Aspects of operating PPV in ministorage fires

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Abstract

‘Positive ventilation attack’, a common firefighting technique in a room fire, is supposed to give better visibility and to lower the air temperature while via operating the positive pressure ventilator (PPV). However, about half of the cases applying PPV were found not to work as expected. This was experienced while fighting against big ventilation-controlled room fires.

A big fire broke out in an old industrial building with mini-storage facilities in Hong Kong, 2016. Post-flashover fire lasted for 108 hours with two firefighters killed. Many questions requiring research effort to answer were raised about this big long fire by different parties. Whether air supply by PPV would increase burning rate to give a big ‘ventilation-controlled’ fire is the most difficult question to answer.

The scientific basis discussing the effect of PPV on a big room fire is reported in this paper. Systematic research has to be carried out for addressing the above question scientifically with full-scale burning tests. It is difficult to compile an investigation report within a short time.

1. Introduction

A number 4 alarm fire broke out in 2016 in an old industrial building with mini-storage facilities [1]. Over 120 firefighters and 30 fire engines were deployed to fight against the fire in an area of 2400 m^2 housing over 200 mini-storage cubicles. The big post-flashover fire lasted for 108 hours before finally extinguished, much longer than 20 hours of the Garley Building fire in 1996 [2,3]. No occupants were trapped inside but two firefighters were killed while taking actions.

Many questions requiring research/investigation effort were raised about this big long fire by different parties [4-6]:

- Is the fire load density over 1135 MJm^{-2} [7], considering that the fire duration is108 hours?
- Any dangerous goods stored and ignited to facilitate flame spread?
- Ventilation-limited fires of different flame colour, or burning flammable liquids?
- Air supply would burn more combustibles to give a big fire while operating the positive pressure ventilation (PPV) to a 'ventilation-controlled' fire [8-10]?
- High concentration of toxic gases, particularly carbon monoxide, emitted upon burning, due to inadequate air for burning and cooling by water?
- Inadequate number of water jets deployed in suppressing the fire with adequate amount of water?
- Protection of firemen by the current protective clothing [8-10] is adequate; only able to stand 1000^{o}C for 8 s, but commented to be too hot in causing thermal stress [11] 5 years ago?
- Any explosions inside the cabin store, say due to liquefied petroleum gas (LPG), explosive clean refrigerant or other flammable liquid?
- Any damages to the structures as the fire lasted for 108 hours and the fire resistance period (FRP) is only 4 hours?

Systematic research has to be carried out for addressing the above queries scientifically with full-scale burning tests [5,6,12]. A fire investigation report using fire models was compiled, even there were many challenges on numerical fire studies [6,13-15]. A clear knowledge on the fire site should be searched carefully before deciding to operate PPV. PPV can only be operated [16,17] after careful evaluation and judgement. Otherwise, the heat release rate might increase for some time with air supply rate increased. Whether operating PPV can reduce temperature, reduce toxic gas levels, and improve visibility during a 'fire attack' in big fire in buildings with complicated geometry and high fire load density should be thoroughly assessed. Firstly, the availability of appropriate openings at the other end of the structure on fire should be identified. Secondly, an appropriate operation condition of the PPV should be determined, if PPV is decided to be used.

All these points of concern suggest that fire commands have to be supported by in-depth research on PPV on big room fires as raised by the public [4,5,8]. This is very hazardous to responsible persons handing firefighting and rescue.

2. Literature Review on PPV

Full-scale burning tests with support from numerical simulations were commonly used to evaluate effectiveness of PPV. An early demonstration [18] of the use of PPV tactics for tall fires was conducted in 1972. Both full-scale and laboratory-scale burning tests [16,19-21] were then conducted afterward to investigate and validate the effect of PPV for fires in residential and tall buildings. These studies show that PPV fans can create higher pressure zone to mitigate or control the spread of fire for improving the safety of firefighters and building's occupants, when positioned properly and deployed in a strategic manner.

Water modelling experiments [22] to demonstrate that PPV can perform well should be justified for fire fighting in big fires on sites storing high amounts of combustibles. Tests to investigate the effects of fire ventilation procedures when fighting against fires in large halls were reported [23] in an engineering workshop. This would give small temperature differences with similar results in different building uses. Action of PPV on fires in large halls was investigated [23]. Results showed that PPV increased the flow rate through openings with turbulent mixing. The stratification of the upper hot smoke layer above the lower layer of cool air was disrupted [23]. Consequently, operating PPV in large halls might jeopardize safety and working conditions to firefighters. Command and control during firefighting operations is a key factor.

