

# Influence of the place of the expiration of gases from the placement at the fire for critical time of formation of dangerous factors of the fire

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**Abstract.** In normative documents for definition of time of approach of critical values of dangerous factors of the fire (DFF) use medium-volume characteristics of temperature, concentration of O<sub>2</sub> oxygen, toxiferous gases and smoke. The purpose of this work – to show that for calculating time of approach of dangerous factors of the fire it is necessary to consider the place of the expiration of gases and their initial parameters. The expressions received in work can serve for determination of values of the dangerous factors of the fire parameters indoors depending on time, taking into account the place of the expiration of gases and their initial parameters. From the dependences given in work it is visible that differences in time taking into account the place of the expiration for the room of 5000 m<sup>3</sup> are made by not less than 30 c with on reaching critical temperature and critical concentration of O<sub>2</sub>. Especially it should be noted that at change of height of a working zone the time difference increases to 40 c with in both parameters.

## 1 Introduction

Death of people at the fires results from action on an organism of dangerous factors of the fire. Treat these factors: temperature of gases indoors, the heat flux falling on people, the under concentration of oxygen, the increased concentration of toxiferous gases, the poor visibility. The last factor works indirectly, increasing a response time of people in a dangerous zone. In recent years in world practice much attention was paid to improvement of criteria of impact on people of dangerous factors of the fire. One of more modern normative documents establishing the specified criteria is the international standard [1]. According to this standard, the critical duration of the fire of  $t_{kr}^T$  on a heat flux and high temperature is determined by a first passage time on the ways of evacuation by an efficient thermal dose of  $Q_{ef}$ . the efficient thermal dose is determined by a formula [1]:

$$Q_{ef} = \begin{cases} \sum_{t_1}^{t_2} \left( \frac{1}{t_k} \right) \Delta t, \text{ if } q < 2,5 \text{ kW/m}^2 \\ \sum_{t_1}^{t_2} \left( \frac{1}{t_k} + \frac{1}{t_R} \right) \Delta t, \text{ if } q > 2,5 \text{ kW/m}^2 \end{cases}$$

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Where  $t_R$  – admissible time of influence of a caloradiance during a time term  $\Delta t$ , mines,  $t_k$  – admissible time of influence of high temperature during a time term  $\Delta t$ , mines,  $q$  - intensity of a heat flux of  $\text{kW/m}^2$ ,  $\Delta t$  – a time term of influence, mines,  $t_1$  and  $t_2$  - border of a time frame during which evacuation of people is possible, mines,  $Q_{ef}^T$  – it is necessary to equate to 1.

According to [2]  $t_{kr}^f$  on toxiferous  $t_{kr}^{T-g}$  gases. is determined by the least of values of a first passage time on the ways of evacuation of an efficient dose of  $X_{ef}^D$  or efficiency concentration of  $X_{ef}^K$  of size equal 1 taking into account a combined effect of all gases.

For determining  $t_{kr}^V$  – visibility loss time, according to [3] it is necessary to consider influence of an optical density of smoke, feature of an arrangement of an inventory of emergency exits. In [4] critical distances of loss of visibility depending on room space and probability of operation of the warning system and management of evacuation and its type are specified.

There are not carried to number of initial factors which need to be considered such as: the place of the expiration of gases from the room on an incipient state of the fire, dependence of initial partial density of oxygen on the reference temperature of the environment. For determining fire risks when the probability of various script of development of the fire [5-8], accounted for of the expiration of gases not with the instantaneous medium-volume parameters and with the particular reference temperature of  $20^\circ\text{C}$  indoors is considered, should not be excluded, at least a priori. For example, in a situation when indoors pressure-tight doors, there are air vents or lamps, it is necessary to consider that gases with parameters of an upper of an affluent zone expire. On the contrary, in case of lack of exhaust lamps and open or leaky doors, on an incipient state of the fire from the room air will expire.

The offered work considers these unaccounted situations within integral model [9].

Initial values of dangerous factors of the fire are accepted to [10] corresponding clean air.

