Vent openings & fire

There's plenty of confusion in the fire service when it comes to creating/using openings to ventilate during firefighting. In Belgium, positive pressure ventilation (PPV) generally isn't initiated until the fire has been put out. This way the ventilation does not affect the fire behavior. In other countries it is customary to start venting during firefighting or even prior to the interior attack. This method of operation, especially prior to the attack, can influence the fire behavior. Even when natural ventilation is used, this will be the case. It is important for the fire service to realize that opening a front door equals natural ventilation. This in turn means that even the Belgian approach (without PPV) can affect the fire's progress.

1 Influence on fire behavior

To understand the influence of making vent openings on fire behavior, one first has to understand fire behavior itself. Herein we discern two different types of fire behavior. On one hand we have the "ventilated" fire behavior en on the other there's the "under ventilated" fire behavior. In order to define these two terms, we first have to explain the two different burning regimes: fuel controlled and ventilation controlled.

1.1 Burning regimes

At the start of a fire only a small amount of material is involved in the combustion. There's more than enough air available to feed the small fire. The characteristics of the material (fuel) and its distribution in the room will determine what happens. Important attributes are the flame spread, the speed at which flames spread over the surface, and heat release rate, the speed at which a fuel produces energy. In the incipient stage of a fire, the fuel controls the fire's progress. That's why it's called a "fuel controlled" fire.

After a while the fire grows larger. The temperature rises while the oxygen concentration decreases. A smoke layer is formed. A little later, the smoke layer will ignite (the rollover). Because of this, radiative heat towards the fuel underneath the smoke layer increases significantly. Flashover occurs. For this scenario to happen, a sufficient amount of air needs to be available. This means that a door or window needs to be opened. Another possibility is that a window (e.g. with a single pane of glass) breaks during the fire's development.

After flashover, the entire room is in flames. The fire draws in its oxygen through any openings it has available. Typically the fire is also exiting from the building. This is because the air supply coming through the opening is insufficient for the fire. Because there's not enough oxygen available inside, a part of the smoke gases is burnt up on the outside. Outside of the room, there's plenty of oxygen. The intensity of the fire is no longer determined by the available fuel. It's the ventilation (the oxygen) that determines what happens. For each kilogram of oxygen that enters the compartment, about 13.1 Megajoule (MJ) of energy can be generated. Practically speaking, 3 MJ of energy can be released per cubic meter of air. When an air flow of 1 m/s is flowing through a 2 m² door opening, it can feed a 6 MW fire. Since the ventilation now determines what is happening, the fire is "ventilation controlled".

1.2 Two types of fire behavior

1.2.1 The ventilated fire behavior

The ventilated fire behavior is made up of 5 stages. The fire starts in the incipient stage and evolves into the growth stage. In both stages the fire is fuel controlled. Next flashover happens. In this stage the transition is made from a fuel controlled regime to a ventilation controlled regime. The fourth stage is the fully developed fire. During this stage the fire is ventilation controlled. When the fuel in the room runs out, the power of the fire will decrease. The need for oxygen drops as well. At some point the fire will return to a fuel controlled state.

