How do people die in fires?

1 Introduction

Every firefighter knows that people die in fires. However they often lack insight into how it actually is that people die. A fire produces smoke and heat. Both of these components are a potential cause of death to human beings. This article takes a deeper look into this. It also takes into mind the implications of that knowledge for our methods of operation. Does the changing fire behavior in any way influence these two factors. If so, how and why does it have an impact?

2 Heat

A fire produces energy. This energy is used to heat up the surroundings. The most important factor is power of the fire or Heat Release Rate (HRR). The HRR of the fire is typically measured in kW or MW. The HRR tells us how much energy, measured in J, is produced each second.

The HRR of the fire is primarily transferred through convection and radiation. A good estimate is that 70% of the HRR is transferred into a convective part while radiation accounts for the other 30%.

2.1 Convective heat transfer

figure 1 Above the candle one can feel the convective part of the heat produced by the flame. *(Photo: Szymon Kokot-Góra)*

The convective heat transfer is responsible for the largest transfer of energy produced by the fire. Convective heat can easily be demonstrated by use of a candle. Hold your hand 10 cm above the candle as shown in figure 1. The heat felt there is that of air rising up (smoke). By holding your hand at the side of the candle, at a similar distance, you can feel the difference between the convective part and the radiant heat.

First, the convective heat is transferred from the fire onto the smoke. The higher the HRR of the fire, the hotter the smoke will be.

However there is another factor that also determines how hot the smoke will become. The height of the smoke layer plays a part in this. A house fire on the floor in a normal sized room will initially have smoke rising for 2,6 meters before hitting the ceiling. During that ascension, air will be mixed into the smoke (see figure 2). The volume of the smoke and the mass of the smoke will both increase continuously during ascension. The more cold air is mixed into the smoke, the lower the final temperature of the smoke will be. Therefore, the smoke arriving at the ceiling of a 5 meter high warehouse will be less warm than in a 2,6 meter kitchen.

In the next stage of the fire, a smoke layer has been formed. Suppose the smoke layer in a typical appartment is one meter thick, then smoke coming from the ground will only rise for one and a half meter. This means less air is mixed in and the smoke will be hotter. Aside from that, the fire will often have increased its heat release rate compared to the initiation stage. So more heat is added while at the same time, less cool air is mixed in. This results in hotter smoke than in the beginning of the fire.

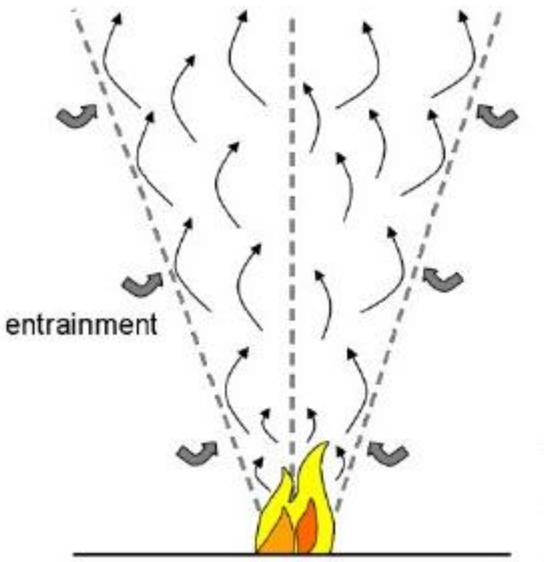

figure 2 While the smoke rises, more and more air is mixed in. This is called entrainment. *(Figure: Edward Johnson)*

The hot smoke layer has now become a source of heat. It will transfer heat onto other objects. The smoke layer is surrounded by walls and a ceiling. The smoke layer is hotter than those walls and ceiling. There will be a convective heat transfer from the smoke onto the walls and ceiling. While smoke is flowing out, it will partially cool down. The walls and ceiling will heat up at the same time. As the walls and ceiling continue to heat up, they will absorb less and less heat from the smoke layer. The convective heat transfer is in fact proportional to the difference in temperature (*ΔT*) between the smoke layer and the walls and ceiling. The walls and ceiling will in turn transfer heat through radiation and conduction.

