Taking a closer look at under ventilated fires

Research into under ventilated is on the rise. Then again, the fire service is facing these fires more and more on the fire ground nowadays. This research is teaching us a lot about the fire behavior of such fires. In this article we will take a closer look at the fire behavior of under ventilated fires.

1 What is the difference between a ventilated and an under ventilated fire?

When a fire starts in a building which has a normal fuel load, at some point in time the fire will become ventilation controlled. This means that the fire intensity is determined by the amount of fresh air that's able to flow into the fire room.

1.1 Ventilated fire progress

When a large window is open, a lot of air can enter the fire room from the start of the fire. This will allow the fire to grow well. A compartment fire that can grow unhindered, will progress into flashover. Flashover means the fire is transitioning from the growth stage into a fully developed fire. All of the fuel inside the room will start to burn. This means that the need for fresh air increases substantially. The openings (windows and doors) are no longer able to provide enough fresh air for the fire. The fire has become ventilation controlled. The moment a fire goes from fuel control to ventilation control, is called the FC/VC point.

A fire that has become ventilation controlled during flashover is called a ventilated fire. After all enough air has to be available from the start to allow the fire to progress into flashover.

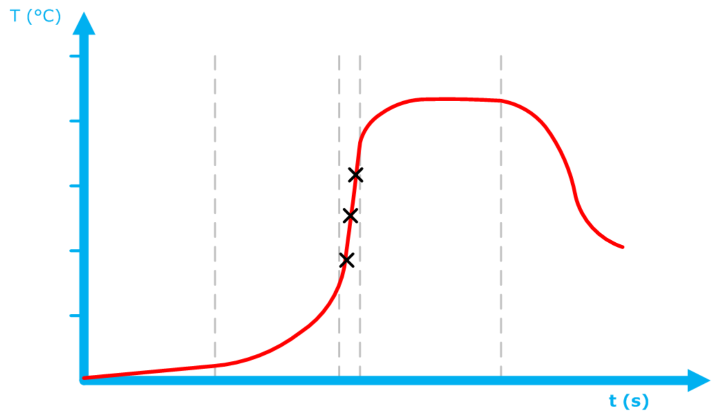

Figure 1 Possible locations of the FC/VC point in the ventilated fire. *(Graph: Bart Noyens)*

Figure 1 shows the graph of the ventilated fire. Actually we don't know for sure where exactly the FC/VC point is in this type of fire development. It is somewhere during the flashover stage, but no one knows for certain where precisely. Some experts state that the FC/VC point may even be situated earlier, slightly before the start of flashover. They compare fire growth to a ship at sea. When you stop the engine of the ship, it will continue to drift onwards for a little while. Therefor they state that enough energy has to be released in a room near the end of the growth stage to allow for flashover. Each 'x' marks a possible location of the FC/VC point. For ventilated fires it doesn't really matter where exactly the FC/VC point is. It's important that firefighters can distinguish a developing fire from a fully developed one because those fires require different tactics.

Aside from that it's extremely important that firefighters can recognize the signs of an impending flashover:

- Intense heat, coming from the smoke layer above
- Dancing angels in the smoke layer, the beginning of roll-over
- A smoke layer that is dropping down swiftly or that is already very low
- The smoke layer becoming turbulent (swirling motion)
- The sudden pyrolyses of flammable objects in the room.

1.2 Under ventilated fire progress

For under ventilated fires, the location of the FC/VC point is extremely important. At an under ventilated fire this point is situated before flashover. This type of fire doesn't have enough air to progress into flashover. The fire wants to follow the ventilated fire graph, but because there's not enough air it's forced into a lower heat release rate. One can compare this to a highway that's undergoing repair works. Typically, the speed limit is lowered to 70 km/h. As soon as drivers see this sign, they will slow down from 120 km/h to 70 km/h. They want to go faster but the sign is limiting their speed, just as the fire that wants to produce more energy but can't. It wants to progress towards a higher heat release rate, but the lack of air is making this impossible.

Figure 2 The speed limit of 70 km/h at highways under construction is a good analogy for an under ventilated fire. The fire wants to burn harder but can't because of a lack of air.

