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MODELLING THE PISTON EFFECT IN SUBWAY TUNNELS USING FIRE DYNAMICS SIMULATOR

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Abstract

The influence of the piston effect in subway tunnels depends on a train speed, the geometry of a tunnel and a train, the types of air flow caused by mechanical ventilation and other variable characteristics. Tables and graphs of changes in air flows generated by the effect of the piston are presented depending on the speed of a train and the degree of fill rate of a tunnel. It is noted that the piston effect is characterized by two phases. At the first stage, the piston effect and the processes of changing physical fields are non-stationary whereas at the second stage, the processes become stable. The speed of the circulation flow created by the piston effect, in accordance with the fill factor of a tunnel, is characterised by a linear relationship; the degree of its growth is directly proportional to the speed of a train. Based on the results from the present paper it is possible to calculate the velocity and consumption of an air flow in an underground space. The maximum value of air flow carried out by the piston effect does not exceed 90-100 m^3/s. It corresponds to the stationary phase of motion, when the tunnel filling factor $\alpha = 0.35$ and train speed is in the range of 40-45 km/h. Based on the obtained numerical simulation results, technological parameters for metro ventilation systems can be calculated more accurately.

Key words: air consumption, circulation flow, computer modelling, oncoming flow, piston effect

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1. Introduction

Themes of the positive influence of the piston effect in subway tunnels, which are discussed in scientific publications, are: the assessment of the underground microclimate, the dynamics of air masses, the quality of fresh air, air exchange in metro stations, tunnels and shafts, peak pressures alignment by different methods etc. Based on the existing important publications in these areas, we would like to emphasise that the results presented in this paper allow the computational determination of airflow parameters caused by the piston effect for the non-stationary phase of movement. Consequently, in this work, the turbulence of the piston effect was analysed; a picture of the qualitative and quantitative distribution of airflow rates was modelled; the unsteady and stationary phases of the piston effect have been distinguished from each other. In addition, the validity of the chosen numerical analysis method for strong turbulent flows, the optimal sizes of the modelling grids was checked and the observance of boundary conditions was investigated. In particular, self-similarity of the continuity equation was proved for any section on tunnel models.

In the tasks performed in presented work numerical experiments such as "aerodynamic pipe" (when the stopped trains' model is placed in a moving air environment) were prepared and performed. Based on the modelling aerodynamic results, parameters of

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the direct streams generated by the piston effect for different location of the train have been calculated.

The main method of present researches is based on a commercial code PyroSim 2016, which uses the open source code Fire Dynamics Simulator (FDS), based on the results obtained on the phenomenological model by the US Department of Nuclear Energy and NIST. Finite Volume Method (FVM) has been presented as the numerical Method for solving aerodynamic problems. FDS is based on high vortex turbulence physical and mathematical models. Around the moving train analogical air flows are formed naturally.

Various ventilation systems for transport tunnels under normal ventilation conditions can be successfully tested on computer models by changing the flow turbulence, aerodynamics and tunnel geometry and considering the effect of transport. Investigation of the development of different scenes of fire in the underground space and saving lives can be successfully modelled with the help of numerical programs PyroSim and PathFinder. Numerical methods give us possibility to investigate risk analysis, disaster and emergency management in transport tunnels, in particular, in subway ventilation systems. The piston effect associated with train movements can be also successfully studied by numerical analysis.

On the other hand, it should be noted that the same effect of the piston can cause an uncontrolled flow of air through the mines between neighbouring stations. This fact is itself important from the safety point of view and, therefore, with the prevention of unauthorised actions in transport tunnels. In addition to uncontrolled air volumes, toxic substances and pathogenic bacteria can penetrate into underground space trough these shafts. Consequently, the piston effect can also have a negative side. In this regard, we consider it is necessary to note that in the cycle of scientific research we want to evaluate qualitatively and quantitatively positive and negative sides of the piston effect; identify medium-integral aerodynamic indicators in order to calculate technological parameters of ventilation. All of this is extremely important considering additional effects in the underground space which will be caused by a moving train and the spread of fire. Our previous works addressed various issues of safe and efficient operation of transport tunnels, studying of possible scenarios for development of underground fires, risk analysis, emergency management and lifesaving opportunities (Ilias et al., 2017; Lanchava et al., 2017a,b, 2019; Moraru et al., 2017; Nozadze, 2018).

