GLOBAL FIRE DYNAMICS UNDER ATTEMPTED SUPPRESSION

V. Novozhilov
The Institute for Fire Safety Engineering Research and Technology, Faculty of Engineering
University of Ulster, United Kingdom

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ABSTRACT

Flashover zone model is modified to account for fire suppression effect. Primary interest in the present study is the action of water (sprinkler) spray on surface of burning fuel, and implications of such action for global fire dynamics. The dynamics is considered in terms of critical conditions for flashover. It is demonstrated that in cases where portions of fuel are shielded from sprinklers (partially suppressed fires), flashover is still possible upon achieving critical conditions. Critical conditions are specified upon simple modification of the existing zone model.

1. INTRODUCTION

Consideration of flashover scenario is quite important for Fire Safety Engineering analysis and design. In recent years, there have been a number of papers addressing this phenomenon both experimentally and theoretically [1-7].

Flashover modelling effort has progressed along the two major directions. The first has been Computational Fluid Dynamics (CFD) approach. This has been attempted, for example, by Luo et al. [1-2]. Research along this direction has been limited due to understandable difficulties associated with the field modelling of such a complex fire transition stage.

More simple, but yet promising approach has been the use of zone models. There are several models, based on the principles of non-linear dynamics, available in the literature. Early attempt to interpret flashover as thermal instabilities is due to Thomas [3]. More sophisticated relatively recent models use one, two or three state variables to predict fire development [4-7]. In the most substantial study [6], the critical conditions for flashover are established in the framework of the thermal explosion theory.

The effect of suppression conditions has been included into this model by Novozhilov [10]. In particular, the effect of heat extraction from the smoke layer on flashover critical conditions has been quantified.

The present study extends the work [10] from slightly different perspective. Instead of heat extraction from smoke layer, the focus here is on the solid fuel cooling and decrease of burning rate due to direct action of the suppressant (water spray). This regime of fire suppression is most important for sprinklers which produce significant fractions of large droplets penetrating to the burning surface.

The present paper examines the critical conditions for flashover for the case of partially suppressed fire. Good examples of such situation are storage rack fires. Upon sprinkler activation over racks, there are normally parts of stored burning materials that are shielded from the action of sprinkler spray. Such fires are difficult to extinguish by automatic fire suppression systems, and in certain circumstances they may possibly reach flashover stage.

The model developed below aims to account for the effect of partial suppression. It is shown that not fully suppressed fire may flashover, and the conditions for such a flashover are revealed.

2. MATHEMATICAL MODEL

Graham et al. model

In the subsequent sections, the flashover zone model by Graham et al. [6] is modified for the case of fire suppression.

To facilitate understanding of modification, this model is reviewed very briefly in the present section.

The essence of the model [6] is the heat balance equation:

$$\frac{d\left(mc_pT\right)}{dt} = \dot{G} - \dot{L} \tag{1}$$

for the upper (hot) layer temperature, where $\dot{G}$ describes the rate of heat gain into the smoke layer, and $\dot{L}$ describes the rate of heat loss from the layer.

The terms describing heat gains and losses depend in a complex way on the fire scenario, compartment geometry, flammability and thermal parameters [6].

In short, heat gains are associated with hot fire plume gases filling the smoke layer. These depend on the burning rate, and the burning rate in turn may be augmented by radiative feedback from the smoke layer to the fuel. This positive feedback loop may lead to flashover.

The rate of heat gain for the smoke layer is given by:

$$\dot{G} = \chi \Delta h_c \dot{m}_f ;$$
$$\dot{m}_f = \frac{A_f}{\Delta h_{fg}} \left[\dot{q}'' + \alpha_U (T) \sigma \left(T^4 - T_0^4 \right) \right] \quad (2)$$

Heat losses from the smoke layer result from mass flow through the opening, radiative losses and conduction through the walls of compartment.

