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FIRE ENGINEERING APPROACH OF PEOPLE EVACUATION ASSESSMENT WITH A PRACTICAL DEMONSTRATION

Abstract: *This article presents some of the possible ways of an examination of people evacuation by fire engineering methods.*

Application of described methods is illustrated in a practical example of an office object. The expansion of fire in a part of characteristic floor of high-rise office is simulated by the selected zone (CFAST) and field (FDS) fire models. Some of the results obtained by the simulation, especially smoke layer decrease in the area and cumulative gas layer temperature, represent limit criteria for examination of safe evacuation from the assessed area.

The article is an example of possible application of combination of manual computational processes and fire models.

Key words: fire safety, evacuation, mathematical modelling.

INTRODUCTION

With increasing complexity of buildings (more complicated technical and technological systems that are conditioning their operation, and the increase in their area, height, more floors in the underground, more people, etc.) the increase of demands for risks assessment in term of fire safety also increases.

In many cases, the application of national safety standards is problematic, almost unrealistic. The way out of these situations is application of more detailed evaluative procedures, fire engineering methods, which can be used as partial or complex evaluative instrument.

This article presents one of the possible ways, when a part of the solution is based on the application of fire models. It also presents simplified computational processes connected to it.

BASIC DESCRIPTION OF EXAMPLE

The method of engineering procedure is applied to multifunctional high-rise object (administrative premises of this object) that are mostly formed by large-area offices, small conference rooms and spaces designed for documents storing.

In the case of fire rise in high-rise objects, the principal aim is to prevent casualties and injuries, and thus ensure the possibility of safe evacuation of people from the object. Therefore, the chosen example concerned with the fire rise in the fire cell of office premises on the area 25 × 30m, situated in the 20th floor (see colour coded area in the fig. 1).

FIRE COURSE ASSESSMENT

After the qualitative analysis, we have developed a scenario of fire in the kitchen during working time (simplified geometry of the assessing part of the floor is pictured in the fig. 2). There is a colour coded kitchen, denoting the centre of the fire scenario. The kitchen door of high-capacity office is open all the time. It is assumed that users of the object did not manage to extinguish the developing fire on time, so people have been endangered by smoke that will spread to the premises of the high-capacity office. Furthermore, we have assumed the effective function of fire dividing constructions, including fire shutter of openings equipped with self-closing device.

Fire development, temperature course and smoke level in the assessed part of the object have been modelled according to the zone model CFAST (Consolidated Model of Fire Growth and Smoke Transport, version 6) [1] and field model FDS (Fire Dynamics Simulator, version 5) [2].

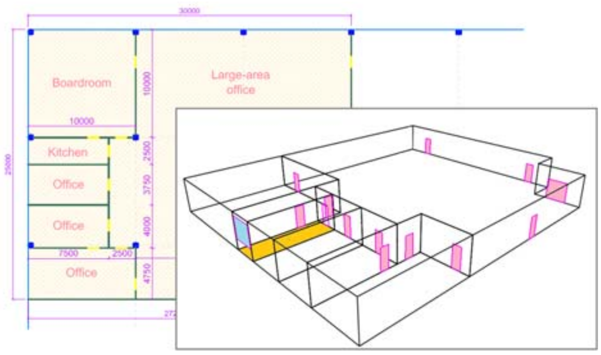

Figure 1. *Simplified geometry of assessed part of the floor*

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The results showed that it is possible to characterize the initial phase of the fire by simple, time-dependent parabolic curve. The curve is known as *t-quadratic fire* curve, where the heat release rate is proportional to square power of time.
The equation can be found in the following form:

$$\dot{Q} = \dot{Q}_0 \left(\frac{t}{t_g}\right)^2 \tag{1}$$

For calculation of the value t_g from quantities used in Czech technical standards can be used conversion relations, which are stated in the Annex H ČSN 73 0802:2009. For non-productive objects according to ČSN 73 0802 and consequential standards, the value t_g is calculated using the fire load and the coefficient of burning rate:

$$t_g = \frac{2000}{a \cdot \sqrt{p}} \tag{2}$$

In the case of the kitchen (p = 25 kg.m^{-2}, a = 1)

$t_g = 2000 / (1 \cdot (25)^{0,5}) = 400$ s.