It is possible to calculate the heat transferred through convection:

$$\dot{Q} = h \times A \times \Delta T \qquad [kW]$$

When smoke flowing through a building meets an opening, the smoke will flow out. This smoke constitutes a volume, a mass of smoke that is exiting the building. This equals a significant amount of energy leaving the building.

When the smoke layer drops down to about half a meter from the floor, firefighters who are engaged in an interior attack will be partially in the smoke layer. The part of their body that is inside the smoke, will absorb heat. In fact, the surface area of the firefighter's body (*A*) which is in the smoke layer, acts very much in the same manner as the walls of the building encompassing the smoke. The smoke layer will transfer heat onto the turnout gear of the crew. How much heat is transferred, will depend on the difference in temperature between the gear and the smoke. The heat will then transfer from the gear onto the firefighter's body through conduction.

If the smoke layer drops down to the floor, any victims lying there will immediately feel the effects of heat transfer onto their body. The clothing they have on, offers little to no protection. The same goes for any victims that are standing at a window, in the flow of exiting smoke gas. They will also receive heat from the smoke. An additional problem here, is that the convective heat transfer is dependent on the speed of the outflowing smoke included in the convective heat transfer coefficient *h*. The convective heat transfer coefficient is determined by a number of different things, one of which is velocity. The faster the smoke is flowing, the more heat it will transfer.

Finally, the smoke layer will transfer a lot of heat through radiation on its way out. The smoke layer will radiate heat onto objects located below it.

2.2 Radiation

Radiation is a form of heat transfer that is well known to everyone. Think of the sensation of the sun shining onto your face on a warm summer's day. Everyone can feel the effect of radiant heat. At a campfire or fire place, this becomes even clearer. Everyone also knows that the radiant heat increases as the distance to the heat source becomes smaller.

At the fire ground, the seat of the fire will be the primary source of radiant heat. The seat of the fire and the flames above it will radiate heat. Radiant heat moves in straight lines. Anything that is *in line of sight* of the fire (and of the flames), will be heated up.

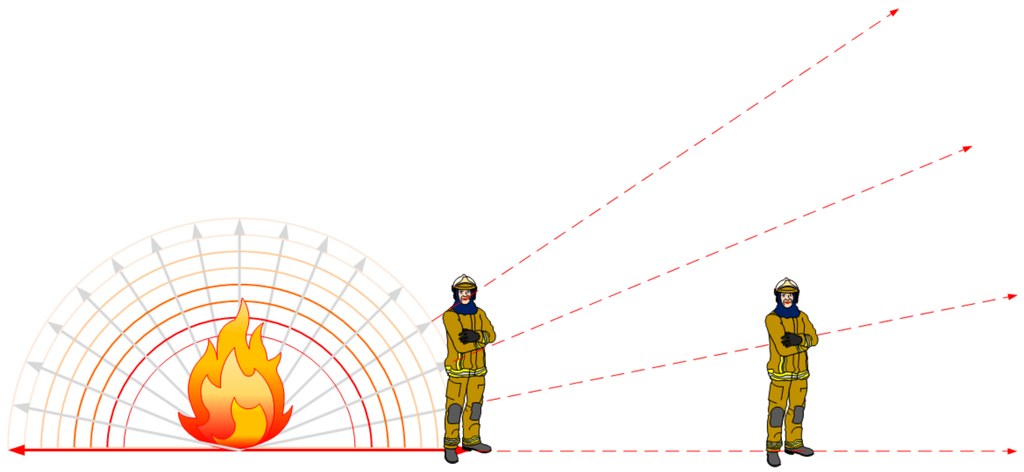

figure 3 Both firefighters in the illustration are of the same size, even if this appears not to be so. The firefighter closest to the flames will absorb a lot more radiant heat. This is illustrated by the number of arrows hitting his body. The further away from the heat source, the less radiant heat (arrows). *(Drawing: Bart Noyens based on an idea of James Mendoza of San Jose Fire Department)*

