^{-1}	Fan velocity = 11.32 ms^{-1}

(c) Fan

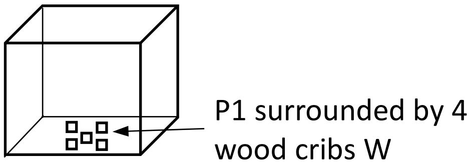
Fig. 1: Schematic of experiments



(a) Scenario S1: 1 pool fire



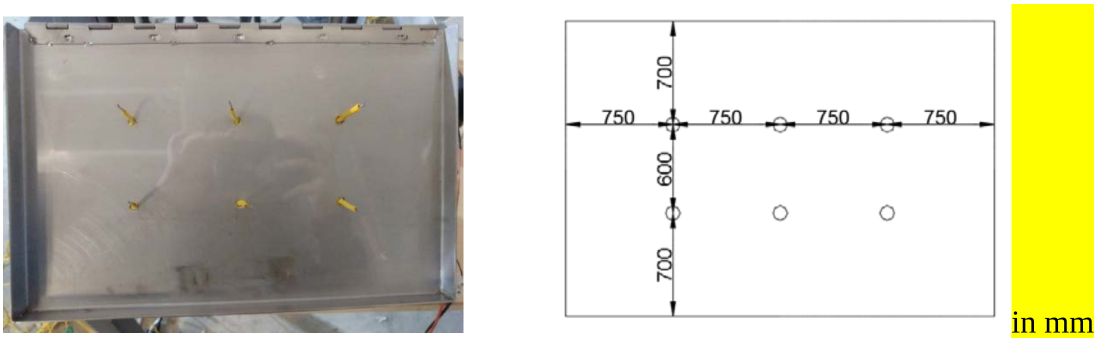
(b) Scenario S2: Centre pool fire surrounded by pools



(c) Scenario S3: Pool fire surrounded by wood crib

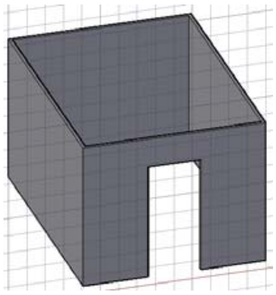
Size: 3 cm × 3 cm × 8 cm

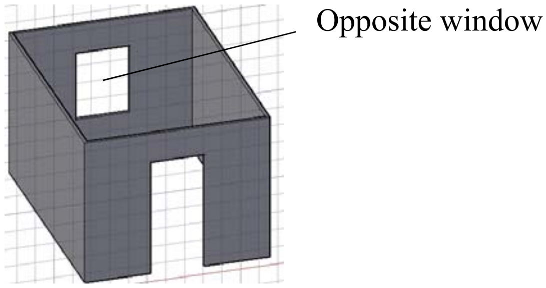
(d) Wood crib



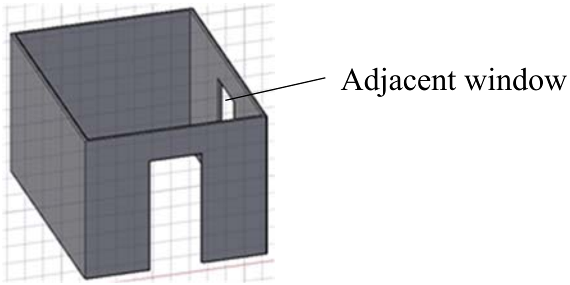
(e) Locations of thermocouples

Fig. 2: Schematic views of experiments





(a) V1: PPV without window (b) V2: PPV with opposite window opened



(c) V3: PPV with adjacent window opened

Fig. 3: The three ventilation arrangements

10 s (Ignited) | 130 s (Growth) | 500 s (Growth) | 720 s (Peak temperature)

