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
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:

\[ Q = Q_0 \left( \frac{t}{t_g} \right)^2 \]  

(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:

\[ t_g = \frac{2000}{a \cdot \sqrt{p}} \]  

(2)

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

\[ t_g = \frac{2000}{1 \cdot (25)^{0.5}} = 400 \text{ s.} \]

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.

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 \( t_e \), which consists of partial time intervals:

\[ t_e = t_d + t_z + t_u \]  

(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:

\[ D = \frac{\sum_{j=1}^{m} E_j}{\sum_{j=1}^{m} A_l} \]  

(4)
**Safety Engineering**

**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]:

\[ v = k - 0.266 \cdot k \cdot D \]  
(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:

\[ F_2 = v \cdot D; F_c = F_s \cdot B \]  
(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 \( t_{u2} \):

\[ t_u = t_{u1} + t_{u2} \]  
(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:

\[ t_u = \frac{\sum v_i \cdot 0.75 t_{u1}}{\sum v_i} + \frac{E}{F_s \cdot B} \]  
(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 °C, 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:

- employees are in the productive age, average physical and psyhical 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 are shown in Tab.1.

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

<table>
<thead>
<tr>
<th>Room name</th>
<th>Number of persons ( E ) (persons)</th>
<th>Area ( A ) (m(^2))</th>
<th>Length of escape route ( L_u ) (m)</th>
<th>Width of escape route ( B ) (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conference room</td>
<td>67</td>
<td>100,0</td>
<td>12,5</td>
<td>1,6</td>
</tr>
<tr>
<td>Office section including separate offices, kitchen and hall</td>
<td>147</td>
<td>636,9</td>
<td>26,0</td>
<td>1,4(^1)</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>Room name</th>
<th>Density of persons $D$ (per.m$^{-2}$)</th>
<th>Movement speed of persons $V$ (m.min$^{-1}$)</th>
<th>Specific flow of persons $F_s$ (per.min$^{-1}$.m$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conference room</td>
<td>0,67</td>
<td>69,0</td>
<td>46,24</td>
</tr>
<tr>
<td>Office section</td>
<td>0,23² (0,54)</td>
<td>71,93</td>
<td>38,84</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Room name</th>
<th>Total flow of persons $F_c$ (per.min$^{-1}$)</th>
<th>Movement time of persons $t_{u1}$ (min)</th>
<th>Movement time of persons $t_{u2}$ (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conference room</td>
<td>73,98</td>
<td>0,14</td>
<td>0,90</td>
</tr>
<tr>
<td>Office section</td>
<td>54,38</td>
<td>0,27</td>
<td>1,90²</td>
</tr>
</tbody>
</table>

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 $t_c$

<table>
<thead>
<tr>
<th>Assessing place</th>
<th>Detection and alarm time $t_d$ (min)</th>
<th>Time to start of evacuation $t_z$ (min)</th>
<th>Time of movement through the object $t_u$ (min)</th>
<th>Required safe escape time $t_c$ (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entry to the hall</td>
<td>1</td>
<td>0,5</td>
<td>2,31</td>
<td>3,85</td>
</tr>
</tbody>
</table>

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 minutes⁴ (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

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⁴ The less suitable value acquired by fire models has been considered.
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\(^{-1}\))
\[ Q \] heat release rate HRR (kW)
\[ Q_0 \] reference heat release rate (1000 kW)
\[ a \] coefficient of burning rate according to ČSN 73 0802
\[ k \] coefficient of persons movement speed (m.min\(^{-1}\))
\[ l_e \] length of escape route (m)
\[ l_{ei} \] length of i-escape route (m)
\[ p \] fire load according to ČSN 73 0802 (kg.m\(^{-2}\))
\[ t_c \] time after initiation (s)
\[ t_d \] detection time and alarm time (min)
\[ t_b \] required time for reaching reference velocity (s)
\[ t_m \] time of persons movement through the building (min)
\[ t_{d1} \] time required for distance overcoming (min)
\[ t_{d2} \] time required for passage trough escape way (min)
\[ t_e \] 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


BIOGRAPHIES

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