

INVESTIGATING POSITIVE PRESSURE VENTILATION

Ofodike A. Ezekoye¹, Stefan Svensson² & Robert Nicks³

¹The University of Texas, Austin

²Swedish Rescue Services Agency

³Austin Fire Department

ABSTRACT

Positive pressure ventilation was investigated. Forty-three experiments were performed on the first, second, and third floors of a three-storey brick building with wooden trusses. The objectives of the experiments were to investigate the effects of distance between fan and inlet, size and numbers of outlets, and volume of building on vent flow rates when using positive pressure ventilation. Four different fans from two different manufacturers with varying characteristics were used. Airflow through outlets was measured. The results shows that flow rate through an exhaust increases with increasing distance between fan and inlet up to some maximum value and a decreasing flow rate after this point. Also, flow rate through an exhaust decreases as volume of the structure increases. In a larger volume more leakage can be expected, thus decreasing the efficiency of positive pressure ventilation. In addition, increasing the exhaust area decreases the flow loss, thus increasing the efficiency of positive pressure ventilation. The number of exhaust openings affects the volumetric flow rate in a nonlinear manner.

INTRODUCTION

Ventilation, in general, and positive pressure ventilation specifically, is an important procedure within the tactical toolbox that most fire departments utilize. Ventilation is required to remove the hot and toxic fire gases that build up within a compartment fire. Hot fire gases contribute to the spread of fire through a building, the heat and toxic gases are hazardous to people trapped inside a burning building, and they generally create hard and dangerous working conditions for fire fighters. Positive pressure ventilation is a technique that has become popular in the fire and rescue service during the last ten years. Positive pressure ventilation (PPV) is a method where air is blown into a building exposed to fire using fans. Consequently the hot air and smoke are blown out of the building. PPV is used to quickly localise the fire and any trapped victims and to remove the heat so that further spreading of the fire is dampened. With increasing constraints of resources associated with staffing and other budget driven considerations, the effective use of technologies and tactics must be carefully reviewed to understand the appropriateness of tactics to most effectively suppress a structure fire. The notion of effective suppression covers safety considerations for fire fighters entering and victims evacuating the structure.

Ventilation is particularly complex because the underlying phenomena are based on quite complex fluid mechanics and combustion physics. For example, the delivered flow associated with positive pressure ventilation into a structure and through a compartment where the fire is burning depends in a complex manner on the type of structure, number of vents that are open, and characteristics of the prime mover (fan).

The present paper first summarizes a number of studies on PPV and draws conclusions from these studies, then presents new experimental studies on flow processes including the effects of numbers and size of exhausts, volume of a building and the effects of the distance between the fan and the inlet when using PPV. Finally, the paper discusses the impact of ventilation on fire temperatures in a post-flashover (well mixed) compartment fire.

PREVIOUS RESEARCH

Mittendorf details early work on positive pressure ventilation¹. The technique has been used in the fire service for a number of years with a nearly equal number of proponents and critics. Until the recent past, very little had been done by the fire research community to quantitatively assess the effectiveness of this technique in minimizing injury and death to trapped victims and fire fighters². While the conditions for fire fighters are likely to be improved by the removal of smoke and heat from the structure by the use of PPV, it is possible that the conditions for a victim caught in the fire structure may be deteriorated because of any changes in the local environment (particularly downwind of the fire) associated with PPV^{3, 4, 5}.

Experiments have shown that the rate of heat release increases by the use of PPV^{5, 6}. Svensson⁵ showed that PPV increases the temperature in rooms on the leeward side of the fire and reduces temperatures in rooms on the windward side of the fire. This suggests that exit openings should be created as close to the seat of the fire as possible. In addition, Kerber and Walton⁶ show that as compared to natural ventilation, positive pressure ventilation caused higher fire room temperatures, increased window gas flows and higher pressure differentials.

Experiments in a large hall showed that PPV increases the flow rate through openings inducing significant turbulent mixing which disrupts the stratification of the upper layer of hot smoke and a lower layer of cool air⁷. Consequently, the use of PPV in large halls may jeopardize safety and working conditions to fire fighters.

Live fire tests in an acquired house were conducted in order to study the effect of PPV attack on the thermal environment downwind of the fire⁸. Three different sizes of fan were investigated and two venting strategies were used: venting the fire room and venting the victim room. The results included conclusions such as when venting the fire room and using PPV, a somewhat higher temperature was observed in the fire room compared to cases without fan application. Also, venting the victim room and using PPV resulted in higher gas temperatures in the victim room at the higher elevations than both fire room vented cases and cases without fan application.