The hot smoke layer will also radiate heat onto objects in its "line of sight". These are the objects located beneath the smoke layer. That means that in close proximity of the fire, a sofa will be heated from two sides. Obviously, the seat of the fire also emits radiant heat. The amount of heat coming from here is usually quite large, however the distance to the sofa might be five meters for instance. The smoke layer will be less warm than the seat of the fire or the flames above it. Yet, the radiant heat transferred from the smoke layer onto the sofa can be much higher because of the smaller distance between the two. For instance, the smoke layer could easily be as close as one half meter to the sofa.

The distance between the source of heat and the receiving object is an important parameter in radiant heat transfer. Radiant heat (quantified in kW/m²) is inversely proportional to the distance squared. This means that the radiant heat transferred becomes four times less as the distance to the heat source doubles. The proportion of radiant heat received in relation to the radiant heat that's emitted, is called the *view* factor. The symbol defining the view factor is Φ. Figure 3 clearly shows that the firefighter who is standing closer to the heat source, is receiving a larger amount of radiant heat than the one who is standing further away.

A second important parameter is the temperature of the heat source. For convective heat transfer, the amount of heat transferred is determined by the difference in temperature between the heat source and the receiver. For radiant heat transfer, things are more complicated. The heat source will emit heat. The amount of heat that is emitted is directly proportional to the temperature in Kelvin to the fourth power. This is somewhat harder to comprehend. Generally speaking, the amount of radiant heat becomes 16 times greater when the temperature in Kelvin doubles. The temperature in Kelvin is 273 higher than when indicated in Celsius. A temperature of 400 Kelvin equals 127 °C. A temperature of 800 Kelvin matches 527 °C. When the temperature of a smoke layer increases from 127 °C to 527 °C, the radiant heat coming from that smoke layer will have increased 16 fold.

Each object will emit radiant heat. The sofa that is heating up, will therefor also be emitting heat. When the sofa has reached a temperature of 77 °C (350 K), it will also emit some heat. It is clear however, that the heat radiating from the sofa is negligible compared to that coming from the smoke layer.

It is possible to calculate the radiant heat transfer:

$$\dot{Q} = \sigma \times \epsilon \times \Phi \times T^4 \qquad [kW/m^2]$$

The radiant heat can just as well be emitted onto victims. Victims lying on the floor or standing on a balcony, can receive radiant heat coming from both the smoke layer and the flames. In practice, we often find victims who have fled out onto a balcony. They are no longer impacted by the smoke, but the radiant heat will still cause (major) burn injuries. A victim standing on a balcony, next to flames exiting from a big glass sliding door, will be burnt. This by itself, is an argument for use of transitional attack. By knocking down the flames, the temperature of the exiting gases will decrease significantly. The radiant heat will quickly become 16 times less. This means that the victim can stay on that balcony for a period that is 16 times longer, before amassing the same amount of radiant heat. It is however important to use the right amount of water during this tactic. The first dozens of liters entering the flaming compartment, will evaporate and draw an enormous amount of energy from the flames. Those flames are actually super-hot gases. When energy is drawn from these gases, they will shrink considerably. The shrinking volume of gases in turn makes place for expanding steam coming from the water that is evaporating. If more water is flown into the room after that, it will mostly evaporate on the walls and ceiling. This time, there will be no volume that is shrinking, just an extra amount of steam being formed. This excess steam will spread out everywhere and can severely hinder firefighters and even harm victims. Closing the nozzle immediately after knockdown has been achieved, is therefore very important.

3 Smoke

Production of smoke depends on the kind of fire. When looking at fires from the viewpoint of "smoke production", we can discern three types of fires: smoldering fires, ventilated fires and under ventilated fires. A smoldering fire is defined as a slow combustion process with low temperatures and without flames. Smoldering fires and under ventilated fires generally produce large amounts of gases (10 times more than ventilated fires). Smoke production is a lot lower at ventilated fires. When dealing with smoldering fires, a lot depends on the size of the fire and how it progresses. For instance, a cigarette could fall somewhere, start a smoldering fire, but that fire will be unable to grow. As long as the surface area of the smoldering fire remains small, production of gases will remain low as well.

