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Forecasting Flashover in a Compartment Fire by Using a Real-time Moving Average from Temperature Recordings

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Abstract: A series of flashover fire tests were carried out using standard wood as fuel with various ventilation, and a comprehensive set of experimental data is presented. Fighting against compartment fires with occurance of flashover could cause fatal consequences on firefighters. This work shows that the potential dangers as flashover can be detected as soon as possible thanks to the comparison between two moving averages in the past calculated from a temperature recording in a very short time. The present study aims to evaluate the possibility of using only commonly available measurements as data to be assimilated into the model. A real-time decision method is developed, allowing to the selection of optimal intervention to minimize firefight occupant exposure to the detected hazard. This approach includes the mathematical analysis which is based on the comparison of two moving averages centered in the past, calculated on the recordings of the smoke temperature. Firefighters would greatly benefit from this predictive method in real time, able to assist their decision making process during operations against a compartment fire. From the safety point of view, the model gives conservative predictions for flashover fire.
Keywords: Compartment fire; Flashover detection: Decision in real time: Moving average; Temperature recording.

1. Introduction

The physical compartment boundaries affect not only the combustion processes, but also the transport of thermal energy, reactants from the chemical reaction zones, and conductive heat loss to the walls. Radiation from the ceiling smoke and walls during the compartment fire significantly enhances degradation of condensed fuels into pyrolysis gases [1]. Flashover is more likely to occur in a highly confined compartment due to noticeable enhancement of radiation heat feedback from smoke/walls, and the most common fire threat to people [2]. As a consequence, fire fighters face uncertain conditions when entering a compartment to attack a fire, and have to make decisions based on their experience. A flashover needs to be detected as earlier as possible, allowing firefighter to escape the risk environment, and to avoid further fire development for reducing loss of material properties. The fundamental challenge of fire forecasting is thus to predict fire spread trend.

Less attention has been given to the use of computational and experimental simulations as an operational tool for fire emergency due to the high complexity of fire spread dynamics that arises from the interaction between condensed fuel and gas phase, and the corresponding physical – chemical processes. The spread rate and mass loss rate of the compartment fire in real-scale with the entire duration of the fire are estimated by expanding the methodology to the use of CFD type fire models [3]. Only when the HRR is well characterized as an input parameter in CFD type fire models, a good agreement with measurements can be obtained [4, 5]. Whileas CFD fire simulations typically take large periods of time to complete, and their results would not be available in time to be of use during an emergency. Motivated by these observations, an artificial intelligence system is proposed to fast forecast the compartment fire development and flashover in advance based on a temperature sensor network and a deep-learning algorithm [6]. The traveling fire and hybrid simulations are explored to solve the spatiotemporal fire evolutions as flashover [7]. An artificial intelligence model is also developed to predict the temperature distribution of a compartment fire in addition to verification by CFD simulations [8]. The assimilation process is separated from the forecast, and then, simple correlations are used to estimate the size of the fire [9]. Focusing on real time forecasting, a zone model is reverted for calculation of fire speed by adjusting the estimated parameters to changes as a function of the fire conditions [10]. A machine learning method is adopted to determine the occurrence of flashover under given fire scenarios [11]. Using some sort of inverse modelling mechanism, generally only the constant fire power can be estimated by infering temperature measurements at the boundaries or within the fire compartment, or visual estimations of the smoke layer height [12]. The fire location can't be simultaneously estimated with the fire size [13]. This issue is addressed by providing multidimensional fire parameter estimation using Bayesian inference together with temperature measurements at ceiling level [14]. Fire characteristics are estimated with video image methodology from camera during the fire via an effective method to ensure visibility in a fire environment such as a room filling with smoke [15]. The data derived from the video footage are cross- referenced where possible in order to increase the credibility of the findings. A data recovery algorithm named as P-flash is proposed, allowing to recover the missing data in case of a sensor was destroyed in a multi-compartment fire [16].

The consensus provided by these works [2, 4, 5, 15] is that the fire evolution can be evaluated from a certain amount of information as temperature, pressure, speed, chemical composition contained and conveyed in smokes. While as, the detailed diagnostics including these measurements create an insurmountable difficulty during a compartment fire. For the purpose of forecasting fire dynamics in the context of emergency response, a moving average method [17] is developed in the current work. The moving average method from temperature recordings as temporal series allows to a detection of a flashover in an early stage. Firefighters would greatly benefit because this predictive method is better suited with a set of optimal intervention in a few seconds, allowing to identify dangerous events and to protect firefighters from the hot smokes against the flashover. The results presented in this study give an outlook for the prediction of flashover, allowing to improve fire safety. The moving average method is a possible alternative or supplement to video image [15] for improving the decision support in real time and therefore the security or the efficiency of firefighters in their operations against compartment fires.

2. Methodology

This method for optimizing intervention management requires: 1) temperature recordings directly from the situation 2) calculation of the moving average is faster than real fire evolution 3) processing results quickly enough, and 4) outputs are easy to interpret with a high confidence level.

A key point is the possibility of transmiting the physical measurements during the emergency outside to a control centre and predicting the impact of different intervention scenarios and procedures, allowing to improve decision supports. In response to this, the moving average method is opening opportunities for new modelling focused on real-time applications. Time scale for calculating different parameters of averaged value in the past is schematized in Fig.1 where the t_{d1} and t_{d2} imply a short term and a long term in the past of the moment t_i, respectively. In a simple step, two moving averages could be defined as a function of the temporal distance, t_i-t_{d1} and t_i-t_{d2}.