The size of the compartment and the ventilation present in that compartment, will determine when the fire transitions from a fuel controlled to a ventilation controlled burning regime. Figure 3 shows several different under ventilated fires next to a ventilated one. The difference between these fires is that each one becomes ventilation controlled just a little bit later than the one before. The "green" fire becomes ventilation controlled first, while the "yellow" fire represents a situation where there's a little more air available. This fire will remain fuel controlled for about a minute longer before it becomes ventilation controlled. Again the "x" represents the FC/VC point for each fire. Now, which fire seems to be the most dangerous?

The obvious answer is the fire that's illustrated by the yellow line. This fire is the last to shift from fuel controlled to ventilation controlled. This means that the temperature inside the room at the time of the FC/VC point is highest in comparison to the other two fires.

If the temperature in the compartment is very low, then so are the risks for the fire service. Suppose for a moment that the temperature of the green line didn't exceed 200 °C, then there won't be much pyrolysis gas. It isn't hot enough to heat up a lot of objects to the temperature threshold at which pyrolysis starts. The temperature at which an object starts to pyrolyze, is highly dependent on the type of material of which it's made up. A good rule of thumb is that above 300 °C there will be plenty of pyrolysis gasses. Objects close to the seat of the fire, will have heated up quickly. This will be because of the radiant heat coming from the flames.

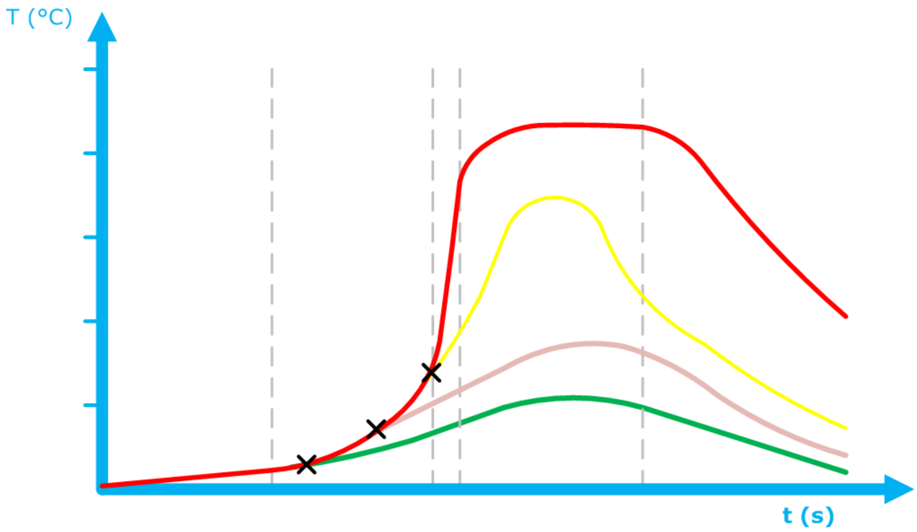

Figure 3 The red line illustrates the ventilated fire progress. The three other lines depict three different under ventilated fires. The green line represents a fire in a heavily insulated and air tight building. This causes the fire to become ventilation controlled early on. The pink line is a fire that has a little more air available. The yellow one is a fire that becomes ventilation limited just before flashover. *(Graph: Bart Noyens)*

Only when the temperature reaches a high enough level in the room and a smoke layer is formed, objects farther inside the room will start to pyrolyze. The radiant heat will largely be coming from the smoke layer. Objects enveloped by the smoke will also start to heat up due to convection.

The location of the FC/VC point on the fire development graph is therefore very important. The higher the temperature has risen the moment the fire becomes ventilation controlled, the more dangerous the fire becomes.

The danger posed by a fire also varies in relation to time passed. At any fire a certain power is generated. This is called the Heat Release Rate (HRR). This means that every second a certain amount of energy (measured in Joules) is produced. However, energy is also lost. In a closed compartment, energy usually is lost because of conduction through walls. This basically means that a certain amount of energy per second is leaving the compartment. The fire is generating power while at the same time, power is lost through walls. At a fuel controlled fire the heat release rate generated by the fire will increase. This HRR will by greater than the HRR going out through the walls.