The course of temperature and smoke layer decrease in assessed premises defined by both fire models can be seen in the Fig. 2 (in the case of FDS fire model, temperature and smoke layer level monitored always in room centres, in the height of 3m).

The course of temperature increase and smoke layer decrease in the kitchen and large-area office are represented in the fig. 2.

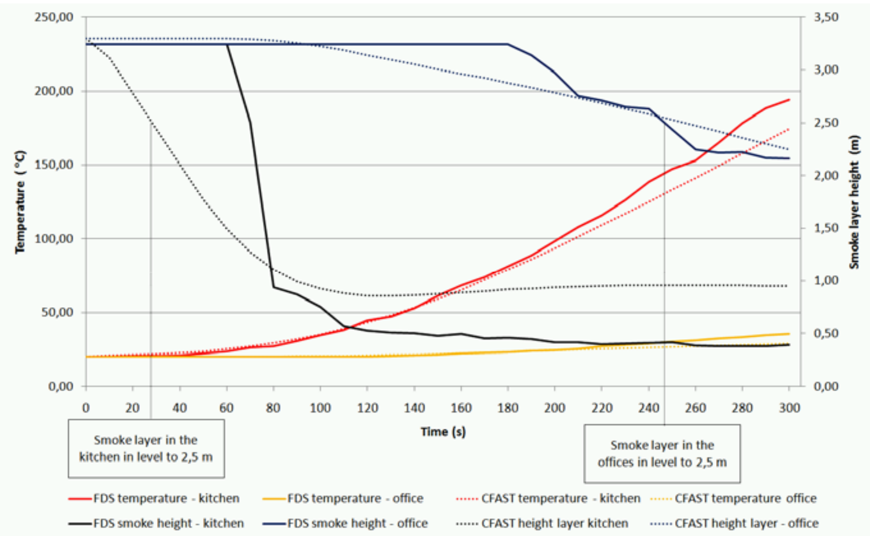

Figure 2. *Illustration of time course of the temperature and smoke layer decrease by models CFAST and FDS*

From the curves acquired by both fire models (CFAST vs. FDS) it is obvious that the results are largely comparable. The result supports a presumption that zone models are in many cases very usable, especially when there is a need to acquire source information during situations with limited range of input information or lack of time space necessary while using field models.

DESCRIPTION OF BASIC PRINCIPLES USABLE AT FIRE ENGINEERING ASSESSMENT OF EVACUATION

During detailed assessment of evacuation is generally always efficient to determine the *required safe escape time* t_c, which consists of partial time intervals:

$$t_c = t_d + t_z + t_u \tag{3}$$

Detection and alarm time t_d is usually split in two time intervals. In the fire detection time, which depends on the design of the device for the early fire detection (e.g. electrical fire detection and fire alarm systems) or on noticing of fire by an user of the object. Second time period is the alarm time, during which is transmitted the information on fire rising to the users of the object either directly or through the warning signals. Activation of warning signalisation can be either immediate or with time delay.

Time to start of evacuation t_z consists of detection time, time needed for deciding (perception and processing the information) and time necessary for activities before leaving.

Time of persons´ movement through the building t_u is time since initiation of persons escape in the object to reaching safe place (e.g. open space). Through suitable calculation methods, it is possible to determine escaping time based on relatively simple relations.

With increasing number and density of persons generally rises also complexity of evacuation. The density of persons can be expressed by equation:

$$D = \frac{\sum_{j=1}^{m} E_j}{\sum_{i=1}^{n} A_i} \tag{4}$$

Speed of movement and flow can be expressed in the interval from 0,54 persons.m^{-2} till 3,8 persons.m^{-2} by the equation [3]:

$$v = k - 0{,}266.k.D \quad (5)$$

Capacity of escape route, also referred to as specific or total flow of persons, represents the number of persons evacuated in time unit by unit of width of escape route, eventually its whole width, and can be expressed by equations:

$$F_s = v.D;\ F_c = F_s.B \quad (6)$$

Time of movement through the building it is possible to determine by sum of time required for distance overcoming t_{u1} and time required for passage through the less suitable place on the escape way t_{u2}:

$$t_u = t_{u_1} + t_{u_2} \quad (7)$$

While solving partial lengths of escape routes it is possible to determine time of persons movement through the building t_u by adjustment of the original equation by *Kikuja Togawa*:

$$t_u = \frac{\sum_{i=1}^{n} 0{,}75 \cdot l_{u_i}}{\sum_{i=1}^{n} v_i} + \frac{E}{F_S.B} \quad (8)$$

