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Mechanics

Numerical Analysis of the Air Flows Induced by Piston Effect in Subway Tunnels

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ABSTRACT. In the present work, by means of numerical analysis of fluids the flows induced by piston effect of train in subway tunnels are assessed. The mentioned streams are in relation with train's speed, geometry of tunnel and train, aerodynamic resistance of tunnel, turbulence of air flows, frontal resistance of train carriage and other variable characteristics of the processes. The mentioned flows allow determination of air consumption by piston effect in underground space. It is also shown in the present paper that for piston effect, caused by the movement of trains in subway tunnels, existence of two phases is characteristic. In the first phase, piston effect has a non-stationary nature, while in the second phase the process is stabilized. For the correct determination of velocities of circulating flows and air consumptions, it is necessary to consider the influence of these phases. In this paper we propose indicator of non-stationarity of the process in the form of simple inequalities. The speed of the circulating flow has significant variations, the degree of non-stationarity of the process for the average statistical length (1200 m) of the subway tunnels and the average train speed in the range of 30-50 km/h should be taken into account. *© 2019 Bull. Georg. Natl. Acad. Sci.*

Key words: oncoming airflow, circulating flow, flow in the annular space, train speed

One of the important factors in terms of air distribution in subway tunnels convenience is piston effect of train movement, which should be comprehensively studied. It should be noted that due to the effect of the piston, uncontrolled air flows in the underground space may occur. Proceeding from this, studying piston effect is a topical and important issue, which draws significant attention of scientists and engineers in recent years.

In the theoretical and experimental works [1-3] dedicated to this subject, the approach is used when air flow moves against static train. Similar approach is performed in the latest works. Some methods of numerical analysis (CFD, FDS) are used for the research [4-6].

The researches performed in this work and the results presented here clearly show the necessity to separate from each other the non-stationary and stationary phases of processes running under the ground, for the purpose of adequate determination of air flows induced by piston effect considering the degree of non-stationarity of the process.

In the simulated problem, the oncoming air flow V_T on a train is given, which flows through a gap between train and tunnel perimeters with the V_G velocity and proceeding from the condition of continuity of air flow, propagates behind the train with the V_T velocity.

To use the results obtained by computer modelling of the train movement in a subway tunnel, it is necessary to present the Figures of distribution of absolute and relative velocities in a tunnel (see Fig. 1).

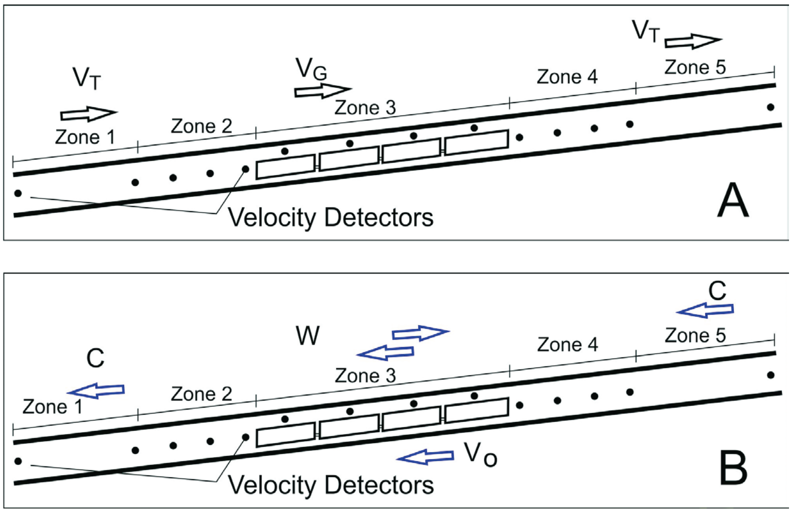

Fig. 1. The scheme of velocities in cases of static and moving trains:

A – Simulated flows: V_T - oncoming flow; V_G – flow in the annular space; B – actual flows: V_0 – speed of a train; C – velocity of a circulating flow; W – velocity of air flow in annular space.