Experiments on fire fighting tactics clearly showed that positive pressure ventilation is a useful procedure, provided that it is used correct and with caution⁹. The use of PPV must in the general case be coordinated with creating exit openings, attack the fire, fire suppression and removal of victims.

In general, more data have been collected and analyzed in the recent ten years showing that there can be significant benefits to the use of PPV. However, there are still a number of effects and aspects of PPV that need to be investigated.

EXPERIMENTS

Objectives

Forty-three experiments were performed on the first, second, and third floors of a three-storey brick building with wooden trusses. The objectives of the experiments were to investigate the effects of distance between fan and inlet, size and numbers of outlets, and volume of building on vent flow rates when using positive pressure ventilation.

Experimental setup

The experimental set-up included a corridor on each floor with four rooms on each side of the building. Figure 1 shows the layout of the first floor, which was typical to each floor of the building. The inlet to the building, D1, was located at one end of the corridor and three rooms, room 1 – 3, on one side of the corridor each had an outlet, W1 – W3 in figure 1, that were used during the experiments. In addition, W4 located on the second floor in room 4 just above room3/W3, was used. W1 – W4 each measured 0,84×1,04 m (w×h), D1 measured 1,07×2,08 m (w×h) and D2 – D5 (D5 to room 4 on the second floor) measured 0,79×2,03 m (w×h).

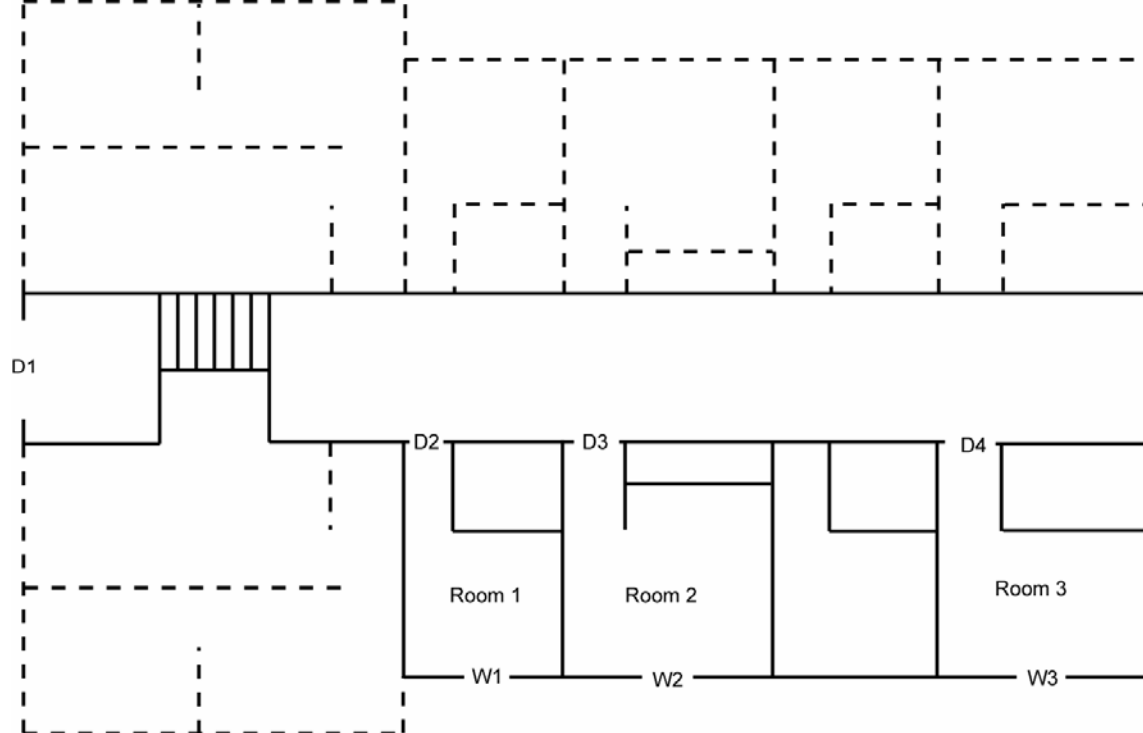


Figure 1; Layout of the 1st floor of the structure (the “Travis-building”, Austin, TX)

Four different fans from two different manufacturers with varying characteristics were placed external to the structure, table 1. These fans were operated at their full capacity when placed at different distances from the external door of the structure. A major design difference between the two types of fans is that fans 3 and 4 are positioned on extendable legs. The tests included the legs extended as well as retracted, determining the effects of the extension in providing airflow through the structure.