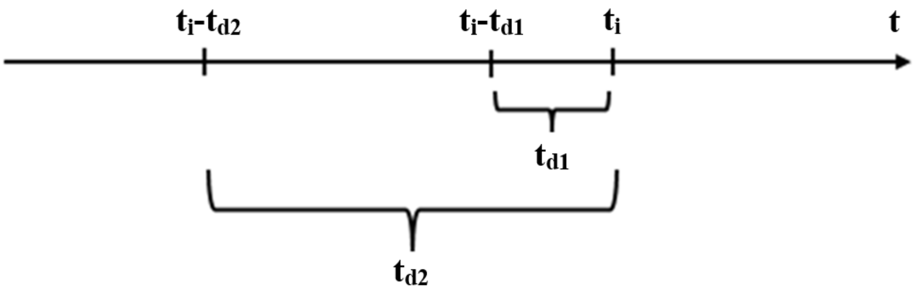


Figure 1. Time scale for calculating the moving averaged temperature in the past

The moving averaged temperature, $\bar{T}$, is based on stochastic intervention model predictions that follow the fire evolution. The temperatures are considered as knowing physical quantities, and the moving average centered in the past is calculated as follow:

$$\overline{\mathrm{T}}(\mathrm{i},\mathrm{N}) = \frac{1}{\mathrm{N}}\sum_{\mathrm{k}=0}^{\mathrm{N}-1}\mathrm{T}(\mathrm{t}_{\mathrm{i}-\mathrm{k}}) \quad (1)$$

Here, T represents the measured temperature at the moment time, t_i and N the interval number. The acquisition frequence, f, of temperature readings with thermocouples and the temporal distance in the past, t_d, allow to determine the interval number, N.

$$N = f\ t_d + 1 \quad (2)$$

Systematic linear correlation could be made between the change of T_i and the time, t_i.

$$T_i = a\,t_i + b \tag{3}$$

This is an important feature of the time marching scheme. In this calculation, the parameters a and b are chosen for obtaining the best possible analysis, allowing to identify dangerous events. The method is not configured in advance but allowing the user to make changes as the situation evolves. The moment time, t_i, at which the moving average is calculated in the past follows such condition: t_i-t_d+a < t_i .

It is convenient to write Eq.(1) in the form:

$$\overline{T}_{i,N} = \frac{1}{N}\sum_{k=0}^{N-1} T_{i-k} \tag{4}$$

According to Eq.(3), the temperature at the moment time, T_i, and the temperature in the past of the moment, T_{i-k} , can be written by the discrete equation:

$$T_i = a\,t_i + b = ai\Delta t + b \tag{5}$$

$$T_{i-k} = a\,t_{i-k} + b = a(i-k)\Delta t + b = ai\Delta t + b - ak\Delta t \tag{6}$$

Substituting Eq.(5) into Eq.(6) yields:

$$T_{i-k} = T_i - ak\Delta t \tag{7}$$

Here, the interval time is computed from the acquisition frequence as follows:

$$\Delta t = 1/f \tag{8}$$

Substituting Eq.(7) into Eq.(4) yields

$$\overline{T}_{i,N} = \frac{1}{N}\sum_{k=0}^{N-1} T_{i-k} = \frac{1}{N}\left[\sum_{k=0}^{N-1} T_i - a\Delta t\sum_{k=0}^{N-1} k\right] = \frac{N\,T_i}{N} - \left[\frac{a\Delta t}{N}\cdot\frac{N}{2}(N-1)\right] \tag{9}$$

$$\overline{T}_{i,N} = T_i - a\Delta t\,\frac{N-1}{2} \tag{10}$$

The calculating interval is defined as

$$I = \Delta t(N-1) \tag{11}$$

Substituting Eq.(11) into Eq.(10) yields

$$\overline{T}_{i,N} = T_i - a\left(\frac{I}{2}\right) \tag{12}$$

Here, a represents the half amplitude of the calculating interval, I. The moving average temperatures at the interval number, N_1 and N_2 are defined as,

$$\overline{T}_{i,N1} = T_i - a\Delta t\,\frac{N_1 - 1}{2} \tag{13}$$

$$\overline{T}_{i,N2} = T_i - a\Delta t\,\frac{N_2 - 1}{2} \tag{14}$$

A mesure of the difference between N_1 and N_2 can be defined as.

$$\overline{T}_{i,N2} - \overline{T}_{i,N1} = -a\Delta t\left(\frac{N_2 - 1}{2} - \frac{N_1 - 1}{2}\right) = -a\Delta t\left(\frac{N_2 - N_1}{2}\right) \tag{15}$$

The coefficient, a, in Eq.(15) can be derived as:

$$a = -\frac{2(\overline{T}_{i,N2} - \overline{T}_{i,N1})}{\Delta t(N_2 - N_1)} \tag{16}$$

Here, N_1 is always smaller than N_2 ($N_1<N_2$) and the interval time is positif ($\Delta t > 0$). The interval numbers, N_1 and N_2, can be translated to the time scale (cf. Fig.1) such as a short term t_{d1} and a long term t_{d2}, respectively. Thus the two moving averages can be defined as: $\overline{T}_{i,N2} \equiv \overline{T}_{ti-td2}$ and $\overline{T}_{i,N1} \equiv \overline{T}_{ti-td1}$. The difference, $\overline{T}_{ti-td2} - \overline{T}_{ti-td1}$, is able to reach a significant signal in case of flashover condition which occurs when the temperature inside a compartment exceeds a certain level.

Two specific events of the fire are selected, the first corresponds to an increasing and decreasing scenario, as illustrated in Fig.2, and the second to a decreasing and increasing scenario in Fig.3. The temperature values are averaged during the two temporal distances in the past from t_{d1}=-15 s and t_{d2}=-30 s, corresponding to a short term and a long one, respectively. It is found that evolution of the temperature at the two temporal distances is completely compatible with the characteristic evolution of a compartment fire. The moving average at t_{d2}=-30 s gives useful information when it is compared to that at t_{d1}=-15 s, because the averaging temperature evolution are clearly visible. The estimation process from the evolution of the average temperature with time progress for the two specific events of a fire can be highlighted as follows:

1) Before 40 s for the first event and after 40 s for the second event, T_{ti-td2} is below T_{ti-td1}. A negative sign of the difference $(\overline{T}_{ti-td2} - \overline{T}_{ti-td1} < 0)$ between the two moving average conducts to a positive sign of the parameter, a, in Eq.(16). This implies that the fire power is going to increase, characterized by an increasing trend of the temperature with time (cf. Eq.3). The fire scenario is treated as dangereous situation with occurrence of an explosion or a flashover.