Room fires with PPV were studied [16] with full-scale burning tests. Additional oxygen provided increased heat release rate to 14 MW for the room fire, but only about 12 MW for room fire without PPV.

Real-scale burning tests were carried out in a 3-storey house to study the effect of PPV on the thermal environment downwind of the fire [16]. A total of 43 experiments performed in 3 different sizes of fan were investigated under two venting strategies: venting the fire room and venting an adjacent room. Numerical CFD simulations conducted using Fire Dynamic Simulator (FDS) version 5 were reported [24] to evaluate the effects of exit vent location on resulting fire room conditions during the application of PPV to a limited-ventilation fire.

A simple flow model was proposed [25] to describe the entrainment into the air cone created by a PPV fan and the results were compared to experimental data. Velocity profiles measured in the air cone of a conventional PPV ventilator were used. The entrainment coefficient and the cone angle were determined for the fan investigated. The correspondence between calculated and measured values was discussed and disparities explained.

Field tests and numerical simulations were performed to study the behavior of PPV tactic [26]. A technique was developed that significantly increases the positive pressure level achieved by a typical PPV operation. CFD simulations were used to optimize PPV deployment. Wind act on fires and can make it very dangerous for the firefighters [27]. PPV operation mitigates the hazards of wind-driven fires, but poor performance with high wind speed. Another strategy using door open area reducers to increase the effectiveness of PPV tactics in firefighting was proposed [28]. Numerical simulation and their experimental results demonstrated that the pressure can be increased significantly. If the resultant static pressure is greater than that created by spread of fire, PPV fan deployment can drive away the flow of smoke, heat, and other combustion products from the stairwells and hallways for improving the safety of firefighters and building's occupants [29-31]. Furthermore, CFD **s**imulation-based analysis and optimization on PPV for fighting wind-driven high-rise fires was reported [27]. A safer environment can be provided for firefighters with the use of wind control devices and PPV.

A case study on assessing the impact of PPV on the building fire with experiments conducted in unused buildings was reported [29]. The ventilation efficiency can be increased by using PPV of fans with higher effective air flow rates. Two scenarios of maximum allowable heat release rate varying from 2.41 MW to 7.12 MW [32] were set up to evaluate the effectiveness of PPV fans with fire in a tunnel and in a subway station.

Applying PPV to prevent the smoke from entering the stairwell was studied [33] using CFD. Staircase pressurization by multiple air supply outlets and 2 air supply outlets next to the fire floor were compared. The minimum pressurization air supply volume flow rates were justified. Correlation of the average pressure in the stairwell on the fire floor and the pressurization air supply volume flow rate was developed. Impact of firefighting intervention on occupant tenability to provide actionable guidance for selecting firefighting tactics was reported [34]. Fire experiments were conducted in a residential structure. Six groups of firefighters with two attack tactics were examined. Gas concentration and temperature measurements were analyzed to give a fractional effective dose.

However, action of PPV in bigger ventilation-controlled fire has not been given adequate attention in the literature. Whether driving air by PPV to the burning objects in a room with different opening provisions would give a bigger fire is still not clear.

3. Small Model Experiments on PPV

In that big mini-storage fire lasting for 108 hours with two firefighters killed [35,36], PPV [e.g. 16] employed was criticized in some media to give a more hazardous fire environment rather than improving the visibility or reducing the temperature inside. Some preliminary opinions on the use of PPV in fire fighting were reported [35].

Two scenarios on fuel-controlled fires scenario and ventilation-controlled fire scenario were conducted by small models reported earlier. Three ventilation conditions including operating PPV with the opposite vent closed, and with the opposite vent open, and without operating the PPV.

Temperature changes and fire spread patterns were captured. It is found that the presence of an opposite vent resulted in fire of smaller size and shorter duration.

4. Different Views on Fire Investigations

The key points on the Mini-storage facility fire at Ngau Tau Kok on 21 June 2016 are summarized [5]. The big fire broke out in an industrial building in Hong Kong, on 11:00 am on 21 June 2016. The fire was upgraded to No. 3 alarm at 12:14 pm, and then to No. 4 alarm at 7:46 pm. It burned for 108 hours, being the longest fire in the history of Hong Kong. The fire claimed the lives of two firemen [37].