Analogical equation was presented in lit. [4] and it is also stated in standards of buildings fire safety in the Czech Republic [5].

Time needed for evacuation will be consequently compared with chosen criteria of acceptability. In the given case the criteria of acceptability chosen were *unsmoked height of space of 2,5 m and limit temperature of gas layer of 200 ℃*, which cumulates under the ceiling construction.

From the previous paragraphs, it is obvious that *time of movement through the building* t_u represents just one of the partial times characterizing *required safe escape time* t_c. While assessing persons' evacuation by fire engineering methods, there will be probably more often used the very *required safe escape time* t_c which can provide more real image of persons evacuation time from the object and be one of the parameters for design of fire safety devices and arrangements.

EVACUATION ASSESSMENT IN THE DEFINED PART OF THE OBJECT

Principles for evacuation of persons assessment

The following characteristics were among the most important data related to evacuation of people:

- dispositional layout of single floors is simple and well-arranged,
- persons are in the visual contact,
- employees are in the productive age, average physical and psychical condition,
- presence of persons with limited movement ability is rare, persons unable of individual movement are not present,
- in the assessing part of the object, there are only persons acquainted with the building,
- persons are present only in day-time and wide awake,
- persons in assessing spaces are regularly educated in the fire protection area,
- there is periodical fire alarm used for training in the object,
- the object is equipped with electric fire signalisation device (EFS) with emergency sound system,
- the EFS device works in the two-stage regime of fire alarm, when the announcement of evacuation by the emergency sound system is in the first stage of signalisation.

At assessing, it is supposed that defined constructional, technical and organisational arrangements will be observed in the course of construction. Fulfilment of defined conditions will be systemically checked in the course of building operation (system of controls in the regular intervals).

Determination of persons movement time t_u by the detailed calculation

In the following paragraphs, parameters of unprotected escape ways will be considered in the characteristic part of the object floor by the detailed calculation reflecting especially density of persons in the assessing premises [3], [6], [7]. The most significant input values vare shown in Tab.1.

Table 1. *Input values for evacuation assessment in the assessed part of the floor*

Room name	Number of persons *E* (persons)	Area *A* (m^2)	Length of escape route l_u (m)	Width of escape route *B* (m)
Conference room	67	100,0	12,5	1,6
Office section including separate offices, kitchen and hall	147	636,9	26,0	1,4[1]

Depending on density of persons, the speeds of persons movement in the premises of conference room and large-area office with related facilities have been determined. Consequently, the specific and total flow of persons for critical places of unprotected escape ways (doorways) up to entry into hall space that is part of the protected escape way has been determined. Output values are stated in the tab. 2.

[1] *On the fixed wing of double wing door between office section and hall there will be installed lever gate.*

Table 2. *Output values for determination of the persons movement time in the assessed part of the floor*

Room name	Density of persons D (per.m^{-2})	Movement speed of persons (m.min^{-1})	Specific flow of persons F_s (per.min^{-1}.m^{-1})
Conference room	0,67	69,0	46,24
Office section	0,23[2] (0,54)	71,93	38,84
Room name	**Total flow of persons F_c (per.min^{-1})**	**Movement time of persons t_{u1} (min)**	**Movement time of persons t_{u2} (min)**
Conference room	73,98	0,14	0,90
Office section	54,38	0,27	1,90[3]

Supposed time of persons movement t_u to the hall spaces is 2,31 minutes.

