Volume XXII 2019
ISSUE no.2
MBNA Publishing House Constanta 2019

Scientific Bulletin of Naval Academy

Fire smoke propagation mode and the importance of ventilation efficiency for emergency situations in subway systems

To cite this article: A. F. Chiojdoiu and V. N. Panaitescu, Scientific Bulletin of Naval Academy, Vol. XXII 2019, pg.177-184.

ISSN: 2392-8956; ISSN-L: 1454-864X

doi: 10.21279/1454-864X-19-I2-021

Fire smoke propagation mode and the importance of ventilation efficiency for emergency situations in subway systems

Alexandru-Florin Chiojdoiu, Valeriu Nicolae Panaitescu

Abstract. It is well known that the efficiency of the ventilation is extremely important in subway systems. The ventilation system is one of the main aspects of subway infrastructure when emergency situations involving fire or massive release of smoke and toxic gases occur inside the tunnels. Otherwise, the performance of the ventilation is the key factor of the subway systems when unfortunate events such as fires, chemical or biological attacks take place as in such situations a large number of victims can occur. The use of efficient ventilation systems, the existence of sufficient evacuation pathways as well as the knowledge by the intervention teams of the phenomena occurring inside a subway tunnel in the event of a fire is a great help for protecting and saving people's lives.

1. Introduction

The development of underground transportation systems is a big necessity to facilitate the transportation of people in urban areas. Fires in subway systems could not only potentially cost human lives and injuries, but also result in significant costs in economic terms.

An underground public transport system is one of the most commonly used solution in modern, overfilled with road traffic, cities. The main advantage of subway system is the ability to move a large number of people from one point of traffic infrastructure to another. With this benefit, comes an increased risk of fire, thus special attention should be given to fire protection. The underground stations represent a special category of construction work, constituted, usually, from long compartments with low height and average of twoo or three escape routes. The fire scenarios connected to the fire of a train show, that growth of fire can be very fast and amounts of smoke produced big enough, to fill such a place in matter of minutes.

The huge number of people in the world's major metropolis has led to an increase in the number of subway networks built worldwide. The fires that take place in the subway stations can have very serious consequences leading to loss of human lives because the subway stations are closed spaces, located underground, where a large number of people circulate. The main cause of death in the event of a fire is the exposure of the population to smoke and toxic gases, and therefore the design of smoke exhaust systems is very important.

2. The piston effect and the piston wind phenomenon

The use of the smoke and toxic gas exhaust systems presents a special importance to fulfill one of the principles of the management of emergency situations, namely the priority of protection and the salvation of people's lives. The efficiency of these systems can be influenced by many factors, such as the exterior wind, the water droplets sprayed by sprinklers, the constructive characteristics of the tunnel and the subway station, etc.

From a constructive point of view, the connection between tunnels and platform of a metro station has three types, namely closed, semi-closed and open. When a train circulates in a tunnel, the air movement is driven along the tunnel and air flow through the tunnel walls is almost completely suppressed. This phenomenon that occurs is known as Piston Effect, and the airflow produced by running train is known as piston wind. In case of the semi-enclosed type or open type subway stations, the piston wind would directly affect the propagation with rapidity of fire smoke inside them. The stratification of smoke layers would be broke by horizontal inertial force which is a characteristic of the phenomenon called the piston wind.

In some countries, such as China, for example, if a fire occurs in platform of metro stations, the intervention teams apply the following procedure which implies the use of two emergency managements of vehicles. One of them is stopping vehicle in tunnel in order to evacuate the passengers and the other is passing the station on fire in order to parking in the next station. Thus, the smoke propagation in metro stations would be effected by the piston wind phenomenon greatly in the second situation.

In the **Figure 1** is presented a sketch of metro station, and the hypothesis that a fire erupted on the subway station platform.