The rate of heat loss from the layer is assumed in [6] in the form:

$$\dot{L} = \dot{m}_{out} c_p (T - T_0)(1 - D) + [A_U - (1 - D) A_V] h_c (T - T_w) +$$
$$(1 - D) A_V h_v (T - T_0) + \alpha_g \sigma [A_U - (1 - D) A_V] (T^4 - T_w^4) +$$
$$\alpha_g \sigma [A_L + (1 - D) A_V - A_f] (T^4 - T_0^4) + \alpha_g \sigma A_f (T^4 - T_f^4) \quad (3)$$

The right-hand side of equation (3) contains six terms, namely

- enthalpy flow out of the vent;
- convective heat loss to walls surrounding the hot layer;
- convective heat loss through the vent;
- radiative heat loss from hot layer to walls;
- radiative heat loss to cold layer and vent;
- radiative heat loss to fuel

The total mass flow rate from the opening is given by:

$$\dot{m}_{out} = \frac{2}{3} c_d \rho_0 A_V \sqrt{2g(1 - D) H_V \frac{T_0}{T} \left(1 - \frac{T_0}{T} \right)} \quad (4)$$

By grouping relevant terms, it has been demonstrated in [6] that the heat balance equation is transformable in the following manner:

$$\frac{d\theta}{d\tau} = 1 + \left(\varepsilon_k - \varepsilon_{R,L} \right) \left(\theta^4 - 1 \right) - \varepsilon_{C,H} \left(\theta - \theta_w \right) - \varepsilon_{out} \left(\theta - 1 \right)$$
$$- \varepsilon_{C,L} (\theta - 1) - \varepsilon_{R,W} \left(\theta^4 - \theta_W^{\ 4} \right) - \varepsilon_{R,f} \left(\theta^4 - \theta_f^4 \right) \quad (5)$$

with the initial condition:

$$\theta(0) = \theta_i$$

Here, ε_{out} is dimensionless scale for enthalpy flow from the vent; coefficients $\varepsilon_{R,j}$ (j = W,L,f) describe radiative losses to walls, lower cold zone and to fire bed, respectively. The coefficients $\varepsilon_{C,k}$ (k = H,L) describe convective losses from the hot layer to the wall surfaces and the vent surface. The exact formulas for the coefficients are given in [6] and not repeated here.

Equation (5) is written for non-dimensional temperature $\theta = T / T_0$ (θ_i is its initial value). In order to non-dimensionalize the equation, the characteristic time $t_* = mc_p T_0 / \dot{Q}_0$ and characteristic heat flux per unit time $\dot{Q}_0 = \chi A_f \dot{q}'' \frac{\Delta H_c}{\Delta H_{fg}}$ have also been introduced.

Temperature of the upper part of enclosure is approximated in [6] by:

$$\theta_w = 1 + \beta (\theta - 1); \; 0 \leq \beta \leq 1 \quad (6)$$

where β measures thermal inertia of a wall.

Upon assumption (6), it is evident that equation (5) can be finally simplified to:

$$\frac{d\theta}{d\tau} = 1 + a_1 \left(\theta^4 - 1 \right) - a_2 (\theta - 1) + a_3 \theta^3 + a_4 \theta^2 \quad (7)$$

The coefficients a_i can be expressed through the coefficients $\varepsilon_{i,j}$ in equation (5) (the details again can be found in [6]).

Equation (7) serves as a basis for implementation of the Semenov's diagram of the thermal explosion (Fig. 1). The thermal explosion theory allows the critical conditions for flashover to be established [6,7,10].

Novozhilov [10] has earlier modified this model for consideration of sprinklers and water mist systems. For the case with water spray influence on the smoke layer, the results [10] are illustrated in Fig. 2. The fire with parameters in flashover region can be transformed into low-intensity, quasi-steady fire upon sufficient extraction of heat from the smoke layer. The point on the plane of governing parameters moves towards critical boundary and crosses it upon increase in the water application rate.

