**Acta Montanistica Slovaca** Volume **21** (2016), number **2**, 146-153

# Comparison of theoretical method of the gas flow in corridors with experimental measurement in real scale

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*The paper describes the principles of ventilation of underground structures, tunnels and corridors. It also presents a theoretical method of assessment of corridor structures where primary monitored values are velocity of spreading, temperature and depth of forehead of smoke wave in dependance on time and distance from the centre of fire. Results predicated by a theoretical method are compared to the values measured in a real large-scale experiment conducted in the tunnel Valík on the D5 motorway in the Czech Republic. This paper evaluates a possible use of theoretical calculation for constructions of tunnels. The presented method is based on a buoyancy of flue gases. At common constructions is the buoyancy effect one of the most significant phenomena, which affects the smoke movement. The specific type of tunnel constructions is the cause of phenomena that fundamentally affect the smoke flow. The importance of a buoyancy effect decreases significantly while the openness for tunnel construstions and the effect of fire ventilation becomes the major influences. These described effects are the cause of significant variances in realized experiments and applied theoretical method. Based on mentioned important discrepancies it is impossible to recommend this presented calculation method for using of tunnel constructions. The method would require an important modification so that would take into account the specifics of tunnel constructions.*

***Key words***: *Corridor, tunnel, velocity, temperature, depth, smoke*

## Introduction

Among the tasks of the mining ventilation it is possible to include the ensuring of sufficient air mass for breathing of people and the work of machines for dilution of harmful, toxic and explosive gases and the creation of optimal climate conditions in the workplace. Mining ventilation can be classified from many points of view. Division into natural and forced ventilation can be considered as a basic one. It is also necessary to mention the basic ventilation systems of mine ventilation, which include central ventilation, transverse ventilation (diagonal, border) and mixed ventilation (combined). Principles for solving of ventilation of coal mines significatly affect the presence of the methane gas. Then we can divide mines into gassy mines non-gassy mines. This classification is the reason of significantly different requirements for mine ventilation. [1]

Although, generally, it is possible to characterize tunnels with a length exceeding 50 m as underground structures, the construction of road and railway tunnels are exempted from this classification according to the legislation of the Czech Republic (they are not considered as underground objects) [2]. In terms of the potential risks of constructions of road and railway tunnels, it is possible to consider this approach, i.e. different requirements on the construction of tunnels and construction of mines, logically. In some ways, the constructions of tunnels are rather similar to „common constructions“ [3, 4]. The difference is also reflected in the ventilation system designs, that is possible to divide into longitudinal and transverse. The aim of the ventilation of tunel is to secure acceptable emission values during ordinary service and to create conditions for dealing with extraordinary incidents. [5]

The classification of tunnel constructions and the requirements for their safety equipment can vary, depending on the national requirements of each country [6]. Certain variances are applied also in the regulations of Slovak Republic. [7]

The occurrence of fires in public and administrative buildings in foreign countries gave the first impetus for the assignment of research works that were supposed to create a system of economically acceptable as well as sufficiently effective protection of people [8]. The priority of all research works of a similar nature is to reduce the consequences of emergencies [9].

One of the significant spheres of this research covered the problems of propagation of smoke in horizontal communications (tunnels, corridors). The experts aimed at creating a method suitable for evaluation of certain parameters of the propagating smoke wave. The most important of these parameters include the propagation velocity of the smoke wave front and the temperature and depth of the smoke wave. As a result, a mathematical model for evaluation of the above stated parameters was created. The model was subsequently implemented in

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the FPEtool zone model (National Institute of Standards and Technology, Building and Fire Research Laboratory, Gaithersburg, Maryland) in the part CORRIDOR [10].

The results acquired by modelling were compared with the experiments carried out in building structures of different geometric dimensions, using fires of various heat output values. In most cases, the correlation between the results stated by the FPEtool model of the part CORRIDOR and the real measured values was evaluated as admissible [8].

The aim of the paper is to compare the results obtained by a calculation method implemented into the FPEtool model to selected values of a real experiment implemented in the Valík tunnel in the Czech Repulic and, consequently, to evaluate a possible use of such method in tunnel constructions.

