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A Model of Fire Growth Intended for Commanders of Rescue and Firefighting Operations

Abstract

The article presented is the first of a series of publications showing the results of studies on the design of model description of development and extinguishing of internal fire. An analytical model of fire growth for a single room with vents is presented. Using the model it is possible to calculate such variable parameters of fire environment as the height of the flame, the temperature of the gas in the hot room, the position of the upper layer above the floor level, visibility range in the smoke and others. In addition, the model allows to determine the appearance times of symptoms of non-linear fire effects (e.g. flashover), with the onset of these effects, as well as the duration of the various fire phases. The developed model of fire growth, can be ultimately implemented in the form of a computer program working in real time, which is currently under preparation. The proposed fire development model can be used either to train the rescue and fire commanders on the simulator or to apply on portable computers during real firefighting operation, after developing appropriate computer program.

Keywords: fire model, internal fire, firefighting operation, zone fire model

Model rozwoju pożaru przeznaczony dla dowódców akcji ratowniczo-gaśniczych

Abstrakt

Artykuł jest pierwszym z cyklu publikacji przedstawiających wyniki badań, dotyczących konstrukcji modeli opisu rozwoju i gaszenia pożaru wewnętrznego. W pracy zaprezentowano analityczny model rozwoju pożaru dla pojedynczego pomieszczenia z otworami wentylacyjnymi. Za pomocą modelu możliwe jest obliczanie zmiennych w czasie parametrów stanu pożaru, takich jak m.in. wysokość płomienia, temperatura gazu w warstwie gorącej w pomieszczeniu, położenie górnej warstwy nad poziomem podłogi, zasięg widzialności w dymie. Ponadto model umożliwia określenie czasów pojawienia się symptomów nieliniowych efektów pożaru (np. rozgorzenia), wraz z początkiem tych efektów, a także czasu trwania poszczególnych faz pożaru. Opracowany model rozwoju pożaru może być docelowo zaimplementowany w postaci programu komputerowego pracującego w czasie rzeczywistym, który obecnie jest w przygotowaniu.

Proponowany model rozwoju pożaru przeznaczony jest do szkolenia dowódców akcji ratowniczo-gaśniczych na symulatorze, jak i do zastosowania bezpośrednio podczas działań w warunkach rzeczywistych, po opracowaniu odpowiedniego programu komputerowego.

Słowa kluczowe: model pożaru, pożar wewnętrzny, działania ratowniczo-gaśnicze, strefowy model pożaru

1. Introduction

The description of internal fire development using the laws of physics and mathematical modelling methods has been known for a long time [1, 2]. Particular interest in the fire modelling has been observed in the last 20 years, when about half of the scientific publications in the field of fire safety engineering are devoted to fire simulations [3, 4]. The main interest of researchers is related to supporting the design of fire-safe buildings, evacuation, research into the causes of fires or new extinguishing technologies [5, 6]. In recent years, some of the fire models have been used in simulators, but their use is very limited [7, 8]. There are no models directly supporting commanders during the rescue and firefighting operations. Such models, in the form of computer programs, with different levels of complexity, would be useful for risk assessment, e.g. nonlinear effects of fire, such as flashover and backdraft, as well as enable the study of the impact of extinguishing activities on the nfire growth and firefighting efficiency. This publication includes a zone fire model for a single room. In subsequent publications, it is planned to extend it to include multi-room models and to extinguish a fire.

2. Main assumptions of internal fire model in the compartment

In internal compartments, regardless of the type of building, a zone fire model was adopted consisting of modules previously validated by various researchers with the following assumptions:

a) flame combustion takes place anywhere in the room, and the parameter describing the flame is its height and the area of the fire (projection of combustion zone on the horizontal surface),
b) heat release rate (fire power) is a square function of its development time,
c) axisymmetric fire convection column including in the patterns describing its size related to the change of its position,
d) circular model of fire propagation with constant average speed was assumed,
e) the minimum rate of heat release needed for the flashover phenomenon, depends on the ventilation conditions prevailing in the given room and the surface of the internal walls,
f) the minimum temperature for the start of flashover is defined as T_{FO},
g) the fire curve T = T(t) is consistent with the classic fire phase representation,
h) the average temperature of the upper layer T_g is calculated from the thermal balance of this layer, ignoring the heat losses caused by radiation to the walls and floor,
i) determination of the position of the upper layer of smoke above the level of the floor in a room with a large ventilation opening (door, large window) is possible until the upper edge of the hole is reached by it,
j) the range of visibility ZW is directly related to the concentration of soot.