In the death inquest of the two firefighters who lost their lives in the fire, the expert witness invited by the Fire Services Department opined that:

- The operation of PPV just outside the door of the unit on fire was effective in creating a functional smoke-free area according to the testimony of an on-site commander of the Fire Services Department. However, it could not completely remove the smoke. This is because the windows of the unit were blocked by advertisement signboards and metal plates, which seriously restricted air flow and hence the removal of smoke.

- Removal of signboards and the timing of removal in firefighting was appropriate. The removal of more signboards might lead give more ventilation and faster spread of fire. The fire started from a faulty air-conditioner on the ceiling, and by simulation the temperature in the fire site was estimated to be as high as 1000^0 C.

- In summary, the strategy and action taken by the firefighting commander were appropriate.

An expert witness appointed by the industrial building pointed out that the firefighting strategy was wrong with comments on the fire as [37]:

- The firefighting team should remove the items inside the mini-storage.
- The team should not attempt to locate the flame and extinguish it.
- The firemen should deal with the stores one by one, not unconsciously going deep into the fire field.
- If it was confirmed that there were no people inside the mini-storage, the strategy should be to extinguish fire from outside to confine the fire.

The coroner accepted that in the tragedy there were inadequacies involving various parties on [37]:

- The staff of the ministorage had neither not received any basic training for responding to a fire breakout, nor were they familiar with using the fire extinguisher and fire alarm bell.
- The mini-storage facility design neither complied with the Buildings Ordinance (Cap. 123) [38], nor was there any system to effectively enforce the provisions in the tenancy agreement, including the prohibition against storage of dangerous goods in the cubicles.

5. Concerns in Applying CFD

Building fires were commonly simulated by Computational Fluid Dynamics (CFD) packages available [13-15] for hazard assessment and disaster management. However, many problems were identified [13,39,40] as in Performance-Based Design (PBD) since the late 1970s. Most of the CFD fire models are not properly validated for studying big room fires including high combustible content with systematic large-scale fire tests. Criticisms on using CFD in simulating smoke movement for big construction projects in the Asia-Oceania (AO) regions are:

- Three-dimensional phenomena make the simulations harder and slower. Instability of the aerodynamics are difficult to archive and sometimes not discussed in detail.
- Ability of studying the turbulent reactive flow for big room fires is doubtful.
- Uncertainty in studying the turbulent exchange flow across free openings such as windows and doors.
- Ability in handling three-dimensional modeling on thermal radiation.
- Ability in handling thousands of chemical reactions in burning.

Empirical parameters in physical models, numerical spatial and temporal discretization parameters and free boundary condition would affect the accuracy of predictions even for studying smoke movement. Pressure distributions were seldom studied with appropriate turbulent parameters and presented in detail.

There is no doubt that CFD predictions must be evaluated properly with experimental studies [41]. Problems on using CFD were identified [14,42]. CFD predictions must be justified [43-51] even for studying smoke movement and control.

Good and bad predicted results by CFD are shown. It is clear that simulating room fires with little amount of combustibles burnt is not always good. Results can be very poor, with large deviation from experiments.

A question:

How can CFD be applied to fire investigation involving that ministorage areas with so much combustibles burnt without any experimental justification?

The authority should not rush to get a fire investigation report to please the public in submitting homework assignments in time!

As reported in a recent conference [6,52-56] on that big ministorage fire lasting for 108 hours on 21 June 2016 in Hong Kong, operating PPV can lead to a more hazardous fire environment rather than improving the visibility or reducing the temperature inside under some ventilation conditions. Firstly, there are different views on operating PPV for firefighting and rescue. Ventilation arrangements should be carefully investigated. Secondly, it is found that the presence of an opposite vent resulted in fire of smaller size and shorter duration. Thirdly, further studies on fire investigation should be confirmed by full-scale burning tests, not just by CFD because of storing so much combustibles in limited space.

Key points to watch are:

- In the past decade, the technique of computational fluid dynamics (CFD) (or called field modelling technique for the case on fire simulation) has been developed and used to some extent for design purpose. Some like Numerical Heat Transfer (NHT). Always call CFD fire model now.

- Although the computing time required was very long, the problem has been improved with efficient numerical schemes and fast computers.

- A three-dimensional simulation can be executed successfully now in a Pentium personal computer with 5 million cells. There should be no problem on doing the 'number crunching' exercises if up to 5 million cells in a Pentium Unix stand-alone workstation is available. CFD model can be applied to simulate the fire-induced field of flow, temperature and smoke concentrations within an enclosure.

