Air distribution in long transportation tunnels of the Baikal–Amur Mainline (BAM)

AM Krasyuk*, IV Lugin** and EL Alferova***
Chinakal Institute of Mining, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
E-mail: *krasuk@cn.ru; **ivlugin@misd.ru; ***alferova_el@mail.ru

Abstract. This paper presents the research findings on air distribution due to piston effect in long railway tunnels. Modeling was performed for a freight train 1 km long in tunnels 3 and 6 km in length by way of numerical experimentation in the ANSYS Fluent environment. As a result, the relations of the air pressure on the front and back surfaces of the train to the train location in the tunnel were obtained, and the aerodynamic drag in the tunnel clearance was evaluated. The results were used to develop a quasi-dynamic model of piston effect for solving problems on static air distribution with network models. The air flow rates calculated for various cross-section tunnels with ANSYS Fluent and a network model exhibited satisfactory agreement. In the meanwhile, the time of solution for a tunnel 3 km long is 4·10^5 shorter with the network model than with 3D model, which is of practical importance in case of multi-variate calculations in ventilation design for railway tunnels.

1. Introduction
The most difficult period in operation of tunnels is winter. During this time, extremely low air temperature and water migration through lining results in ice formation in tunnels, which endangers operating safety. To ensure efficient distribution of warm air lengthwise a tunnel, it is necessary to solve the problem on the combined effect of air heaters, tunnel ventilation and piston effect. This paper is focused on modeling piston effect in long tunnels of BAM.

Many researchers engaged themselves with piston effect of moving trains in tunnels [1–6]. The studies mostly discussed tunnels to 1000 m long and trains not longer than 150–200 m. In this paper, the freight train has the length of 1300–1500 m. In long railway tunnels, for instance, the Severomuisky Tunnel, such train travels for 25 min. In this case, when the train is entering the tunnel within 90–100 s, the excess air pressure on the front surface of the locomotive initiates air flow in the tunnel and in the tunnel clearance. When the train is fully in the tunnel, rarefaction arises on the back surface of the train tail car. Rarefaction also participates in the air flow in the tunnel and changes air flow velocity in the tunnel clearance. The, as the train moves in the tunnel, the aerodynamic drag decreases between the loco front face and the tunnel outlet while it increases between the train tail and the tunnel inlet. This process lasts for round 20 min. As soon as the loco leaves the tunnel, the increased pressure on the loco front face is excluded from the process of air flow in the tunnel. When the full train gets out of the tunnel, air, by inertia, flows in the tunnel for some time. Evidently, air distribution in long railway tunnels features a very complex dynamics. Moreover, it governs the dynamics of train airflow when moving in the tunnel, i.e. the dynamics of heat absorption from the tunnel. It is required to understand these mechanisms to develop efficient ventilation flow charts for
tunnels; thus, investigation of air exchange and air distribution in due to piston effect in long transportation tunnels is a topical problem.

The method of modeling air distribution due to piston effect in subway tunnels was proposed I [2]. When tested in practice, the modeling results agreed well with actual measurements of air flow rate in the subways in Novosibirsk and Yekaterinburg. The proposed method allows taking into account air flow dynamics due to piston effect in simple static network models.

This study aimed to develop a mathematical model of air distribution due to piston effect in railway tunnels.

2. Methods and materials

The basic elements to construct a network scheme of a tunnel are [7 –11]: portals, line, tunnel, ventilation shafts and crossings. Another thing

— To account for natural draft: fictitious sources of pressure;
— To account for piston effect: piston effect model including fictitious draft sources describing variation in pressure at the front and behind the train, drag in the tunnel clearance and induced drag.

Modeling of piston effect with static air distribution uses the method from [2]. In this method, the pressure difference in front of and behind the train is simulated by two fictitious sources—fans. This made it possible to describe adequately the air pressure fronts on the front and back faces of the train. The fans were interconnected via the aerodynamic drag conformable with the tunnel clearance drag.

The natural draft modeling used the method from [12] the pressures of the fictitious sources of the natural draft were calculated by the basic law of thermodynamics, depending on the elevation difference of the tunnel portals, Δh, and the air temperature [13].

The parameters of elements included in the piston effect model for a surface railway tunnel and a subway tunnel differ essentially. First, the ratio of cross section areas of the tunnel and train car. In the subway, a train car overlaps round 50% of the tunnel areas, while in the railway tunnels on the ground surface, e.g. the BAM tunnels, this overlapping is 18%. Second, the length of a freight train is ten times as much as the length of subway train. This greatly influences the aerodynamic drag in the tunnel clearance. Furthermore, the attenuation coefficient is also unknown for railway tunnels with described parameters. To find these parameters for the piston effect mode, the calculation experiment was carried out in the ANSYS environment. The average train velocity is 37–45 km/h [14, 15], the length of a tonnage freight should be not more than 75 cars (there 57 on average, without regard to loco, empty train is 105 cars, passenger train is 24 cars). The length of a freight car is 16.7 m, the length of a passenger car is 23.6 m. the equivalent radius of the car cross section is 1.73 m. The cross section area of the tunnel was assumed in accord with the BAM tunnels of the same structure, length and service load (Baikal Tunnel, Kuznetsovsky Tunnel). Thus, we considered tunnels 300 and 6000 m long, with hydraulic radius of 4 m, with a running freight train 1000 m long. The atmospheric pressure was assumed as 101325 Pa, the air temperature was 25°C. The geometrical sizes of the tunnel and train conform with reality, with conversion to the equivalent sizes for solving the formulated 2D axially symmetric problem. Such formulation saves the FEM model size and computational time. The problems were solved in the nonstationary formulation using the dynamic network in ANSYS Fluent 14.5 in the paralleling mode on cluster G6 with 48 cores at the Siberian Share-Use Super Computer Center (Siberian Branch RAS).