3. Modules intended for calculating fire parameters

3.1. Fire parameters

The area covered by the fire (fire environment) is quantified by the following parameters:

a) heat release rate $\dot{Q}$ (fire power) [kW]
b) flame height H_f [m]
c) area of combustion zone A_c [m^2]

d) heat release rates in individual fire phases and their duration (including time for flashover)
e) average temperature of the upper layer T_g [°C]
f) position of the upper layer above the floor level Z [m]
g) mean concentration of the i-th combustion product in the room (single-zone model) x_i [kg/kg]
h) average oxygen concentration in the room (backdraft condition) x_{O2} [kg/kg]
i) visibility range in smoke ZW [m].

3.2. Heat release ratio (power of fire)

The heat release rate can be described as a quadratic function of its duration with the dependence:

$$\dot{Q} = \alpha \cdot (t - t_i)^2 \tag{1}$$

where:
α – fire growth coefficient [kW/s^2],
t_i – incubation time (time from the moment of ignition to the appearance of flame combustion with sufficiently high emission of energy) [s],
t – duration of fire [s].

In fact, the values of α for most materials/products and material systems are in the range from 0.001 to 0.2 kW/s^2. Table 1 shows four values of the coefficient assigned to fires of different development speed. The average fire risk in a hotel room is 0.012 kW/s^2. Using small flame sources of fire (matches, lighter) experimental studies indicate incubation times for:
a) wooden cabinets: 30 s – 50 s,
b) mattresses: 60 s – 120 s,
c) upholstered chairs: 60 s – 100 s,
d) carpets: 90 s – 100 s [13].

In the following subchapters, calculation formulas of the model are given, allowing to determine the values of selected fire parameters during the action. Some of the dependencies also include characteristic parameter values enabling calculation for a wide range of materials and combustion conditions.

Table 1. The rate of fire development described by the fire development coefficient *α* consistent with the classification according to NFPA 204M [9]

The rate of fire development	Example of combustible material	Value of coefficient α kW/s^2
Slow	Well-packed paper materials	**0,003**
Medium	Traditional furniture	**0,012**
Fast	Mattresses made of polyurethane	**0,047**
Very Fast	High storage warehouse	**0,19**

3.3. Flame height

To determine the average flame height, the Cox experimental pattern for the luminous flame was used [10]:

$$H_f = 0{,}2 \cdot (k \cdot \dot{Q})^{0{,}4} \tag{2}$$

The coefficient k is specified for the combustion zone located far from the walls of the room (k = 1), next to the wall (k = 2) and in the corner (k = 4). $\dot{Q}$ should be inserted in kW. The radius describing the bending of the flame under the ceiling r_f (Figure 1) can be approximated by the following formula proposed for the first time by Heskestad and Hamada [11]:

$$r_f = 0{,}95 \cdot (H_f - H) \tag{3}$$

where:
H – room height [m].

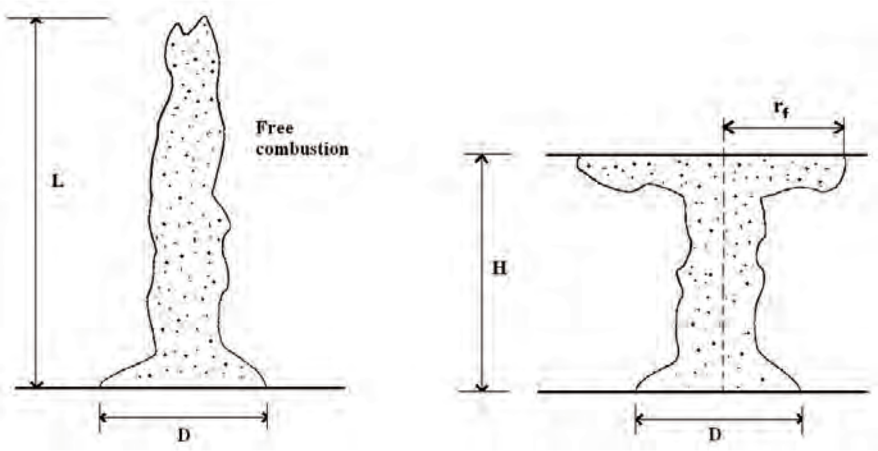

Fig. 1. Spread of flames under the ceiling [11]

3.4. Surface of combustion zone

Assuming the development of a fire surface with circular geometry, the surface of the combustion zone A_c can be determined from the following relationship:

$$A_c = \pi \cdot v_p^2 \cdot (t - t_i)^2 \tag{4}$$

where:
v_p – average speed of flame spread [m/s]

The ranges of average flame spread speed are given in Table 2.