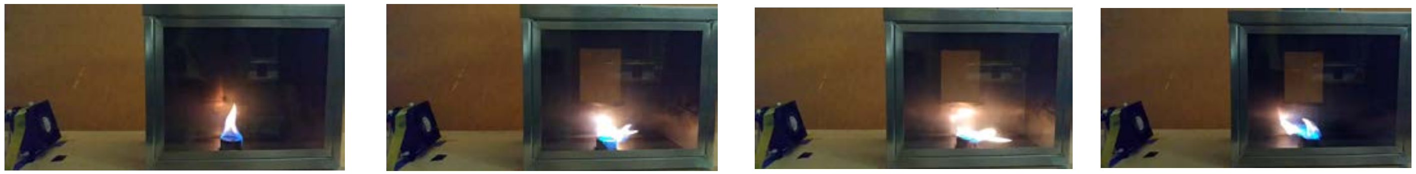
(a) V0

10 s (Ignited) | 130 s (Fan operated) | 310 s (Fluctuation) | 600 s (Fluctuation)

(b) V1: All window closed

10 s (Ignited) | 120 s (Window open) | 130 s (Fan operated) | 600 s (Fluctuation)

(c) V2: Opposite window opened



10 s (Ignited) | 120 s (Window open) | 130 s (Fan operated) | 600 s (Fluctuation)

(d) V3: Adjacent window opened

Fig. 4: Results of S1

10 s (Ignited) | 130 s (Growth) | 550 s (Growth) | 730 s (Peak temperature) | No adjacent source ignited

(a) V0

10 s (Ignited) | 130 s (Fan operated) | 310 s (First Peak) | 400 s (Second peak) | Ignition sequence of fire sources

(b) V1: All windows closed

10 s (Ignited) | 120 s (Window open) | 130 s (Fan operated) | 700 s (Fluctuation) | Ignition sequence of fire sources

(c) V2: Opposite window opened

10 s (Ignited) | 120 s (Window open) | 130 s (Fan operated) | 450 s (Fluctuation) | Ignition sequence of fire sources