The difference between the work [10] and the present derivation is that only the influence of fire suppression system on hot smoke layer was considered in [10]. In contrast, the focus of the present model is on action of water spray on the solid fuel. In particular, decrease of the burning rate, which occurs due to suppression, is quantified and incorporated into the existing zone model.

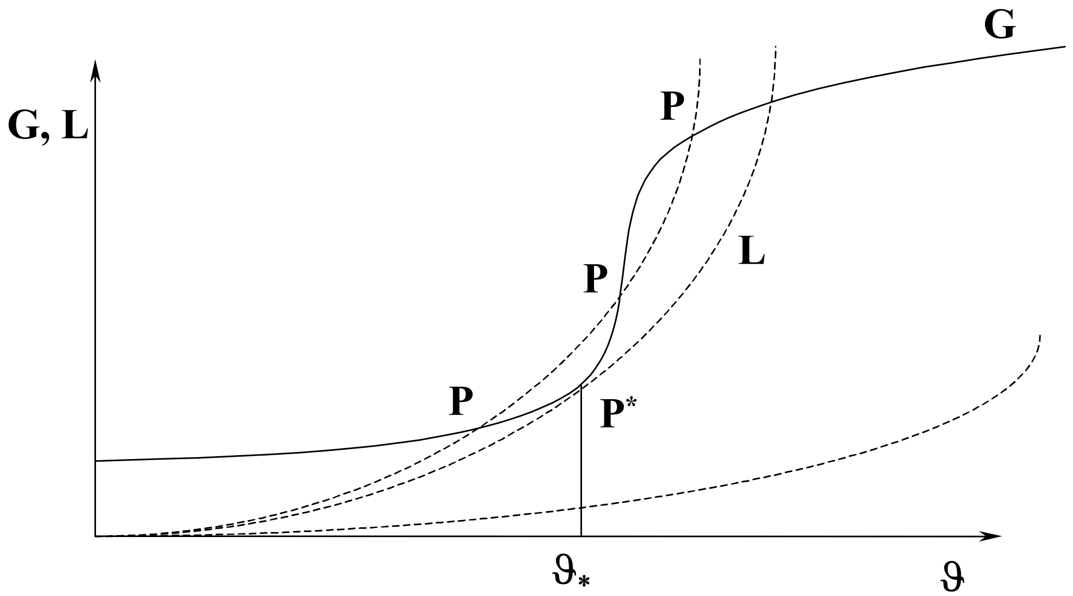


Fig. 1: Semenov's diagram for thermal explosion or flashover

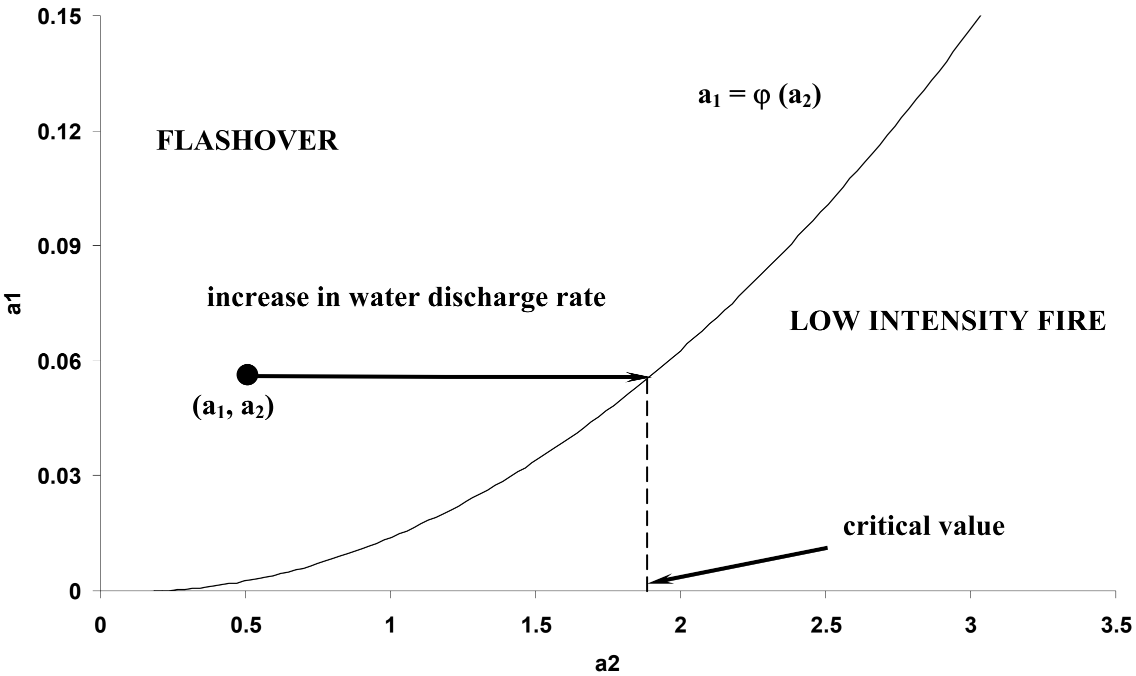
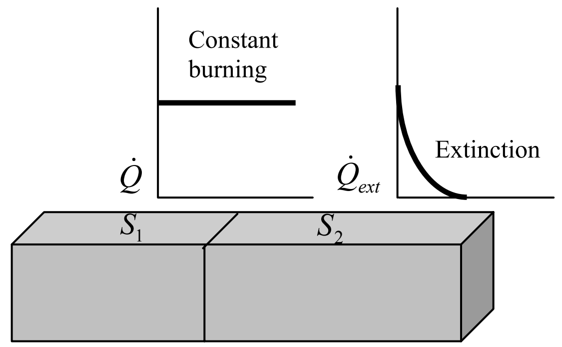


Fig. 2: Effect of heat extraction from smoke layer on critical conditions for flashover [10]

Global suppression model

In order to modify the model [6] for the case of spray influence on the fuel, let us assume that fire is partially suppressed. This general situation is illustrated schematically in Fig. 3 where S_1 is burning area free from the action of spray (constant burning rate), and S_2 is burning area