Table 2. Average ranges of flame spread [12]

Type of building, combustible material	Average range of flame spread speed cm/s*
Residential buildings, hotels	0,8–1,3
Hospitals	1,0–5,0
Polyurethane foam	1,2–1,5

* flame spread speed in the first phase of the fire is assumed to be equal to the value taken from table 2, reduced by half, i.e. 0,5 v_p.

3.5. Heat release rates in individual fire phases and their duration

Fig. 2 shows a schematic diagram of the heat release rates in individual fire phases and their duration.

1. Heat release rate for flashover

To calculate the heat release rate for flashover $\dot{Q}_{FO}$, the well-known correlation expression from the Thomas' experimental studies was used [13]:

$$\dot{Q}_{FO} = 7{,}8 \cdot A_T + 378 \cdot A_0 \cdot H_0^{1/2} \text{ [kW]} \tag{5}$$

where:

A_T – total internal surface of the room, minus the area of the ventilation opening [m²],

A_0 – area of the ventilation opening [m²],

H_0 – height of the ventilation opening [m].

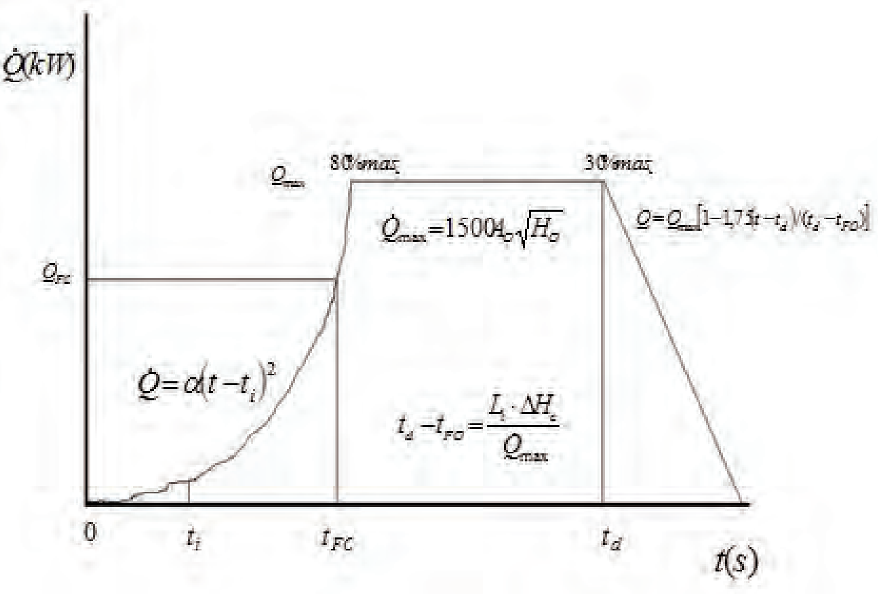

Fig. 2. Heat release ratio during fire in the compartment and duration of fire phases [14]

2. Time to flashover

Time to flashover $\boldsymbol{t_{FO}}$ can be directly calculated from the following formula (1):

$$t_{FO} = t_i + \sqrt{\frac{\dot{Q}_{FO}}{\alpha}} \quad [\mathrm{s}] \tag{6}$$

3. Maximum power released inside the room

The maximum power released inside a fire room can be determined from the following correlation relationship proposed by Huggett [15]:

$$\dot{Q}_{max} = \dot{m}_{max} \cdot 3000\ kJ/kg = 0{,}5 \cdot A_0 \cdot \sqrt{H_0} \cdot 3000\ kJ/kg = 1500 \cdot A_0 \cdot \sqrt{H_0} \quad [\mathrm{kW}] \tag{7}$$

where:

$\dot{m}_{max}$ – maximum air mass flow into the room [kg/s]

4. Duration of the developed phase of the fire

The duration of the developed fire phase $\boldsymbol{t_b}$ can be estimated approximately by the following relationship [14]:

$$t_b = t_d - t_{FO} = \frac{L_t \cdot \Delta H_c}{\dot{Q}_{max}} \quad [\mathrm{s}] \tag{8}$$

hence:

$$t_d = t_{FO} + \frac{L_t \cdot \Delta H_c}{\dot{Q}_{max}} \quad [\mathrm{s}] \tag{9}$$

where:

L_t – mass of materials in the room being incinerated in the phase of developed fire

– ½ of the mass of materials stored in the room [kg],

ΔH_c – combustion heat [kJ/kg].