Determination of required safe escape time t_c from the assessed part of the floor

At detailed assessment of the persons evacuation, it is advisable to set necessary time for persons evacuation t_c, when is possible to proceed according to the equation (1) of the article. Determination of *detection and alarm time* t_d and *time to start evacuation* t_z can pose certain problem in practice, where it is necessary to estimate stated values. It is necessary to realise that stated values can take the same or higher values than self *time of persons movement through the building* t_u. For assessment, we can use [8].

Based on the assumptions stated in the previous paragraphs, determination of time needed for evacuation has been shown in the tab. 3.

Table 3. *Determination of the time needed for evacuation in the assessed part of the floor* t_c

Assessing place	Detection and alarm time t_d (min)	Time to start of evacuation t_z (min)	Time of movement through the object t_u (min)	Required safe escape time t_c (min)
Entry to the hall	1	0,5	2,31	3,85

Time needed for evacuation to the entry of protected escape way is 3,85 minutes. Time of smoke layer decrease in the premises of large-area office to the level of 2,5m is approximately 4 minutes[4] (see fig. 2). Temperature of smoke layer in the assessed premises will not exceed 200°C (see fig. 2). Defined criteria of acceptability in terms of safe persons evacuation assessment can be evaluated as satisfactory.

Assessed parameters, i.e. smoke layer decrease and temperature course in the assessed part of the floor, stated by model CFAST are presented in the fig. 3.

Smoke layer level and temperature stated by FDS model in the assessed part of the floor in the time of 300 s, are shown in the fig. 4.

Commentary on the possibilities at more complex proceeding of evacuation assessment

In the previous paragraphs, we described a more detailed proceeding of evaluation of some parameters used at escape ways assessment, i.e. time needed for persons evacuation, time for filling of premises with smoke gases to the level 2,5m and smoke layer temperature course in the characteristic part of the floor. Although similar evaluation of the above described parameters requires using of fire engineering methods, it is the assessment of the easiest determinable parameters.

The safety of persons on the escape ways can be also assessed by another parameters, e.g. visibility in the space, toxicity of combustion products. Determination of these parameters is however usually more complicated, sensitive to precise entering conditions (e.g. type and amount of flammable material, which is in the assessing premises) and changes during building operation.

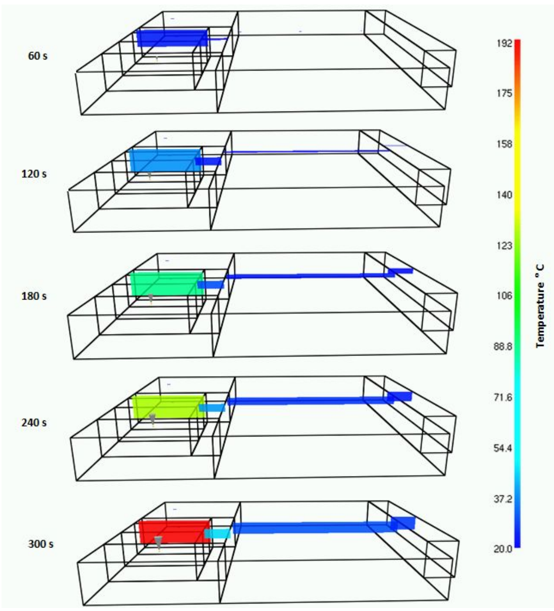

Figure 3. *Illustration of smoke layer decrease and temperature course in the assessing part of the floor*

[2] *At movement speed determination was respected lower limit of utility of equation (3), then 0,54 persons.m^{-2}.*

[3] *The value is related to 70 % of persons of all rooms in the assessing part of the floor.*

[4] The less suitable value acquired by fire models has been considered

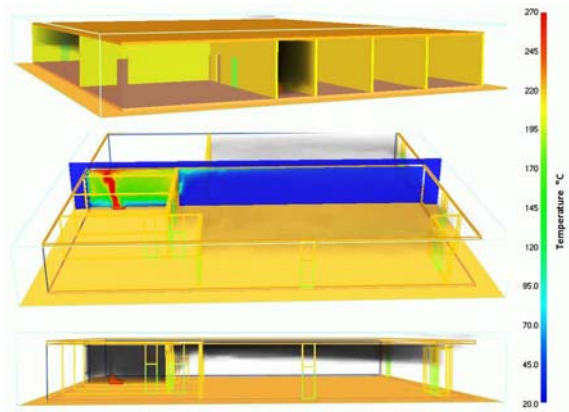

Figure 4. *Illustration of the smoke layer level and temperature in the assessing part of the floor*

CONCLUSION

This article elaborates on the possibility of fire models CFAST and FDS usage for fire dynamics assessment on the specific case of the defined part of the object, when the temperature direction and smoke layer level have been evaluated. In this case, the results of both models achieve the good equality.