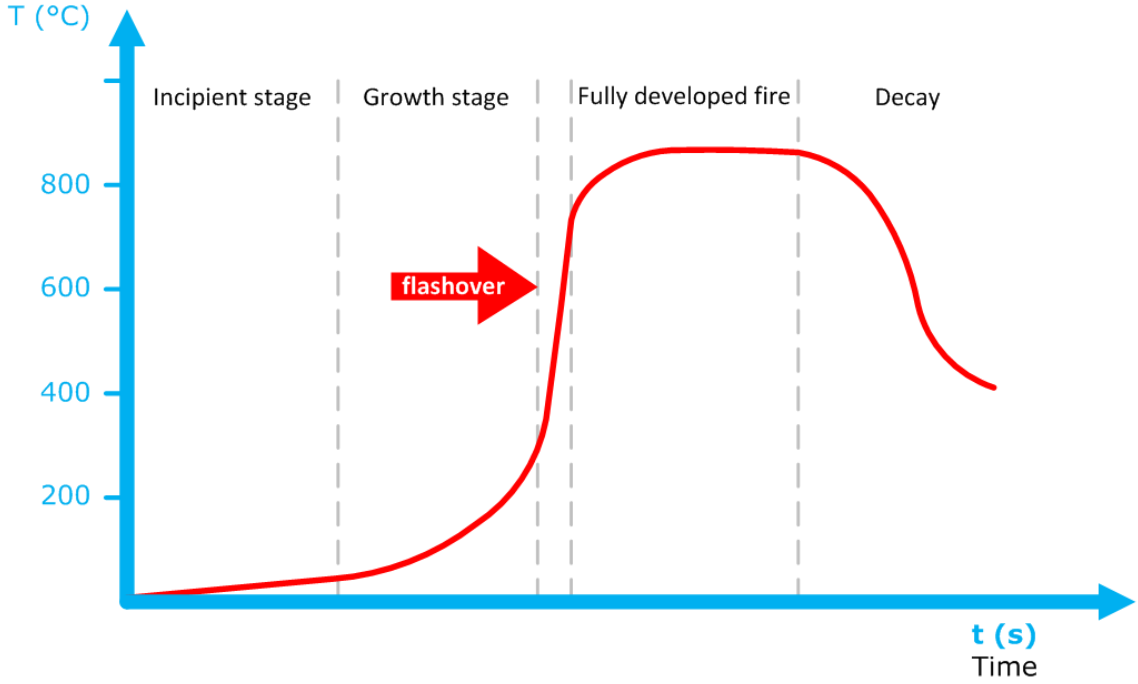

Figure 1 The ventilated fire behavior *(Graph: Karel Lambert)*

The ventilated fire behavior starts out fuel controlled, then it transitions into a ventilation controlled regime and subsequently ends up again in a fuel controlled regime.

1.2.2 The under ventilated fire behavior

The under ventilated fire behavior starts out the same as the ventilated fire behavior. In the incipient stage the fire is fuel controlled. This is also the case in the growth stage. The difference is in the availability of ventilation openings. When there are little to no vent openings, the oxygen concentration will drop rapidly. The fire will become ventilation controlled before flashover can happen. The fire will remain ventilation controlled until the fire goes out or until it is extinguished by the fire service.

"An under ventilated fire is a fire that became ventilation controlled before flashover."