Smoke is mixture of gases, solid particles (soot) and liquid particles in suspension. Different gases are being produced as well. CO_2 and CO are two important gases in smoke alongside pyrolysis gases. When nitrogen is present in the fuel of the fire, substances such as HCN are also formed. Finally, there will often be some part oxygen left in the smoke. The level of oxygen in the smoke will obviously be far less than the normal 21% that is present in the air. The smoke will rise in the shape of a plume toward the ceiling where it will form a smoke layer. The composition of the smoke layer is not fixed. It is constantly shifting. Inside the smoke layer, there will be some localized combustion in certain parts. This depends on the temperature and available oxygen. The level of CO in the smoke layer is directly proportional to the temperature in fuel controlled fires and is inversely proportional to the temperature in ventilation controlled fires. The levels of the different gases in the smoke layer is constantly changing. It is a very complex phenomenon.

4 Effects on the human body

4.1 Effect of heat

When our skin is heated, we first feel a pleasant sensation. Again think of the sun radiating its heat onto our skin. But everyone knows what sunburn is. Each of us has had first degree burns because of staying too long in the sun. That pleasant sensation can result into burn injuries due to long exposure. The radiant heat coming from the sun on a warm summer's day is about 1 kW/m². Prolonged exposure to this level of radiation can lead to first degree burns.

The temperature of the skin could be heated further. This can be done by convective or radiant heat transfer as explained above. The human pain threshold is about 43 °C. When skin is heated up beyond this point, pain will be felt. The higher the temperature and the larger the surface area that is burning, the more pain will be caused. This pain can even cause people to jump out of windows, even when it is certain they will not survive the fall.

First degree burns, with the typical redness of the skin, will occur when the skin temperature reaches 48 °C. At a temperature of 55 °C, second degree burns will start to form. These kind of burns are characterized by blisters. At higher temperatures, third degree burns will occur. This means that skin at the burn spot is completely destroyed.

Of course there is a difference in temperature between the skin of someone and that of smoke for instance. Because of heat transfer (either radiant and/or convective), the skin will heat up.

Firefighters are often faced with both convective as radiant heat transfer. They are often working inside smoke of a particular temperature while at the same time being exposed to a certain amount of radiant heat (measured in kW/m²). The US organization NIST has formulated a graph that indicates the effect of both forms of heat transfer. The graph also takes into account the protective effect of turnout gear.

The graph by NIST is, of course, a simplified model of reality. Still it offers a good initial estimate on how long it is safe for firefighters to operate in certain conditions before they get burn injuries.