Airflow was measured using five hot-film anemometers. The anemometers have a range of 0,2 m/s to 20 m/s with a resolution of 0,03 m/s. The anemometers were placed in the exit vent (W1 – W4) of a particular room during any given test, one located 0,075 m from each corner and one in the middle of the vent.

Table 1; Fan specifications provided by manufacturers

#	Model	Fan Diameter [m]	Power (kW)	Rated flow rate(m ³ /s)
1	Tempest DD 18-H-5.5	0,46	4,1	6,97
2	Tempest DD 24-H-6.5	0,61	4,85	9,25
3	Ventry Honda GX120	0,51	2,98	7,7
4	Ventry Honda GX200	0,61	4,85	13,5

Table 2; Overview of the tests

Test #	Fan #	Floor	Exhaust	Distance between fan and D1 [m]	Flow through exhaust [m ³ /s]	Volume [m ³]	Comments
1	1	1	W1	0,61	0,44	130	
2	1	1	W1	1,22	0,55	130	
3	1	1	W1	1,83	0,76	130	
4	1	1	W1	2,44	0,81	130	
5	1	1	W1	3,05	0,69	130	
6	1	1	W1	3,66	0,61	130	
7	1	1	W3	2,44	0,82	189	
8	1	2	W4	2,44	0,36	1641	
9	4	1	W1	0,61	0,67	130	stand retracted
10	4	1	W1	1,22	0,87	130	stand retracted
11	4	1	W1	1,83	0,93	130	stand retracted
12	4	1	W1	2,44	1,28	130	stand retracted
13	4	1	W1	3,05	1,33	130	stand retracted
14	4	1	W1	3,66	1,32	130	stand retracted
15	4	1	W3	3,05	1,36	189	stand extended
16	3	1	W1	0,61	0,50	130	stand extended
17	3	1	W1	1,22	0,48	130	stand extended
18	3	1	W1	1,83	0,84	130	stand extended
19	3	1	W1	2,44	1,06	130	stand extended
20	3	1	W1	3,05	0,96	130	stand extended
21	3	1	W1	3,66	0,90	130	stand extended
22	4	1	W1	3,05	1,11	130	stand extended
23	4	1	W1	3,05	0,97	465	stand extended
24	1	1	W1	2,44	0,72	130	
25	1	1	W1+W2	2,44	0,61	221	2 rooms, 1 exhaust
26	4	1	W1+W2	2,44	0,90	221	stand extended, 2 exhausts
27	4	1	W1+W2	3,05	1,02	221	stand extended, 2 exhausts
28	1	1	W1+W2	2,44	0,58	221	2 exhausts
29	1	1	W1+W2	3,05	0,50	221	2 exhausts
30	4	1	W1	0,61	0,87	130	stand extended
31	4	1	W1	1,22	0,95	130	stand extended
32	4	1	W1	1,83	1,15	130	stand extended
33	4	1	W1	2,44	1,38	130	stand extended
34	4	1	W1	3,05	1,41	130	stand extended
35	4	1	W1	3,66	1,39	130	stand extended
36	4	1	W3	3,05	1,24	189	stand extended
37	4	2	W4	3,05	0,56	1641	stand extended
38	2	1	W1	0,61	0,62	130	
39	2	1	W1	1,22	0,64	130	
40	2	1	W1	1,83	0,85	130	
41	2	1	W1	2,44	0,72	130	
42	2	1	W1	3,05	0,53	130	
43	2	1	W1	3,66	0,32	130	

Results

The experiments showed that that the flow rates measured through the exit vents were significantly lower than the rated flow rates of the fans, figures 3, 4 and 5. Factors that may cause such large deviation between the rated flow rates and the measured values are being investigated. Even if there is

a bias in the experiments, this bias would occur across all the tests that were conducted and would still allow comparison between the different fans and the different configurations in which they were tested.