When – measured per second – more energy is being produced than there is being lost, temperature will rise. Shortly after the FC/VC point, temperature will continue to rise for a little while longer. The HRR of the fire will stagnate or even drop. But it will take a few seconds before the HRR lost through the walls will exceed the HRR generated by the fire. As soon as there's more energy being lost than produced, temperature will start to decline. Again the analogy of the ship can help to illustrate matters. The power to ship's engines may have been limited, but nevertheless the ship will continue drifting forwards for quite some time. The HRR of the fire is limited but the temperature will keep on rising because

– despite the power being limited – more heat is still being generated than there is being lost.

The speed at which energy is lost will depend on the temperature in the room, the temperature outside and the temperature of the wall. Aside from this, certain characteristics of building materials (heat conductivity, density and specific heat capacity) also play an important role. The thickness of the various layers in the wall (e.g. drywall, brick, insulation) matters as well.

An important question to ask is: "When does the fire service create an opening?" As soon as firefighters open a door, fresh air will rush in and smoke will flow out. That fresh air can cause the HRR of the fire to increase. The faster the air track going in, the more dangerous the fire.

When we take a second look at Figure 3, we can see that timing is extremely important on the fire ground. When firefighters open the door the moment the yellow line has reached its peak, the risk will be far greater than when it would happen at the pink line's peak. However, it is also clear to see that the temperature will decrease rather quickly. Suppose no one notices or reports the fire, and fire crews open up the door an hour or more after the FC/VC point has been passed. In that case the fire will possibly have gone out by itself. Typically, the temperature inside won't be very high and the velocity of the air track will be limited. Now it becomes clear that the pink line at its peak is a more dangerous situation than the yellow one which has lost all of its heat.

To evaluate the risk, we have to account for two things:

- When did the fire become ventilation controlled? (How hot was it at the time?)
- How hot is it still in the compartment when firefighters open the door?

2 Pressure

During an under ventilated fire, peculiar pressure patterns can occur inside a compartment. A fire will cause temperature to rise. The smoke is much hotter than the temperature of the surroundings. Anything that's heated up, will expand. If the fire is happening in a room of which the door has been left open, then smoke will flow out. This will partially compensate the rise in temperature. Because of a large opening being present (about 2 m² in the case of a door), the fire will be unable to build up pressure.

If doors and windows were to remain shut, a different set of patterns will emerge. The room will gradually fill up with smoke. Temperature in the room will rise. This will cause the pressure inside the compartment to rise as well. As long as the fire has enough air, the HRR will increase. Temperature inside the room will rise accordingly. The oxygen inside will start to run out. At some point, the fire will reach the FC/VC point as described above. Heat production will decrease while the energy loss through walls will remain more or less the same. The temperature will reach a peak after which the high energy losses will cause the temperature to drop swiftly.

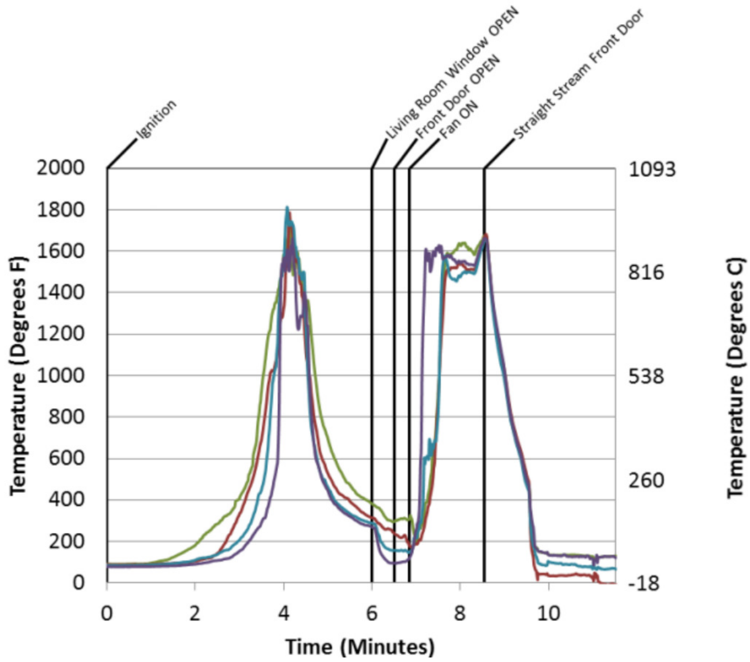

Figure 4 Temperature graph of one of the UL tests. The temperatures shown are those measured inside a living room where the seat of the fire was located. The different colors indicate different heights of measurement: Green: 2,1 m; Red: 1,5 m; Blue: 0,9m; Purple: 0,3m. It's clear that the temperature rises at first and then drops down again. *(© Figure: UL FSRI)*