2) Between crossing of T_{ti-td2} and T_{ti-td1} at about 40 s translates to a change in event. Since the difference between the two moving average tends to zero $(\overline{T}_{ti-td2} - \overline{T}_{ti-td1} = 0)$, the fire power is momently stabilized with a temperature reaching a plateau (a=0 in Eq.3).

3) After 40 s for the first event and before 40 s for the second event, T_{ti-td2} surpasses T_{ti-td1}. A positive sign of the difference $(\overline{T}_{ti-td2} - \overline{T}_{ti-td1} > 0)$ between the two moving averages centred in the past at t_{d1} and t_{d2} conducts to a negative sign of the parameter, a, in Eq.(16). This means that the fire power is going to decrease, characterized by a decreasing trend of the temperature with time (cf. Eq.3). The fire scenario is considered as a safer situation.

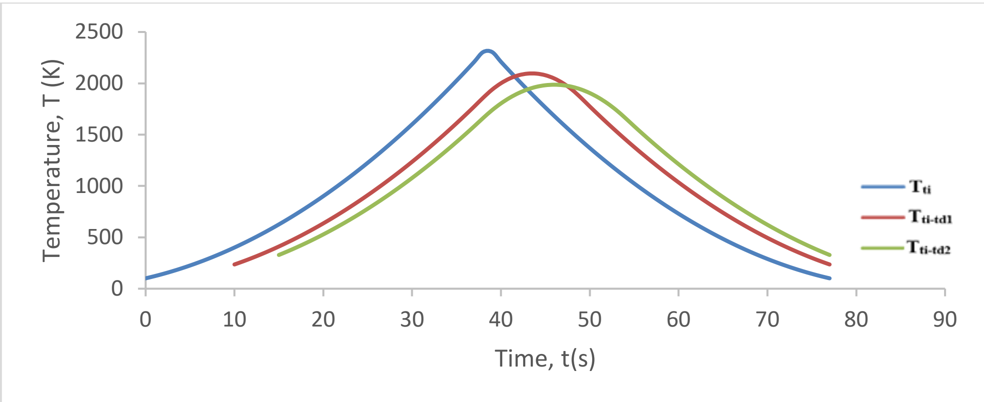


Figure 2. History of temperature and comparison of the two moving averages from the temperature recordings centered in the past for increasing and decreasing scenarios

For those simulations to be useful, they need a certain degree of precision and resolution that can only be provided by averaging temperature. It appears that the useful information is lost with the temporal distance in the past above 60 s for moderate fire duration. When the difference between averaged value and the real one is moderate, a clear tendency towards the true value can be appreciated. The convergence towards the true value is evident for all selected initial guesses, which confirms that the methodology is not sensitive to the exact fire scenario as long as it is reasonably close by averaging time, e.g. 30 s.

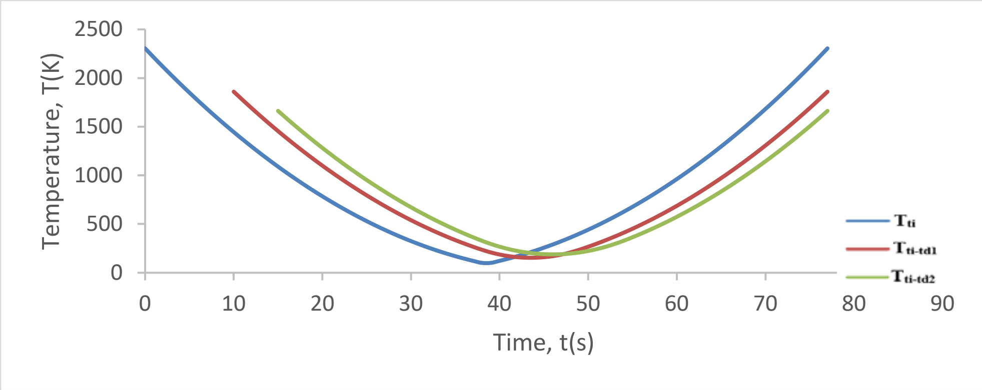


Figure 3. History of temperature and comparison of the two moving averages from the temperature recordings centered in the past for decreasing and increasing scenarios

3. Experimental set-up

The problem addressed is the selection of optimal intervention in real-time. An optimal intervention is defined here as the moment that produces the minimum flashover risk, while keeping firefighters forward towards the hazard. The purpose of the model is to provide the firefighters, emergency manager optimal operation positions in real-time. The validity of the model is evaluated for two tests. Although the method is applied to a representative sample, this model does not correspond to any compartment in particular, it is a typical layout of a compartment.

The developed method has been first tested in a full-scale compartment with different fire scenarios. A schematic of the 2D view of the experimental facility and locations of the temperature measurements inside compartment are presented in Fig.4(a,b). The experiment has been made in a compartment with 12 m in length and 2.5 m in height/width. Aiming to simulate realistic building conditions, the wood cribs of 120 baguettes, which were widely investigated in the bench-scale test [18], with initial weight of 250 kg is placed inside the compartment. Fire scenarios with flaming conditions for the ignition of wood cribs has been forced by the use of a Bunsen burner.

The burning rate, $\dot{m}$ (kg/s), can be approached by a linear semi-empirical correlation (17) via a regression rate, v_p (m/s), of one baguette [19].

$$\dot{m} = \frac{4}{D_{bag}} m_0 v_p \left(1 - \frac{2v_p t}{D_{bag}}\right) \tag{17}$$

Here, m_0 (kg) represents the initial mass of wooden cribs, and t (s) time. The regression rate, v_p, is typically related to a width, D_{bag} (m), of square baguette in wooden cribs with a value of 6 cm in this study.

$$v_p = 2.2 \cdot 10^{-6} \cdot D_{bag}^{-0.6} \text{ (m/s)} \tag{18}$$

The peak in the theoretical heat release rate of the fire is about 1900 KW, which is estimated by multiplying the calculated burning rate (Eq.17) by the heat of combustion of wood, taken equal to 20 MJ/kg [18].