The air resistance to the moving train on the open track and in the tunnel, as well as straight and reverse air flows in the tunnels, always caused a great interest from the point of view of optimal design of ventilation systems of rail tunnels and metro. In a review paper, Pan et al. (2013) covered the latest time publications on the piston effect in subways and compiled the most relevant information about the mechanism of the piston effect. In their paper also the piston effect's influence was evaluated and the modality on how it can be effectively utilized is presented. Similar questions were previously posed and successfully solved theoretically in the paper of Abramovich, (1939), and in papers of Tsodikov (1975) and Xu (1987). Last two papers are experimental works. In part of these papers' trains are static, and complex non-stationary aerodynamic processes are studied by moving fluids: air or water. In the last paper the model was performed in large diameter cylinders for static trains, and the air environment moves by means of ventilators.

The use of the piston effect for supplying "unorganized fresh air" is considered in scientific works of Zhang and Li (2018) and in Yang et al. (2018) where the piston effect is considered as one of main factors prompting the ventilation flow and as a result, is considered as a large reserve of savings energy. The noted works present the results of field experiments conducted for this purpose. Similar experiments together with numerical analysis were performed by Gross (2014), in which it was noted that the entry and exit of trains in the station is associated with a distinct piston effect which is responsible for effective ventilation of subway facilities and air exchange depends strongly of train characteristics. The analogical results are presented in the paper of Jia et al. (2009) which indicate that the piston effect has a significant influence on the flow field in a station and it plays an important role in natural ventilation. In the work of Gonzalez et al. (2014) unsteady air flows were investigated and on a basis of numerical modelling, mainly qualitative results are presented. Circulation streams for developed turbulent flows are also considered in the work of Xue et al. (2014). In the last work, dynamic meshes were used to simulate the effect of the piston. According to these studies, mentioned circulation flows have a great importance for dilution of harmful air impurities in metro stations, as well as in reducing the cost of air conditioning. In their article, Zhang et al. (2017) noted that the ventilation flow caused by the piston effect not only improves the ventilation of the underground space, but also has a positive effect on the efficient operation of ~~a~~ the ventilation equipment. The purpose of the study is to present a universal equation that determines the efficiency of the ventilation flow, initiated by the piston effect. In their paper, Juraeva et al. (2011) discusses the piston effect on air curtains and decides on their optimal deployment based on numerical analysis, which leads to a decrease in the amount of radioactive substances and bacteria in the ventilation air of a metro. In the work of Lin et al. (2008) it is noted that at metro stations and tunnels the piston effect causes circulation of large air flows necessary for optimal operation of the ventilation.

Reducing the high air speed caused by of the piston effect and increasing comfort for passengers are the major issues discussed in most of above publications. For example, in the aforementioned paper of Jia et al. (2009), as in Kim and Kim (2009), vertical shafts are being proposed for this scope. In the last work, the influence of location of vertical shafts was investigated with the aim of quenching peak values of the pressure of the piston effect. According to Zhu et al. (2017) bypass tunnels play an important role in reducing the piston airflow entering of stations, and reducing the piston effect of the station environment. The influence of high and low pressure zones caused by the piston effect indicates the need for the elaboration of flexible ventilation system to ensure passenger comfort. 3D presentation of the problem of piston effect in tunnels was proposed by Wang et al. (2011). In the paper of Yan et al. (2014) same issues are discussed such as changing boundary conditions of numerical modeling when metro tunnels are equipped with one or two vertical shafts.

Obviously, the piston effect of moving train has a great theoretical and practical importance in the management of air flow, in the dilution of harmful air impurities, in reducing the cost of air conditioning and in other matters for the optimal design and functioning of ventilation systems. Consequently, a comprehensive study of the piston effect is an actual modern problem. Due to the fact that the nature of the piston effect is mainly characterized by non-stationary behavior, results of quantifying the non-stationary phase given in this article may be of practical interest.