A train moving with the speed V_0 will induce the circulating flow moving in front of it with the velocity of *C*, and also induces the flow following train behind it and moving with the same velocity *C*. In the space between train and perimeter of a tunnel, air flow occurs with the velocity of *W*. This velocity depends on the difference of pressures between the front and end of the train, as well as on ejection caused by the movement of a train.

Considering the specific values of these factors, the velocity vector *W* can be directed towards the train movement, as well as in opposite direction.

The calculation of the coefficient α of tunnel filling by a train is possible by means of the following formula:

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

where F is the area of the middle transverse section of train carriage, m^2; f – the area of tunnel cross-section, m^2.

We will introduce the designation

$$\omega = \frac{V_T}{V_0}, \tag{2}$$

where V_T is the velocity of the ram air flow on a train, m/s; V_0 – the velocity of a train movement, m/s.

The following relations between the above-mentioned velocities are valid:

$$V_T = V_0 - C; \tag{3}$$

$$V_G = V \pm W. \tag{4}$$

Proceeding from the continuity equation for f and $(f-F)$ cross-sections and considering formula (1)

$$V_T f = V_G (f-F); \tag{5}$$

$$V_G = \frac{V_T}{(1-\alpha)}. \tag{6}$$

In conditions of simulation as well as actual conditions, it is possible to calculate the velocity of flown air using formula (5).

The results of numerical simulation for air velocity, for air flow in front of train and air, flown through the annular space, are given in Fig. 2, which show that the dynamics of development of ventilation flows can be practically divided into two phases: I – a non-stationary phase and II – a stationary phase. These phases characterize all the air flows, which are induced by piston effect of a moving train.

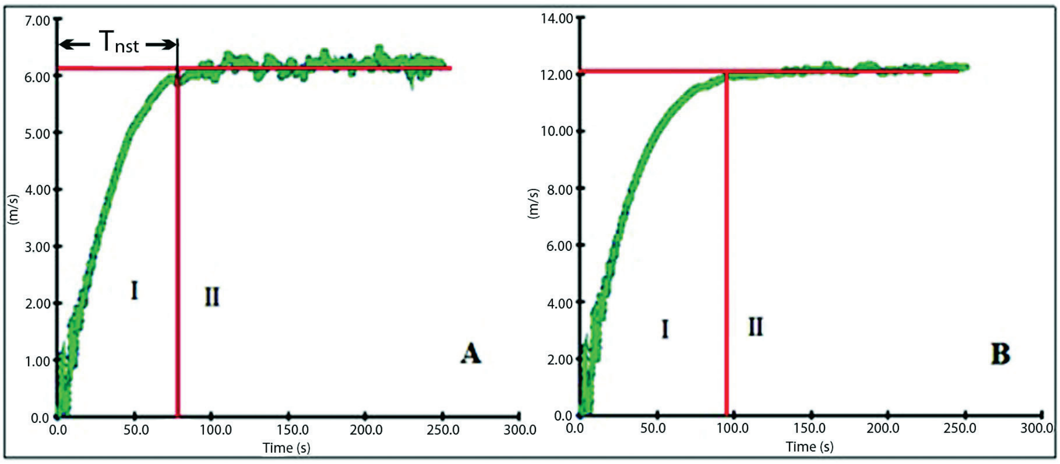

Fig 2. The variability of the oncoming air flow velocity in time, when the first carriage of a train (its length is 80 m) is in distance of 130 m from the place of a joint between the station and the tunnel: A – nature of variability of the oncoming air flow; B - nature of variability of the velocity in the annular space; I – non-stationary phase; II – stationary phase; the time of modelling – 600 s; T_{nst} – duration of the non-stationary phase, s.