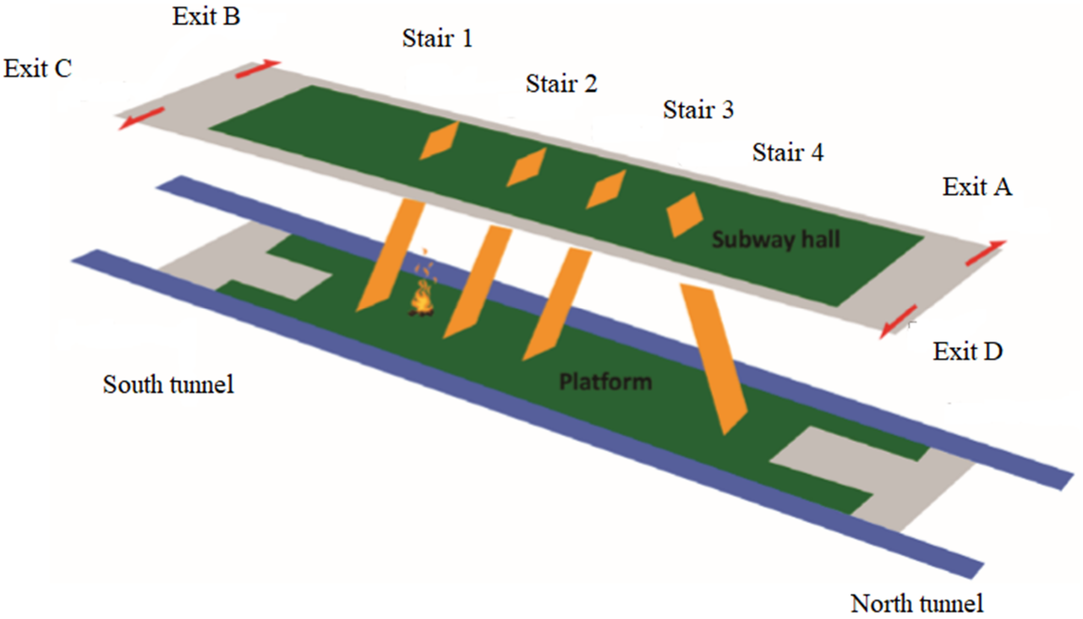


Figure 1 The sketch of metro station

3. The equation of the platform fire and the 3D flow of piston wind

The platform fire and the 3D flow of piston wind can be described by the equations (1) (2), (3) which are shown below.

a) The mass conservation equation [1]

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0, \qquad (1)$$

where ρ - mixture density, t - time, x_i - spatial coordinate in i direction, u_i - velocity component in i direction.

b) The momentum equation [1]

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} + \rho g_i + F_i, \qquad (2)$$

where x_j - spatial coordinate in j direction, u_j - velocity component in j direction, p - static pressure, $\tau_{ij} = \mu(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i})$ - component of shear stress tensor, μ - dynamic viscosity, g_i - acceleration due to earth's gravity in i direction, F_i - source in i direction.

c) The energy equation [1]

$$\frac{\partial}{\partial t}(\rho h) + \frac{\partial}{\partial x_j}(\rho u_i h) = -\frac{\partial}{\partial x_i}(k_{tc} + k_{tci})\frac{\partial T}{\partial x_i} + S_h, \quad (3)$$

where h - heat transfer coefficient, k_{tc} – the molecular thermal conductivity, k_{tci} - the thermal conductivity caused by turbulence diffusion, T – temperature, S_h - the volumetric heat sources.

The two-equation model $k - \varepsilon$ has been used in order to solve engineering turbulence problems. Thus, the $k - \varepsilon$ model can be used to solve the smoke turbulent flow. The governing equation of turbulent kinetic energy k and the turbulent dissipation ε is shown in equations (4) and (5) [1]

$$\rho\frac{\partial k}{\partial t} = \frac{\partial}{\partial x_j}\left[(\mu + \frac{\mu_t}{\sigma_k})\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon; \quad (4)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} = \frac{\partial}{\partial x_j}\left[(\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j})\frac{\partial k}{\partial x_j}\right] + \frac{\varepsilon}{k}$$
$$[c_1(G_k + G_b)(1 + c_3 R_f)] - c_2\rho\varepsilon, \quad (5)$$

where k - turbulent kinetic energy, $\mu_t = 0{,}09$, σ_k, σ_ε - empirical constants in turbulent models with two equations, G_k, G_b - the turbulent kinetic energy production term generated by velocity gradient and buoyancy, ε - turbulent dissipation, R_f – non-dimensional number and the constants $C_1 = 1{,}44, C_2 = 1{,}92, C_3 = 0{,}80$.

4. Use of mechanical and natural ventilation systems in subway stations

The fire in a subway station is an emergency situation of increased complexity given the large number of passengers and possible consequences that can affect people's lives.

The direct exposure to fire is not the main danger to passengers' life in these situations since the most of the victims were caused by the smoke inhalation. Indeed, in the case of a subway fire, there are a lot of toxic gases released due to incomplete combustion of different materials. In addition, the smoke exhaust is more difficult to be properly achieved within underground systems as the toxic gases are gathered in almost complete enclosed spaces.

