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About Air Pumping through Openings in a Room Fire

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Abstract

The air pumping effect of a fire plume would give higher air intake rate through vertical openings in a room fire. The phenomenon was proposed in 1976, studied again in 2012 and revisited again. The main application is to explore optimum operation scheme of positive pressure ventilation to handle big hazardous fires. The big ministorage fire in 2016 faced numerous challenges. Air pumping of such a big fire should be studied further. This article pointed out the key works reported in the literature. Derivation of the key equations for the air intake rate through vertical openings found in the literature and application of Computational Fluid Dynamics are reviewed for further studies on big fires.

1. Introduction

The airflow rate through an opening in a compartment fire is important in determining the potential fire hazards [1-4]. Numerous efforts have been made to derive the correlation of airflow rates across the opening as reviewed in 2010s [5-7].

The first most widely applied approach was the pressure hydrostatic model by Kawagoe [8]. The temperature difference between the indoor hot gas and outside cool air gives the driving force for drawing outside air in and ejecting hot gas out. Correlation expressions were derived empirically from burning tests for airflow rates across openings. A linear expression was derived for relating the airflow rate across an opening with the ventilation factor. There were numerous studies [9-13] as reported in the literature since then with some new articles [14-16].

Positive pressure ventilators (PPVs) are widely used in firefighting [17-19], known as 'positive ventilation attack' in many places, to improve visibility and reduce air temperatures. However, PPV is not always effective as experienced. The scheme was criticized on the big ministorage fire [20-23] lasting for 108 hours occurred on 21 June 2016 in Hong Kong because two firefighters were killed. There were reports by the media that operating PPV led to a more hazardous fire environment rather than improving the visibility or reducing the temperature inside.

It should be noted that most building fires at the post-flashover stage are ventilation controlled. At least four key factors would affect the burning duration of the postflashover fire. These are the air intake rate, hot gas temperature, heat release rate of the combustibles, and heat flux lost at the compartment boundaries. A higher air intake rate due to the pumping action of the fire plume would give a bigger fire.

2. Doorway Flow Equations from Hydrostatics

As reviewed [5,6], mass flow rate through a vertical rectangular opening due to temperature differences had been studied extensively in the literature [8,9]. Examples are those reported by Quintiere and Den Braven [10] from Bernoulli's equation.

The mass air flow rate $\dot{m}_{air}$ though the opening of area A_w, height H and discharge coefficient C_d in a room with hot gas density ρ_F and temperature T_F, outside air density ρ_o and temperature T_o was derived in a book [11]:

$$\dot{m}_{air} = \frac{2}{3} A_w C_d \sqrt{2gH} \rho_o \left[p + \frac{1}{q^3} \right]^{\frac{1}{2}} \tag{1}$$

where g is acceleration due to gravity and

$$p = \frac{\rho_F - \rho_o}{\rho_o} \tag{1a}$$

$$q = 1 + \left(\frac{\rho_o}{\rho_F} \right)^{\frac{1}{3}} \tag{1b}$$

Expressing changes in density $\Delta\rho$ and temperature ΔT as:

$$\Delta\rho = \rho_o - \rho_F \tag{2}$$

$$\Delta T = T_F - T_o \tag{3}$$

Slight changes in pressure on ideal gas gives:

$$\frac{\Delta\rho}{\rho_F} = \frac{\Delta T}{T_o}$$

or

$$\frac{\Delta\rho}{\rho_o} \approx \frac{\Delta T}{T_o} \tag{4}$$

Putting in $\rho_o \sim \rho_F$ everywhere except at $\Delta\rho$:

$$q^{\frac{2}{3}} = 8^{2/3} = 2\sqrt{2}$$

This gives and empirical relation on $\dot{m}_{air}$ (in kgs^{-1}) reported by Awbi [12,13]:

$$\dot{m}_{air} = \frac{1}{3} C_d A_w \rho_o \sqrt{\frac{gH\Delta T}{T_o}} \tag{5}$$

3. Air Pumping Action

A hydrostatic pressure equation was set up by Rockett [9] to relate the pressure inside and outside the fire room. The total plume flow upward at the height with thermal discontinuity at the layer interface must be equal to the flow of gas out of the room. The total air entrainment rate below the thermal discontinuity is equal to the airflow rate into the room. An empirical expression of the plume flow gives the neutral plane height.

The pumping effect due to fire-induced current in the room was studied by Harmathy [4] using an analytical model. That was extended by [5] to get the airflow rate across the door.

Computational Fluid Dynamics (CFD) [24-43] can be applied to study the doorway flow. CFD was applied to study possible air pumping action [1,2,4] due to a plume in a compartment fire. A fire plume would entrain more air through openings in the compartment. Consequently, air intake rates through the opening would be higher than estimated from a hydrostatic pressure model.

CFD was applied [5-7] to study possible air pumping action [1,2,4] due to a plume in a compartment fire. It was demonstrated [5] that a fire plume would entrain more air through openings in the compartment. Consequently, air intake rates through the opening would be higher than estimated from a hydrostatic pressure model. This point is illustrated by CFD predictions [24-43] even with a pre-flashover fire. A room fire before flashover would have a thermal plume, and so the pumping effect is very obvious and studied. A fire plume might not form in a post-flashover fire, depending on the amount of combustibles. Air pumping action will be higher for openings of lower ventilation factors. This agrees with the empirical equation on airflow rate across openings deduced by Harmathy [1,2,4] with experimental data on post-flashover fires. However, studies were limited.

4. Positive Pressure Ventilation

Before operating a PPV [44-60], a thorough understanding of the fire site is required. To prevent the heat release rate from increasing due to the increased air supply rate, PPVs are only operated after careful evaluation and judgement. Using a PPV effectively [61,62] reduces the temperature and toxic gas levels. Several aspects of the big ministorage fire had been reported recently [19]:

Firstly, different views on operating PPV for firefighting and rescue were summarized. Ventilation arrangements including the locations of PPV and exhaust openings in a room should be carefully investigated for better understanding the efficiency of PPV in firefighting.

Secondly, action of operating PPV in a room fire studied by physical scale modelling was discussed. 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.

Thirdly, fire investigation should be supported by full-scale burning tests in the fire investigation report, not solely by CFD because of storing so much combustibles in limited space. Free CFD software is commonly used and there is no guarantee that the software is appropriate for simulating such big room fires. Problems identified in the application of CFD [63-97] properly should be handled.

Key problems proposed are:

- Effect of turbulence caused by PPVs.
- Increasing heat release rate.

Translating research results on those new knowledge into operational decision guidelines and fire safety management: Using fire science data to improve command and control during firefighting operations.

Ventilation-controlled room fires in mini-storage areas fire 2016 was a big lesson to learn. PPV causes a larger fire, faster heat release, and more toxic smoke. Therefore, operational guidance on PPV use is required to avoid converting ventilation-controlled fires into large fires. Supporting research is necessary. Mini-storage areas often have many small rooms connected by corridors to give a complicated enclosure. During that big fire [20-23], firefighters could only see smoke coming out of the doors of some rooms or corridors. They could not tell which rooms had fires.

5. Conclusion

The understanding of post-flashover ministorage fire is very limited. Several firemen were killed while fighting against big ministroage ventilation-controlled fires after flashover. More studies should be carried out to identify the right fire-fighting techniques. It is proposed to study airflow rate across openings with heat release rate measured simultaneously as reported earlier on justifying flashover equations.

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