Heat losses in train movement in transportation tunnels in different operating conditions

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Abstract. The paper describes the results of numerical modeling of heat exchange between trains and air in transportation tunnels operated in the conditions of dry continental climate in Siberia and Russian Far East in cold seasons. The modeling uses a nonstationary 2D axially symmetrical formulation. The relationships have been obtained for the components of heat balance in transportation tunnels and the outside air temperature and the process conditions of operation of the tunnel entry equipment.

1. Introduction

In operating long railway tunnels in Siberia and in the Far East of Russia, ice grows on the surface of inner lining in cold seasons. The long tunnels mean tunnels having length more than two lengths of an average freight train, i.e. more than 2 km. Ice formation takes place in such tunnels under lower air temperatures, due to freezing of groundwater which ingresses in the tunnels through lining. The subcool control in the 15 km-long Severomuysky Tunnel provides equipment of the tunnel faces with gates [1] which are opened to pass a train then are shut after it, and with warm air curtains having total heat capacity of 3 MW [2]. However, it has appeared to be insufficient. At the air temperature below minus 20 Celsius, total ice coating which is removed from the tunnel per one shift can reach 5 cbm in volume. Moreover, the multiple freeze–thaw cycles accelerate frost fracturing, which can lead to an accident. Thus, it is of the current concern to study tunnel heat loss as a cause of its undercooling. It is necessary to know heat loss in heating of a cold train and incoming cold air in order to determine the required capacity of heating equipment of ventilation systems.

A moving train in a tunnel is wrapped in warm air. In a tunnel with gates, air flow velocity in the clearance between the train and the tunnel walls depends on the air flow rate pushed by the train in the opposite direction of the train movement, and is equal to the product of the train velocity and the train cross area. In case of an open tunnel, such flow rate is only observed at the initial instant of the train entry to the tunnel. Later on, the flow rate in the opposite clearance space lowers in the tunnel, and train-side air flow becomes stable due to the piston effect caused by the train in the tunnel.

2. Total heat loss calculation

Earlier [3], we calculated air flow rates through the tunnel and in the tunnel wall–train clearance for the tunnels 3 and 6 km long, without face gates. We solved a nonstationary problem on a moving train, with a reconstructible mesh domain in a two-dimensional axially symmetric formulation using aerodynamic analysis module Ansys Fluent [4]. The input data were: equivalent inner diameter of the tunnel—8 m; equivalent diameter of train—3.5 m; train velocity—11.1 m/s; train length—1 km; master cross section...
area—9.62 m³; train–tunnel clearance—40.62 m². These average data were obtained from the statistical analysis of in-use performance of railroad tunnels and trains in Siberia and Russia’s Far East [5–9]. For the statistics, we chose trains composed of freight cars, tank cars and low-sided cars as wells as the Baikal–Amur Mainline tunnels, namely, Severomuysky, Baikal and Kuznetsovsky Tunnels.

For a tunnel with gates, it is assumed that the gates shut the tunnel faces completely and overall air volume pushed by the train flows in the clearance, for this reason, air flow velocity in the clearance is constant during uniform travel of the train in the tunnel. For the analysis of thermodynamic processes during heat exchange between the cold train and the tunnel air and in order to assess overcooling of the tunnel in cold season, the aerodynamic model [3] is added with characteristics of thermophysical properties of the tunnel air, materials the train is made of, the freight, tunnel lining and rock mass surrounding the tunnel. Is is assumed that the freight is coal, the train cars are made of steel, lining is concrete and the enclosing rock mass is composed of granite.

In the earlier numerical experiments for tunnels 6 km long, the computation time using 48 computer cores clustered with Ansys Fluent at the Siberian Supercomputer Center made 46 days. Aimed to reduce the computer time and capacity in long tunnel modeling, an aerothermodynamic model has been developed to model a tunnel section not longer than a train length without the mesh to be reconstructed as the train moves. To this effect, the model is changed from the coordinates connected with the immobile wall of the tunnel to the coordinates connected with the immobile wall of the train. Airflow is assigned by the air flow velocity in the clearance, and the train movement in the tunnel is assigned as the opposite movement of the tunnel wall at the velocity equal to the train velocity. Figure 1a gives the axial flow velocities in the clearance during train travel in the tunnel 6 km long from the earlier model and from the modified model with the coordinate system connected with the immobile train. The measurement point is the middle of the train. It is seen that the curves qualitatively and quantitatively coincide, and a small quantitative difference is due to the modified model scenario of the air temperature of minus 20 Celsius and the air in the clearance at the middle of the train is cool, i.e. its volume density is higher and, accordingly, the flow rate and velocity are lower. Since the heat exchange between the train and the tunnel air follows the mode of induced convection, the sameness of the quantitative–qualitative conditions of airflow leads to the sameness of the heat exchange processes.