For partial density of toxiferous gases and an optical density of smoke:

$$\rho_0^{CO} = 0, \rho_0^{CO_2} = 0, \rho_0^{HCl} = 0, \mu_0 = 0.$$

For the partial density of oxygen as initial value the  $\text{kg/m}^3$  undertakes that corresponds to  $T=27^\circ\text{C}$  temperature. The initial value of temperature undertakes actually possible

$\rho_0^{O_2} = 0,27$ , but there corresponds  $T=27^\circ\text{C}$ . For example, for  $T_0 = -20^\circ\text{C}$  of  $\rho_0^{O_2} = 0,296$   $\text{kg/m}^3$  for  $T_0 = 0^\circ\text{C}$  of  $\rho_0^{O_2} = 0,32$   $\text{kg/m}^3$ .

## 2 Materials and Methods

Parameters of the expiring gases at the fire for integral model of an incipient state of development of the fire indoors are regulated in [9] and are determined by a formula:

$$\frac{F_{kr} - F_0}{F_{p,d} - F_0} = \left( \frac{y}{h} \exp\left(1,4 \frac{y}{h}\right) \right)^{-1}, \quad (1)$$

$F_{kr}$  — critical value of an average state variable;

$F_{p,d}$  — the dangerous factors of the fire marginal value in a working zone;

$F_0$  — the dangerous factors of the fire initial value;

$$\frac{y}{h} \exp\left(1,4 \frac{y}{h}\right) = Z$$

$y$  – the coordinate of a working zone counted from a surface of a floor, m;

$0 \leq y \leq h$ ;

$h$  – height of the room, m.

The formula (1) gives communication between local value of the DFF parameter at the level of a working zone  $y = h/2$  (height of this zone is not limited) with medium-volume value of this  $F_{kr}$  parameter.

The local value of the DFF parameter at height  $y = h/2$  (a half of height of the room) according to the given expression corresponds to medium-volume value of this parameter. If to designate medium-volume value  $\bar{F}_m$ , and local value of  $F_y$ , then communication between  $\bar{F}_m$  and  $F_y$ , provides the regulated DFF critical value at its limiting admissible value at height of a working zone. However this value distribution of DFF on height does not correspond to the maintenance of DFF in volume of the room as the integral on height accounted for offered distribution to 33% exceeds the common maintenance of the considered DFF indoors, and for the partial density of oxygen its negative value at height  $3h/4$  is possible.

To eliminate the existing defects of value distribution of DFF on height, it is necessary to carry out its correction [9]. Correction is that the DFF parameters depending on height are defined by expressions:

- $y < 0,65h$ :

$$F_y = F_0 + (\bar{F}_m - F_0) \left( \frac{y}{h} \exp \left( 1,4 \frac{y}{h} \right) \right)^{-1}; \quad (2)$$

- $y \geq 0,65h$ .

$$F_y = 1,615\bar{F}_m - 0,615F_0. \quad (3)$$

These expressions give for  $y < 0,65h$  the  $F_{kr}$  values coinciding with calculated on (1), and for  $y \geq 0,65h$  (that happens seldom)  $F_{kr}$  it is possible to calculate, using (3):

$$F_{kr} = \frac{F_{p,d} + 0,65F_0}{1,615}. \quad (4)$$

A visual idea of distribution of the DFF parameters on height of the room is given to tab. 1 and fig. 1.