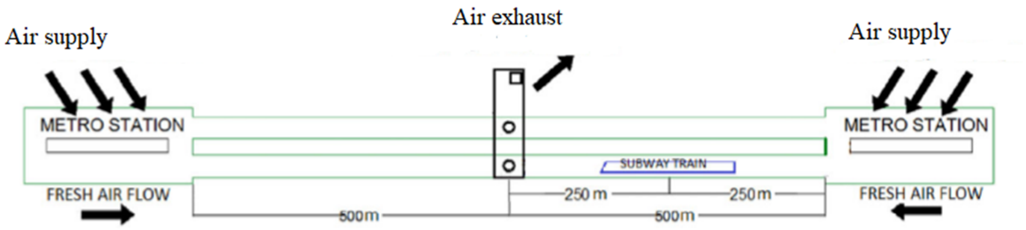
The ventilation system is one of the main aspects of subway infrastructure when emergency situations involving fire or massive release of smoke and toxic gases occur inside the tunnels. The main objective is that the ventilation system used to give the expected yield to one of the most bleak scenarios. This scenario assumes that a subway train has stopped inside a tunnel, which requires the emergency evacuation of all passengers.

In order to evacuate smoke from a fire, two types of ventilation can be used: mechanical and natural.

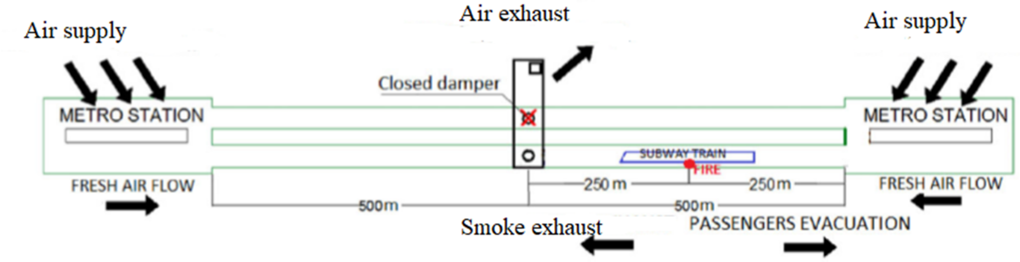
4.1. Mechanical ventilation

Two ventilation strategies can be used:

- ✓ tunnel ventilation fan system represented by the existence of a mid-tunnel fan plant located in separate construction, in conjunction with subway stations mechanical ventilation as presented in **Figure 2 -** configuration „A”**;**
- ✓ end-of-station fan plants in conjunction with subway stations mechanical ventilation as presented in **Figure 3 -** configuration „B”**;**



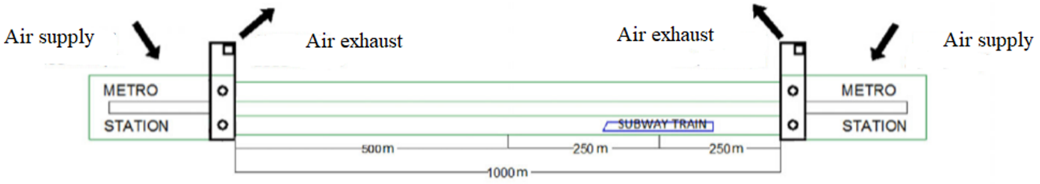
Normal operating mode



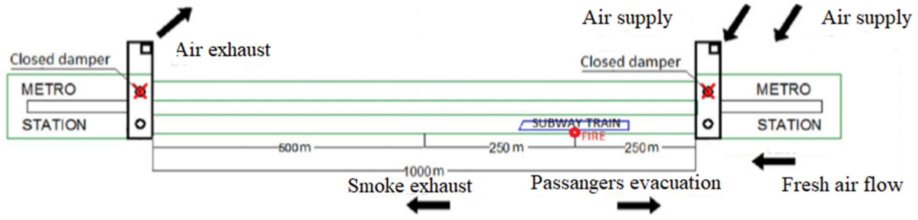
Emergency (fire) operating mode

Figure 2 Ventilation system configuration „A”

In order to change the operating mode from normal mechanical ventilation to emergency (fire) ventilation, in the configuration “A”, the supply airflow of the ventilation plants in the stations are brought to the appropriate fire situation, while the exhaust airflow of tunnel ventilation fan system is changed to a higher flow rate. Thus, the damper of the tunnel ventilation fan system, communicating with the tunnel area where there is no fire, is closed.