3. Results

Figures 1 and 2 present the modeling results: pressures and flow rates per sections; pressures on the front and back surfaces of the train, as well as in the middle of the tunnel.

Sections 1–1 and 3–3 (Figure 1a) are spaced from the inlet and outlet portals at 10 gauges; section 3–3 is in the center of the computational domain; section 2–2 is intermediate and situated in the middle of the tunnel. The time scale in Figure 1a contains representative time moments and spans: 0–9 s—speedup of the train; 10.8 s—loc front face (LFF) crosses the inlet portal; 14.85 s—LFF crosses
section 1–1; 100.9 s—tail car back face (TBF) crosses the inlet portal; 150.7 s—LFF crosses section 2–2; 277.8 s—LFF crosses section 3–3; 281 s—LFF crosses the outlet portal; 371.2 s—TBF crosses the outlet portal (the train is fully off the tunnel); 373–382 s—the train decelerates; 382 s—the train stops for 1 min.

**Figure 1.** (a) Longitudinal section of tunnel: A—train enters the tunnel; B—train is in full in the tunnel; C—train leaves the tunnel; D—full train is off the tunnel; (b) air flow rates in sections 1–1, 2–2 and 3–3; $t$ is $t$ is the time.

**Figure 2.** Air pressure at the front surface of the loco and at the back surface of the tail car: 1—average pressure at LFF; 2—average pressure at TBF; 3—average pressure trend for LFF; 4—average pressure trend for TBF.

4. Discussion

The air flow rate depends on the train location in the tunnel (Figure 1b). At the train velocity of 40 km/h, at 100.9 s when the train is in full in the tunnel, the air flow rate in section 1–1 begins changing otherwise. This change happens at different times for trains of different lengths. For the freight train 1000 m long (average length), this change takes place at 100.9 s, and the air flow rate grows from 0 to 94 m³/s. By approximating the air flow rate $Q_T$ (m³/s) in the tunnel until complete entrance of the train in it, we obtain the relation between the air flow rate in the tunnel and the train length: $Q_T=1.05·t-15.65$, where $t$ is the moment of time, s. Modeling of air flows in the railway tunnels 3 and 6 km long
shows that the flow rate due to piston effect of a train running at a constant velocity is piecewise function dependent on the train location in the tunnel. In the time interval between the loco entrance and the tail car entrance in the tunnel 3 km long, \( Q_T = 1.05t - 15.65 \), in the tunnel 6 km long, \( Q_T = 0.7t - 10.4 \). In the time interval between the tail car entrance in the tunnel and the loco exit from the tunnel 3 km long, \( Q_T = -0.0016t^2 + 0.883t + 22 \), for the tunnel 6 km long, \( Q_T = -0.00039t^2 + 0.36t + 30.8 \). Thus, in the tunnel of 3 km in length, for an empty freight train (i.e. maximum length) 1750 m long, the kink in the air flow rate curve takes place at 157.7 s, and the flow rate grows up to 148.3 m³/s; for a passenger train of maximum length 570 m—at 51 s (the flow rate at this time makes 40.6 m³/s); for a passenger train of standard length 360 m—at 32.4 s (the flow rate is 21.9 m³/s). The in situ measurements of air flow rate in the Severomuisky Tunnel are given in [16]. The authors determined that the maximal air flow rate due to piston effect was 153 m³/s. Thus, we have that the model and in situ data disagree by 7%.

Using Figure 2, we find the extra pressure of the fan simulating the front face of the loco and the rarefaction behind the tail car. The air distribution due to piston effect in a long railway tunnel is modeled in three stages: the train enters the tunnel; the train is running in the tunnel; the train exists from the tunnel. Figure 2 shows the lines of the pressure trends at the front and back surfaces of the train in the listed stages. We assume that the pressure of the fan simulating the front loco face is equal to the average value of the trend in the respective section. Thus, when the train enters the tunnel, \( P_f^1 = 124 \) Pa; when the train is running in the tunnel, \( P_f^2 = 60 \) Pa; when the train exits from the tunnel, \( P_f^3 = 60 \) Pa. Accordingly, in case of the fan simulating the back surface of the tail car, \( P_b^2 = 60 \) Pa when the train is running in the tunnel and \( P_b^3 = 40 \) Pa when the train exists from the tunnel. From Figure 2a, we find the attenuation (dissipation) factor \( R_d(S) \), \( k_\mu \), versus the spacing \( S \), m, m, between the loco front and the tunnel section selected for determination of air flow rate:

\[
R_d(S) = 5 \times 10^{-13}S^3 - 9 \times 10^{-10}S^2 + 7 \times 10^{-7}S - 8 \times 10^{-3}.
\]