Input values acquired by fire models were used as a basis for detailed assessment of persons evacuation executed through "manual" calculations. Evaluation was used to prove that the stated criteria of acceptability have not been exceeded. The article demonstrates the possible combination of sophisticated tools, fire models with simplified calculation process for application in a certain case.

SYMBOLS

A room or compartment area where are people (m^2)
B width of escape route (-)
D density of persons (persons.m^{-2})
E number of persons (persons)
F_s specific flow of persons (pesons.min^{-1}.m^{-1})
F_c total flow of persons (person.min^{-1})
$\dot{Q}$ heat release rate HRR (kW)
$\dot{Q}_0$ reference heat release rate (1000 kW)
a coefficient of burning rate according to ČSN 73 0802
k coefficient of persons movement speed (m.min^{-1})
l_u length of escape route (m)
l_{ui} length of i-escape route (m)
p fire load according to ČSN 73 0802 (kg.m^{-2})
t time after initiation (s)
t_c required safe escape time (min)
t_d detection time and alarm time (min)
t_g required time for reaching reference velocity (s)
t_u time of persons movement through the building (min)
t_{u1} time required for distance overcoming (min)
t_{u2} time required for passage trough escape way (min)
t_z time to start of evacuation of persons (min)
v speed of movement (m.min^{-1})
v_i i-speed of movement (m.min^{-1})

REFERENCES

[1] NIST National Institute of Standards and Technology, Building and Fire Research Laboratory [online]. URL: http://<cfast.nist.gov> [cit. 22.10.2010]. Last revision 04.07.2009.
[2] NIST National Institute of Standards and Technology, Building and Fire Research Laboratory [online]. URL: http://<fire.nist.gov/fds> [cit. 24.01.2011]. Last revision 22.11.2010.
[3] GWYNNE, S. M. V., ROSENBAUM, E. R.: Employing the Hydraulic Model in Assessing Emergency Movement. *SFPE Handbook of Fire Protection Engineering*. Fourth Edition, Section 3, Chapter 13. Quincy: National Fire Protection Association, 2008, s. 373-396, ISBN-10:0-87765-821-8, ISBN-13: 978-0-87765-821-4.
[4] PREDTEČENSKIJ, M., MILINSKIJ, I. *Evakuace osob z budov*. Praha: Svaz požární ochrany, Svazek 30, 1972, 272 s.
[5] ČSN 73 0802 *Požární bezpečnost staveb - Nevýrobní objekty*. Praha: Úřad pro technickou normalizaci, metrologii a státní zkušebnictví, 2009.
[6] FOLWARCZNY, L., POKORNÝ, J. *Evakuace osob*. Ostrava: Sdružení požárního a bezpečnostního inženýrství v Ostravě, Edice SPBI Spektrum 47, 2006. 125 s. ISBN 80-86634-92-2.
[7] ISO/TR 13387-8 *Fire safety engineering Part 8: Life safety - Occupant behaviour, location and condition*. Geneva: ISO International organization for Standardization, 1999, 36 s.
[8] HOSSER, D.: *Leitfaden Ingenieurmethoden des Brand-schutzes*. Braunschweig, Technisch-Wissenschaftlicher Beirat (TWB) der Vereinigung zur Förderung des Deutschen Brandschutzes e.V. (vfdb), 2009, 386 s.

BIOGRAPHIES

Petr Kučera was born in Ústí nad Labem, in the Czech Republic, in 1978. He received the diplomas in fire safety and civil engineering and the Ph.D. degree in fire safety from the VŠB – Technical University of Ostrava (VŠB-TUO), Faculty of Safety Engineering.

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