Normal operating mode



Emergency (fire) operating mode

Figure 3 Ventilation system configuration „B”

As evidenced by the configuration “B”, the normal operating mode of stations mechanical ventilation is changed in case of fire, the ventilation plant in the farthest station from the train on fire is turned off while the supply airflow of the ventilation plant located in the nearest station to the train on fire is increased to a higher flow rate. In addition, one of the two end-of-station fan plants, which operated both on “exhaust mode”, switches on “supply mode”, located in the closest station to the train on fire, while the other one (in the farthest station from the train on fire) remains on “exhaust mode”. The two dampers, communicating in the stations with the tunnel where there is no fire, are closed.

The results obtained from the research conducted using the simulation methodology both in normal conditions and in the situation of a fire have shown that both ventilation alternatives can be used successfully. Thus, the evacuation of passengers to the nearest metro station has been made safe. Passengers were not affected by high temperatures, high CO or CO_2 concentrations, or high air velocities.

The excellent operation of mechanical ventilation systems involves, in most cases, the efficient activity of several subsystems. Thus, when the fire suddenly happens, there is a probability that staff cannot always recognise the source of fire properly and take the most effective measures. The natural ventilation used for the evacuation of smoke has proved to be an effective option, both in terms of low costs and in terms of maintenance compared to mechanical ventilation.

4.2. Natural ventilation

Regarding the natural ventilation it turns out to be an effective alternative for smoke control in case of fire. After using the theoretical analysis and the numerical method it is ascertained that, the main factors that directly influences high yield of the smoke exhaust system, when setting shafts for the hall layer, are the total ventilation area and the height of the shafts. The multistage shafts can be used for smoke control in the platform layer. Thus, the strong stack effect formed in this layer can bring many benefits. To accentuate the stack effect phenomenon and form the best smoke flow ways, the solutions are to increase the smoke screen height and also to close all the existing platform screen doors.

Thus, the natural ventilation implies the use of shafts for the the platform layer, or for hall layer.

To do the natural ventilation for the hall layer, it is necessary to set shafts on its ceiling and to account of certain factors such as the geometric dimension, the location and the amount of the shafts. The construction of these shafts involve certain costs and difficulties. This methodology is based on the theory of two-zone model. Because the hall layer has a large inner space, the stable smoke layer and the boundary between the two different zones may not be clearly formed during the fire.

The **Figure 4** shows the side view of a subway hall layer, where $\dot{m}_p$ - plume mass flow rate, $\dot{m}_e$ and $\dot{m}_d$ - mass flow rates out of and into the hall layer, A_e and A_d - outlet and inlet openings, H_e and Z - ceiling and smoke layer heights, ΔP_i - pressure difference across the lower opening.

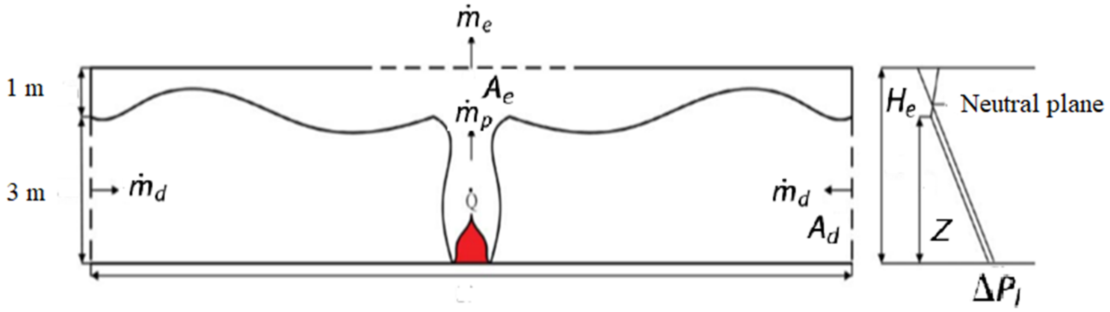


Figure 4 Natural ventilation with the ceiling vent and pressure differences.

On the using the shafts for the platform layer it is ascertained that there is no space enough to set ceiling shafts directly connected to the ground. Though it may be possible to use ceiling shafts of the adjacent tunnels for natural ventilation. In these conditions the smoke from the fire may flow into the hall layer due to the weak negative pressure formed in the platform layer.