subjected to the action of spray (Heat Release Rate (HRR) decreasing with time). The ratio between the two areas is given by parameter ς which can take any value between zero and one.

The expression is needed to describe the HRR on the suppressed part of the fuel, S_2 in Fig. 3.



$$0 < \zeta = S_2 / (S_1 + S_2) < 1$$

Fig. 3: Difference in burning rate histories between shielded and unshielded portions of fuel. Quasi-steady burning rate is assumed on the shielded portion of fuel, and exponential decay in burning rate on the unshielded.

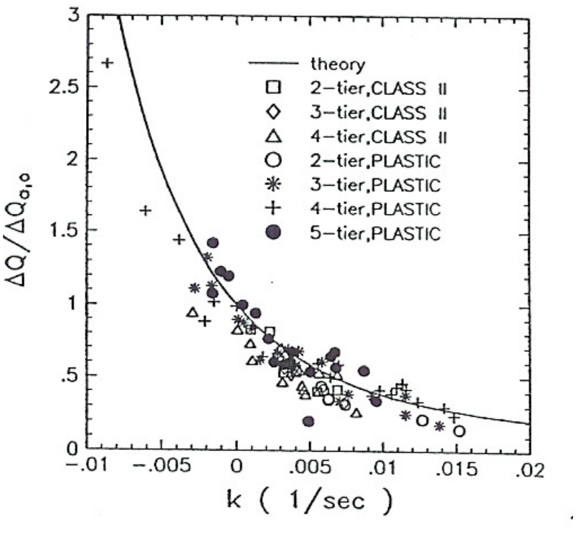


Fig. 4: Test data by Yu et al. [9] and its correlation with the fire suppression parameter *k* ("extinction constant")

Existing data on suppression [8,9] suggest that the HRR of fire drops exponentially for realistic burning objects subjected to action of sprinkler sprays. This is illustrated in Fig. 4 for various commodities. The simple theory has also been put forward to explain the exponential decay.