The mass outflow rate ($\dot{m}_{out}$) from the opening geometry of a compartment is calculated [20] as follows:

$$\dot{m}_{out} = 0.41 \rho_a A \sqrt{h} \tag{19}$$

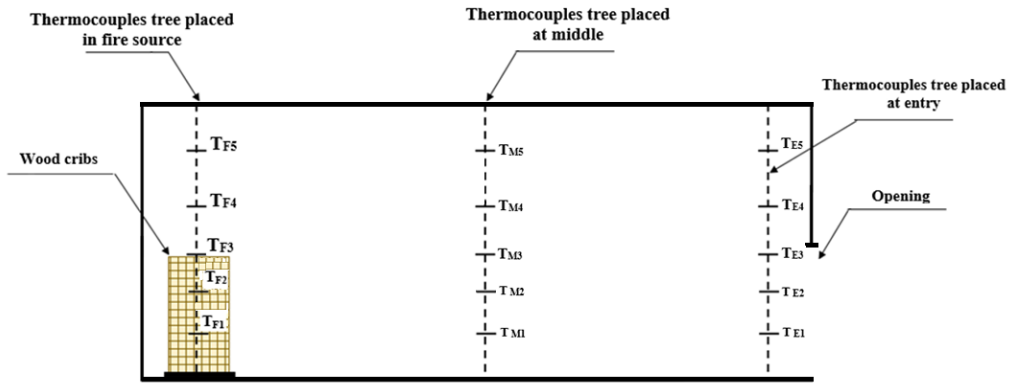
The mass inflow rate can be derived from the mass conservation at the opening:

$$\dot{m}_{air} = \dot{m}_{out} - \dot{m}_{fuel} \tag{20}$$

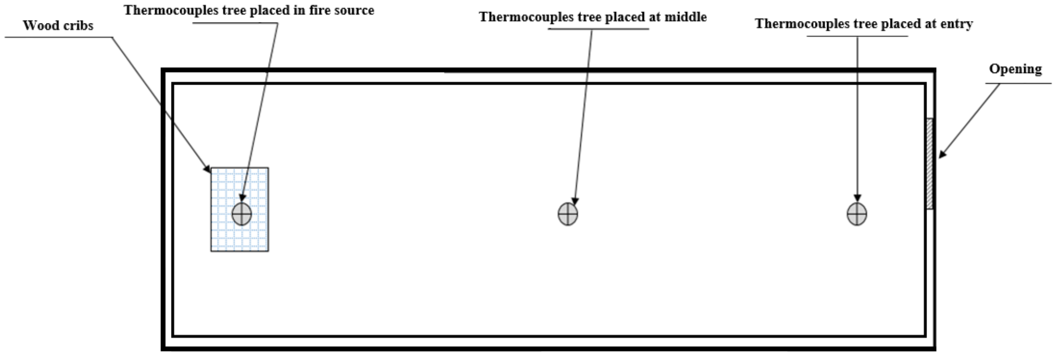
The internal heat release rate ($\dot{Q}_{in}$) is derived from the air entrainment inside compartment:

$$\dot{Q}_{in} = \dot{m}_{air} Y_{O_2} \Delta H_{O_2} = (\dot{m}_{out} - \dot{m}_{fuel}) Y_{O_2} \Delta H_{O_2} \tag{21}$$

Here, Y_{O_2} and ΔH_{O_2} are respectively the ambient mass fraction of oxygen and the amount of energy released per unit mass of oxygen consumed (13100 kJ/kg). In this work, a length scale ratio with 1.7 m in height and 1 m in width for the opening has been proposed. With this opening geometry, the internal heat release rate can reach to a peak in HRR of about 2200 kW which is higher than the theoretical HRR of 1900 kW. Thus the fire considered here corresponds to well-ventilated conditions, and combustion is limited at the interior of the compartment.



4a) Side view with arrangement of the thermocouples



4b) Top view with the location of the fire origin

Figure 4. Layout of the full-scale test facility with compartment length scales of the order of 10 m

The thermocouples are used to measure the temperature at various positions to identify the fire dynamics. There are three vertical arrays, and each of the profiles comprises 5 chromel-alumel thermocouples (K type) of a 0.5 mm wire, positioned at a height of 0.4, 0.7, 1.1, 1.7 and 2.3 m above the floor. The first array of thermocouples was positioned at the location of the fire origin (T_{F1-5}). The second array of thermocouples was located at the middle (T_{M1-5}) of the compartment and the third one was positioned at entry (T_{E1-5}). Temperatures were recorded and analysed with the LabView software. The uncertainty in the measurement of gas temperature could originate from the thermocouple response to conversion of the flame or gas temperature in digital signal. Moreover, in fire environment with an accumulation of soot particles and reactions, a radiation correction is necessary to ensure the accuracy of flame temperature measurement due to the radiation heat exchanges from thermocouples to the exterior. Besides, the flame temperature variation is related to the thermocouple diameter via convection, and a decrease in diameter of the thermocouple causes a reduction in flame temperature. More details on the uncertainty in gas temperature measurement are provided in the literature [21]. The response time of the thermocouples used in the experiment is close to a second by including all the above factors, giving an uncertainty of roughly 5% in the measurement of gas temperature.