Considering the average density of the fire load Q_d (e.g. according to the standard PD7974-6:2004 for hotels equal to 310 MJ/m^2) the total mass of combustible materials (without knowing it directly) can be determined from the following relationship [14]:

$$\mathrm{M} = 2L_t = \frac{Q_d \cdot S_p}{\Delta H_c} \tag{10}$$

where:

S_p – total surface of the room [m2]

5. Total duration of fire

The total time t_c is obtained as the sum of the time for flashover, the duration of the expanded phase and the fire reduction time, calculated from the relationship describing the linearly decreasing heat release rate for the condition $\dot{Q} = 0$ (Fig. 2), i.e.:

$$t_c = t_d + t \tag{11}$$

where: $t = 1{,}57t_d - 0{,}57t_{FO}$ or $t = 1{,}57t_b + t_{FO}$ (12)

3.6. The average temperature of the upper layer

The presented module is the original, obtained for variable heat release rate depending on the time squared, the proportionality resulting from McCaffrey's and other $T_g \sim Q^{2/3}$ [16]. The following exponential relationship was obtained for the temperature of the upper layer:

a) for $t \leq t_i$ and $T_g = 20°C$
b) for $t > t_i$ and the mean temperature of the upper layer – T_g is determined by the scaling procedure with the following relationship:

$$T_g = \xi \cdot \alpha^{2/3} \cdot (t - t_i) + 20 \tag{13}$$

where:

ξ – a constant calibrated for the flashover conditions in the convection column, which can be determined from the following relationship (usually in practice it is assumed that TFO = 600°C):

$$\xi = \frac{T_{FO} - 20}{\alpha^{2/3} \cdot t_{FO}^{4/3}} \tag{14}$$

3.7. Height of the upper layer above the floor level

Fig. 3 shows the position of the upper smoke layer and other characteristic parameters associated with the fire.

The value of the parameter Z is determined using the following relationship resulting from the Yamana-Tanaka model [17]:

$$Z = \left[\frac{0,20}{\rho_g} \cdot \left(\frac{\rho_\infty^2 \cdot g}{c_p \cdot T_\infty} \right) \cdot \frac{\alpha^{1/3}}{S} \cdot \frac{2(t - t_i)^{5/3}}{5} + \frac{1}{H^{2/3}} \right]^{-3/2} \tag{15}$$

where:

S – area of the room filled with smoke [m^2],

ρ_g – average air density in the upper smoky layer [kg/m^3],

ρ_∞ – average air density in the lower cool layer [kg/m^3],

T_∞ – average air temperature in the lower cool layer [kg/m^3].

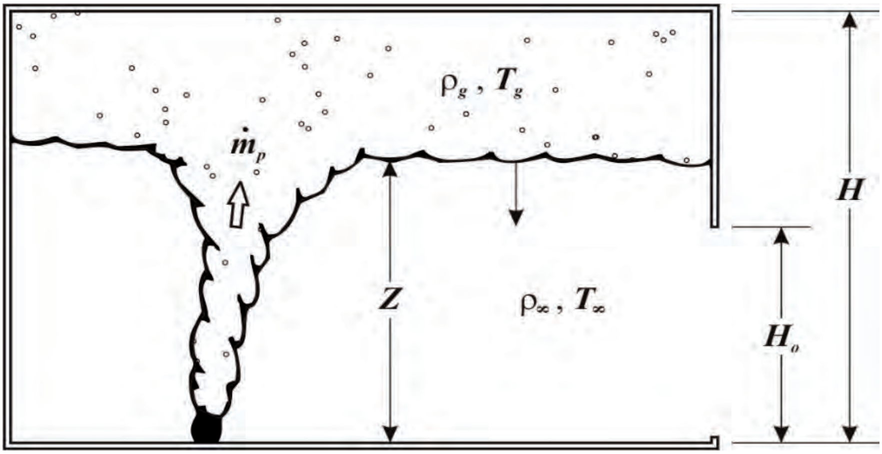

Fig. 3. Location of the smoke layer above the floor level Z, specified for $H_o \geq Z$ [17]

3.8. Average concentration of the i-th combustion product and oxygen in the room

The concentration of any combustion product in a closed room, assuming good mixing of gases, can be determined directly from the mass storage equation for a given product in the form [12]:

$$x_i = \frac{\beta \cdot \alpha \cdot Y_i}{V_p \cdot \rho_g \cdot \Delta H_c} \cdot \frac{1}{3} \cdot (t - t_i)^3 \tag{17}$$

where:
β – combustion efficiency factor [–],
Y_i – emission of the i-th combustion product [kg/kg],
V_p – room volume [m^3].