This model by Yu et al. [9] has the form:

$$Q_a(t) = \Delta\dot{Q}_{a0} \frac{(1 - exp[-k(t - t_0)])}{k(t - t_0)} \tag{8}$$

where $Q_a(t)$ is the cumulative total heat release in a time period starting from water application t_0, $\Delta\dot{Q}_{a0}$ is a reference cumulative heat release in a time period assuming the fire stopped growing at the start of water application.

The fire suppression parameter k ("extinction constant"), having units of inverse time, is a function of material thermal and flammability properties, burning rate per unit burning surface area and water application density [9].

Starting from equation (8), one can easily derive its equivalent form in terms of instant HRR:

$$\dot{Q}(t) = \dot{Q}(t_0) exp[-k(t - t_0)] \tag{9}$$

which is more convenient for application in the zone model.

Modification of the Graham et al. model

In order to modify the model, the heat gain term is written as follows:

$$\dot{G} = \chi \Delta H_c (1 - \zeta) \dot{m}_f + G(0) \zeta \, exp[-kt] \tag{10}$$

where

$$\dot{m}_f = \frac{A_f}{\Delta H_{fg}} \left[\dot{q}'' + \alpha_U(T) \sigma (T^4 - T_0^4) \right] \tag{11}$$

$$G(0) = \frac{\chi \Delta H_C A_f}{\Delta H_{fg}} \left[\dot{q}'' + \alpha_U(T) \sigma (T_i^4 - T_0^4) \right] \tag{12}$$

In line with Fig. 3, the first term on the right-hand side of equation (10) describes the heat release rate of unsuppressed fuel, and the second term describes the HRR for the fraction of fuel being suppressed.

According to the described phenomenological suppression model, the second term drops exponentially from its initial value $G(0)$. It is assumed that there is no influence of radiative feedback on burning rate under extinguishment. For this reason, the radiation part of feedback in equation (12) is evaluated at initial temperature. This initial temperature for the considered scenario can be estimated as typical sprinkler activation temperature.

Bearing in mind that equation (5) is the result of non-dimensionalizing equations (1) to (3) for $\zeta = 0$, it is easy to see that for the general case $0 < \zeta < 1$, the result would be:

$$\frac{d\theta}{d\tau} = 1 + (1-\zeta)\varepsilon_k\left(\theta^4 - 1\right) + \zeta\varepsilon_k\left(\theta_i^4 - 1\right)exp[-kt]$$
$$-\varepsilon_{R,L}\left(\theta^4 - 1\right) - \varepsilon_{C,H}(\theta - \theta_w) - \varepsilon_{out}(\theta - 1) - \varepsilon_{C,L}(\theta - 1)$$
$$-\varepsilon_{R,W}\left(\theta^4 - \theta_W{}^4\right) - \varepsilon_{R,f}\left(\theta^4 - \theta_f^4\right) \qquad (13)$$
$$\theta(0) = \theta_i$$

3. ANALYSIS OF THE MODEL

Further, in line with equations (6) and (7), temperature evolution can be analysed upon rewriting equation (13) in a more convenient form:

$$\frac{d\theta}{d\tau} = 1 + A_1\left(\theta^4 - 1\right) - a_2(\theta - 1) + a_3\theta^3 + a_4\theta^2 +$$
$$\zeta\varepsilon_K\left(\theta_i^4 - 1\right)exp\left(-k\frac{mc_pT_0}{\dot{Q}_0}\tau\right) \qquad (14)$$

where

$$A_1 = \left[(1-\zeta)\varepsilon_K - \varepsilon_{R,L} - \varepsilon_{R,f} - \left(1-\beta^4\right)\varepsilon_{R,W}\right]/a_0$$

or

$$A_1 = a_1 - \zeta\frac{\varepsilon_K}{a_0} \qquad (15)$$

and a_1 is the "original" coefficient (in the absence of suppression, $\zeta = 0$), defined in the model [6].