4. Results and discussions

The results of the first full-scale compartment are presented and discussed in this section. Figure 5(a, b, c) shows history of the gas temperature recorded from the five measurement points of the thermocouples (cf. Fig.4a) installed at the location of the fire origin (T_{F1-5}), the middle (T_{M1-5}) and the inlet of opening (T_{E1-5}). This is a simple Graphical User Interface allowing the user to visualiser the main output thermocouple signal. The compartment fire scenarios can be said to follow the four characteristic stages:

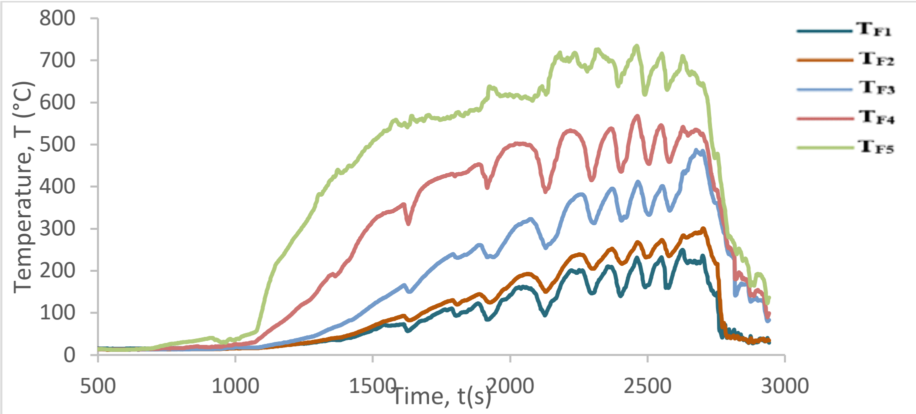
1) Fire developes slowly as its early stage during about 1000 s, because the virgin solid fuel is first preheated by a burner to its vaporization temperature, pyrolyzing it, and igniting the flammable mixture of pyrolyzate and oxygen.

2) The initial growth phase of the fire up to 1500 s is characterized by a quick increasing trend of the temperatures.

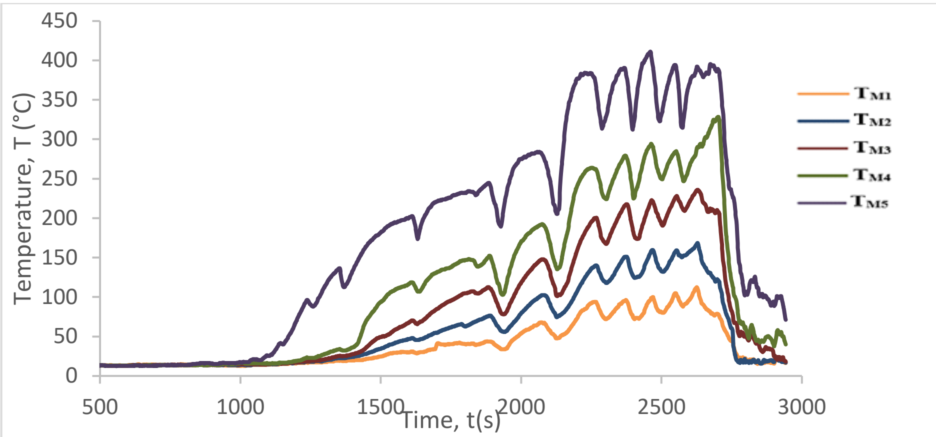
3) Starting from 2100 s, during this fully developed phase, the smoke temperature near the ceiling reaches to a plateau of about 750°C with oscillations at the location of the fire origin (cf. Fig.5a). At the flashover stage,

radiation heat flux on the fuel surface reaches 20 kW/m^2 once the smoke temperature is above 500°C. In the case of the flashover, the maximum radiation from the measurement can reach up to 50 kW/m^2 when the smoke temperature reaches 800°C. Even at the inlet of opening (cf. Fig.1b), the smoke temperatures are higher than 350°C near the ceiling of the compartment, closing to the self-ignition temperature of the CO and unburnt hydrocarbon gas.

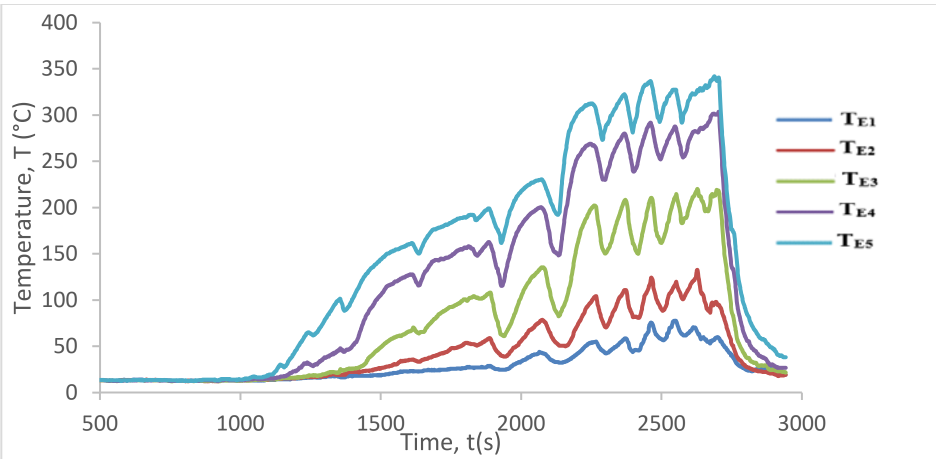
4) The fire lastes for about 50 min. During the decay phase, the fire weakens with a sharp decrease in temperature, and finally stops due to burnout of the wooden load.



5a) at the fire origin



5b) at the middle of compartment



5c) at the inlet of opening

Figure 5. History of the gas temperature recorded from thermocouples inside the compartment at the different measurement points

The two moving averages centered at t_{d1}=-15s and t_{d2}=-30s at a distance of 20 cm under the ceiling at the fire origin (T_{F5}) are illustred in Fig.6a to detect flashover in an early stage of the compartment fire development. The average correctly reproduces histories with time of the real temperature. Due to the logarithmic dependency between temperature and time, difference between the two moving averages is able to predict even small temperatre changes between T_{ti-td1} and T_{ti-td2}. The interpretation is orientated on the threshold of smoke temperature above 500°C for an evidence of flashover. Therefore, in order to highlight various specific events of the fire, the difference in moving averages is adapted for early fire detection starting from 1900 s.

1) Between 1900 s and 1950 s, T_{ti-td2} is below T_{ti-td1} with an increasing trend of the temperature.