In January 2015, I was attending a new series of tests of Underwriters Laboratories' Firefighter Safety Research Institute (UL FSRI) in Chicago. For some years now, UL has been doing high quality research into firefighting. Each year they build two houses in a large testing facility. Then these houses are set on fire several times. The goal of the research is to study new firefighting tactics in safe and repeatable conditions.

The aim of the January research was to assess the efficiency of Positive Pressure Attack (PPA). This means the use of positive pressure ventilation prior to extinguishment.

Figure 4 illustrates what has been described above. The fire causes an increase in temperature. Because the oxygen is running out inside the room, the fire is passing the FC/VC point. Next, there is a massive drop in temperature. After the initial ignition, there's an incipient stage. A hot smoke layer can be seen forming itself after about 1,5 minutes: The green line indicates temperatures at 2,1 m above floor level. After about 2,5 minutes, the temperature at 1,5 above floor level starts rising. This means that the smoke layer has dropped below 1,5 m. Shortly after, the temperature shoots up from around 200 °C (400 °F) to 982 °C (1800 °F) all within four minutes of the start of the test. One minute later however, the temperature has dropped down again to 200 °C (400 °F). The speed at which the temperature drops, is influenced by the amount of insulation and the characteristics of the materials used.

During the first four minutes of the fire, the pressure in the room will increase. Figure 5 illustrates the importance of the rise in pressure. The overpressure in the compartment reaches 150 Pa. This is about equal to a force of 15 kg/m² surface area. If there is a door in the room with a 2 m² surface area, the hot smoke will exert a force of 30 kg onto the door panel. There have been documented cases abroad where residents were not able to flee their homes because the high pressure in the room prevented them from opening the door.

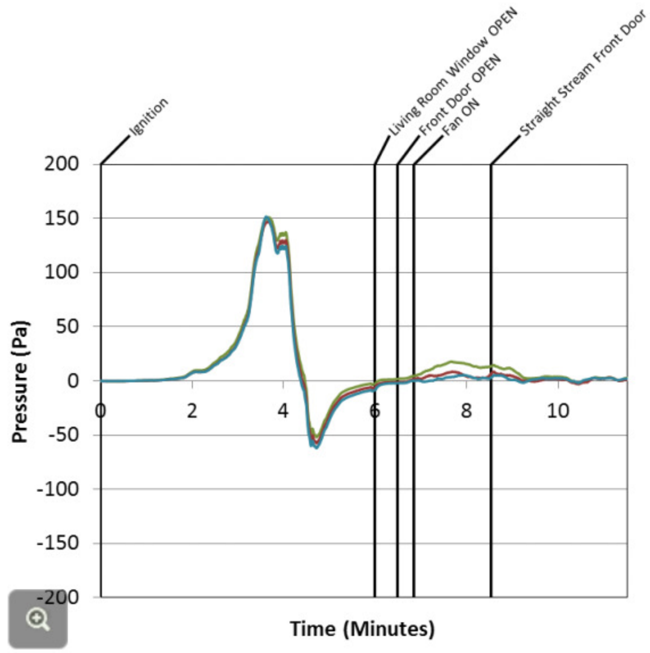

Figure 5 The change in pressure of the test. It is clear that the increase in pressure is tied to the rise in temperature. Once the peak temperature has been reached, the pressure starts to go down. *(© Figure: UL FSRI)*

The overpressure will cause smoke to be pushed out through cracks. Because of this exiting smoke, the pressure build remains limited.