For walls with large thermal inertia $a_3 = a_4 = 0$ [6]:

$$\frac{d\theta}{d\tau} = 1 + A_1\left(\theta^4 - 1\right) - a_2(\theta - 1) +$$
$$\zeta\varepsilon_K\left(\theta_i^4 - 1\right)exp\left(-k\frac{mc_pT_0}{\dot{Q}_0}\tau\right) \qquad (16)$$
$$\theta(0) = \theta_i$$

The exponential term may make significant contribution to equation (16) only for $\tau < \approx \frac{1}{k \cdot t_*}$. It can be easily estimated that those values of τ normally cover probable flashover times.

For example, for typical value of extinction constant $k \approx 0.01$ (Fig. 4) and example of small compartment (0.4 m x 0.4 m x 0.4 m), considered in [6], the contribution is important as long as $\tau < \approx 10^2$. For comparison, typical flashover times (Fig. 7 in [6]) are of the order $\tau \approx 2-8$. Same conclusion can be easily reached for large-scale compartments.

Therefore, the influence of the exponential ("extinction") term in equation (16) need to be taken into account.

However, the real influence of this term depends on the compartment temperature at the start of suppression (initial condition for equation (16)).

Sprinkler activation temperatures are normally low compared to flashover compartment temperatures. This implies that in the case of sprinkler activation, the third term would be small compared to the first two terms in equation (16). The reason is that it contains fixed initial (sprinkler activation) temperature. Therefore, the ratio between the first (or second) and third terms quickly rises with the rise of smoke temperature θ.

In such a case, critical conditions can be easily found by modifying the results [6]. The latter specify the critical conditions in the form of the curve $a_1 = \varphi(a_2)$ (Fig. 2). Considering modification of the coefficient a_1 following from equation (15), the critical condition for the case of partial suppression can be written in the general form:

$$a_1 = \varsigma\frac{\varepsilon_K}{a_0} + \varphi(a_2) \qquad (17)$$

The meaning of the formula (17) is straightforward: the larger is area undergoing suppression (i.e. larger ς, Fig. 3), the higher rate of heat gains (described by coefficient a_1) is required to achieve flashover.

The situation is illustrated in Fig. 5. This reproduces the calculations of the example given in [6] for the small compartment (0.4 m x 0.4 m x 0.4 m). The curves 1,3,5 and 7 are identical to the work [6]. They correspond to the same value $a_1 = 0.01$ and different values of a_2. The critical value of the coefficient a_2 was found in [6] to be $a_2 = 0.89$. For higher rates of heat losses the temperature does not experience flashover rise (for example, curve 7).

The curves 2,4 and 6 are computed for the present suppression model with $\varsigma = 0.5$ (half of the fuel area being suppressed).

It is seen that partial suppression of fire delays the development of flashover (curve 2 compared to curve 1; curve 4 compared to curve 3). Moreover, it is easy to see that the critical conditions are also affected. For the original model the temperature reaches quasi-steady value (low-intensity fire) at $a_2 = 0.89$. However, in the presence of suppression, the temperature profile levels out already at $a_2 = 0.8$ (curve 6). In contrast, the original model shows flashover behaviour at such value, curve 5.

The change in critical conditions is fully described by the formula (17). Influence of the exponential term for the considered example is below 1%.