## Material and methods

### Basic factors influencing the moment of flue gases in corridors and tunnels

The movement of smoke occurring as a result of fire in corridors and tunnels as well as other building structures is influenced by a complex of factors of larger or smaller importance. The basic factors influencing the movement of smoke in the above-mentioned structures include mainly:

- chimney effect,
- effect of standing vehicles,
- wind,
- buoyancy effect,
- increase of volume of gases,
- ventilating and air conditioning equipment. [5]

The final pressure influencing the movement of gases in corridors or tunnels may be expressed by the equation [5]:

$$p_c = \sum_{i=1}^{n} \Delta p_i \qquad (1)$$

where

$p_c$ final pressure (Pa),

$\Delta p_i$ partial pressure difference (Pa).

The factors mentioned earlier in this paper influence the movement of gases either separately or, which is most often the case, by accumulation of all the phenomena described earlier or at least by accumulation of some of them.

In case of the movement of gases in the corridors that are closed constructions, the most important factors affecting mainly the initial phase of the propagation of gases include the buoyancy and the effect of ventilation and air conditioning equipment. The chimney effect usually reaches insignificant values. The influence of wind and the increase of volume of gases due to a fire have to be considered in relation to a particular situation. The occurrence of standing vehicles is not assumed here.

The tunnels that are characteristic of a considerable air or gas penetrability due to their technical layout (openness of the tunnel fronts) represent a different situation. The effect of wind and the installed ventilating and air conditioning equipment are regarded as the major factors affecting the movement of gases in tunnels. A part of this equipment is designed to provide the protection targets for the event of fire; these safety air conditioning systems may not be put out of service when a fire occurs. The influence of buoyancy and the standing vehicles has to be considered in relation to a particular situation. The influence of the chimney effect and the increase of volume of gases usually represent insignificant values, the former becoming more important in relation to increasing inclination of a tunnel.

The scope of each of the acting factors is an individual matter and should be evaluated solely in relation to a particular situation. When making actual calculations, it is purposeful to take into consideration the losses (local and caused by friction) occurring during the movement of gases in corridors and tunnels.

### Propagation of flue gases at the practical experiment in a road tunnel

In some cases, prior to putting the tunnels into operation, fire tests are carried out to verify the effectiveness of fire safety equipment and, in particular, of fire ventilation. The tests are necessary especially in case of complex or non-standard ventilation systems. In some cases, in particular when simple ventilation systems are used, the real tests can be substituted by reduced-scale tests or by modelling. [11]

On 22nd May – 26th May 2006, the large-scale fire tests were carried out in the tunnel Valík on the D5 motorway in the Czech Republic.

The experiment, which involved two tests, was designed to simulate a fire at the heating output of 5 MW. In case of the given heating output and the geometrical dimensions of the tunnel, we presumed the smoke release at the volume of 20 $m^3.s^{-1}$. During the experiment, a number of fire parameters were examined (especially temperature of flue gases, surface temperature of engineering structures, velocity of air flow and smoke flow, smoke opacity and decrease of layer of flue gases).

As regards the problems analysed in this paper, the most important characteristics appear to be the values of velocity of flow of gases. These values were measured at both tunnel fronts and approximately midway along its length as well. The variables were measured continuously and the values of some of them are stated in Table 1 [12].

*Tab. 1. Average values of the measured variables related to the flow of gases.*

| **Output values of measurement** | **1st test** | **2nd test** |
|---|---|---|
| **Average velocity of air in the Pilsen tunnel front** [$m.s^{-1}$] | 4,5 | 4,7 |
| **Average velocity of air in the middle part of the tunnel** [$m.s^{-1}$] | 1,8 | 2,7 |
| **Average velocity of air in the Prague tunnel front** [$m.s^{-1}$] | 2,5 | 2,6 |
| **Maximum temperature on the surface of the tunnel's engineering structure** [°C] | 139,6 | 122 |
| **Maximum temperature of flue gases in the tunnel** [°C] | ≈ 195 | ≈ 250 |

The partial results of undertaken experiments are not presented in this paper because of their complex evaluation or interpretation of achieved results. The values of velocity of flow of gases were stated here merely for the purpose of general comparison of the values acquired by experimental measurement with the values determined by the presented theoretical method.

### Theoretical method for the propagation of flue gases in corridors

On the basis of the experiments carried out, the parameters of the propagating smoke wave in corridors were derived [13]. The following mathematical relations are focused on the determination of the propagation velocity, temperature and depth of the smoke wave. The equations stated below were derived from the experiments carried out in closed constructions and thus do not take into consideration some other factors that are characteristic of open tunnel structures (e.g. wind).