There were clear differences between different fan flows with nominally same power rating. In the indicated power ratings there were differences as large as 50% between the flow output of the largest rated fan and the least rated fan. This suggests that factors other than the motor rating of the fans should be considered as being important when a fire department selects fans for use in PPV. All previous research suggests that more flow rate is always better than less flow rate when considering the effectiveness of PPV. As an example, fan 1 has approximately 10% lower rated flow rate than fan 3, but almost a 40% more powerful engine. In addition, fan 3 is slightly larger in diameter than fan 1, table 1.

It was found that the measured flow rate through the exhaust increased with increasing fan distance away from the external inlet vent to a maximum value and then fell after some point, figure 3. Fan 4 (tests 9 – 14 and 30 – 35) had the highest flow rates through the exhaust. This case showed a monotonic increase in the volumetric flow rate through the compartment vent and a flattening of the flow rate at the largest distances. Also, there is less than a 5% difference in flow rate at the maximum flow rate values between fan 4 with legs extended and legs retracted. A fan with extended legs should provide less ground effects and better entrainment characteristics.

The larger diameter fan (fan 2) had superior flow rate characteristic relative to the smaller diameter fan (fan 1) at fan to door distances less than approximately 1,7 m. Following this distance the smaller diameter fan had better flow rate characteristics. This was not seen in fans 3 and 4. In these fans the larger diameter fan always showed better performance than the smaller diameter fan.

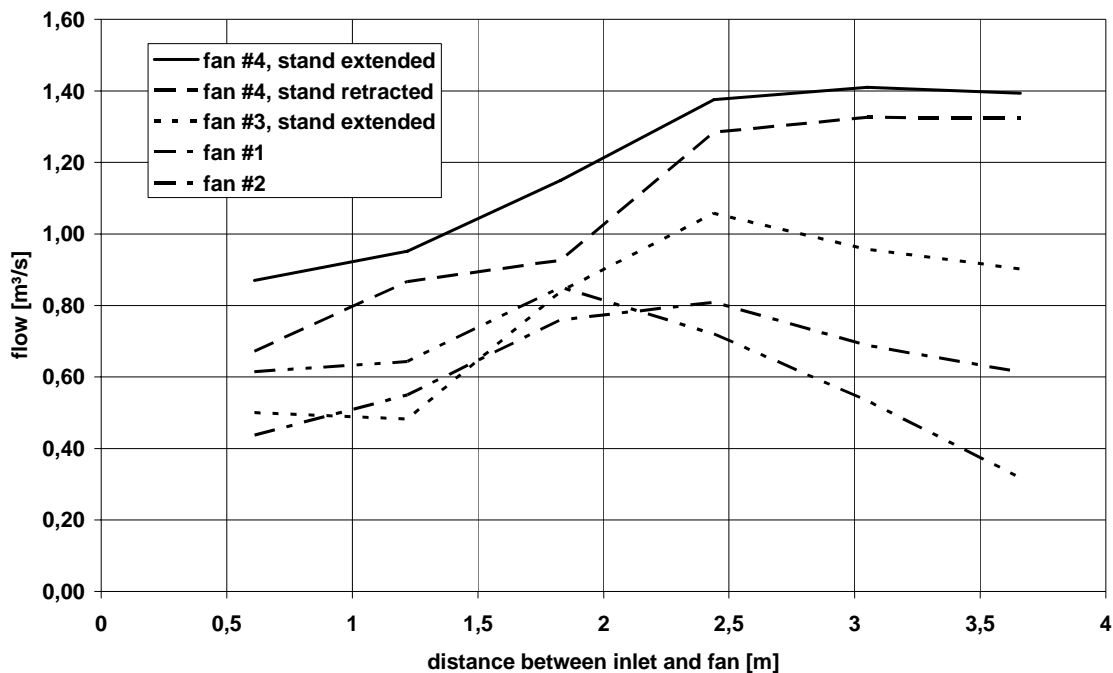


Figure 3; Exhaust flow as a function of fan distance between inlet and fan

Figure 4 shows the exhaust flow as a function of the volume of the structure. The figure shows that the flow rate through the exhaust decreases as volume of the structure increases. An increase of the total volume of the structure of approximately 1000%, without changing the number or size of exhausts, decreases the exhaust flow rate with approximately 50%.