Influence of sprinkler activation time (and exponential term in equation (16)) becomes more apparent with the rise of sprinkler activation temperature. This is illustrated in Fig. 6. Since activation time is determined by the sprinkler temperature rating and smoke temperature history, such influence is fully described in the present model by the variation of the sprinkler activation temperature, θ_i. Fig. 6 presents temperature curves for the sprinkler temperature ratings in the range $69-237C$. Note that before sprinkler activation, the evolution of smoke layer temperature is described by equation (16) with the suppression effects absent: $A_1 = a_1; \varsigma = 0$. As seen from Fig. 6, even for high temperature ratings, the influence on flashover induction times is small. The reason for this has already been mentioned: activation temperature is much lower than typical flashover critical temperature (i.e. characteristic temperature at which thermal instability occurs). Therefore, evolution of the system essentially shapes up at much later times than the sprinkler activation time.

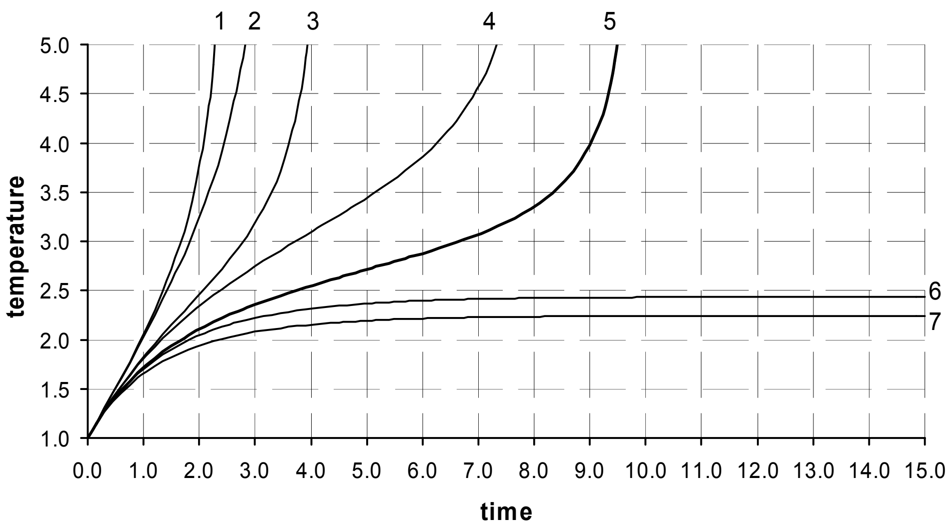


Fig. 5: Temperature histories for original model without suppression [6] and the present model. Fire compartment conditions correspond to example considered in [6].

Non-dimensional sprinkler activation temperature 1.14 (69 C)