### Propagation velocity of smoke wave

The propagation velocity of the smoke wave may according to [13] be determined by the equations:

$$x_{(t+\Delta t)} = x_{(t)} + \int_{t}^{t+\Delta t} \bar{v}\,dt \tag{2}$$

$$v_{front} = v_0 \cdot \left[ \frac{T - T_0}{T} \cdot e^{(-3Kx_{(t)})+B} \right] \tag{3}$$

$$B = \frac{T - T_0}{T} \cdot e^{(-6Kx_{(t)})} \tag{4}$$

$$K = \frac{\alpha \cdot W_{cor}}{3m_{wave} \cdot c_p} \tag{5}$$

where

$x_{(t+\Delta t)}$ position of the smoke wave front at time $t+\Delta t$ [m]
$x_{(t)}$ position of the smoke wave front at time $t$ [m]
$\bar{v}$ average velocity between the times t and $t+\Delta t$ [$m.s^{-1}$]
$v_{front}$ position of the smoke wave front [$m.s^{-1}$]
$v_0$ initial velocity of smoke wave [$m.s^{-1}$]
$T$ initial temperature of smoke wave [K]
$T_0$ ambient air temperature [K]
$K$ constant [$m^{-1}$]
$B$ variable used in equation (15) [-]
$\alpha$ heat transfer coefficient [$kW.m^{-2}.K^{-1}$]
$W_{cor}$ width of corridor [m]
$m_{wave}$ mass flow of smoke [$kg.s^{-1}$]
$c_p$ heat capacity of gases [$kJ.kg^{-1}.K^{-1}$]

### Temperature of smoke wave

The temperature of the smoke wave may according to [13] be determined by the equations:

$$\bar{T} = \frac{1}{(L - x_0)} \int_{x_0}^{L} T_{(x)} dx \tag{6}$$

$$T_{(x)} = T_0 + (T - T_0) \cdot e^{(-3Kx_{(t)})} \tag{7}$$

where

| | |
|---|---|
| $\bar{T}$ | average temperature of smoke wave at the distance from $x_0$ to $L$ [K] |
| $L$ | smoke propagation distance in corridor [m] |
| $x_0$ | initial position of smoke wave [m] |
| $T_{(x)}$ | temperature of smoke wave at point x [K] |
| $T_0$ | ambient air temperature [K] |
| $T$ | initial temperature of smoke wave [K] |
| $K$ | constant [$m^{-1}$] |
| $x_{(t)}$ | position of the smoke wave front at time t [m] |

### Depth of smoke wave in a corridor

The depth of the smoke wave may according to [13] be determined by the equations:

$$D = \frac{m_{wave} \cdot t \cdot T}{T_0 \cdot \rho_0 \cdot \xi \cdot W_{cor}} \tag{8}$$

$$\xi = x_{(t)} + \frac{1}{3K} \ln\left( \frac{T_0}{T} + \left(1 - \frac{T_0}{T}\right) \cdot e^{(-3Kx_{(t)})} \right) \tag{9}$$

where

| | |
|---|---|
| $D$ | depth of smoke wave [m] |
| $m_{wave}$ | mass flow of smoke [$kg.s^{-1}$] |
| $t$ | time [s] |
| $T$ | initial temperature of smoke wave [K] |
| $T_0$ | ambient air temperature [K] |
| $\rho_0$ | ambient air density [$kg.m^{-3}$] |
| $\xi$ | variable used in equation (8) [m] |
| $W_{cor}$ | width of corridor [m] |
| $x_{(t)}$ | position of the smoke wave front at time t [m] |
| $K$ | constant [$m^{-1}$] |

Selected characteristics of the spreading of layer of smoke in the corridor are shown in the Figure 1.

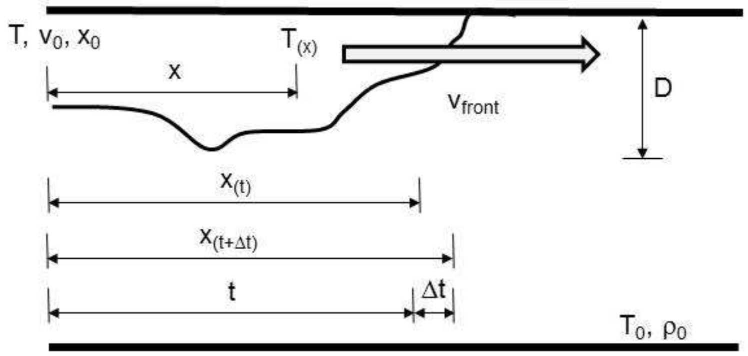

*Fig. 1. Characteristics of the spreading of layer of smoke in the corridor.*

At present time, a number of research papers also deal with the assessment of parameters of a spreading smoke layer. The parameters are assessed by using a numerical or analytical method, as the case may be [14]. In addition, fire models, especially Computational Fluid Dynamics (CFD), are intensively used [15, 16].