This paper, as it was mentioned, presents an analysis of results obtained by numerical model of the piston effect for different train speeds, when the tunnel filling coefficient is changed in the range of $\alpha = 0.35 - 0.61$.

2. Material and methods

2.1. Initial data for modelling

The modern level of computer technology development allows for dynamics of ventilation flows in the subway tunnels with a high accuracy to describe through numerical simulation. The paper discusses the nature of distribution of ventilation flows caused by the piston effect in metro tunnels which significantly affect the ventilation parameters of subway. The problem was posed for conditions of the tunnels of Tbilisi Metro, the base models were made by the following data: length of tunnel - 1200 m; Area of the tunnel cross section - 16 m^2, length of train - 80 m; Train speed - 10.0; 12.0; 15.0 m/s; Acceleration of the train - 1.0-1.2 m/s^2; The train cross section - 6.25 m^2; the tunnel full resistance coefficient - $\xi_T = 9.34$; the frontal resistance coefficient of the wagon - $c_w = 0.95$. Modelling and calculations were performed using PyroSim 2016 software environment.

2.2. Statement of the problem

Since rolling stock modelling is not possible in the commercial code Pyrosim 2016, we set the inverse problem. For solving this problem numerical experiments were prepared and performed in Metro tunnel as like in "aerodynamic pipe" when the stopped train is placed in a moving air environment, as it was mentioned above. On the left portal of the tunnel boundary condition - static pressure was set, which causes movement of air. The direct and inverse problem modelling schemes are presented below on Figs. 1 and 2.

Fig. 1 shows scheme speeds of airflows of moving train in the tunnel: V_0 - the speed of the train movement; C - the speed of air flow caused by the piston effect at the front and rear of the train; W- backflow through the annular space. In the annular space between perimeters of train and tunnel, backflow with the speed W takes place. The value and direction of velocity W depends on difference in dynamic pressures between first and last carriage of the train and geometry of annular space. The magnitude of the marked speed is also affected by the ejection of air due to the motion of the train, as well as the friction between the return flow of air and air in the space between wagons. The air cushion between wagons intensively circulates and aerodynamically interacts with the main return flow.

Depending on specific values of the above factors, the vector of velocity W may be directed towards the train movement as well as its opposite direction. Numerical modelling was performed in the tunnel for the 5 different zones selected in advance according to the location of the train.

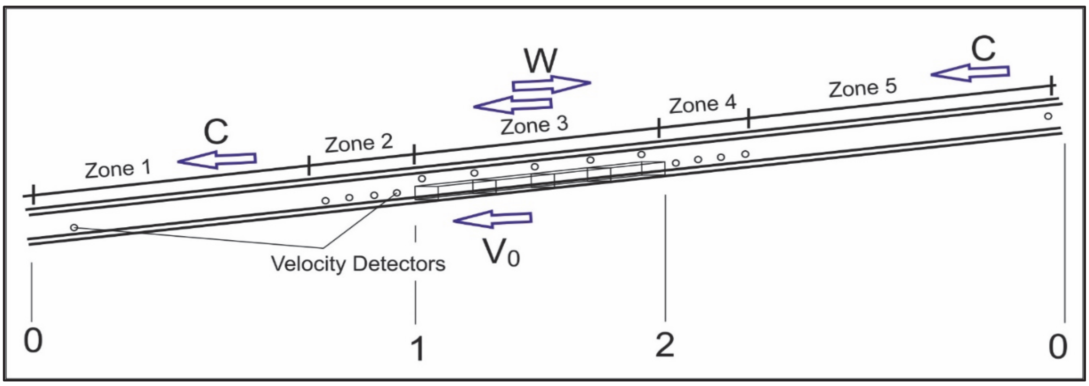

Fig. 1. The scheme for absolute speeds in case of train movement in the tunnel:
V_0 - the speed of the train movement; *C* - the speed of air flow caused by the piston effect at the front and rear of the train;
W- backflow through the annular space