As shown in **Figure 5**, where PSD is platform screen doors, six shafts are set on the ceiling of the platform layer with the location snapped to the upper shafts. The height of these shafts was set as 3 m so there existed a short distance between the lower and the upper shafts. Thus, the height of the steady-state smoke layer is about 3 m in the hall layer. The lower shafts will have little effects on the smoke control efficiency in the hall layer. However, to the platform layer fire, the lower shafts can exhaust smoke efficiently and transfer the smoke to the upper shafts. At last, the smoke in the platform layer will be exhausted to the outside by the multistage shafts.

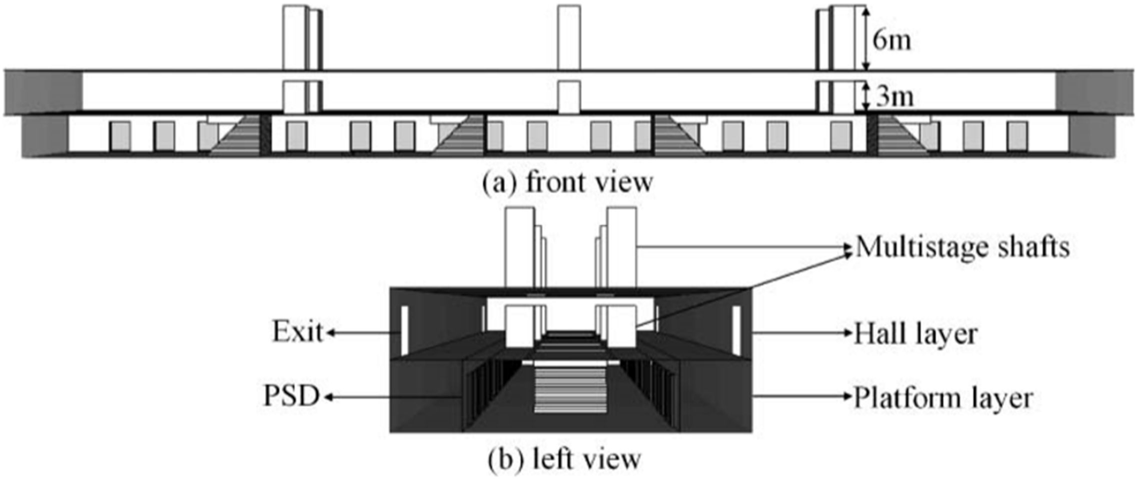


Figure 5 Full-scale subway station model with multistage shafts

The stack effect phenomenon has a great influence in the case of using multistage shafts for smoke control in the platform layer. In general, the stronger of the stack effect, the better efficiency of exhausting smoke by the shafts. The strength of stack effect mainly depends on the negative pressure formed in the fire region. Thus, more paths for smoke flowing out or air flowing in will reduce the negative pressure and weaken the stack effect.

5. Motion equation of airflow, monoxide carbon and carbon dioxide

In order to determine the effectiveness of the ventilation systems (related to airflow and pollutant dispersion), we can consider a mixture air–carbon monoxide (CO) – carbon dioxide (CO_2) with the following properties:

– the mixture is an ideal gas, consisting of three perfect gases (air, CO, and CO_2);

– the mixture is an incompressible Newtonian fluid; – there is no chemical reaction between the three gases (air, CO, and CO_2);

– heat and mass transfer interactions (Soret and Dufour effects) in the mixture are negligible;

– mixture density: ideal gas law formulation, depending on the mixture temperature and the mass fraction of each species (air, CO, and CO_2););

– mixture specific heat capacity: mixing law formulation, based on mass fraction average of the three species (air, CO, and CO_2);) heat capacities;

– mixture thermal conductivity and viscosity: determined by means of kinetic theory;

– diffusion coefficient: constant values, CO in air: $2 \times 10^{-5}\, m^2/s$; CO_2); in air: $1{,}6 \times 10^{-5}\, m^2/s$; [5].