1 – original model (no suppression), $a_1 = 0.01$, $a_2 = 0.0$

2 – present model (suppression), $a_1 = 0.01$, $a_2 = 0.0$, $\varsigma = 0.5$

3 – original model (no suppression), $a_1 = 0.01$, $a_2 = 0.5$

4 – present model (suppression), $a_1 = 0.01$, $a_2 = 0.5$, $\varsigma = 0.5$

5 – original model (no suppression), $a_1 = 0.01$, $a_2 = 0.8$

6 – present model (suppression), $a_1 = 0.01$, $a_2 = 0.8$, $\varsigma = 0.5$

7 – original model (no suppression), $a_1 = 0.01$, $a_2 = 1.0$

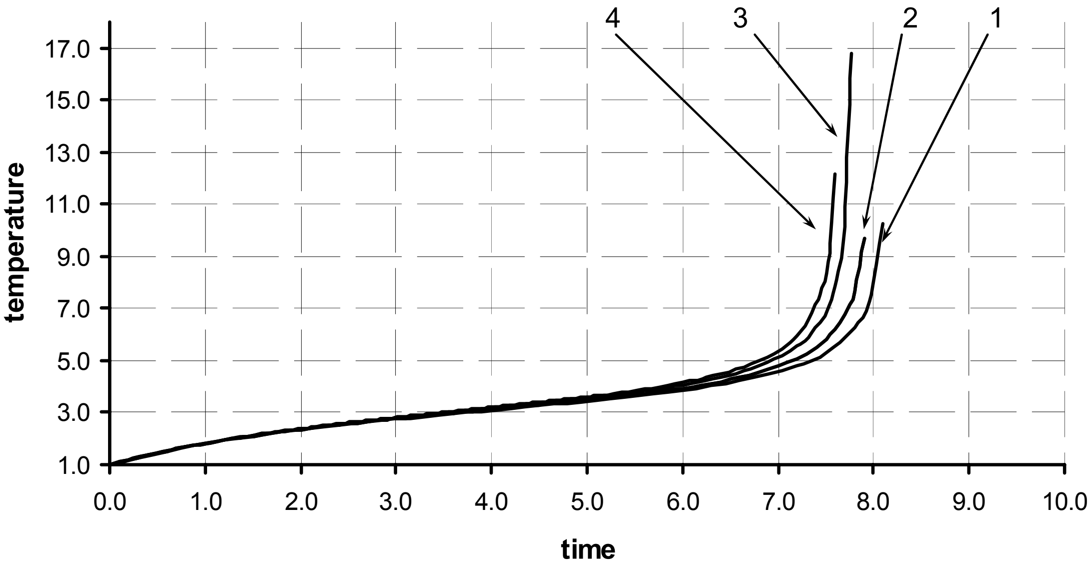


Fig. 6: Influence of sprinkler activation temperature on flashover induction period

$a_1 = 0.01$; $a_2 = 0.5$; $\varsigma = 0.5$

1 – non-dimensional activation temperature 1.14 (69 C)
2 – non-dimensional activation temperature 1.4 (147 C)
3 – non-dimensional activation temperature 1.6 (207 C)
4 – non-dimensional activation temperature 1.7 (237 C)

With the small influence of activation time, fraction of total burning area subjected to suppression (i.e. parameter ς) is a dominant factor.

It should be noted, however, that the exponential term will be quite important if extinguishment process starts at sufficiently high compartment temperature, that is at quite late stages of fire. This may be, for example, a result of fire brigade intervention, or manual operation of fixed extinguishment system. If this is the case, equation (16) can be easily integrated numerically in order to establish critical conditions for flashover.

4. CONCLUSIONS

The temperature history equation, resulting from the zone model [6], has been modified to account for the effect of partially suppressed fire.

The derivation of the modified equation is based on transformations of existing phenomenological data extracted from suppression tests involving large variety of commodities.

Analysis of the equation reveals that upon early attempted suppression, the critical conditions separating flashover and low-intensity fire are determined by unsuppressed area of combustibles. The modified critical conditions have been obtained in the form of equation (17).

On the other hand, if suppression attempt is delayed until later stages of fire development, the details of extinction process on suppressed part of the fuel become important. In this case, the derived equation may be integrated numerically to obtain compartment temperature history for specific suppression conditions. This would then lead to conclusion on possibility of flashover in a given scenario.

NOMENCLATURE

A	surface area
c_d	vent discharge coefficient
c_p	specific heat
g	gravity acceleration
$\dot{G}$	rate of heat accumulation in the smoke layer
D	fractional height of the thermal discontinuity plane
h	convective heat transfer coefficient
H	height
ΔH_c	heat of combustion
ΔH_{fg}	heat of gasification
k	extinction constant
$\dot{L}$	rate of heat losses from the smoke layer
m	mass of smoke layer
$\dot{m}_f$	fire burning rate
$\dot{q}''$	flame feedback to fuel surface
Q_a	cumulative heat release of fire
$\dot{Q}_0$	heat release rate of fire

t time
T temperature

Greek Symbols

α emissivity
β measure of thermal inertia of walls
ε_i, $\varepsilon_{i,j}$ dimensionless heat transfer parameters
χ combustion efficiency
ς fraction of total burning area subjected to suppression
θ non-dimensional temperature
ρ density
σ Stefan-Boltzman constant
τ non-dimensional time

Subscripts

0 ambient
c convective
g gas/smoke
f fuel
i Initial
L low layer
U upper ayer
V vent
W wall

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