Table 3; Effects of compartment size on flow rate through exit vents

Volume	Tempest DD 18-H-5.5 (m ³ /s)	Ventry Honda GX200 (m ³ /s)
1 st Floor small volume	1,59	2,76
1 st Floor large volume	1,58 (< 1% drop)	2,58 (< 1% drop)
2 nd Floor largest volume	0,67 (~42% drop)	1,05 (~38% drop)

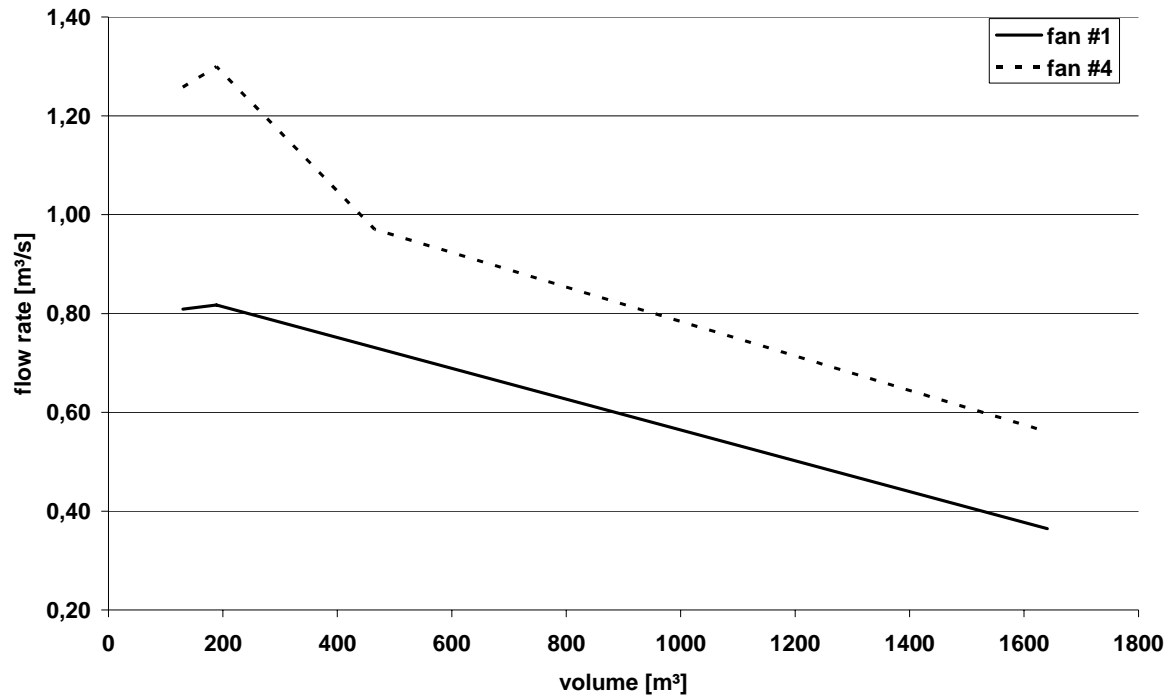


Figure 4; Exhaust flow as a function of volume of building

The number of exhaust openings and also the total exhaust area affects the total flow rate out of the building, figure 5. Increasing the exhaust area, by opening a second window, makes the flow through the first window decrease by approximately 25%. Consequently, the number of exhaust openings affects the volumetric flow rate in a nonlinear manner.