As soon as the fire reaches its peak temperature, the expansion of smoke gas is halted. The smoke is not being heated up any further. When the temperature inside the room declines, the smoke will cool down as well. But as long as there is overpressure inside the compartment, the smoke will keep on getting pushed out. This will cause the overpressure to gradually decrease, much like a bicycle tire slowly going flat.

Gases that are heated up, will expand. Gases that are cooled, will contract. When the gases contract, the overpressure will diminish even further. After all they take up less volume when they are cooled. Since some of the smoke has been pushed out, the remaining cooler gases will no longer fill the entire room. Cooling causes the pressure inside the room to change into an under pressure. This experiment measured an under pressure of 50 Pa. Next, fresh air will be drawn in through the same cracks until the interior pressure matches the exterior one.

If we were to put Figure 4 on top of Figure 5, we could easily see that both phenomena are tied to each other. The pressure increases while the temperature rises. Video footage of the experiment shows smoke escaping through all the cracks. Once the FC/VC point has been passed, the temperature starts to go down. At the same time, the pressure starts to drop as well. The video shows the outward flow of smoke suddenly stopping. The inward flow of fresh is not visible to the naked eye.

Finally, it's important to note that the graphs above illustrate a single test. Other tests resulted in other pressure patterns. The change in pressure and temperature is dependent on numerous parameters. Certain graphs can look totally different from the ones depicted above.

3 Arrival of the fire service

Now we have to ask ourselves: "How can we use the knowledge above in the field?"

Figure 6 Smoke is flowing out a window. By looking at the color, flow velocity, … one can determine the severity of the situation. *(© Photo: Warre St-Germain)*

Upon arrival at the fire ground everyone must try to get an idea of what's going on inside the burning building. Especially company officers and chief officers need to form a correct image of the situation. By looking at ventilation openings, their size and location, firefighters can try to determine whether they're facing a ventilated or an under ventilated fire. When a door is open and smoke is flowing out, it's likely the fire is ventilated.

The situation is different however when the fire service arrives at a building that's completely closed up. When all of the windows and doors are closed, there's insufficient ventilation to fully progress the fire. Of course this needs to be considered in the right context. In a modern house, compartment volumes are on the small side and the fire will most likely be unable to break a window or force an opening through the outer construction layer of the building. Fire crews can assume that the ventilation profile will stay unchanged until they make entry. In a factory hangar with a large volume however, it is possible for the fire to grow significantly before becoming ventilation controlled. After all, a very large amount of air is available in such a large hangar. Aside from that, it's possible that a plastic construction element in the wall (e.g. a gate) or roof (e.g. a transparent corrugated sheet) will melt. This will create an opening through which ventilation occurs.

It is possible though, while taking into account the size of the building, to assess whether a fire is ventilated or under ventilated by looking at the openings in walls and roofs.

3.1 Under ventilated fire shortly after the FC/VC point

When no openings are present, one needs to look at the smoke flowing out. In the section above we explained that a growing compartment fire builds up pressure. The positive pressure will cause smoke to be pushed out through cracks and gaps. The higher the pressure, the more smoke will flow out and the faster it will flow.

When smoke is being pushed out, then obviously there's a large overpressure inside the compartment. This means a high temperature has been reached inside as well. If at that time, a door is opened to gain entry, a fierce flow will be created. Smoke will be pushed out violently and air will be drawn in. Typically, a tunnel of air is formed. The larger part of the door is used to vent out smoke, while at the bottom air tunneling appears. This situation will not last though. Because of the large opening, the overpressure will decrease. There will still be an inward flow of air and an outward flow of hot smoke. But this situation

Figure 7 During this under ventilated fire, temperature inside is running very high. The overpressure inside will push smoke out. *(© Photo: Zbigniew Wozniak)*

will progress rapidly. A ventilation induced flashover will most likely follow. In rare cases even a backdraft may happen.

The situation illustrated above is clearly recognizable on the fire ground. Firefighters can understand what's going on if they have been educated in under ventilated fire development and the buildup of heat and pressure. What happens when the door is opened, can be illustrated again using the "highway under construction" analogy. Before the construction works, drivers had to slow down to 70 km/h. However, most drivers are in a hurry and want to go back to doing 120 km/h as quickly as possible. As soon they leave the area under construction, they pass a sign indicating that the lowered speed limit no longer applies. All of the drivers will accelerate until they are once again doing 120 km/h. A fire, like the one described above, will progress quickly once it gets the air it needs. The fire will "accelerate" towards the maximum HRR it can achieve with amount of air currently allowed in through the door opening.