**Table 1.** Distribution of the DFF parameters on height of the room

DFF parameter	Value of parameter with a height of a working zone, m					
	0	$h/8$	$h/4$	$3/8h$	$h/2$	$\geq 0,65h$
Temperature, °K, T	$T_0$	$0,15\bar{T} + 0,85T_0$	$0,355\bar{T} + 0,645T_0$	$0,525\bar{T} + 0,475T_0$	$\bar{T}$	$1,615\bar{T} - 0,615T_0$
Partial density:						
- oxygen $\rho^{O_2}$	$\rho_0^{O_2}$	$0,15\bar{\rho}^{O_2} + 0,85\rho_0^{O_2}$	$0,355\bar{\rho}^{O_2} + 0,645\rho_0^{O_2}$	$0,525\bar{\rho}^{O_2} + 0,475\rho_0^{O_2}$	$\bar{\rho}^{O_2}$	$1,615\bar{\rho}^{O_2} + 0,615\rho_0^{O_2}$
- toxiferous gases $\rho_{t,g}$	0	$0,15 \bar{\rho}^{t,g}$	$0,355 \bar{\rho}^{t,g}$	$0,525 \bar{\rho}^{t,g}$	$\bar{\rho}^{t,g}$	$1,615 \bar{\rho}^{t,g}$
Оптическая плотность дыма $\mu$	0	$0,15\bar{\mu}$	$0,355\bar{\mu}$	$0,525\bar{\mu}$	$\bar{\mu}$	$1,615\bar{\mu}$

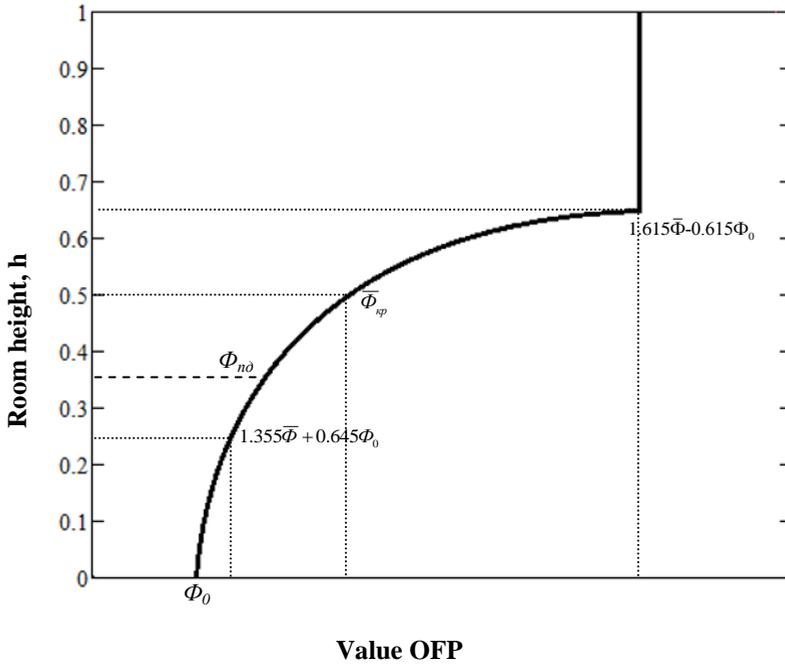
### The expiration of cold air from the lower levels

From the equation of balance of weight we have:

$$\frac{d\rho_m V}{dt} = \psi - G_g, \quad (5)$$

where  $\rho_m$  — the medium-volume density of gases indoors,  $kg/m^3$ ;

$V$  - volume of the room,  $m^3$ ;  
 $\psi$  — mass rate of a burnup,  $kg/s$ ;  
 $G_g$  — a consumption of the pushed-out gases,  $kg/s$ .



**Fig. 1.** Value distribution of OFP on room height

Expression for a mass stream of cold gases follows from the equation of balance of energy [9]:

$$G_g = \frac{Q_{fire}(1-\phi)}{C_p T_0} \tag{6}$$

Where  $Q_{fire}$  — thermal emission in the center of combustion, J;  $Q_{fire} = F_g \psi_{ud} Q_n^r \eta$ ;

$F_g$  — the burning area,  $m^2$ ;

$\psi_{ud}$  — the specific speed of a burnup of combustible material,  $kg / (m^2 sec)$ ;

$Q_n^r$  — the lowest combustion heat of combustible material, J/kg;

$\eta$  — incompleteness of combustion, %;

$\phi$  — the coefficient of heatlosses in walls satisfying to expression

$$\phi = \frac{Q_w}{Q_{fire}} ;$$

$Q_w$  — a total heat flux in protections, J;

$C_p$  — the thermal capacity of air,  $kJ / (kg \text{ } ^\circ K)$ .