The concentration of the i-th product in the upper layer in the room with the vent

In case of a room with opening through which smoke flows, being in a two-zone system inside the room, the concentration of the combustion product in the upper layer can be described by the following dependence [12]:

$$Z = \frac{\beta \cdot \dot{m}_s \cdot Y_i}{\dot{m}_1} \cdot \left(1 - e^{-\frac{\dot{m}_1}{V_p \cdot \rho_g} \cdot (t - t_i)}\right) \quad (18)$$

where:
$\dot{m}_s$ – mass burning rate of the material [kg/s],
$\dot{m}_1$ – mass stream of gases (smoke) flowing through the vent from the room [kg/s].

Average concentration of oxygen in the room

The concentration of oxygen in a closed room or with leaks, assuming good mixing of gases, can be obtained directly from the mass preservation equation for this atmosphere component, which takes a direct part in combustion reactions [12]:

$$x_{O_2} = 0{,}23 - \frac{\beta \cdot Y_{O_2} \frac{\alpha}{\Delta H_c}}{V_p \cdot \rho_g} \cdot \frac{1}{3} \cdot (t - t_i)^3 \quad (19)$$

where:
Y_{O2} – oxygen consumption factor [kg/kg]

In case of a decrease in the concentration of oxygen flowing into the combustion zone, the heat release rate $\dot{Q}$ decreases, according to the following relationship [18]:

$$\dot{Q}(x_{O_2}) = \dot{Q} \cdot \frac{tanh[800 \cdot (x_{O_2} - x_{LOL}) - 400] + 1}{2} \quad (20)$$

The above formula determines the dependence of the rate of heat release from the oxygen flowing into the combustion zone, in case of a significant decrease in the oxygen concentration (below the value of the so-called lower oxygen concentration x_{LOL} usually taken as 0.12). The value taken as a constant means the rate of heat release above the lower oxygen concentration. Identification of the achievement of the state of the system characterized by the lower oxygen concentration, signals the potential for the generation of large amounts of flammable thermal decomposition products and combustion in the room. Thus, it signals the emergence of the explosion hazard of the fire gases or the backdraft effect.

3.9. Visibility range in smoke

The range of visibility in smoke is calculated from the equation for smoke generated during the flame combustion of solid polymers [19, 20]:

$$\mathrm{ZW} = \frac{0{,}000375}{x_s} \tag{21}$$

where:
x_s – smoke particle concentration (mass fraction) [–]

The reduction of the visibility range in the corridor adjacent to the room with the fire source can be calculated from the following relationship:

$$ZW_k = \frac{0{,}000375 \cdot V_k \cdot \rho_g}{\dot{m}_d \cdot t} \tag{22}$$

where:
V_k – volume of corridor [m^3],
$\dot{m}_d$ – a stream of smoke particles entering through the room door to the corridor [kg/s].

4. Examples of model calculations for one room with a corridor

4.1. Free fire scenario

For example, calculations were made for one room serving as a hotel room connected to the corridor (Figure 4).

Fig. 4. Diagram of the rooms layout in which the fire develops

The source of fire is in the middle of the hotel room with closed doors to the bathroom and corridor and a closed window. The corridor is also closed. The combustion zone increases, the thickness of the upper smoke layer increases and its temperature increases. When the temperature reaches 300°C, the glass breaks and smoke flows out off the window. After a certain time, when the temperature reaches about 350°C, the wooden door begins to burn. They are unsealed and in the temperature range 500–550°C they are completely burned down. During the destruction of the door, gradually more and more smoke flows out of the door opening into the corridor. The corridor gradually becomes smoky. After reaching the temperature of around 600°C, flashover in the room is observed (combustion covers the entire volume of the room). The flame bursts out through the window and the door of the room.

4.2. Dimensions of rooms and vents as well as other input data

For the purpose of calculation, the following dimensions of rooms and ventilation openings have been adopted:
a) H = 3 m - room height,
b) $A_o = 3.06\ m^2$ - the total surface area of the window,
c) $A_T = 89.32\ m^2$ - inside room area (without bathroom) after deducting the area of open windows,
d) $S = 18\ m^2$ - room size without a closed bathroom,
e) $H_o = 1.7$ m - window height,
f) $V_p = 54\ m^3$ - the volume of the room,
g) $H_{go} = 2.5$ m - location of the top edge of the window relative to the floor
h) $W_d = 0.9$ m - width of the room door,
i) $H_d = 2$ m - door height,
j) $A_d = 1.8$ m2 - door surface area.