(d) V3: Adjacent window opened

Fig. 5: Results of S2

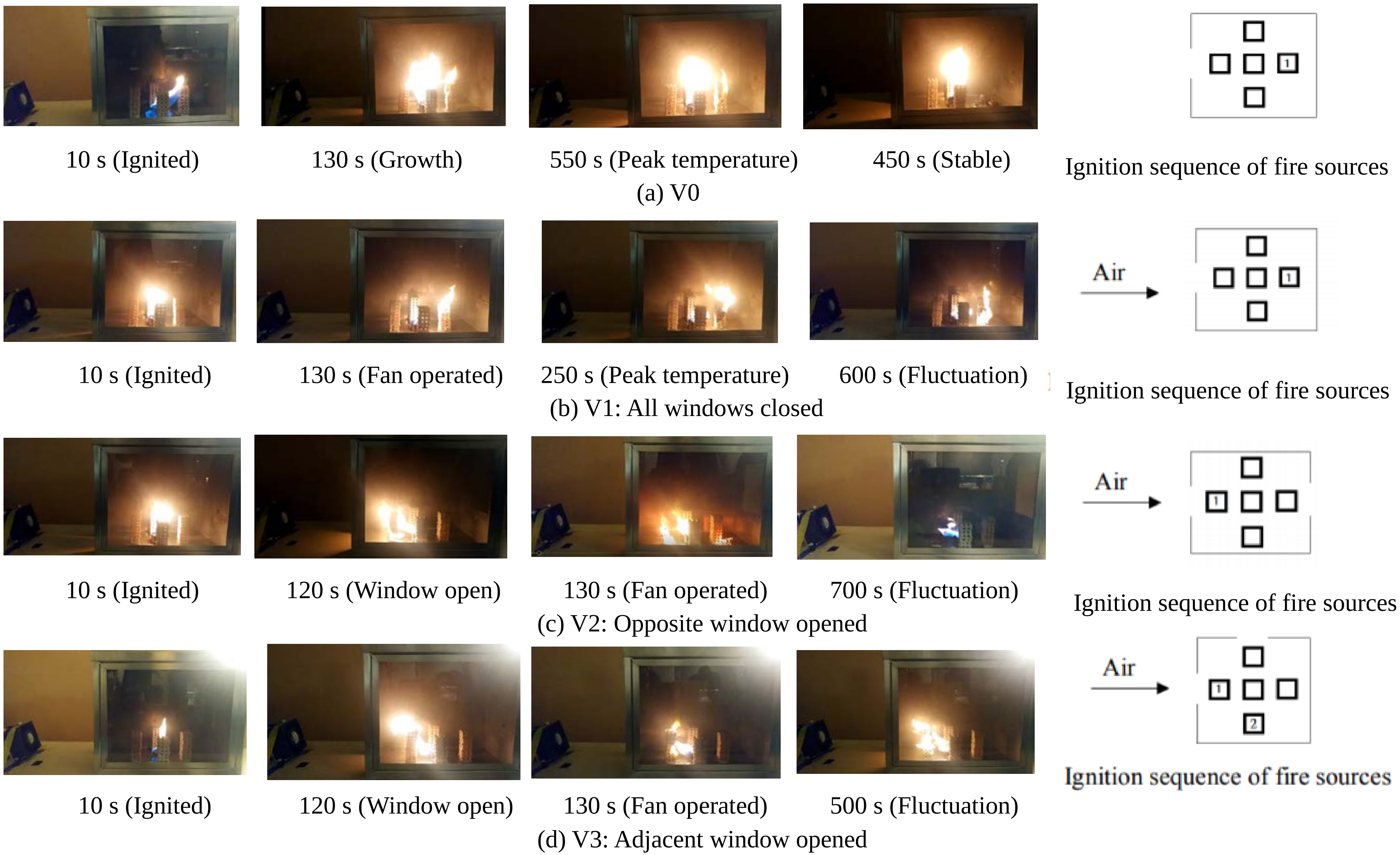


Fig. 6: Results of S3

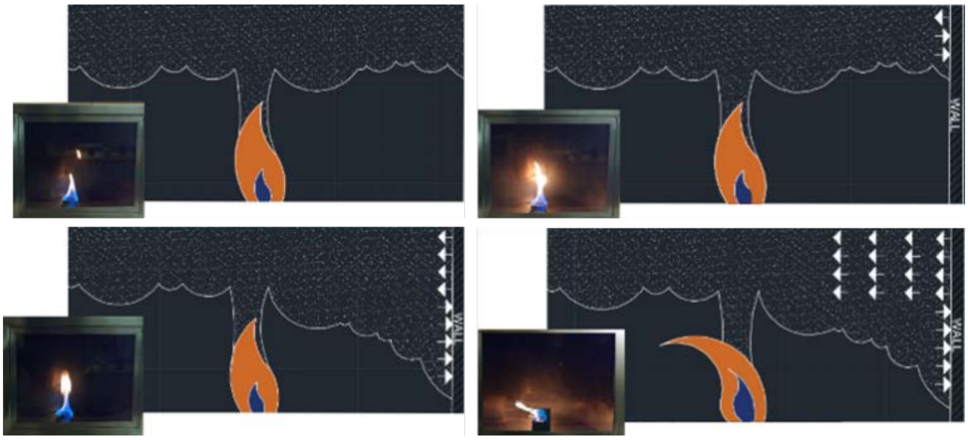
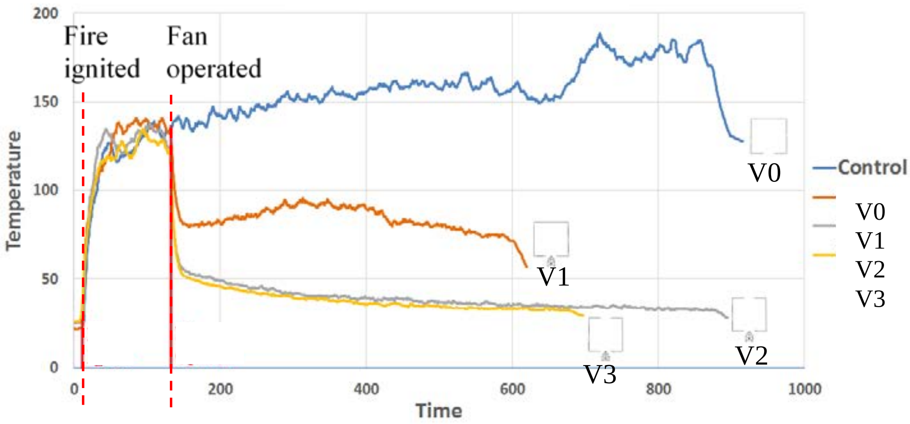
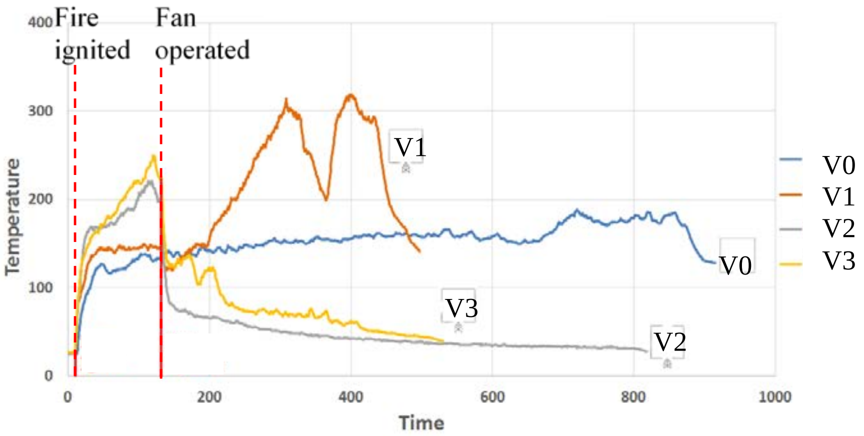


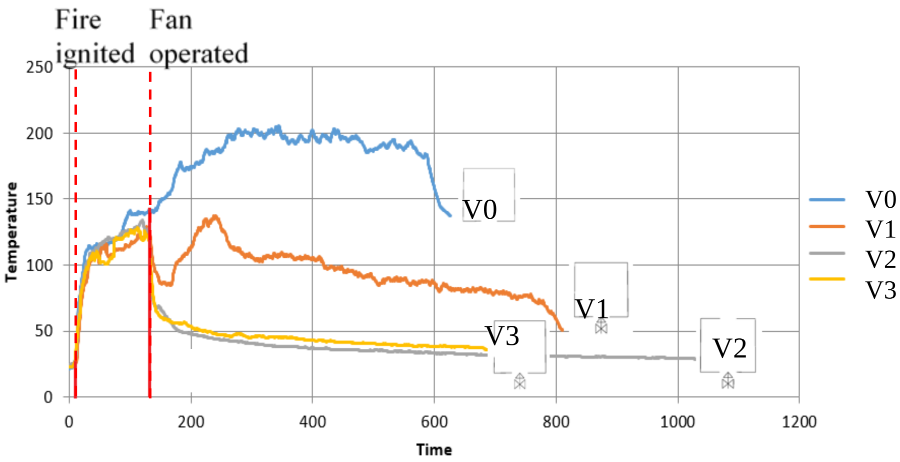
Fig. 7: Initial fire patterns



(a) S1: One burning pool



(b) S2: One burning pool surrounded by four pools



(c) S3: Pool fire surrounded by wood cribs

Fig. 8: Gas temperature measured

(a) Unidirectional flow (b) Bidirectional flow

Fig. 9: Air flows in room model