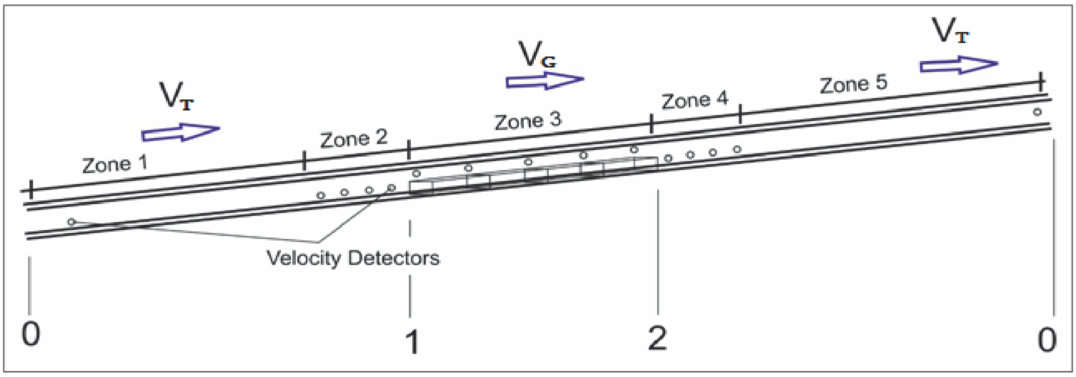

Fig. 2. The scheme of relative speeds in case of stopped train:
V_T - the speed of the oncoming flow ahead of the train (the similar value has the flow speed in rear part of the train);
V_G - the relative speed of backflow through annular space

In the above zones, the nature of the changing velocity flow was determined. In each zone the speed detectors were distant from each other in different distance. For example, in the first and fifth zone detectors have been placed at every 100 meters (see Fig. 2: Zones 1 and 5). In the second and fourth zones, at ahead and rear of the train on the length 20 m of the tunnel, the detectors were separated from each other by 5 m (see Fig. 2: Zones 2 and 4). The speed detectors in annular space were deployed at each 20 m (see Fig. 2: Zone 3).

2.3. Analytical method

The tunnel filling coefficient can be calculated using Eq. (1):

$$\alpha = \frac{F}{f} \tag{1}$$

where F - is area of the wagons cross section, m^2; f- is cross section of the tunnel, m^2.

The variation of the tunnel filling coefficient for the conditions of Tbilisi metro is in the range α=0.25-0.50, and the computer modelling was carried out for values α = 0.25-0.61. The velocities noted can be calculated using Eq. (2):

$$V_T = V_0 - C \tag{2}$$

where V_T - is the speed of the oncoming flow ahead of the train, m/s; V_0 - is train movement speed, m/s (km/h); C - is the speed of air flow caused by the piston effect at the front and rear of the train, m/s.

In the case of a stopped train, the air velocity in the annular space can be determined from Eq. (3):

$$V_G = V_0 - W \tag{3}$$

where: V_G - is stream speed in the annular space, m/s. The remaining values have already been determined.

Based on the continuity equation we can write (Eq. 4):

$$V_T f = V_G (f - F) \tag{4}$$

From which by means of simple transformations and with consideration of Eq. (1), Eq. (5) is obtained:

$$V_G = \frac{V_T}{(1-\alpha)} \tag{5}$$

Relationship between the speed of the oncoming flow V_T and the speed of the train V_o was examined for rail tunnels by (Abramovich, 1939). The railway tunnels with length differ from the subway tunnels, by which the process shown on the Fig. 2 is stabilized in them. Most important studies of Abramovich have also differed from the results presented here. Abramovich observed the train model on aerodynamic pipe with appropriate geometric and dynamic scales. Relationship between these velocities is given as follows (Eq. 6):

$$\frac{V_T}{V_0} = \frac{1}{1 + \dfrac{1}{(1-\alpha)\sqrt{\xi_T \dfrac{f}{F_e} \dfrac{1-\alpha}{1+0.004n\dfrac{S_w}{F_e}}}}} \tag{6}$$

where: ξ_T - is the tunnel full resistance coefficient in according for: the length of the tunnel (l, m), the length of the train (L, m) and the equivalent radius of the tunnel (R, m); F_e - is equivalent area of the wagon, m^2; n - is number of wagons in the composition; S_w - is the surface area of the wagon excluding the bottom area, m^2.