## Results and discussion

The theoretical method described in the previous part of this paper enables to predicate some of the parameters concerning the propagation of flue gases in corridors. The method was applied to the corridor of the dimensions 12,5/8,15/180 m (width/height/length), where the flue gases propagate in one direction only. The data were selected in order to correspond to the geometrical dimensions of the building structure inside which the practical experiment, described in the following paragraphs, was carried out. The input values for the computational simulation, especially the initial temperature of flue gases, were taken from the values acquired by the measurement at the practical experiment for the sake of their mutual comparability (Tab. 1). For the purpose of comparison it was assumed that the average temperature of flue gases approached the highest temperature measured on the surface of the engineering structures.

Table 2 shows the forecasted parameters of the smoke wave and the values acquired by application of the equations (2 to 9) stated earlier in this paper. The results represent average values or values determined at the end of the corridor.

*Tab. 2. Parameters of smoke wave determined by calculation [17].*

| Parameters of smoke wave | 1st test | 2nd test |
|---|---|---|
| **Initial velocity of smoke wave** [m.s$^{-1}$] | 1,5 | 1,38 |
| **Velocity of flue gases at the end of corridor** [m.s$^{-1}$] | • 0,56 | • 0,55 |
| **Average velocity of flue gases** [m.s$^{-1}$] | • 0,94 | • 0,89 |
| **Time interval for covering the distance of 150 m at the average velocity of flue gases** [s] | • 191 | • 202 |
| **Temperature of smoke wave at the end of corridor** [°C] | • 28,6 | • 28,2 |
| **Depth of smoke wave at the end of corridor** [m] | • 2,11 | • 2,23 |

Some of the parameters determined by the calculation are shown in Figures 2 and 3.

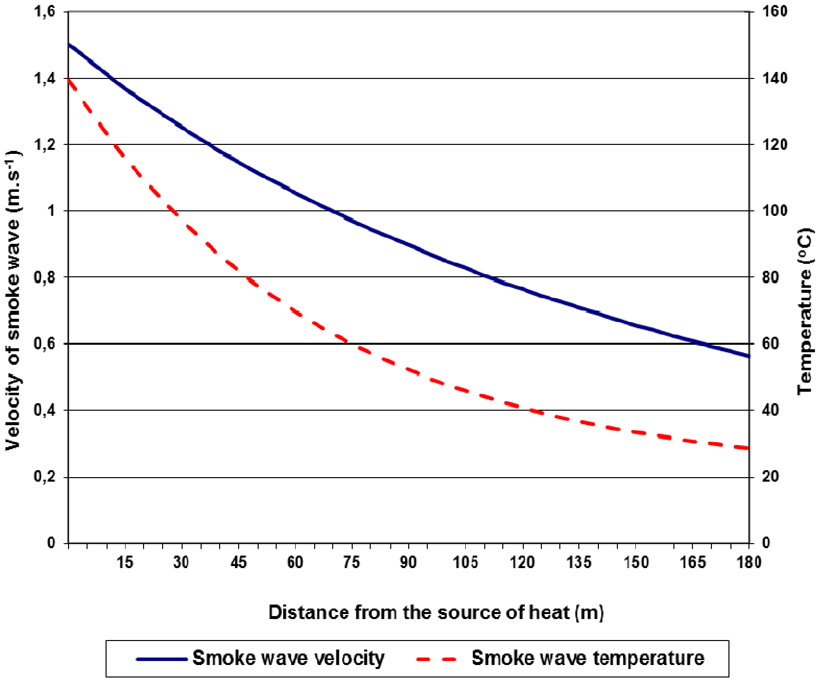

*Fig. 2. Parameters of smoke wave determined upon the input values of 1st test [17].*