We integrate the equation (5), and taking into account communication  $\rho_m T_m = \rho_0 T_0$  (where

$T_m$  — medium-volume temperature indoors, K;  $\rho_0$  — the initial density of air indoors,  $kg/m^3$ ,  $T_0$  — reference temperature indoors, K) which is a consequence of a condition of constancy of pressure indoors that demonstrates leakage of the room, we receive a first passage time of critical temperature at the fire:

$$t_{kr}^T = \left[ \left( 1 - \frac{T_0}{T_{kr}} \right) \frac{B}{A} \right]^{\frac{1}{n}}, \quad (7)$$

Where  $B = \frac{C_p T_0 \rho_0 V}{(1-\phi) Q_n \eta}$ ;  $A = \int \psi_{ud} F_g dt$ .

For a case of the circular fire:

$$F_g = \pi U_1^2 t^2 \rightarrow A = \frac{\psi_{ud} \pi U_1^2 t^3}{3},$$

where  $U_1$  — the peripheral speed of flame spread on the square on which fire loading, m/s is placed.

Similarly we receive expressions for critical first passage times of critical values of partial density of oxygen, partial density of toxiferous gases and an optical density of smoke:

$$t_{kr}^{O_2} = \left[ \frac{(\rho_0^{O_2} - \rho_{p,d}^{O_2}) V Z^{-1}}{L^{O_2} A \left( 1 + 0,233 \frac{V \rho_0}{B L^{O_2}} \right)} \right]^{\frac{1}{n}} \quad (8)$$

Where  $\rho_0^{O_2}$  — the initial partial density of oxygen in air,  $\text{kg/m}^3$ ;  $\rho_0^{O_2} = 81,9/T_0$ ;

$\rho_{p,d}^{O_2}$  — marginal partial density of oxygen;  $\rho_{p,d}^{O_2} = 0,226 \text{ kg/m}^3$ ;

— предельно допустимая парциальная плотность кислорода; = 0,226

$L^{O_2}$  — oxygen consumption at combustion of combustible material,  $\text{kg/kg}$ ;

$$t_{kr}^{t.g} = \left[ \frac{\rho_{p,d}^{t.g} V Z^{-1}}{L^{t.g} A} \right]^{\frac{1}{n}}; \quad (9)$$

$\rho_{p,d}^{t.g}$  — marginal partial density of toxiferous gas,  $\text{kg/m}^3$ ;

$L^{t.g}$  — selection of toxiferous gas at combustion of combustible material,  $\text{kg/kg}$ ;

$$t_{kr}^{\mu} = \left[ \frac{2,38 / L_{p,d} V Z^{-1}}{D A} \right]^{\frac{1}{n}}; \quad (10)$$

$D$  – smoke-generating ability of combustible material,  $\text{Np}^2/\text{kg}$ ;

$L_{p,d}$  — marginal visibility range, m.

Expressions (7) – (10) are formulas for calculation of time of approach of the DFF critical values at the expiration of cold air through the lower apertures of the room.

### The expiration of hot gases from top levels of the room

From balance of energy provided that  $\frac{dP_m}{d\tau} = 0$ , ( $P_m$  - middle pressure indoors, Pa) we have:

$$Q_{fire} \eta (1-\phi) = C_p T_{ist} G_g \rightarrow \frac{Q_{fire} (1-\phi)}{C_p T_{ist}},$$

where  $T_{ist}$  — temperature of the expiring gases, K.

Follows from balance of weight:

$$V \frac{d\rho_m}{dt} = - \frac{Q_{fire} (1-\phi)}{C_p (4T_m - 3T_0)}. \quad (11)$$

Let's define time of approach of bottlenecks of dangerous factors of the fire at height no more  $0,65h$  because with such heights the balance of masses will remain.