2) Between crossing of T_{ti-td2} and T_{ti-td1} at the moment of about 1950 s translates to a change in event. Starting from 1950 s to 1980 s, T_{ti-td2} surpasses T_{ti-td1}, implying an decreasing trend of the smoke temperature due to flame oscillations induced by buoyancy-induced flow.

3) In the period of 1980 s to 2090 s, the difference tends to zero even there are oscillations in both the averages. This signfies that the fire is momently stabilized and the temperature reaches a plateau with a temperatures higher than 625°C. This situation conducts to the possible appearing of a flashover with regarding the self-ignition temperature of CO and all unburnt gas.

4) Between 2090 s and 2130 s, T_{ti-td2} becomes once again lower than T_{ti-td1}, implying that the temperatures are going to increase.

5) In the period of 2130 s to 2140 s, there are flame oscillations due to moment lack of oxygen nearby the fire source. T_{ti-td2} surpasses again T_{ti-td1}, conducting to a decrease of the temperature, but its level remains high, implying that the situation remains again dangerous.

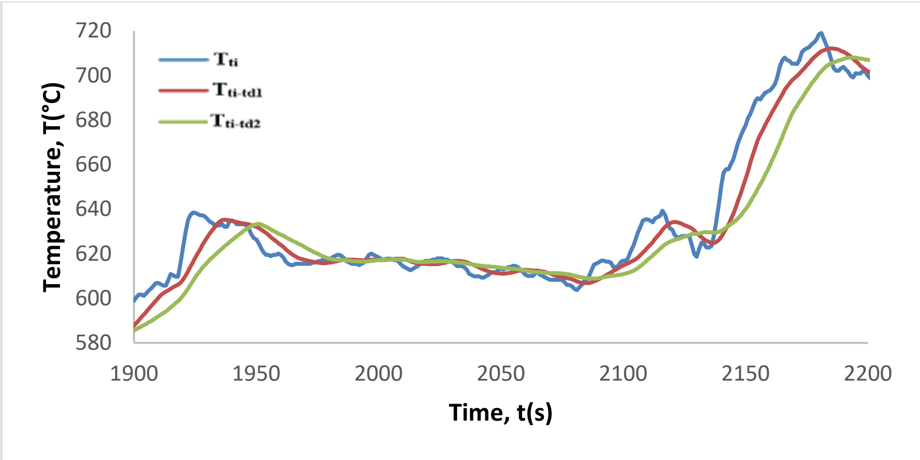
6) Starting from 2140 s to 2190 s, T_{ti-td2} becomes agains lower than T_{ti-td1} with a remarkable difference of 20°C between them, implying that the beginning of the flashover due to a strong increase in temperatures from 500 to 750°C. Finally, a well-known dangerous event named as the flashover occurs with a heating source set in a temperature higher than 700°C at t=2190 s.

Evolution of the two moving averages centered in the past at the entry of opening (T_{E5}) and at the middle of compartment (T_{M5}) follow the same trend, as shown in Fig.6(b, c). Occurrence of decreasing or increasing scenario in smoke temperature inside the compartment can be identified with a deviation of the between crossing delay in time mainly due to smoke circulation inside compartment. However, it is not possible to detect dangerous events such as flashover due to lack of information on the maximum smoke temperature near the ceiling. Flashover inside the compartment could be satisfactorily estimated by examining evolution of the temperature under the ceiling nearby the fire origin. This information is very important for the firefighter commander in order to improve its decision capacities in real time. Since calculation of the averaged value runs in real time, the method is sufficiently robust for flashover occurrence assimilation. Ultimately, the moving averages centered in the past is by definition useful or indeed worthy of being called a forecast because it can be delivered before the flashover happens, i.e. because its lead time is positive. This is considerably less data required in previous publication [12], where typically time histories of local temperatures are assimilated into the model.

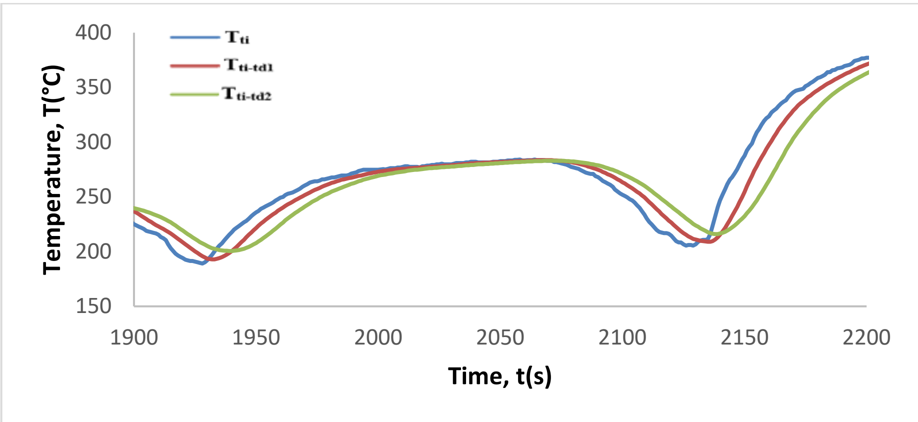
Under-ventilated compartment fires induce dense black smoke containing toxic gases such as carbon monoxide, that covers ceiling lights and darkens compartment spaces. Smoke spreading is a serious threat to people's evacuration and rescue activities. One of the ways to control smoke in compartment consists in applying a forced ventilation procedure. During operation, particularly in confined fire situations, ventilation by using portable fans with a jet velocity in a range of 5-10 m/s has to be used in order to draw smoke outside, and this allows to protect firefighters. The ventilation helps to guide firefighters to entry into an unfamiliar environment with a presumed emergency situation. At the evacuation stage in case of a compartment fire, control of smoke backlayering assures smoke clear path for firefighters upstream of the fire. At the fire fighting stage, this measure provides access to the fire site for fighters.