Based on Table 1, the value of the fire growth coefficient α = 0.015 kW/s^2 corresponding to the approximate average fire development characteristic for hotels was assumed. An incubation time of 60 s corresponding to the time of initiation of this type of fires was assumed. The mass of burnt materials in the developed phase L_t = 176 kg and the average heat of combustion of wood and wood-based materials ΔH_c = 20,000 kJ/kg were also adopted. Taking into account the location of the fire source, it was assumed that in formula (2) the coefficient k = 1. According to Table 2, the flame propagation velocity v_p = 0.5 cm/s was assumed in the first phase of the fire until flashover, while in the subsequent v_p = 1 cm/s. It was assumed that the flashover temperature was T_{FO} = 600°C. The following parameters were adopted for the lower (cool) layer of air: temperature T_∞ = 20°C, density ρ_∞ = 1.2 kg/m^3 and isobaric specific heat c_p = 2020 J/(kgK). The air density in the upper layer was determined from the ideal gas equation assuming constant pressure. The efficiency of the combustion reaction β = 1 (total combustion), the oxygen consumption factor Y_{O2} = 1.2 kg/kg [12] and the emission factor of the smoke particles Ys = 0.06 kg/kg [21] corresponding to wood materials and wood-based were taken for calculation. A safe range of visibility was assumed in an unknown building of 15 m.

4.3. Calculations of fire parameters

To estimate the duration of the fire and its individual phases, heat release rate for flashover, the maximum power released after flashover, the time to flashover and the duration of the phase of the developed fire were calculated first. For this purpose, formulas (5)–(9) and input data given in chapter 4.2 were used.

1. <u>Heat release rate to flashover</u>

$$\dot{Q}_{FO} = 7{,}8 \cdot A_T + 378 \cdot A_0 \cdot H_0^{1/2} = 7{,}8 \cdot 89{,}32 + 378 \cdot 3{,}06 \cdot \sqrt{H_0} = 2182\ kW$$

2. <u>Time to flashover</u>

$$t_{FO} = t_i + \sqrt{\frac{\dot{Q}_{FO}}{\alpha}} = 60 + \sqrt{\frac{2181}{0{,}015}} = 441\text{ s}$$

3. Maximum heat power released after flashover

$$\dot{Q}_{max} = 1500 \cdot A_0 \cdot \sqrt{H_0} = 1500 \cdot 3{,}06 \cdot \sqrt{H_0} = 5985\ kW$$

4. Duration of developed phase of the fire

$$t_b = \frac{L_t \cdot \Delta H_c}{\dot{Q}_{max}} = \frac{176 \cdot 20000}{5985} = 588\ s$$

Other fire parameter values calculated on the basis of the relationships given in Chapter 3 are given below. The results are summarized in tables for selected times differing by 60 s to exceed time t_{FO} and 120 s after exceeding this time, based on previous calculations as 960 s. The exception here is the heat release rate, the value of which increases only in the first phase of the fire, and after flashover it is approximately constant and equal to the maximum fire power after flashover. In this case, the computation time was 600 s.

5. Heat release rate

Table 3. Selected values of heat release rate

No.	Time [s]	Heat release rate* [kW]
1	60	0
2	120	54
3	180	216
4	240	486
5	300**	864
6	360	1350
7	420	1944
8	480	2646
9	600	5985

* the table presents theoretical values of the heat release rate calculated on the basis of the formula (1)

** after about 300 seconds, a drop in the oxygen concentration in the rooms will cause a significant reduction in the heat release rate, however, due to the falling windows in the rooms more or less at the same time, the oxygen concentration increases to ensure further combustion

6. The average height of the flame and the radius of the bend under the ceiling

In order to calculate the average flame, height and its possible bending under the ceiling, where $H_f > H$ the formulas (2) and (3) were used accordingly. The listed values at selected time points are given in Table 4.

Table 4. Selected values of average flame heights and the radius of the bend under the ceiling

No.	Time [s]	Average flame height [m]	Radius of the flame bend under the ceiling [m]
1	60	0	–
2	120	1.0	–
3	180	1.7	–
4	240	2.4	–
5	300*	3.0	0
6	360	3.6	0.5
7	420	4.1	1.1
8	480	4.7	1.6
9	600	5.7	2.6
10	720	6.7	3.5
11	840	7.7	4.4
12	960	8.6	5.3

* after about 300 s, the flame begins to touch the ceiling of the room, assuming that the rate of the heat release will remain at the same level

7. Diameter of combustion zone and surface of the fire (projection of the combustion zone on the horizontal surface)

To calculate the surface of the fire, the formula (4) was used. The diameter of the combustion zone was determined based on the previously calculated circular area of the fire. The listed values at selected time points are given in Table. 5.