- Current development is up to a stage that the flow and temperature field can be simulated successfully by taking the burning object as a heat source. To the best of knowledge, combustion effects of the burning process had not been simulated successfully apart from using the simple chemical reacting system approach, although attempts were made in the Sweden/U.K. project on using flamelet model to develop a chemistry library.

- The field model is still a natural convection problem good only for predicting the flow field driven by buoyancy at distance away from the fire source. Flame spread process cannot be simulated realistically without studying the combustion chemistry. But the predicted results are good enough for building services engineers to assess the performance of fire protection systems.

- The thermal power resulted by a fire in an enclosure is of the order of megawatt, such as that produced by burning a polyurethane foam sofa. The resultant flow is turbulent with the use of turbulence models, the averaged values of the air flow variables including the momentum, density, pressure, enthalpy and smoke concentration are solved.

- In the primitive variable formulations, the presence of the pressure causes difficulty in incompressible flows because there is no explicit equation available to calculate it.

- A usual practice is to treat the pressure using a "guess-and-correct" procedure. The momentum equations are first solved for a guessed pressure field to obtain a tentative velocity field.

- Approximate equations for calculating corrections to this guessed pressure field (or, in some instances, the pressure field itself) are then derived from the momentum and continuity equations. These equations are solved, the pressure field is updated, and the velocity field is corrected to satisfy the continuity equation.

- The popular decoupling methods fall into two categories:
  - First are those in which the pressure correction equation was used both to update the pressure and correct the velocities, i.e. variations of the SIMPLE procedure.
  - Second are those in which the pressure correction equation was used only to correct the velocities, with a separate Poisson equation used ot calculate the pressure.

Verification and Validation (V&V) of Fire Models are important [57-60]:

- Verification does not assert whether the solutions from a code are physically valid or not, but only determines the level of accuracy achieved by a code through purely numerical exercises.

- Validation is the process of estimating the level of accuracy of a CFD fire simulation by comparison with experimental data and provides evidence for how accurately the computational simulates reality.

- Verification and validation are working on two different aspects:
  -Verification: focusing on the equations.
  -Validation: concerning about solving the right equations

There are eight fundamental but essential rules:

- Checking the completeness of technical documentation;
- Checking the scientific ground by independent experts;
- Source code checking by independent experts;
- Analytical solution comparison;
- Benchmark fire code comparison;
- Grid size and time step refinement exercise;
- Monitoring the residual error of governing equations;
- Validation with experimental results.

CFD fire models:

- Experimental validations have not been studied in a way as for the zone models.

- Very limited experimental works for verifying field models.
- Data reported by Steckler et al. was performed originally for studying the doorway flow but had been used repeatedly.
- Good and bad results shown in [61].

6. Public Concerns

After the incident, there are more inspections on ministorage areas by FSD. Ministorages without adequate FSI were warned but seldom charged. There are concerns on whether current regulations are adequate [62].

In fact, FSD knows well how to proceed with their resources allocated, they know much better than others. The problem is similar to illegal parking or driving over 50 km per hour in downtown on inadequate staff.

Fire regulations had been established on the first point under Fire Ordinances by Fire Services Department; and Building Ordinances by Buildings Department. Fire safety has to be provided by :

- Passive building construction and active fire engineering systems;
- Fire safety management;
- Fire safety culture.

Second and third points above have to be done by the owners and users themselves.

In long term, there were questions on whether the government should issue license.

However, ministorage areas are not so crowded as shopping malls, subway stations or train cars during rushing hours. Evacuation should not be a big problem, if egress provided accordingly. Limiting the fire load and providing appropriate active fire engineering systems following the regulations should be appropriate. Establishing a licensing system must be supported by different parties.

In conclusion, existing fire regulations appear adequate. The requirements are actively updating and upgrading to face new challenges. Fire safety management is important as demonstrated by the big Garley Building Fire. Alerting better fire safety culture to citizens is much better.

7. Conclusion

Many questions requiring research effort were raised about the 'positive ventilation attack' firefighting technique in buildings. It might not work as expected, particularly while fighting against big ventilation-controlled room fires as demonstrated in the number 4 alarm big fire in 2016.

Driving more air by PPV to such a fire would lead to more complete burning of combustibles stored inside. Systematic research with full-scale burning tests has to be carried out. An operation guidance on the proper use PPV is required to avoid converting the ventilation-controlled fire to a big fire.

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