A real forecast fire scenario is considered to investigate the consequences of applying air intake via fans on compartment fire behavior. The experiment has been made in a hospital chamber with 6 m in length, 5 m in width and 3 m in height. This compartment represents a typical lounge in a residential occupancy with a number of different combustible items located in pre-defined positions, and a specific ignition source. Aiming to simulate realistic building conditions, an expendable solid fuel is employed, including a wood table, a chair, an armchair made of imitation leather, a wardrobe full of clothes, another table with a computer and a TV, and two beds with blankets. The original mass of the condensed fuel was about 300 kg. The selected meterials reflected a typical living room and the mixted crib contained 50% wood, 20% PE and 10% PVC. In this real forecast scenario, the growth rate of the fire and its origin were not be known before hand. The first ventilation, V1, began about 5 minutes after the fire start, representing the mean usual time between the alert and the arrival of the firefighters on the spot. The second ventilation, V2, starts at about 8 min when the performance of the first ventilation is degrading to prevent the smoke from spreading upstream.

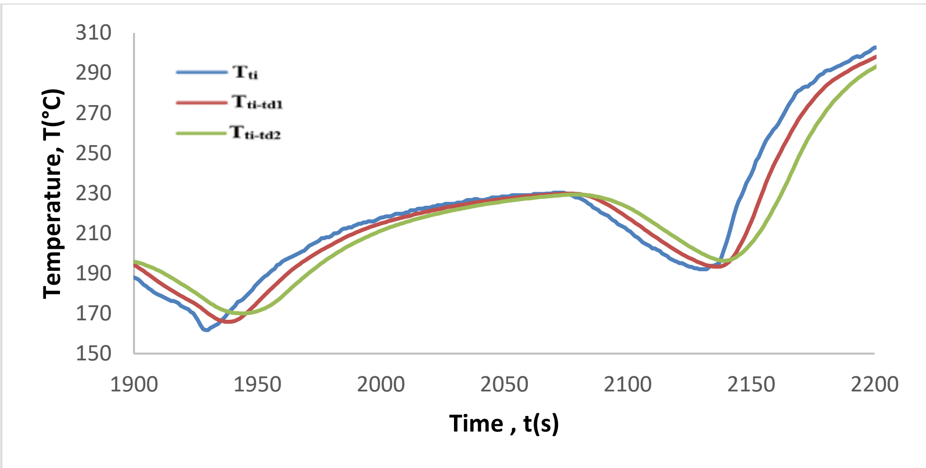
The effects of ventilation for directing air flows on the smoke temperature via movement control is shown in Fig.7. Four positions for the measurement of temperature are chosen according to a specific firefight strategy for the safest intervention positions during the fire progression. The measured temperature, T_1, is in the upper level 30 cm under the ceiling just close to the door. The T_2 is taken at a height of 80 cm above the floor at the middle of the compartment, corresponding to knees-to-head for a firefighter. The T_3 is taken in the lower level at a height of 30 cm above the floor at the middle of the compartment. The T_4 is taken at a height of 30 cm under the ceiling just in front of the glass window opposed to the door.



6a) at the fire origin (T_{F5})



6b) at the middle of compartment (T_{M5})



6c) at the entry of opening (T_{E5})

Figure 6. Comparison of the two moving averages with history of temperature at a height of 30 cm under the ceiling

At the early stage without ventilation, the temperature close to the door (T_1) reaches a plateau with a value of about 600°C. The temperature reaches a relatively steady period from 3 min onwards with a temperature level which is close to auto-ignition temperature of carbon monoxide and unburnt gas, contained in great amount in the smoke of compartment fires. Just after this plateau, a sudden rise of the temperature occurs to a level higher than 800°C under the ceiling (T_1). This phenomenon is well-known as the possible appearing of a flashover, and the first forced ventilation is activated at this moment of t=5 min, indicated as V1. After the transient stage, the temperature under the ceiling (T_4) in front of the glass window reaches to the value of 1000°C. Window in the burn room was cracked at about 4 min and before the fire reached flashover point, the window glass was totally dislodged at about 5 min as a consequence of the spread of harmful fire. The ventilation located in front of the door of the compartment created an air inflow, which forced the smokes to be drawn outwards through the opening, and conducts to a global decrease in the temperature. Nevertheless, by applying the first ventilation, the oxygen drawn inwards by the air flow allows to provide a sufficient amount of oxygen to trigger ignition in the zone where a mixture is fuel rich. This results in another sudden violent rise of the temperature starting from 7 min. This implies that the first ventilation (V1) is not again powerful enough to draw outwards all the smoke produced by the fire. Activating the second air ventilation at t=8 min, as indicated by V2, clearly enhances the capability of the first air inflow, conducting to a sufficient force to carry all the hotter smoke to flow outwards thanks to an external ejected flame, as shown in Fig.8. The flow of combustion gas is discharged to the outside, so the dangers of flashover and fire spread are much better controlled, characterized by a sharp decrease in smoke temperaturte. This results in an insufficient heat feedback to condensed fuel, and as a consequence, stops the gas fuel supply inside compartment.

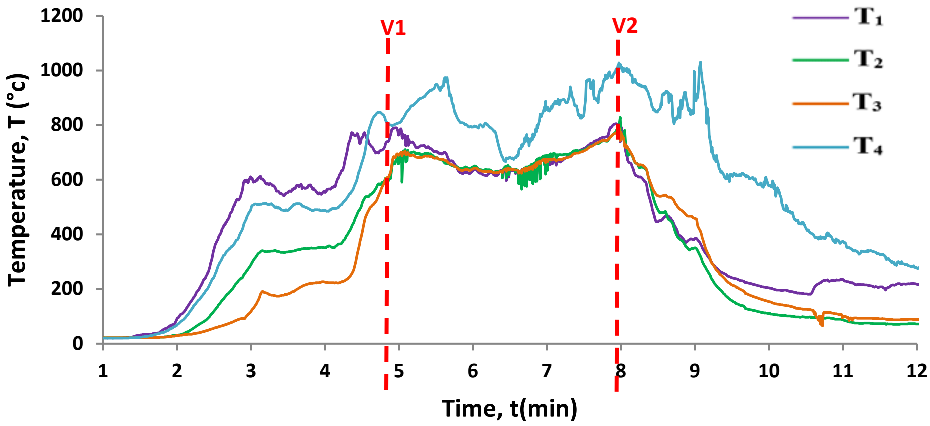


Figure 7. Evolution of the temperature during the test by applying two portable fans

Figure 8. Ejected façade fire from compartment window due to the ventilation

The two moving averages centered at t_{d1}=-15 s and t_{d2}=-30 s under the ceiling close to the door (T_1) which is considered as a strategic location for firefighters, are illustred in Fig.9. The ventilation efficiency on various specific events of the fire in firefighting can be highlighted as follows:

1) During the initial growth phase starting from 2 minutes, $T_{ti\text{-}td2}$ is below $T_{ti\text{-}td1}$, implying an increasing trend of the smoke temperatures.