The relation between the velocity V_T of the oncoming flow and the velocity V_0 of the train is [1]:

$$\frac{V_T}{V_0} = \frac{1}{1 + \dfrac{1}{(1-\alpha)\sqrt{\xi_T \dfrac{f}{F_w} \dfrac{1-\alpha}{1+0.004n\dfrac{S_w}{F_w}}}}}. \tag{7}$$

The coefficient of full resistance of a tunnel is calculated by means of the formula:

$$\xi_T = 1.5 + 0.007\frac{l-L}{R}, \tag{8}$$

where l is the length of a tunnel, m; l = 1200; L – the length of a train, m; L =80.

The equivalent area of a train carriage is calculated by considering the value of the coefficient of frontal resistance

$$F_w = c_w F\ ,\qquad (9)$$

where c_W is a coefficient of frontal resistance of the train carriage.

Considering the formula (2), the formula for calculation of train's velocity will be the following:

$$V_0 = \frac{V_T}{\omega}\ .\qquad (10)$$

Considering the formula (3), the formula for calculation of the velocity of circulating flow will be the following:

$$C = V_0\left(1-\omega\right)\ .\qquad (11)$$

The air flow rate induced by piston effect can be determined by the formula:

$$Q = Cf\ .\qquad (12)$$

By considering the function relation between the dynamic flow induced by the piston effect and the velocity of a train, expressed by the formula (11), the calculation of an induced air flow should be done by considering the non-stationary phase usually omitted. This calculation in the mentioned papers were performed only considering the values of a stationary phase.

The necessity of such approach should be considered in terms of the average statistical length of subway line tunnels and the time for developing piston effect. To calculate the duration of piston effect, it is necessary to consider the time of acceleration (deceleration) needed to achieve the nominal velocity and the circumstance that an impact of piston effect practically ceases in the moment when a train enters a station.

$$T_P = T - \frac{3}{2}t_{tr} = T - \frac{3V_{oi}}{2a}\ ,\qquad (13)$$

where T_P is duration of impact of piston effect, s; T – full time of train movement between two neighbour stations, s; t_{tr} – duration of acceleration (deceleration) phase of a train, s; V_{oi} – simulated velocities of a train, m/s; a – acceleration of a train, m/s^2; for the Tbilisi Subway a = 1 m/s^2.

For characterization of piston effect, it is possible to introduce the dimensionless coefficient, the parameter of non-stationarity

$$K = \frac{T_{nst}}{T_P}\ ,\qquad (14)$$

where K is a coefficient of non-stationarity of the process; T_{nst} – duration of non-stationary process, s.

Actual processes of manifestation of piston effect go with various relation of non-stationary and stationary phases, on which a volumetric rate of air flow depends. The calculation of the latter is possible using the inequalities given below:

$K \geq 1$ – the process occurs only in a non-stationary phase;

$K > 1$ – the process is mixed (occurs in both phases);

$K << 1$ – the process can be considered stationary.

If $K \geq 1$, then the volumetric rate of air flow is calculated by using the following formula:

$$Q_P = f\,C_i / 2 \;; \tag{15}$$

If $K < 1$,

$$Q_P = f\,C_i\left(1 - \frac{K}{2}\right); \tag{16}$$

If, $K << 1$, then the volumetric rate of ventilation air flow should be calculated using the formula (12), which was known before this research.

Proceeding from the above-mentioned, using the formulas (11)-(16), it is possible to consider the non-stationarity of a process during the calculation of the flow rate for the ventilation air, caused by the piston effect. This substantially affects the results. The main results are graphically presented in Fig 3.