The tunnel resistance complete coefficient is calculated using Eq. (7):

$$\xi_T = 1.5 + 0.007\frac{l-L}{R} \tag{7}$$

All of the input symbols in Eq. (7) have already been interpreted. The equivalent area of the wagon is calculated by considering the value of the frontal resistance coefficient (Eq. 8):

$$F_e = c_w F \tag{8}$$

where c_w- is the frontal resistance coefficient of the wagon.

The air consumption originated by means of piston effect can be determined by Eq. (9):

$$Q = Cf \tag{9}$$

where Q - is air consumption, m^3/s.

2.4. Numerical modelling of inverse problem

Considering the relative motion of air for stopped train when only air flow will move, computer modelling was conducted. The speeds scheme, which was modelled, is shown in Fig. 2. The train's first carriage was located in the subway tunnel at different distance of the portal. As shows on Fig. 3 this distance is 200, 300 and 400 m. Ventilation flow rate was measured at different points of the tunnel. On the basis of numerical experiments, the purpose of the research was to demonstrate that characteristics of the air parameters in the tunnel depend on different speed of the moving train. Since rolling stock modeling was not possible, we set the reverse simulation problem. For solving this problem were prepared and performed numerical experiments in Metro tunnel as like in “aerodynamic pipe" when the stopped train is placed in a moving air environment, with average speed of 6.0; 7.0; 8.0; 10.0 and 12.0 m/s was given.

The different mesh size simulation view is presented in Fig. 4. Generally, in numerical experiments the number and size of the finite elements are very important since they are able to give correct numerical solution. During our numerical experiments the optimal size of the base Finite Volume element is 0.5x0.5x0.5 meters.

The recommended size of a standard finite cubic element is indicated by the authors of the commercial code (LES method). For present simulation, the optimal finite cubic element dimension varies in the range D * = [0.4 - 1.4] m according to NIST recommendations. We studied the accuracy and convergence of the solution of different mesh size (for sizes 1x1x1 m, 0.63x0.63x0.63, 0.5x0.5x0.5x,0.25x0.25x0.25 m). Within the specified dimensions, the problem of solving the tasks has not been observed.

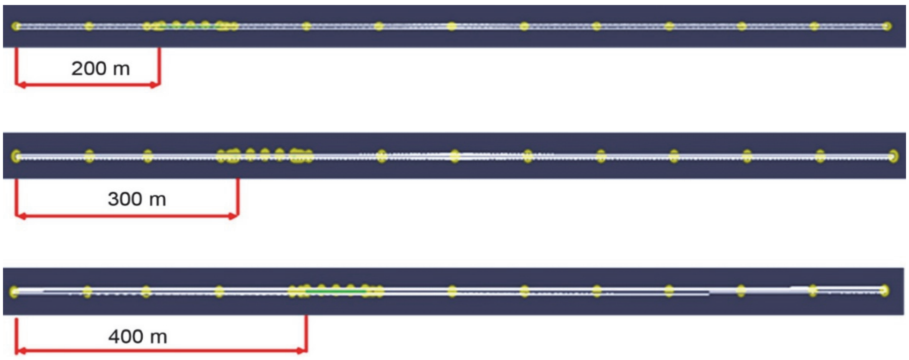

Fig. 3. The layout of the train and detectors of speed during numerical modelling: (The points show the speed detectors)