In order to represent the pollutant transport and diffusion, we can introduce equations expressing the conservation of the CO and CO_2 mass fraction (defined as the ratio of that species mass contained in a given volume to the total mixture mass contained in the same volume). These equations are added to the elementary equations governing a turbulent non-isothermal airflow (conservation of mass, momentum, energy, and turbulent quantities). These conservation equations can be written as a classic convection–diffusion equation, in a tensor notation [5]

$$\rho \frac{\partial}{\partial x_i}(u_i m_{i'}) + \frac{\partial}{\partial x_i} J_{i',i} = S_{i'}. \tag{6}$$

In equation (6), the left-hand side terms stand for the convective term (where $m_{i'}$ - species mass fraction, CO or CO_2) and diffusion term respectively (with $J_{i',i}$ - CO diffusion flux or CO_2 diffusion flux), while the right- hand side term $S_{i'}$ represents source/sink term.

The diffusive term in equation (6) integrates both classical aspects of diffusion, molecular and turbulent [5]

$$\frac{\partial}{\partial x_i} J_{i',i} = \rho \frac{\partial}{\partial x_i}\left(D_{i',m} \frac{\partial m_{i'}}{\partial x_i}\right) - \frac{\partial}{\partial x_i}\left(-\overline{u_i' m_i'}\right) \tag{7}$$

where $D_{i',m}$ stands for the species (CO or CO_2) molecular diffusion coefficient and $u_i' m_i'$ signifies the turbulent mass flux of CO or CO_2, u_i' being the velocity fluctuation.

Finally, the mixture flow modeling took into account a three-dimensional, turbulent, non-isothermal flow. The turbulence modeling is based on the standard $k-\varepsilon$ two-equation turbulence model as this approach was the most used for numerous engineering applications with good results. The $k-\varepsilon$ turbulence model was used in similar studies, leading to realistic descriptions of the mean air–smoke. On the other hand, detailed investigations of the flow turbulent structure based on more sophisticated turbulence models do not substantially improve the results since the impact of these detailed turbulent structures on the air–smoke flow is minimum and can be neglected. Concerning the near wall treatment of the flow, this approach is based on standard wall functions.

6. Conclusions

The phenomenon of piston wind have a great influence on massive smoke and toxic gases inside the subway stations and one of the following is the change in the flow field. Thus, the form of flow field in platform is irregular, and the direction of air flow at stairs and entrances of tunnels reverse several times, with the entrance of running train. The smoke's propagation in subway stations is accelerated by the piston wind.

Regarding the mechanical ventilation, the both ventilation strategies taken into consideration lead to the safe evacuation of passengers. This is due to the fact that once they have left the train, as the access to the nearest station is not disturbed by air velocities that may cause difficulty in walking, high temperatures or dangerous levels of CO and CO_2 to human health.

The natural ventilation implies the use of shafts for the the platform layer, or for hall layer. An advantage of the use of natural ventilation is low cost respectively low maintenance, compared to mechanical ventilation. Thus, the strong stack effect formed in this layer can bring many benefits. To accentuate the stack effect phenomenon and form the best smoke flow paths, the solutions are to increase the smoke screen height and also to close all the existing platform screen doors.

However, regardless of the situation (upgrading existing metro network or design optimization of new metro lines), the main objective is establishing efficient ventilation solutions for emergency situations in subway systems.

References

[1] ZHONG W., TU R., YANG J. P., LIANG T. S., „*A study of the fire smoke propagation in subway station under the effect of piston wind*", JOURNAL OF CIVIL ENGINEERING AND MANAGEMENT ISSN 1392-3730 / eISSN 1822-3605 2015 Volume 21(4): p.514–523.

[2] WU F., JIANG J., ZHOU R., ZHAO D. & SHI L. „*A new natural ventilation method for fire-induced smoke control in a common subway station*", INTERNATIONAL JOURNAL OF VENTILATION, DOI: 10.1080/14733315.2017.1356056, 2017.

[3] WĘGRZYŃSKI W., KRAJEWSKI G., SULIK P., „*Choosing a Fire Ventilation Strategy for an Underground Metro Station*", 8th International Conference 'Tunnel Safety and Ventilation' 2016, Graz.

[4] LI Y. Z., INGASON H., LÖNNERMARK A., „*Correlations between different scales of Metro carriage fire tests*", SP TECHNICAL RESEARCH INSTITUTE OF SWEDEN, FIRE TECHNOLOGY, SP Report 2013:13.

[5] TEODOSIU C. I., ILIE V., DUMITRU R. G., TEODOSIU R. S. „*Assessment of ventilation efficiency for emergency situations in subway systems by CFD modeling*", BUILD SIMUL (2016) 9: 319–334 DOI 10.1007/s12273-015-0269-9.

[6] Https://www.ansys.com.