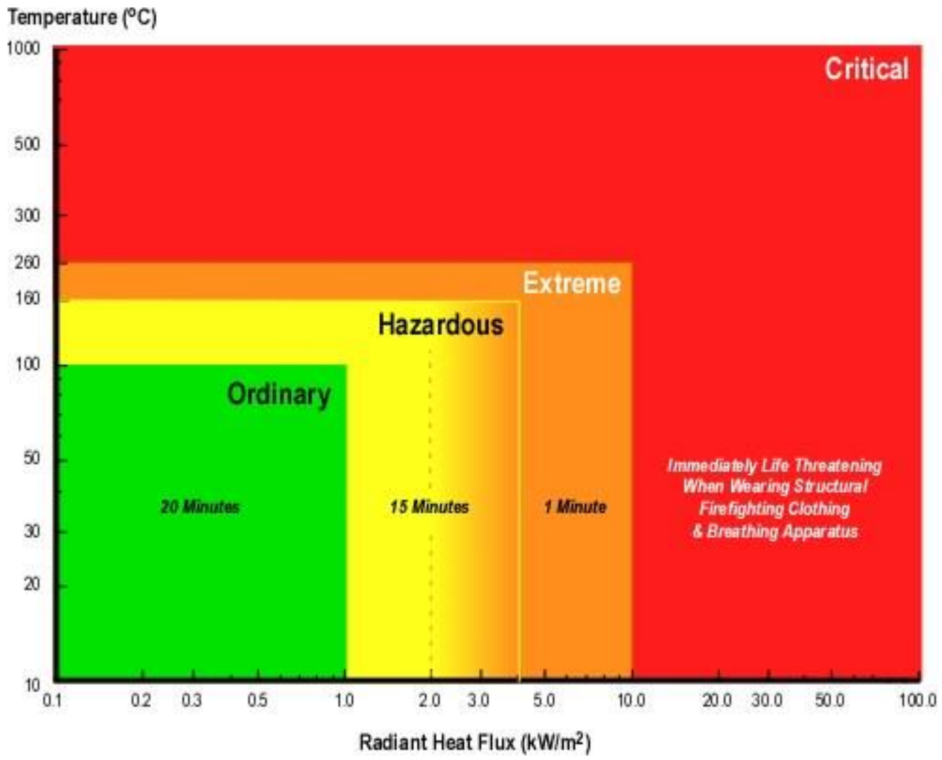

figure 4 Thermal exposure limit in relation to radiant heat flux and environment temperature.
(Graph: NIST)

4.2 Effect of smoke

Smoke is literally made up of hundreds of different substances. Still, the effect of smoke on the human body can be illustrated by taking a look at certain key gases and the interaction between these gases.

Smoke causes a wide array of problems for human beings:

- Smoke partly consists of irritants.
- Smoke partly consists of asphyxiants (CO, CO^2, HCN, …)
- Smoke has lowered levels of oxygen.

The irritant gases in smoke will negatively affect eyes and lungs. At high concentrations, they will cause genuine pain. On top of that, smoke does not allow light to travel through it. This means that you cannot see through smoke very well. The thicker the smoke, the less you can see. All of these characteristics make it very difficult for people to walk through smoke. The physical health of a potential fire victim plays a role as well. Senior citizens and small children will more quickly succumb to the effects of chemical irritants than adults in good shape. It goes without saying that people with reactive airway disease will experience physical problems a lot quicker when exposed than a person with normal health.

People that have been exposed to irritant gases can develop numerous health issues even after the exposure has ended. They are not completely out of the woods yet, after they have been moved out of the smoke. During the first 24 hours after exposure, an inflammation of the lungs could occur which can be fatal. When such inflammations are adequately treated or prevented altogether, most victims show a full recovery within 3 months. Only when a house fire victim leaves the hospital, can we truly say that we saved a life. Often it are the combined efforts of the fire service, that "saves" the lives of house fire victims, and medical services that make sure they stay alive.

Smoke also partly consists of CO. In a fire, CO levels often reach 5.000 to 10.000 ppm. These are very high concentrations. CO attaches itself to the hemoglobin in the blood stream. Hemoglobin is the protein in the red blood cells that transports oxygen. Hemoglobin can be seen as a set of trucks carrying oxygen from the lungs towards the rest of the body. When one of those trucks is loaded with CO, it can no longer transport oxygen. If too many of these trucks are carrying CO, then the supply of fresh oxygen is greatly reduced. The amount of CO is quantified in %COHb. High CO levels in the blood stream are the main cause of death for people trapped in house fires. For human beings, *Haber's rule* applies. Haber states that CO poisoning is dependent on both the exposure time and the level of CO in the atmosphere. This means that an exposure of five minutes to a concentration of 1.000 ppm has the same effects as being exposed to 500 ppm for ten minutes.

Smoke often also consists of hydrogen cyanide. Concentrations of 1.000 ppm are possible in fire scenario's. HCN is also a toxic gas, and is up to 25 times more poisonous than CO. The effect of HCN, must be added on top of the effects of CO. HCN in smoke will cause victims to lose consciousness even quicker than would be the case without

HCN. This further shortens the time that victims have to evacuate. Finally, it is worth noting that Haber's rule does not apply to HCN. People will not survive for long in HCN levels of 200 ppm and above.