Table 5. Selected values of diameter of combustion zone and fire area

No.	Time [s]	Diameter of combustion zone [m]	Fire area [m^2]
1	60	0	0
2	120	0.60	0.283
3	180	1.20	1.130
3	240	1.80	2.543
4	300	2.40	4.522
5	360	3.00	7.065
6	420	3.60	10.174
7	480	3.89	11.873
8	600*	4.79	18.000

* after about 558 s, the fire area covers the whole area of the room

8. Average temperature of the upper layer

To calculate the average temperature of the upper layer, the formulas (13) and (14) were used. Its values in selected time moments along with a brief description of its accompanying phenomena are provided in Table 6.

9. Position of the upper layer in the room

In order to calculate the position of the upper layer (smoke) relative to the floor, the formula (15) was used. Its values in selected time moments along with a brief description of its accompanying phenomena are provided in Table 7.

Table 6. Selected values of the average temperature of the upper layer and accompanying phenomena

No.	Time [s]	Temperature of the upper layer [°C]	Phenomena description
1	60	20	Without changes in temperature

continued tab. 6

No.	Time [s]	Temperature of the upper layer [°C]	Phenomena description
2	120	122	Temperature below critical value
3	180	196	Temperature closed to the critical value
4	240	278	Window panes start to break if they are closed
5	300	367	Windows without panes and flame reaches the ceiling. Wooden door to the corridor begins to burn
6	360	462	The flame bends under the ceiling, creeping flames in the upper layer. The door is partially destroyed
7	420	563	Intensive flames in the upper layer, the moment of flashover is approaching. The door to the corridor is completely burned out
8	441	600	Flashover and flames burst through the window and door
9	480	800	Flames in a whole room

Table 7. Selected values of the position of the upper value and brief description of the accompanying phenomena

No.	Time [s]	Location of the upper smoke layer* [m]	Phenomena description
1	60	3.00	Without visible smoke
2	80	2.90	Smoke layer about 10 cm thick. The conditions for safe evacuation are met

continued tab. 7

No.	Time [s]	Location of the upper smoke layer* [m]	Phenomena description
3	100	2.67	The layer of smoke has reached a thickness of more than 30 cm and is still at a safe distance from the head, although the thermal radiation from the upper layer can already be clearly felt.
4	140	2.06	The layer of smoke has reached the thickness of almost 100 cm and is located at a distance of several dozen centimeters from the human head. It is still possible to evacuate safely (the temperature of the upper layer has not yet reached the critical value) and the extinguishing action carried out in a standing position
5	180	1.45	The smoke layer is below the level of the head and, moreover, its temperature is approaching the critical value. In this situation, the evacuation is very difficult, the firefighting action is possible only in the heavily inclined position, most often in the kneeling position
6	240**	0.78	The smoke layer is less than 80 cm above the floor. At about the time windowpane start to crack and smoke flows out through the window opening. Evacuation and practically firefighting is no longer possible
7	300	0.42	The windows are without glass and smoke flows out through the window opening, which causes a partial reduction of smoke and a slight increase in the location of the upper layer in the room

continued tab. 7

No.	Time [s]	Location of the upper smoke layer* [m]	Phenomena description
8	360	0.23	As a result of partial destruction of the door, the smoke, in addition to flowing out through the window opening to the outside, also gets through the destroyed door to the corridor
9	420	0.13	According to the model used, the position of the upper layer is just above the floor, however, due to the free flow of smoke through the window and door openings, practically its level is well above the calculation level. It depends mainly on the amount of smoke produced as a result of combustion and mass streams of smoke flowing out of the window and door openings

* the table presents the theoretical values of the position of the upper smoke layer calculated on the basis of formula (15)

** after approx. 240 s, the computational value of the upper layer position will differ from the actual position of the upper layer due to the outflow of smoke first through the window opening and later the door.

10. Average concentration of the oxygen in the room

During combustion, the oxygen concentration is reduced. This reduction will take place until the window is destroyed (cracking and falling out of windows) or the door is unsealed (burning out). If the oxygen concentration inside the room reaches the value close to 0.1 mass fraction, there may be a threat of backdraft. In order to calculate the average oxygen concentration, the formula (19) was used. Its values in selected time moments along with a brief description of its accompanying phenomena are provided in Table 8.