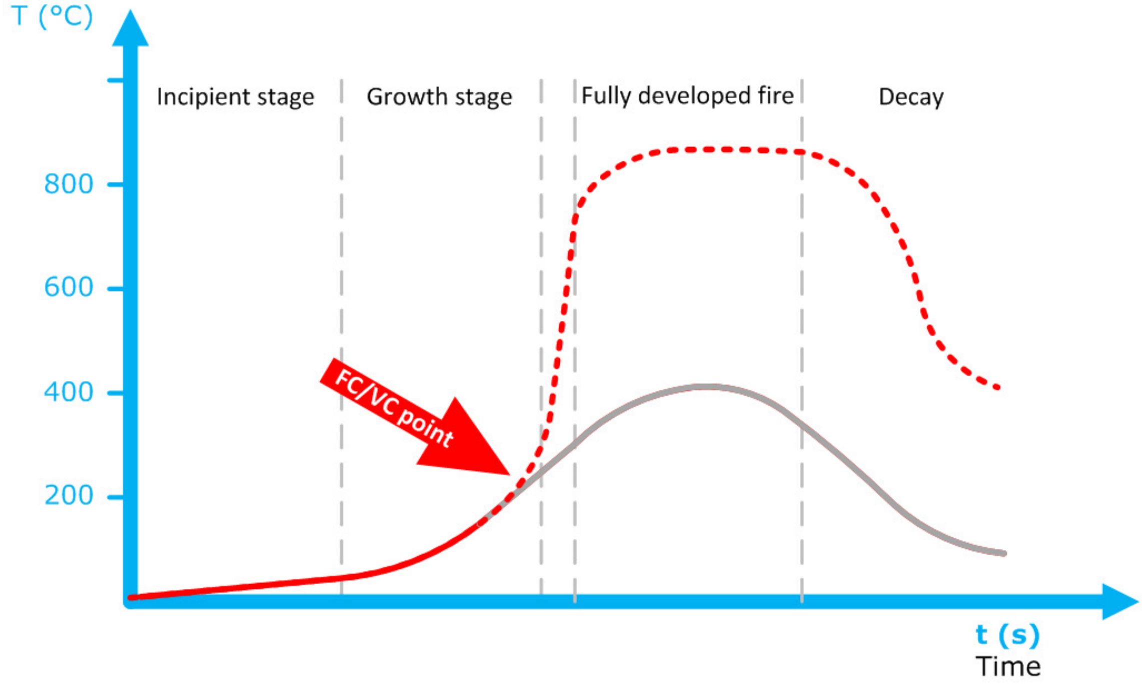

Figure 2 The under ventilated fire behavior: the red line indicates the part that is the same for both types of fire behavior. The dotted red line depicts the natural or ventilated fire behavior while the gray line depicts the under ventilated fire behavior. *(Graph: Karel Lambert)*

The under ventilated fire also starts out as fuel controlled but passes into a ventilation controlled regime a lot sooner. This occurs before flashover. The fire remains ventilation controlled until it dies out or until it is put out.

1.3 Influence of ventilation

In the US it is custom to vent during firefighting operations. This usually means that extra vent openings are made. This can be achieved by breaking windows (horizontal ventilation) and by creating openings in the roof (vertical ventilation). Most of the time natural ventilation is achieved. This means no positive pressure fans are used. Youtube hosts countless videos of fires where ventilation causes the situation to get out of hand.

Then again, at some point in time, someone thought up this tactic. In the US this tactic is credited to Benjamin Franklin (1706-1790). This inventor and fireman devised the tactic to get rid of smoke during firefighting operations. The tactic has yielded very good results for years on end. This is because the fire behaved differently in the past. Fuel was mainly made up of natural products where nowadays the fuel in a house is primarily made up of oil derivates. Steve Kerber showed that the time to flashover has decreased immensely. This time used to be about 30 minutes in the 50s and has nowadays been reduced to 3 to 4 minutes. This means that now fires are fuel controlled for a much shorter period than in the past.

Applying ventilation at a fuel controlled fire has a very limited effect. What happens to the fire is determined by the characteristics of the fuel after all. This explains why ventilation has been a standard tactic in the US for so long. Up until late in the 20^{th} century it was a very good tactic.

In modern buildings the fire becomes ventilation controlled very fast. When the fire has become ventilation controlled before flashover, we're dealing with an under ventilated fire. This kind of fire is happening more and more lately. When an opening is created in the wall of a room in which an under ventilated fire is burning, the heat release rate of the fire will rise. With this type of fire the ventilation determines what happens. By making an opening, extra ventilation is made available to the fire. There are different formulas for calculating the maximum power a fire can generate depending on the surface area and the height of the opening. Opening a door that's 2 m high and 0.9 m wide, can cause the fire's power in the room to increase to 3 or 4 MW. Breaking a window of 2 m wide and 1.5 m high, will feed a 4.7 to 5.5 MW fire.

Therefore, ventilation has to be very carefully handled when dealing with under ventilated fires. The heat release rate of the fire will always increase after the opening has been made. Firefighters in the US are becoming increasingly aware of this. Amongst other things, it has led to the introduction of a "door man". This firefighter makes sure the entry door stays shut as much as possible. By applying this principle, the fire's heat release rate is limited.

2 Effectiveness of vent openings

Another important question which arises is that of the size of the vent openings. A lot has been written about this topic in firefighting literature. In the US an exhaust of 4 by 4 ft (1.2 m by 1.2 m) has long been considered standard. This is a hole of 1.44 m². Recently it has been suggested that this is no longer large enough. An opening of 4 by 8 ft is used more often nowadays. This equals 2.88 m².

In Europe creating openings in the roof is not common practice. We usually keep to opening or breaking windows. In such cases, the size of the exhaust is most of the time dictated by the size of the windows available. Opening windows is preferable to breaking them. An open window leading to an unwanted ventilation flow, can usually be closed up again. This isn't the case for broken windows.

By keeping the inlet and outlet in a specific proportion to each other, ventilation can be performed in the most efficient way possible. This means that the highest possible flow can be achieved through a certain opening.

To determine this ideal proportion, a distinction has to be made between natural and positive pressure ventilation. The following paragraphs relate to situations where one opening is completely used as the inlet and another opening is completely used as the exhaust. This is usually the case in vertical ventilation. In practice, horizontal ventilation quickly becomes more complex. A lot of the time, openings are used in two directions. Every opening has a double flow coming through. It's impossible to simplify this particular phenomenon. Therefore we will keep things simple in the following sections.