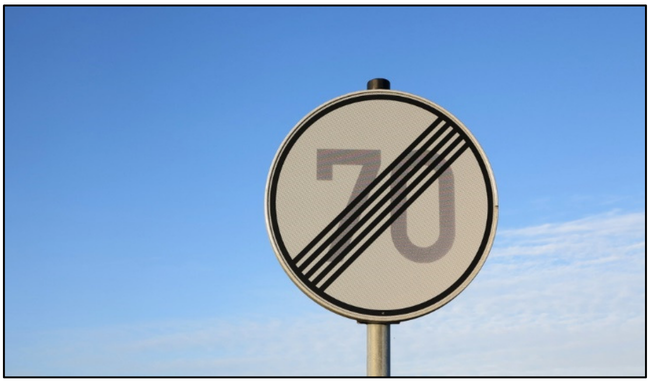

Figure 8 At the end of the construction site, the speed limit is lifted. A fire has a limited HRR because of a lack of air. As soon as a door is opened, that restriction is lifted as well and the fire will progress into a ventilation induced flashover. *(Photo: shutterstock)*

3.2 Under ventilated fire in underpressure

The section above explains how an under ventilated fire will suffocate itself. Both temperature and pressure will decrease inside. The outward flow of smoke will halt. More often than not, the smoke has left some traces. Patches of soot can be seen around windows and doors. These soot stains can be the only visible signs that a fire has been or is burning inside. It's not really clear from the outside whether a fire has reached its underpressure stage or whether it has gone out completely.

If the fire service arrives on scene at night, these kind of signs will easily be missed. After all, there's no visible smoke. Hence, it is extremely important not to draw any conclusions from the fact that there's nothing to see. Ed Hartin from the US uses the following phrase: "Nothing showing means exactly that: nothing!" In cases where there's nothing showing from the outside when firefighters arrive, there's nothing going on most of the time.

However, this may lead to routine and complacency. Only when a door has been opened, will it become clear whether or not there's anything going on.

When the fire is in an uderpressure stage, opening a door will cause a swift and turbulent inward flow without smoke exiting at the same time. That inward flow may be so strong that it's impossible to close the door again. Such a flow indicates that an intense fire has been burning inside. Figures 4 and 5 show an inside temperature of around 200 °C while the underpressure at that time is 50 Pa. If fire crews were to open a door in such conditions, a ventilation induced flashover will occur within a reasonably small timeframe (two to four minutes).

This is a familiar scenario for firefighters and can easily be explained as well with an understanding the relation between fire development, openings into the compartment, temperature and pressure. It is important for commanding officers to recognize these signs so they realize what is going on. That way they can adjust their tactics accordingly and tackle the fire both safely and effectively.

3.3 Under ventilated fire long after the FC/VC point

There is also a third possibility of the fire having long gone out by itself. Figure 3 shows three different under ventilated fires. The yellow line illustrates a fire matching the graph in Figure 4. The temperature rises significantly before the lack of oxygen takes its effect. It is clearly shown that the temperature also decreases swiftly afterwards. In modern houses it is highly unlikely that a window will fail. The volume will therefore remain closed up. After some time, the fire will go out due to a lack of oxygen. The hot smoke will transfer its energy onto the walls the same way hot air does. And after a while, the temperature will again reach the levels that were present before the fire.

When the fire service opens a door in these kind of situations, very little inward flow will be created. There is hardly any pressure difference with the outside environment. Aside from that, the temperature difference between the smoke and the outside air is next to none. Any eventual flow will be forming itself slowly. This again is a very noticeable scenario for fire crews. A thermal imaging camera will show almost no increase in temperature on the inside. When the fire has gone out completely, that temperature will remain the same. A thermal imaging camera is therefore a valuable tool when advancing into an under ventilated fire. In the event that there is still a seat of fire left and the HRR increases, the TIC will allow firefighters to perceive this before they start feeling the rise in temperature through their turnout gear.

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