11. Visibility range in the room

In order to calculate the visibility range in the room, the formulas (21) and (17) were used. Its values in selected time moments along with a brief description of the phenomena are provided in Table 9.

Tabela 8. Selected values of average oxygen concentration and brief description of accompanying phenomena

No.	Time [s]	Average oxygen concentration [kg/kg]	Phenomena description
1	120	0,229	oxygen concentration close to the initial
2	180	0,217	oxygen concentration begins to decrease slowly, but it is not yet a threat to humans and has no significant impact on combustion
3	240	0,179	there is a visible drop in oxygen concentration, which may pose a threat to human health in the long term, a small impact on the combustion process is almost unnoticeable
4	280	0,127	the concentration of oxygen approaches the limit value at which the onset of a rapid reduction in the power of fire and the generation of flammable gases occurs, being in this atmosphere is a serious threat to health and even life
5	300*	0,090	oxygen concentration falls below the limit at which backdraft may occur, the fire power practically decreases to zero, oxygen concentration mortal to man

* after about 300 seconds, the increase of temperature in the room causes the windows to break, which in turn causes a rapid increase in the oxygen concentration to a level allowing further free combustion.

Table 9. Selected values of visibility range in the room and brief description of accompanying phenomena

No.	Time [s]	Visibility range [m]	Phenomena description
1	100	>15	ensured safe evacuation
2	104	14.8	the range of visibility is smaller than the assumed minimum, although it allows for safe evacuation from the building

continued tab. 9

No.	Time [s]	Visibility range [m]	Phenomena description
3	110	9.9	the visibility decrease is less than 10 m, but it still provides sufficient visibility in a small hotel room
4	120	5.6	the range of visibility is greater than 5 m (greater than the distance between opposite walls), and thus allows for a safe evacuation from the hotel room, especially since the smoke zone is above the human head
6	140	2.2	the range of visibility has already decreased to just over 2 m, but due to the location of the upper zone (above 2 m) there is still the possibility of evacuation from the room
7	180	0.6	the range of visibility has fallen below 60 cm, and the upper layer is already low enough that evacuation from the room is very difficult and only possible in a very inclined position
8	200	0.3	the minimum range of visibility, exceeded the temperature of the upper layer and its position practically prevents evacuation from the room
9	300	0.05	safe evacuation from the room is impossible due to its complete smoke

4.4. Analysis of calculation results

A fire was set up in the hotel room, with an adjacent corridor. Changes in the number of fire parameters in the room have been determined. Assuming the rate of the fire growth determined by the coefficient $\alpha = 0.015$ kW/s^2, there is a continuous increase in gas temperature in the room until the flashover for 441 s and a sudden transition to the fire phase developed with temperature maximum approx. 800°C. During this time, the height of the flame increases, the flame begins to bend under the ceiling and the surface of the fire also grows, reaching after 360 s approx. 7 m^2. Observing the increasing height of the flame during the action, you can estimate the power of the fire and the approaching flashover. Creeping flames in the upper layer (after 420 s) are a direct symptom of flashover. The outflow of smoke from the room after 80 seconds from the flame ignition, signals a fire. After about 300 seconds, the oxygen concentration is reduced to the level at which the combustion reaction speed decreases, the fire power decreases and the large amounts of flammable incomplete and incomplete combustion products are released. Under these conditions, when there is a sudden supply of oxygen from the outside (breaking the window, opening the door), ignition of fire gases or a backdraft effect may occur. The calculations show that after the same time the temperature of the gases in the room increases to 300°C, which may cause window panes to crack and destroy. As a result, good ventilation can be created, which prevents backdraft.

5. Summary

Presented selected, validated models of internal fire structure elements, along with an accounting example, are used to recognize the impact of various factors on the calculated fire parameters such as temperature, visibility range, oxygen concentration and others, and can be a preliminary assessment of the speed of achieving critical environmental conditions. It is possible, at the beginning of the fire, to calculate the duration of the fire growth phase, where it is still possible, to carry out the rescue operation directly in the room with the fire source. We use higher-order computational tools to assess and design the fire safety of buildings. Computer programs based on the complex zone and field models are so complex and time-consuming that they cannot be used in practice during the rescue and firefighting operations. However, the proposed simple computational structure, in the form of an application for a laptop, tablet or smartphone, could serve as an aid to the commanding rescue and fire-fighting during the real fire.

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