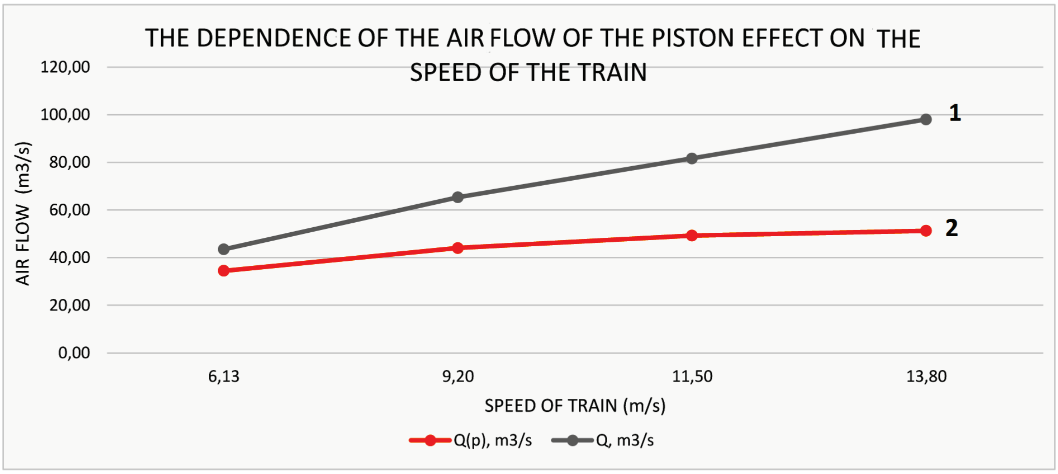

Fig. 3. The rate of air flow, induced by piston effect, depending on a train's speed: 1, 2 – air flow rates, without considering and with considering K coefficient.

The main result of the present work is characterization of air flows induced by piston effect, considering the non-stationarity nature of the process, which is caused by the existence of non-stationary and stationary phase of the process development. It is shown that when calculating the flows induced by piston effect, for the average statistical length of the subway tunnels (1200 m) and nominal speed of trains (30-50 km/h), the non-stationary phase of a ventilation flow induced by piston effect, significantly affects the volume of a flown air. If a non-stationary component of the process is not considered, an inaccuracy in the amount of 25-45% is expected during the determination of the air flow rate.

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მექანიკა

მეტროს გვირაბებში დგუშის ეფექტით აღძრული ჰაერის ნაკადების რიცხვითი ანალიზი

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(წარმოდგენილია აკადემიის წევრის ე. მეძმარიაშვილის მიერ)

წარმოდგენილ ნაშრომში დენად გარემოთა რიცხვითი ანალიზის მეთოდით შეფასებულია მეტროს გვირაბებში მატარებლის დგუშის ეფექტით აღძრული ნაკადები. აღნიშნული ნაკადები დაკავშირებულია მატარებლის სიჩქარესთან, გვირაბისა და მატარებლის გეომეტრიასთან, გვირაბის აეროდინამიკურ წინაღობასთან, ჰაერის ნაკადების ტურბულენტურობასთან, ვაგონების შუბლურ წინაღობასა და პროცესის სხვა ცვალებად მახასიათებლებთან. მატარებლის სიჩქარისა და გვირაბის მატარებლით შევსების კოეფიციენტის მიხედვით შესწავლილია მატარებლის წინ, უკან და ღრეჩოში გადადინებული ჰაერის ნაკადები, რომელთა მეშვეობით შესაძლებელია დგუშის ეფექტით მიწისქვეშა სივრცეში მოწოდებული ჰაერის ხარჯის განსაზღვრა. წარმოდგენილ ნაშრომში აგრეთვე ნაჩვენებია, რომ დგუშის ეფექტისათვის დამახასიათებელია ორი ფაზის არსებობა. პირველ ფაზაში პროცესი არასტაციონარულია, ხოლო მეორე ფაზაში იგი სტაბილიზდება. ცირკულაციური ნაკადის სიჩქარისა და ჰაერის ხარჯის მართებულად გაანგარიშებისათვის საჭიროა პროცესის არასტაციონარულობის მხედველობაში მიღება. ნაშრომში შემოთავაზებულია პროცესის არასტაციონარულობის მაჩვენებელი კოეფიციენტი მარტივი უტოლობების სახით. პროცესის არასტაციონარულობის მხედველობაში მიღებით ცირკულაციური ნაკადის სიჩქარე არსებით ცვალებადობას განიცდის მეტროს გადასარბენების საშუალო სტატისტიკური სიგრძისა (1200 მ) და მატარებლის მოძრაობის საშუალო სიჩქარისათვის (30-50 კმ/სთ).

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