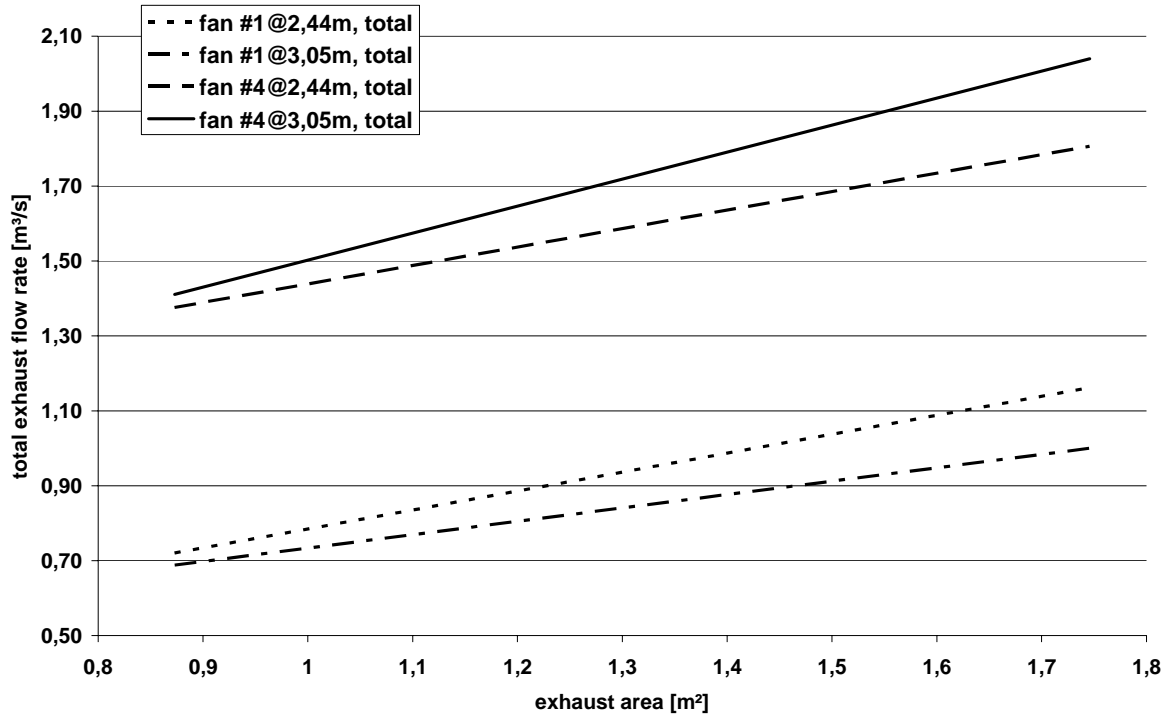
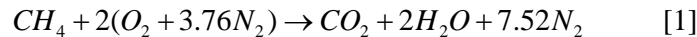


Figure 5; exhaust flow as a function of exhaust area

DISCUSSION

Inadequate flow rates through a compartment in which a fire is burning could be one of the most dangerous scenarios that one can imagine associated with PPV. A ventilation controlled fire which is fed oxidant through the use of an improperly placed fan or through the use of an undersized fan can lead to a dangerous condition.

A way to look at these results is by thermodynamic analysis of the temperature in a compartment that is fueled with a gas burner. Consider a 1 MW natural gas fire in one of the 37m² suites on one of the floor of the structure. The stoichiometric equation for methane combustion is:



The natural gas flow rate associated with 1 MW is 0,02 kg/s. The mass flow rate of air required for stoichiometric combustion is 0,345 kg/s. At typical environmental conditions this requires a flow rate of approximately 0,35 m³/s. As expected, that the fan flowrates are always much larger than the flowrates associated with stoichiometric combustion. Without accounting for heat losses to the walls of the compartment, a simple scaling estimate for the average temperatures in the compartment is:

$$T_{AVG} \approx \begin{cases} T_{\infty} + \frac{\dot{m}_F \Delta H_c (1 - \chi_{RAD})}{c_p (\dot{m}_A + \dot{m}_F)} & \phi < 1 \\ T_{\infty} + \frac{.21 \dot{m}_A \Delta H_{c,O} (1 - \chi_{RAD})}{c_p (\dot{m}_A + \dot{m}_F)} & \phi > 1 \end{cases} \quad [2]$$

The temperatures shown below are associated with a radiative loss fraction of 30%. While the temperatures are still significantly hotter than actual fire room temperatures, the trend in the shape of the temperature profile is consistent with what one would find in a fire enclosure.