2.1 Natural ventilation.

Ventilation basically means transporting a mass of smoke from inside to outside. Because it's not possible to create a vacuum, this mass of smoke has to be replaced by an equal mass of air. In the case of natural ventilation, the smoke will leave the building because of buoyancy. This upward force is the result of the difference in density (~temperature) between the air and the smoke. For ventilation to work properly, enough fresh air has to flow into the building. Research showed that an effectiveness of about 90% is achieved when the inlet is double the size of the outlet for any given outlet. This is further reduced to 80% effectiveness when the inlet is the same size as the outlet (see Figure 3).

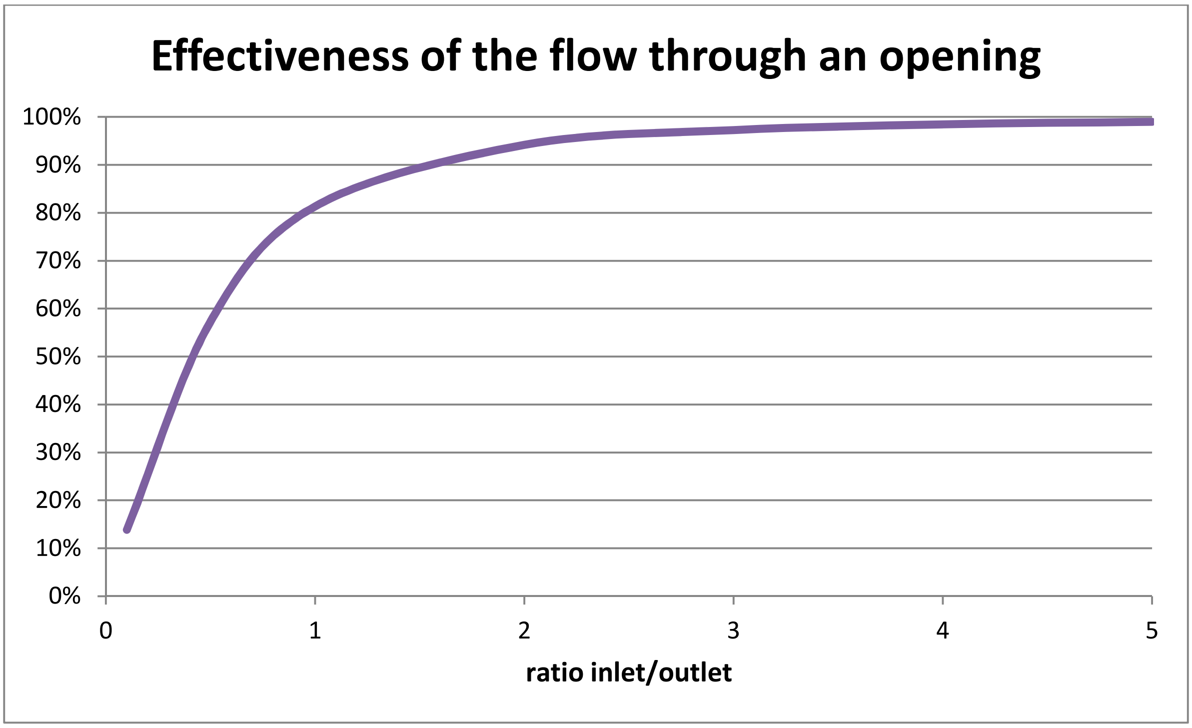

Figure 3 Flow effectiveness in relation to the proportion between the inlet and outlet for smoke with a temperature of 300 °C. When the inlet is twice the size of the outlet, the effectiveness becomes 94%. When the inlet is the same size as the outlet, effectiveness is reduced to 81%.