Having integrated (11), we will receive:

- at  $y_{ist} = 0,65h$ ,  $T_{ist} = 1,615T_m - 0,615T_0$ ,

$$t_{kr}^T = \left\{ \frac{B}{A} \left[ 1,615 \ln \frac{T_{kr}}{T_0} + 0,615 \left( \frac{T_0}{T_{kr}} - 1 \right) \right] \right\}^{\frac{1}{n}} \quad (11a)$$

From balance of mass of oxygen we have:

$$V \frac{d\rho_1}{dt} = -L^{O_2} \psi - \rho_{1ist} \frac{Q_{fire}(1-\phi)}{C_p T_0 \rho_0} \quad (12)$$

$\rho_{1ist}$  – density of the expiring gases,  $kg/m^3$ .

Having integrated (12), we will receive:

- at  $y_{ist} = 0,65h$ ,  $\rho_{1ist} = 1,615\rho_1 - 0,615\rho_0^{O_2}$ ,

$$t_{kr}^{O_2} = \left[ \frac{B}{1,615A} \ln \left( \frac{1 + \frac{\rho_0^{O_2} V}{BL^{O_2}}}{1 + \frac{(1,615\rho_{kr}^{O_2} - 0,615\rho_0^{O_2})V}{BL^{O_2}}} \right) \right]^{\frac{1}{n}}; \quad (12a)$$

From balance of mass of toxiferous gas we have:

$$V \frac{d\rho_2}{dt} = L^{tg} \psi - \rho_{2ist} \frac{Q_{fire}(1-\phi)}{C_p T_0 \rho_0} \quad (13)$$

Having integrated (13), we will receive:

- at  $y_{ist} = 0,65h$ ,  $\rho_{2ist} = 1,615\rho_2$

$$t_{kr}^{tg} = \left[ \frac{B}{1,615A} \ln \left( \frac{1}{1 - \frac{1,615\rho_{kr}^{tg} V}{BL^{tg}}} \right) \right]^{\frac{1}{n}}; \quad (13a)$$

From balance for an optical density we have smokes:

$$V \frac{d\mu_1}{dt} = D\psi - \mu_2 \frac{Q_{fire}(1-\phi)}{C_p T_0 \rho_0} \quad (14)$$

Having integrated (14), we will receive:

- at  $y_{ist} = 0,65h$ ,  $\mu_2 = 1,615\mu_1$

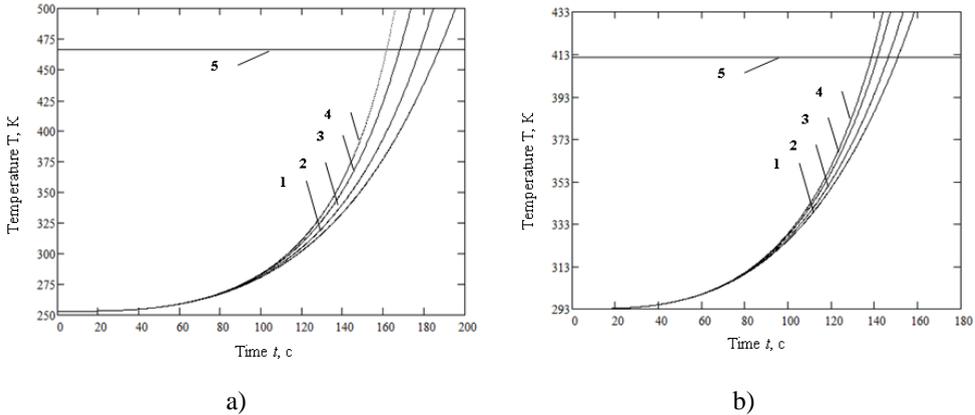
$$t_{kr}^{\mu} = \left[ \frac{B}{1,615A} \ln \left( \frac{1}{1 - \frac{1,615\mu_{kr} V}{BD}} \right) \right]^{\frac{1}{n}}; \quad (14a)$$

### 3 Results

The dependences given above 7 – 14 allow to define values of the DFF parameters indoors over time taking into account the place of the expiration of gases.