5. Conclusions
The obtained results enable the quasi-dynamic investigations of air flows due to piston effect in long railway tunnels using static network models of air distribution. As a consequence, the design period of tunnel ventilation system can be shortened. For example, the computation time of air flow rates in the tunnel 6 km long totaled 1089 h in the ANSYS Fluent environment, while the quasi-dynamic calculation of air distribution using a network model took \( 2.7 \times 10^{-4} \) h. Thus, the resultant reduction in the computation time is \( 4 \times 10^5 \).

The numerical experiments have found that the main operational influencer on air exchange due to piston effect of trains running in long railway tunnels is the train length, considering the fact that geometry of tunnels and velocity of trains in different tunnels in Siberia and Russia’s Far East differ insignificantly. Dynamics of air flow rate in a tunnel when a train is running in it behaves as: 1—a linear function during the train entrance in the tunnel; 2—an exponential function after the train is in full in the tunnel; 3—as a linear function when the train exists from the tunnel.

The authors have developed the quasi-dynamic model of piston effect in long railway tunnels for solving problems of air distribution using static network models. The air flow rates calculated in different cross section of tunnels in ANSYS Fluent and with network model agree well. In the meanwhile, the problem solution time for a tunnel 3 km long is \( 4 \times 10^5 \) time shorter with the network model, which is of practical significance for ventilation system design in railway tunnels.

Acknowledgements
This study was supported in the framework of the Basic Research program, Project No. AAAA-A17-117091320027-5.

References
[1] Lugin IV and Vitchenko AA 2014 Maintaining required temperature conditions in the Severomuysky Tunnel in cold season using the tunnel ventilation facilities J. Fundament.
[2] Krasyuk AM and Lugin IV 2007 Investigation of the dynamics of air flows generated by the
disturbing action of trains in the metro Journal of Mining Science 43(6) pp 655–661
[3] Rivero JM, González-Martínez E and Rodríguez-Fernández M 2019 A methodology for the
prediction of the sonic boom in tunnels of high-speed trains Journal of Sound and Vibration
446 pp 37–56
[4] Iliadis P, Soper D, Baker C and Hemida H 2018 Experimental investigation of the
aerodynamics of a freight train passing through a tunnel using a moving model Proceedings
of the Institution of Mechanical Engineers Part F: Journal of Rail and Rapid Transit
[5] Liu M, Zhu C, Cui T, Zhang H, Zheng W and You S 2018 An alternative algorithm of tunnel
piston effect by replacing three-dimensional model with two-dimensional model Building
and Environment Vol 128 pp 55–67
[6] Liu M, Zhu C, Zhang H, Zheng W, You S, Li B and Xue P 2017 Mathematical modeling and
sensitive analysis of the train-induced unsteady airflow in subway tunnel Journal of Wind
Engineering and Industrial Aerodynamics Vol 171 p 67–78
[7] Project Documentation on Construction of the New Baikal Tunnel between Delbichinda and
Daban Statins of the East Siberian Railway Section 3: Enginering and design solutions for a
linear object. Artificial structures 201 Stroi-Trest (in Russian)
[8] Gendler SG, Smirnyakov VV and Soloviev AN 2006 Ventilation and heat conditions in the
Lysogorsky Railway Tunnel GIAB Special Issue 1 pp 133–145
[9] Gendler SG and Pleskunov VA 2009 Selecting efficient airing circuit for the Kuznetsovsky
Tunnel GIAB Special Issue 13: Aerology pp 81–89
[10] Gendler SG 2005 Venitaltion problems in transportation tunnels GIAB Special Issue: Safety pp
281–295
[11] BAM Tunnel Project. Objects. Available at: http://www.btpnsk.ru/objects
[12] Lugin IV and Alferova EL 2010 Modeling natural draught effect in ventilation network of
shallow subways Proc. Young Sci. Conf.: Miners’ Descendants Vol 2 pp 64–69 (in Russian)
[13] Construction Code SP 131.13330.2012 Construction Climatology Effective as of Jan 1, 2013
Moscow (in Russian)
[14] Brief Year Summary. Review. 2016. Russian Railways Company Annual Report Available at:
http://ar2016.rzd.ru/ru/company-overview/highlights
[15] Improvement of Freight Traffic. Promotion of Client-Orientedness .Operation Results 2016
Russian Railways Company Annual Report Available at: http://ar2016.rzd.ru/ru/operating-
results/customer-focus/ improved-freight#initiatives-to-improve-customer-service-quality
[16] Gendler SG, Smirnyakov VV and Sokolov VA 2005 First results of ventilation network tests in
the Severomuysky Railway Tunnel GIAB Special Issue S2 pp 272–281