2) When the difference between $T_{ti\text{-}td2}$ and $T_{ti\text{-}td1}$ tends to zero in the period of 3 – 5 min, the fire is momently stabilized and the temperature reaches a plateau with a level of roughly 550°C.

3) After between crossing at the moment of 4 min, $T_{ti\text{-}td2}$ is below $T_{ti\text{-}td1}$ with a difference of about 20°C between the two moving averages. A sudden drastic increase in temperature signfies the possible appearing of a flashover because occurrence of well-known dangerous event named as the flashover is in the temperature range of 500-600°C.

4) By applying the first ventilation at the moment of 5 min, $T_{ti\text{-}td2}$ surpasses $T_{ti\text{-}td1,}$ implying that the temperatures are going to decrease. Although the temperature remains stable, but a high level of temperature of 600°C conducts again to a dangerous situation.

5) Starting from 7 min, $T_{ti\text{-}td2}$ becomes lower than $T_{ti\text{-}td1}$ in a short period. This event clearly shows that the first ventilation, which was efficient at the beginning, becomes insufficient. This is due to the fact that it brings in fresh air that increases the combustion dynamics without being powerful enough to force all the burnt gas to flow outward.

6) Thanks to use of the second ventilation at the moment of 8 min, $T_{ti\text{-}td2}$ surpasses again $T_{ti\text{-}td1}$ up to the end of the fire. Applying the two ventilations allows to force all the combustion gas outside the compartment, and reduce quickly the temperatures level below 220°C. Such situation is considerd under control and completely secured.

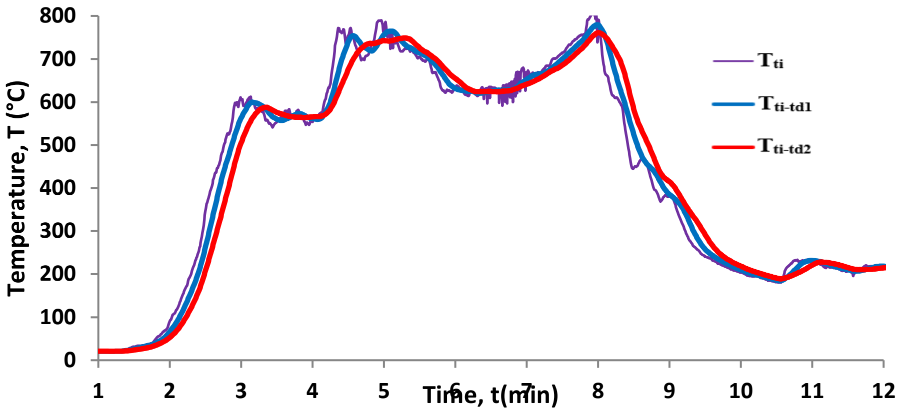


Figure 9. History of temperature inside the burning room and comparison of the two moving averages from the temperature (T_1) recordings under the ceiling

5. Conclusions

Considering the firefighter's need for easy to interpret information for decision-making, the moving average method can provide consistent and reliable results. The model is essentially stochastic, quick and easy to use, and can generate or process the results within a few seconds because the time distance in the past of each moving average is below 30 s. The method has been tested in a representative compartment fire. Bench-scale and large scale tests show similar good results in terms of flashover detection. These findings indicate that when the moving average of a long term ($T_{ti\text{-}td2}$) is always lower than the one of a short term ($T_{ti\text{-}td1}$) in a longer period with a remarkable difference of 20°C between them, a sudden drastic increase in temperature occurs. This signfies the possible appearing of well-known dangerous event named as the flashover which finally, occurs when the smoke temperature is in a range of 500-600°C. On the other hand, use of the comparison of two moving averages is useful to detect potential dangers, and to protect firefighters as a function of the efficiency of the ventilation. The method is flexible and provides strategies based on the safest intervention positions. Therefore, it is argued that the proposed mothod can be used to support timely decisions during actual fire incidents for generating optimal intervention strategy in real-time.

The comparison between two moving averages can be made by the records of the temperatures provided by sensors at strategic locations. While it might be possible that buildings of the future incorporate sensors as thermocouples, it is likely that emergency response systems will have access to temperature for the foreseable future either before the intervention on the fire, i.e. during the construction, or the intervention on the fire. In the first case when sensors have been placed during the construction, the information can be collected and sent in real time to a control centre and/or to the fire department centre, thus the firefighter commander can have information about the fire before going on site. During the intervention on the fire, if there are no sensors placed during the construction, other kinds of sensors can be used. Sensors can be brought either by firemen on the fire suit, or placed on strategic locations. These sensors are able to give their position and to send information outside to a control centre, especially temperatures.

While results of this novel contribution are promising, the proposed method has no automatic prevision over a temperature plateau. It is also possible to get information about temperatures using an infrared camera outside. This camera may be placed on the floor or brought by a drone. This last technique can be combined with the moving average method to have a global view of the situation around the fire. For fast developing fire scenarios, the highest safety needs the most successful system from a combination of heat release rate and temperature. The growth rate of the fire needs to be estimated together with the location of the fire origin, thus giving a more complete characterisation of the fire to produce meaningful forecasts. All these means allow to improve the security and efficiency of the firefighters in their fight against compartment fires, and consequently reduce human and goods losses.

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