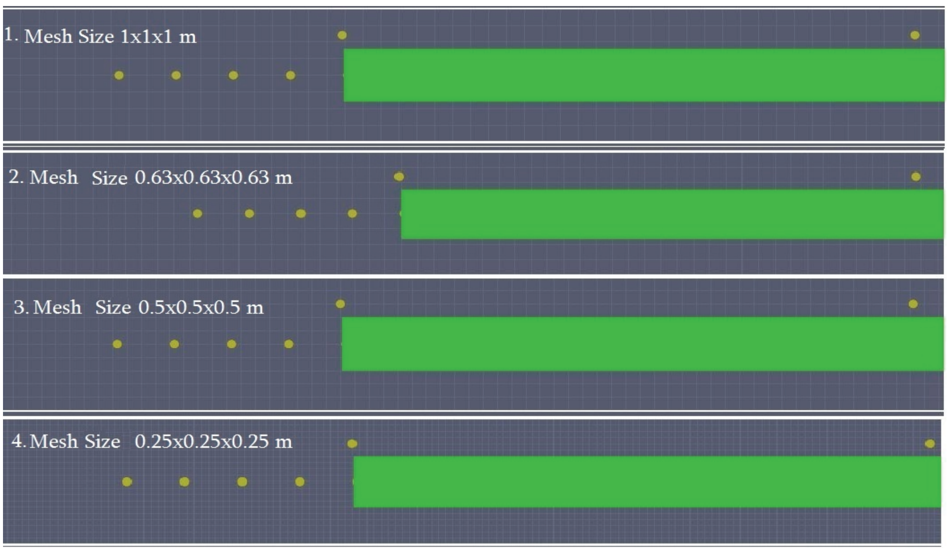

Fig. 4. Mesh size range

Based on the aerodynamic results of this modelling and by means of the appropriate theoretical model, which make relation between speeds of air flow during direct (Fig. 1) and equivalent invers problem (Fig. 2), parameters of the direct problem have been calculated - the air flow speeds, generated by the piston effect for each location of the train.

3. Results and discussion

3.1. Theoretical analysis of inverse problem

The speed of the oncoming flow V_T is a pre-set value according to the simulation conditions. Relationship between the oncoming flow and the speed of the train, which is the unchanged size for the given specific values of the tunnels and train is given by Eq. (6). Eq. (2) determines the speed of air flow ahead of the train *C* originated with the piston effect. Using Eq. (9), air expenditure initiated by the piston effect *Q* can be calculated and with Eq. (5) - stream speed in the annular space V_G. Thus, there is theoretically possible to determine all the technological indicators that are interesting for ventilation. Calculating of numerical values, when the train consists of 4 wagons, is included in Table 1.

Based on the theoretical results obtained the validation of numerical simulation can be assessed.

3.2. Numerical results

It is also worth noting that the Reynolds number for metro and other transport tunnels is large, therefore in tunnels of subway there is a highly developed turbulent movement, even in the case of a relatively low speed of moving air. In engineering practice, the simplified empirical method is often used (Tsodikov, 1975), where the difference of dynamic pressure in front and behind train is adopted as constant.

The results of numerical modelling showed that this difference of dynamic pressure changes in time. This means that during this time, non-stationary turbulent processes takes place. For this reason, it is impossible to exactly calculate the result for air flow rate in front and behind of the train by empirical method of Tsodikov. Fig. 5 shows one of the simulation results, from which it can be seen that on the starting of process, the train encounters a stationary flow of air. The dynamic pressure before the train is characterized by a value of 86.4 Pa. Between the first and last wagons during the movement of the train there is a fluctuation of pressure, which does not stabilize even after 250 seconds. The noted time interval is more than enough to overcome the distance between two neighbouring metro stations when the train moves with speed in the range of 30-40 km/h. Here, a pronounced nonstationary character of the proceeding processes is observed. It is seen from the figure that at the initial moment of time (t = 0 s) the pressure increment is 6.4 Pa, which is steadily increasing, and after t = 250 seconds is about 41 Pa.