Smoke also has high concentrations of CO_2. This gas causes the human body to hyperventilate. The natural goal for our bodies is to get the CO_2 out of the blood stream. However, hyperventilation makes it that the other toxic gases are inhaled even faster.

The concentration of oxygen inside the smoke has been reduced. Sometimes, there is hardly any oxygen left of the original 21%. Low levels of oxygen are very dangerous. During a house fire, the level of oxygen is often still survivable close to the floor. Inside the smoke layer, concentrations of 1% have been measured. Added to that is the high temperature of the smoke layer. People that breath in that kind of smoke, often have little chance of getting out alive. There have been cases reported, where people open a door to a fire compartment and suddenly find themselves in heavy smoke flowing out. Even after a single draw of breath inside the smoke, they succumb and fall unconsciously to the floor.

Smoke has a number of other gases in it such as NO_x, but these usually are of lesser significance.

Generally speaking, smoke has three effects on the human body:

1. Irritant gases severely hamper evacuation. Eyes become teary and airways start to ache. This can even cause victims to collapse.
2. The levels of gases to which victims are exposed, can cause them to become disoriented, lose consciousness or even die. CO and HCN are the most important gases in this regard.
3. High levels of irritant gases can even result in a victim's death after being rescued from the fire by causing inflammation of the lungs and pulmonary edema.

75% of the victims that die from smoke inhalation are found in rooms other than where the fire originated. So victims primarily die because of the effects of smoke. Professor David Purser developed a model to calculate the effects of smoke. He comes up with an approximation of the dose that a person absorbs: the *fractional effective dose (FED)*. With it, he states that half a second in an environment of 1000 ppm of CO is not as bad as 10 minutes in an environment of 100 ppm. As soon as the FED rises above a set value, victims lose consciousness. When the FED rises even further, they die.

5 First save victims, then extinguish the fire?

The different paragraphs above explain how victims are compromised by the effects of smoke. The quickest way of increasing their odds of survival, is to remove the victims from the smoke. In order to achieve that, victims have to be found first. This is often very difficult, especially in larger compartments.

A second way to improve the survivability odds of victims is by removing the smoke. To achieve this goal, the fire service has to ventilate. By diluting the smoke with fresh air, the concentration of both irritant and toxic gases will drop while the concentration of oxygen will rise. That extra oxygen however could have drastic consequences for the fire, especially when it has not yet been put out.

Ventilation can therefor become a dangerous tactic on the modern day fire ground. Only when dealing with (small) smoldering fires, can it be done in relative safety. For other fires (ventilated and under ventilated) it is important that prior to ventilation, extinguishment is started. It is often hard to guarantee that the extinguishment effort will be successful. At the start of the fire attack, the exact location of the fire is often not (entirely) clear. It is then impossible to ventilate without first doing something about the fire. Otherwise, it may well be the case that the fire will grow in such a way that victims perish due the effects of heat.

In order to save human lives, smoke has to be removed. Ventilation is the solution to that problem. But in order to be able to ventilate without having the fire grow significantly due to the added oxygen, the fire has to be knocked down first. That is how we can save lives. Due to changed fire conditions (as opposed to 50 years ago) we can no longer save before we extinguish. The fire has to be put out first so that we can ventilate and save lives (or save lives and ventilate).

First, put the fire out!

6 Bibliography

[1] *Merci B (2010) Active fire protection: Smoke and heat control, course of the Post graduate Studies in Fire Safety Engineering, UGent*

[2] *Gottuk D, Lattimer B (2016) Effect of combustion conditions on species production, in SFPE Handbook of fire protection engineering*

[3] *Purser D (2016) Combustion toxicity, in SFPE Handbook of fire protection engineering*

[4] *Galea E (2011) Human behavior in fire, course of the Post graduate Studies in Fire Safety Engineering, UGent*

[5] *Lambert K, Baaij S (2018) Brandverloop: Technisch bekeken, tactisch toegepast, 2de editie*