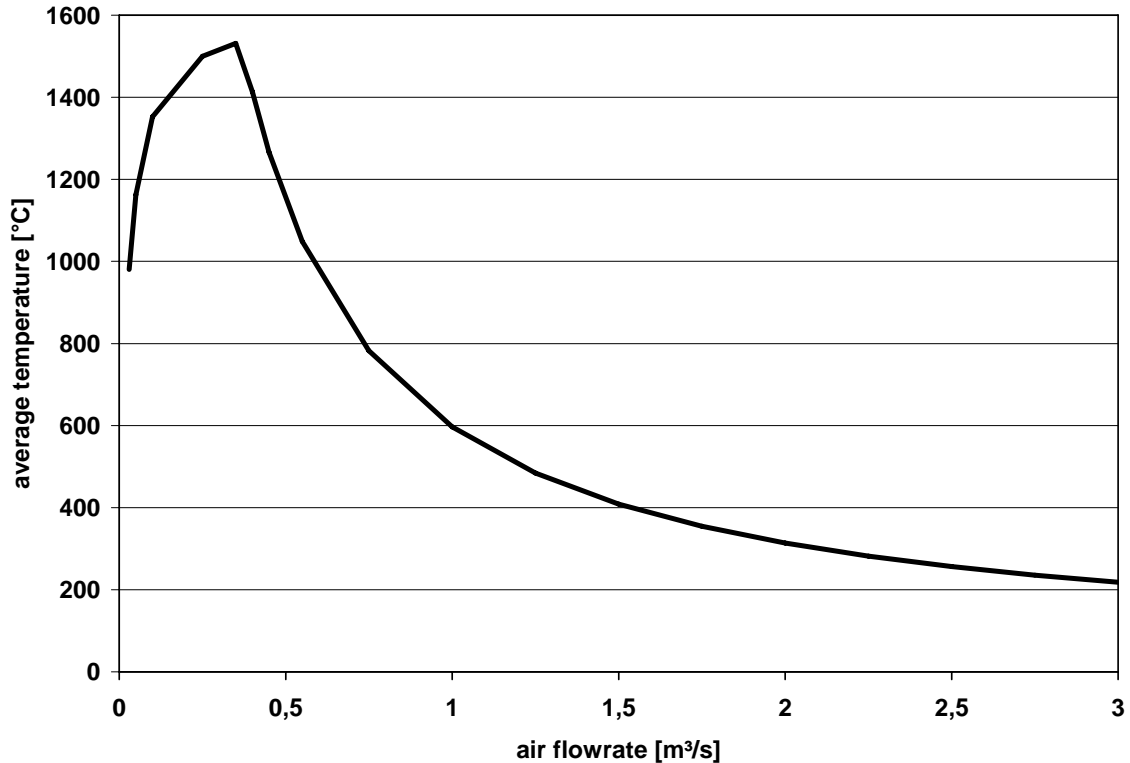


Figure 6; Mixed temperature as a function of air flowrate for a 1MW gas burner fire

On the fuel rich side (underventilated fire), note that near the peak temperature the profile is somewhat flat. This suggests that perturbations in the air flow rate around the peak are generally more dangerous (allow higher temperatures) on the underventilated side. Further, on the underventilated side, the products of combustion are flammable and are more toxic. These issues generally are incentives to drive the system towards the overventilated regime.

The placement of fans in relation to inlet external vents is, unfortunately, an art and not yet a science. Rules of thumb associated with getting a seal around the door go in the right direction since these rules recognize the importance of generating full entrainment by the fan. For the tests that we conducted, the angle of inclination of the fan relative was not optimized. It should be noted that in general this will also have an effect on the optimal distance to the door. For a fire department the process of specifying which fans to purchase is complicated. Factors include the maintenance and operability of the fans but also should include some basic tests on the capability of the fans to deliver adequate flow. Our tests show that beyond the engine power rating of a fan, other factors must be investigated before the selection process has been completed.

In some cases, manufacturers of fans assert that flow rate increases with distance between fan and door based on an assumption of conservation of momentum. Certainly, the total volume of air does increase with distance, while the average velocity of the flow decreases. The measurements indicate that the flow rate through the exhaust increases with increasing distance between fan and inlet up to some maximum value and a decreasing flow rate after this point. This indicates that the assumption that the most important mechanism controlling the flow rate is conservation of momentum is valid only over a range of the fan distance to door. In addition, flow from the fan hitting the walls next to the inlet as well as the ground creates turbulence. This tends to make the flow rate through the exhaust vent to decrease.

There is less than a 5% difference in flow rate at the maximum flow rate values between fans with legs extended and legs retracted. This was a rather surprising finding since a fan with extended legs should provide less ground effects and better entrainment characteristics than a fan resting on the ground.

Flow rate through an exhaust vent is determined by a number of factors besides the distance between the door and the fan. It is reasonable to assume that these factors include power of the engine, diameter of the fan, angle of inclination of the fan, shape of the blades, and lay-out of the inlet.

The implication for larger volumes (structures) is that more leakage can be expected in these by volume larger structures which negatively affect ventilation effectiveness. In one test sequence, the volume available for flow through the 1st floor of the structure was expanded using moveable barriers. In addition, the effects of opening doors to studio apartments (flats) that had well maintained windows were explored. This showed that there was less than a 1% change on average in the volumetric flow rate associated with changes in the 1st floor volume. In addition, there was a significantly greater difference in the measured flow rates when a second story window was used for ventilation. For those cases an approximately 40% drop in the flow rate relative to cases where the first floor were vented were found.