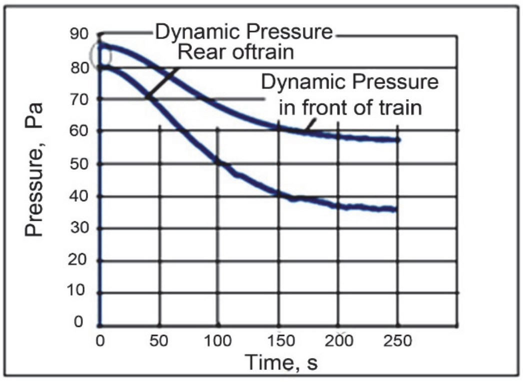

Fig. 5. Changing of dynamic pressure between first and last carriages of the train according to results of computer modelling

In the numerical experiments presented, various flow rates were realized as a boundary condition on the left portal of the tunnel, and it was shown that the value of the average speed changes in time. If consider that the passage time of the subway between neighbouring stations at different speeds is near 90-150 seconds, it can be argued that piston effect in subway tunnels generates basically non-stationary air currents.

Changing the boundary value of the speed of oncoming flow ahead of the train in numerical experimentation have been carried out according to the development of dynamic pressure and its variation. The results obtained can be analysed by one of the numerical experiments considering the dynamical change rate of the flow speeds in right portal of the tunnel, as well as in the annular space between the perimeters of tunnel and the train (Figs. 6 and 7).

Table 1. Air flow indicators that were originated with a 4-car train piston effect

V_T, *m/s*	V_0, *m/s (km/h)*	V_G, *m/s*	C, *m/s*	Q, *m³/s*
6.0	7.68 (27.6)	8.0	1.68	26.9
8.0	10.24 (36.8)	10.7	2.24	35.8
10.0	12.80 (46.1)	13.3	2.80	44.8
12.0	15.36 (55.3)	16.0	3.36	53.8

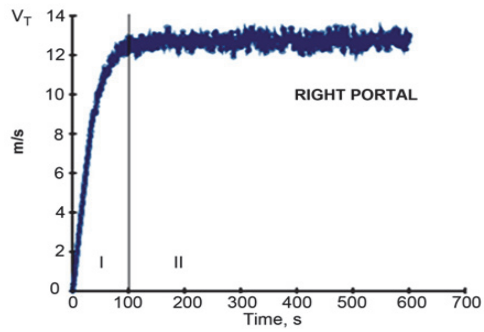

Fig. 6. Dynamics of the speed of oncoming flow ahead of the train for the right portal when it's maximum value is 12 m/s

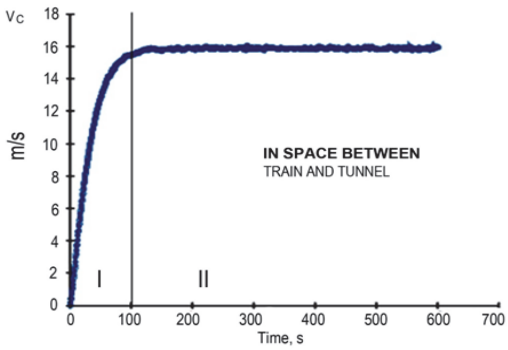

Fig. 7. Dynamics of the stream speed in the annular space when speed of oncoming flow ahead of the train is 12 m/s

Based on the presented numerical results from Figs. 6 and 7 is possible to clearly divide dynamics of air flow into two phases: I - non-stationary and II - stationary. The duration of the non-stationary phase on these drawings is 100 seconds. In presented speed range of numerical simulation the duration of the non-stationary phase changes in the range of 90-140 seconds. It is possible to note that the field of speeds in the tunnels of Tbilisi metro is mainly non-stationary.

3.3. Accuracy and reliability

Figs. 8, 9 below show the results of the calculation of the inverse problem for an average theoretical speed of 7 m/s and train location 300 m from the left portal of the tunnel (see also Fig. 3). The presented results show that the continuity equation for each grid size is performed with sufficient accuracy. At the same time, according to the theoretical analysis of the flow velocity, the best result ensures the grid size of 0.5x0.5x0.5 m for modelling the inverse problem. It is noteworthy that the results obtained from presented numerical experiments of the oncoming flow ahead of the train and stream speed in the annular space are in good agreement with theoretically calculated appropriate values (see also Table 2).