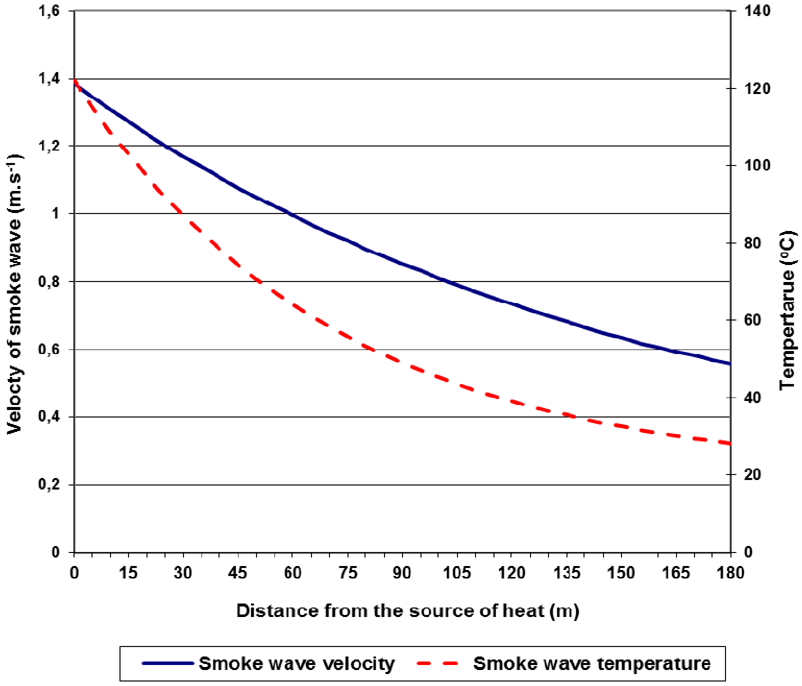

*Fig. 3. Parameters of the smoke wave determined upon the input values of $2^{nd}$ test [17].*

Upon comparison of the calculated (Tab. 2) and measured (Tab. 1) values we may state that the values reach mutually significant variations. It is obvious that the velocity of flow of gases caused by the buoyancy effect need not be a dominant factor in the tunnel structures.

It is clear from the practical experiment carried out in the road tunnel Valík that acting of the wind together with the compulsory ventilation (jet fans) has a major effect on the velocity of flow of gases in tunnels. As stated in Table 1, the values of average velocity of the flow of gases ranged from 1.8 to 4,7 m.s$^{-1}$. These values are markedly higher than the average values of velocity of the flow of gases caused by the mere buoyancy effect, which ranged from 0.89 to 0.94 m.s$^{-1}$ (Tab. 2).

However, the movement of gases in road tunnels, which are open structures to a great extent and at the same time are equipped with technical devices ensuring ventilation, is substantially influenced by other aspects, different from the corridors in closed structures. In terms of smoke wave propagation, such openness of structures and influence of ventilation equipment can be considered essential. In comparison with the mentioned phenomena, the others, in particular the buoyancy effect, are of minor importance.

Development of fire and thus the flow of smoke in tunnels may have a significant impact on other fire safety equipment, e.g. an automatic sprinkle system [18].

## Conclusion

The paper describes general principles of ventilation of mines and differences concerning constructions of tunnels and corridors. Also there is presented the theoretical method for the determination of selected parameters of smoke spreading in structures of corridors. The method was derived experimentally, whereby the essence of this method is evaluation of spreading of smoke waves based on the buoyancy effect.

The use of presented theoretical methods for evaluation of smoke movement in constructions of corridors must be regarded as problematic. The buoyancy effect may represent a minor effect from the point of view of the relevant smoke wave characteristics, especially its propagation velocity. Without taking into consideration the other factors, the described theoretical method is applicable only to the closed building structures.

Also in closed construction objects, it is necessary to take into account other factors which can influence the movement of gases in constructions.

Although the development of a model of fire FPEtool has bee completed, it is possible to consider the presented method as usable in the future. For the tunnel constructions would be necessary to significantly modify the method so that reflects the specifics of tunnel contructions. This can be the subject of a future work for researchers. I any case, it is necessary to respect the limits of the method related to conditions of experiments, on which the method has been created. The alternative of the solution is to apply an other calculation method, which will report a more favourable agreement in results.

***Acknowledgement**: This article arose with the support of the Ministry of Interior in Czech Republic no. VG 20122014074 called "Specific assessment of high-risk conditions for fire safety with the use of fire engineering methods".*

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