A numeric example might clear things up further. Suppose a room has to be vented which has a door (width x height : 1 x 2 m) and four windows of each 1 m². Suppose the smoke gas has a temperature of 300 °C. If one window is opened to serve as an exhaust and the door functions as the inlet, an inlet/outlet ratio of 2 is formed. This leads to an effectiveness of 94% (in relation to the maximum theoretical flow capacity) through the outlet. Per second, 2.67 kg of smoke will be vented from the building. If a second window is opened up, the inlet/outlet ratio will drop to 1. The effectiveness for each separate window will decrease to 81%. However, the total surface area of the combined exhaust is doubled. This means that 1.61 times the maximum theoretical capacity of a single window is achieved. Which in turn is better than 0.94 times that capacity with just one window. In effect, 4.81 kg smoke per second is vented. When all four windows are opened up, the inlet/outlet ratio drops to 0.5. The effectiveness for each window is now 57%. However there are now four open windows. This means that 2.28 times the theoretical capacity of a single window is achieved. For this example, this results in 7.26 kg/s. When even more windows are opened, the effectiveness per window will drop further. If the outlet is three times the size of the inlet, opening up extra windows becomes pointless.

Summed up it can be stated that an inlet/outlet ratio of 2/1 for a single opening yields the highest effectiveness. Opening up more windows leads to a lower effectiveness per window but also to a higher total vent flow. When a 1/3 proportion has been reached, it's no longer useful to open up any more windows. It is important to keep in mind that this is valid for vertical ventilation. The door is completely below the smoke layer and the windows are above the neutral plane. The windows are completely used as an exhaust.

2.2 Positive pressure ventilation

For positive pressure ventilation, the proportion between inlet and outlet needs to be different to achieve an optimal flow. The proportion is opposite to that of natural ventilation. In other words, for an optimal flow the outlet needs to be twice the size of the inlet. In the example above, this means that optimal effectiveness is achieved when all four windows are opened. Then the inlet/outlet ratio is 1/2. The flow is not created by the difference in temperature between the smoke and the air, but is forced by the fan. Again it is possible to enhance the effect of the ventilation by opening up more windows. Just as it's the case for natural ventilation, it is pointless to aim for a ratio smaller than 1/3.

Figure 4 Positioning of two positive pressure fans in V-formation. *(Photo: Frank Meurisse)*

3 Wind

In the section above, we examined flow effectiveness of a single opening without taking into account any local conditions. In reality this isn't the proper way of doing things. Before any vent openings are made, we have to check whether there's any wind and in which direction it is blowing.

In the case of natural ventilation, the wind will have a large influence. It's therefore imperative to always try to vent "with the wind". This means that the inlet has to be created on the side on which the wind is blowing (windward side). Preferably the exhaust has to made on the opposite side (leeward side). Even when the exhaust is made in an inclined roof, it's best to follow this rule. When it's impossible to do so, a highest possible effectiveness should be attempted for the vent opening (see above).

Positive pressure ventilation means the situation is less dependent on the wind. Venting against the wind can be attempted in a limited way. In such situations the outlet can be kept small. This will lead to a larger overpressure inside. For small wind velocities this can be sufficient to overcome the pressure of the wind. This may be useful for situations in which it’s not possible to create openings on the leeward side. However it’s important to realize that this option is very limited. Research has shown that PPV fans typically found in fire engines, can build up an overpressure of 26 Pascal. This is about equal to the pressure built up by a 20 km/h wind. Venting opposite to the direction of the wind will only work with very low wind velocities. Several sources mention a threshold of 10 km/h. For wind speeds lower than this, venting against the wind is effective. Above this speed, the effectiveness drops very quickly.

4 Bibliography

[1] *Lambert Karel, New insights into ventilation, De brandweerman, May 2011*

[2] *Hartin Ed, www.cfbt-us.com*

[3] *Kerber Steve, Impact of ventilation on fire behavior in legacy and contemporary residential Construction, 2011*

[4] *Kerber Steve, Analysis of changing residential fire dynamics and its implications on firefighter operational timeframes, Fire Technology, vol. 48, p 865-891, 2012*

[5] *Merci Bart, Active fire protection II: smoke and heat control, postgraduate studies in fire safety engineering, Universiteit Gent, 2010*

[6] *Svensson Stefan, Fire Ventilation, Swedish Rescue Services Agency, 2000*

[7] *Christian Gryspeert, personal communication, 2014*

[8] *Kerber Steve, Madrzykowski Dan & Stroup David, Evaluating positive pressure ventilation in large structures: high-rise pressure experiments, NISTIR 7412, Gaithersburg, MD, USA: National Institute of Standards and Technology, 2007*

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