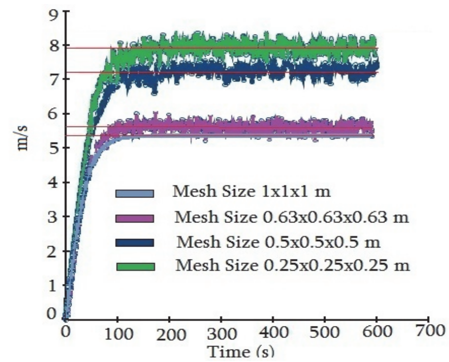

Fig. 8. Incoming flow realization in numerical simulation of inverse problem (Speed sensor location is 100 m from left portal of tunnel)

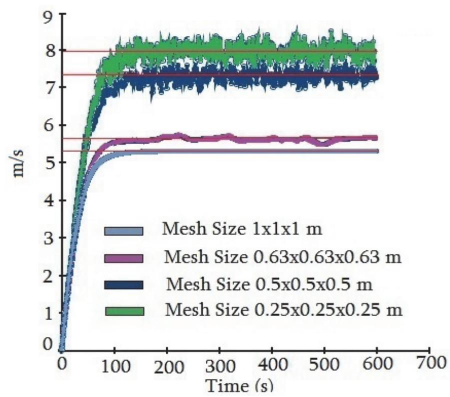

Fig. 9. Outgoing flow realization in numerical simulation of inverse problem (Speed sensor location is 500 m from left portal of tunnel)

3.4. Determination of air speed depending on train speed

Using the presented results should be taken into consideration that the piston effect caused by the train movement will work with the tunnel ventilation system in sequence mode. Using Eq. (9) is possible to calculate air consumption created naturally with help of moving train's speed. For this purposes it is necessary to determine circulation flow speed C (Fig. 10).

Table 2. Comparison of the results obtained by numerical experiments and theoretical analysis

N	*The speed of oncoming flow (theory)* V_T*, m/s*	*The speed in the annular space (theory)* V_G*, m/s*	*The speed of oncoming flow (experiment)* V_{T_EX}*, m/s*	*The speed in the annular space (experiment)* $V_{G\text{-}EX}$*, m/s*
1	6.0	8.0	5.45	7.50
2	7.0	9.3	7.2	8.9
3	8.0	10.7	8.00	10.80
4	10.0	13.3	10.00	13.50
5	12.0	16.0	12.00	15.9

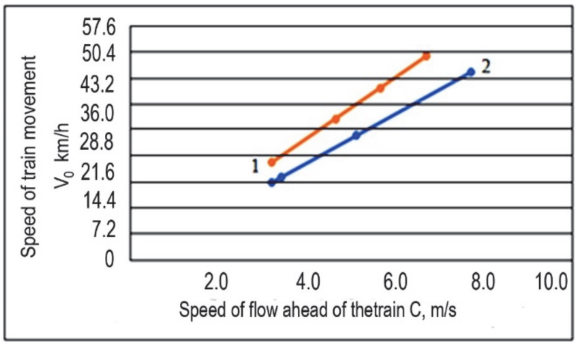

Fig. 10. Changing of circulation flow speed *C* by the speed of the train when: 1 - $\alpha = 0.57$; 2 - $\alpha = 0.61$

4. Conclusions

As a result of numerical experiments, it is shown that the dynamics of the circulation flow and backflow in the annular space is characterized by stationary and non-stationary phases, which should be taken into account in determining the flow velocities that arise by moving train. Duration of non-stationary phase for taken initial and boundary condition is up 90-140 s.

The speed of the circulation flow created by the piston effect, in accordance with the tunnel filling factor, is characterized by the linear relation, and the extent rate of its growth is directly proportional to the speed of the train.

Maximum value of the air consumption carried out by the piston effect for the train's speed of the 40-45 km/h range, does not exceed 90-100 m^3/s for the tunnel fill coefficient $\alpha = 0.25$.

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