In fig. 2 and 3 change of temperature and density of  $O_2$  to critical value depending on time and the place of the expiration on room height is shown.

Apparently from drawings, at change of reference temperature not only the difference between temperatures of the gases expiring from the lower and top levels of the room, but also critical values of the DFF parameters indoors changes.



**Fig. 2.** Change of temperature of gases at the reference temperature in 253 K (a) and 293 of K (b) depending on time and the place of their expiration on room height: 1 — 0,65h; 2 — 0,5h; 3 — 0,25h; 4 —  $h = 0$  (cold gases); 5 — critical temperature for the room of 5000 m<sup>3</sup>, 6 m high; combustible substance – cotton.

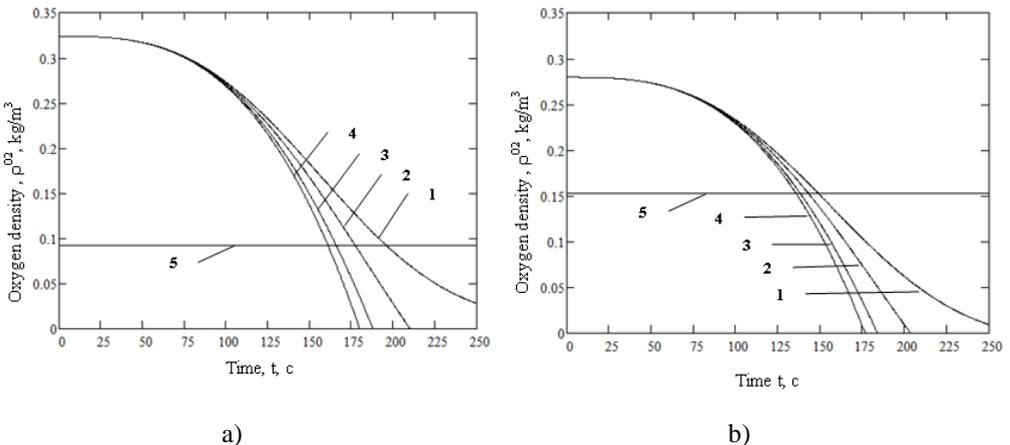
In tab. 2 values of a first passage time of critical values for temperature and density of oxygen are given in the different height of the expiration.

**Table 2.** First passage time of critical values for temperature and density of oxygen are given in the different height of the expiration.

Parameter	Reference temperature indoors, K	First passage time the parameter of critical value, sec, with an expiration height			
		0,65h	0,5h	0,25h	$h = 0$
Temperature of gases	253	186.8/152.6	178.0/148.0	167.8/142.8	160.6/139.8
	293	150.8/121.3	146.4/119.3	141.4/117.0	138.5/115.7
Oxygen density	253	196.15/137.5	177.4/133.6	165.9/129.6	161.1/127.6
	293	148.9/112.2	143.1/110.4	138.2/108.7	135.7/107.6

Notes:

1. Data are provided for the room of 5000 m<sup>3</sup>, 6 m high; combustible substance – cotton.
2. Over line 1,7 m given for height of a working zone, below the line — 2,7 m are provided.



**Fig. 3.** Change of partial density of oxygen at the reference temperature in 253 K (a) and 293 of K (b) depending on time and the place of the expiration on room height: 1 — 0,65h; 2 — 0,5h; 3 — 0,25h; 4 —  $h = 0$ ; 5 — critical value of partial density O<sub>2</sub> for the room of 5000 m<sup>3</sup>, 6 m high; combustible substance – cotton.

## 4 Conclusion

The expiration of gases from more low levels of rooms, that is with the under maintenance of dangerous factors of the fire, also leads to decrease of critical heating-up periods of dangerous factors of the fire in comparison with the accepted offer on the expiration of gases with medium-volume indexes of dangerous factors of the fire, which in turn affects the calculation of the time of evacuation of people from the room or building.

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