Examining the exhaust flow as a function of the volume of the structure, figure 4, indicates that the flow rate through the exhaust decreases as volume of the structure increases. An increase of the total volume of the structure with more than 1000%, without changing the number or size of exhausts, decreases the measured exhaust flow rate by approximately 50%. We can specify the functional relationship between the measured flow rate Q_M and leakage flow rate Q_L as.

$$Q_M + Q_L = Q_o \quad [3]$$

where Q_o is a constant flow rate that should be associated with the fan characteristics. The leakage flow rate can be bounded using the American Society of Heating Refrigeration and Air Conditioning (ASHRAE) data on building infiltration⁹. As noted in the ASHRAE Fundamentals, older construction generally operates with infiltration rates between 0,8 and 1,2 Air Changes per Hour (ACH). This suggests a 400m³ structure will have a leakage rate of approximately 0,1m³/s while a 1000m³ structure would have a leakage rate of 0.28 m³/s. The leakage rate then can be expressed as

$$Q_L = \frac{V}{3600} \quad [4]$$

or the measured flow rate is to first order

$$Q_M = Q_o - \frac{V}{3600} \quad [5]$$

For fan 4 this results in

$$Q_M = 0,88 - \frac{V}{3600} \quad [6]$$

The slope nearly matches the slope of the experimental curve.

The number of exhaust openings and then also the total exhaust area affects the total flow rate out of the building, figure 5. Increasing the exhaust area, by opening a second window, makes the flow through the first window decrease by approximately 25%. This is a reasonable result since flow rate, and thereby flow loss in the exhaust decreases. Consequently, the number of exhaust openings affects the volumetric flow rate in a nonlinear manner.

Finally, computational fluid dynamics (CFD) simulations of the air flow in the test house were conducted. These simulations show that significant mixing and losses occur as the fan jet impinges on the stairway going from the first floor to the second floor. In fact, there are conditions that show backflow through the top of the front door when the fan is improperly aligned. Further, the simulations show that the flow through the window vent is not symmetric due to the flow turning in the exit vent compartment. Finally, the simulations show that if the building and hallway volume further down the hallway from the door of the vented compartment are not vented and do not have much leakage, the volume is nearly stagnant. This suggests several tactical consequences. If the fire is located beyond the door of a compartment that is vented, the PPV process will have little effect on the fire. Also, smoke and toxins that exist beyond the vented region will remain in those regions until they are otherwise vented.

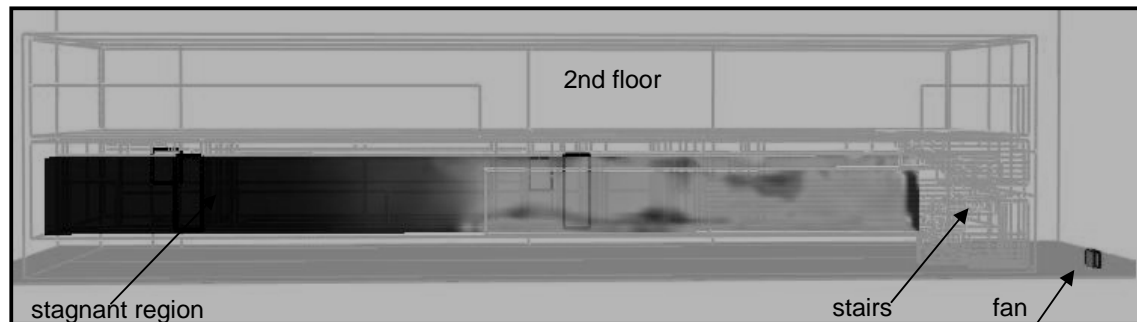


Figure 7; Results from CFD simulations of the air flow during the experiments.

CONCLUSIONS

Flow rate through an exhaust increases with increasing distance between 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. In a larger volume more leakage can be expected, thus decreasing the efficiency of positive pressure ventilation.

Increasing the exhaust area decreases the flow loss, thus increasing the efficiency of positive pressure ventilation. The number of exhaust openings affects the volumetric flow rate in a nonlinear manner.

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