Figure 1. (a) Curves of axial flow velocity in the clearance between the tunnel and train, in the middle of the train; (b) model design of aerothermodynamic processes of train airflow during travel in the tunnel; \( t_{\text{train}} \)—initial temperature of train, °C; \( t_{\text{clear}} \)—air temperature in the clearance, °C.
Similarly to the aerodynamics research of train travel in a tunnel, the problem is solved in the axially symmetrical nonstationary formulation. The aerodynamic calculation pattern is shown in Figure 1b. Geometrically, the model represents a side elevation of the tunnel section with the train. The train moves left to right. In order to reduce the mesh volume, we analyze not the whole car but its outward part of the freight (coal) 0.5 m thick and car wall (steel) 0.005 m thick. This thickness a priori exceeds the value of the heated zone of the car during the train travel in the tunnel less than 15 km long; for this reason we set an adiabatic condition at the boundary of the inner wall of the train: Q_{iw} = 0 W, where Q_{iw} is the heat flow at the inner wall of the train (unheated zone). The initial temperature of the train (car steel and freight), t_i, is equal to the open air temperature as the train entering the tunnel long remains outside it and contacts with open air. It is assumed that the train is totally cooled off in the time of its travel across the open to the tunnel. The tunnel lining is set as a mobile wall with velocity U_{tw} (m/s) equal to the train velocity, and with constant temperature t_{tw} = +5 °C as the train always displaces toward the tunnel section with the uncooled wall. The airflow of the train is warm, comes in the clearance from the right side at the velocity U_{aircl} (m/s) and at the tunnel air temperature t_{tun} = +5 °C. The velocity U_{aircl} is determined as the difference between the real velocity of the train and the airflow velocity in the clearance, found in terms of the air flow rate in the clearance. The U_{aircl} is constant in the tunnel with gates and variable in the open tunnel.

We have determined the nonstationary heat flow from the tunnel air to the cold train, i.e. the heat loss to be compensated to maintain the present temperature of 5 °C in the tunnel. These heat losses are calculated for the open air temperatures of –20, –30, –40 and –50 °C assumed from the research [10].

Figure 2 describes the calculated total heat losses in the open tunnel and in the tunnel with gates, including heat lost in heating of the train wall and cold open air entering the tunnel. In the tunnel without gates, the heat loss can reach 18 633 kW at the open air temperature of –50 °C, and the major heat is lost to heat inlet cold air flow. Heat loss in the tunnel 6 km long is less than in the tunnel 3 km long due to less cold air inflow in the tunnel, which is explained by the higher aerodynamic resistance of the tunnel.

**Figure 2.** Total heat losses in tunnel (a), (b) without gates and (c), (d) with gates.
In the tunnel with gates, for the most time of the train travel, heat is only lost in heating of the train. As the train leaves the tunnel, extra heat is lost in heating of the cold air flowing into the tunnel through the gates. Finally, the maximal total loss of heat reaches 15 934 kW and this is a peak level. The averaged total loss of heat during train travel in different-type tunnels is given in Table 1.

Table 1. Averaged total heat loss, kW

| Tunnel length and type | Outside air temperature, °C |
|------------------------|-----------------------------|
|                        | –20 | –30 | –40 | –50 |
| 3 km, no gates         | 6 134 | 8 826 | 11 678 | 14 713 |
| 3 km, gates            | 3 696 | 5 251 | 6 856 | 8 520 |
| 6 km, no gates         | 5 565 | 7 986 | 10 537 | 13 236 |
| 6 km, gates            | 3 290 | 4 654 | 5 859 | 7 480 |

3. Conclusions
The implemented research findings show that the heat loss in heating of a train in a tunnel is higher in the tunnel without gates than in the tunnel with gates as in the latter case, the heat transfer coefficient is higher due to the higher velocity of the train airflow. In the longer tunnel without gates, the heat loss in the train heating is lower. In this case, the train side air flow formed in the tunnel decreases the train airflow velocity in the train–tunnel clearance.

In the railroad tunnels 6 km long without ventilation gates, heat lost in heating of the train is lower than in the tunnels 3 km long but the heat loss in heating of inlet air flow through the faces is higher. The maximal total heat loss in the tunnel 3 km long without ventilation gates, at the outside air temperature of 50 deg below zero is 18.6 MW. In the tunnels equipped with ventilation gates, heat loss in the train heating is higher due to higher velocity of the train airflow but the loss of heat in heating of inlet cold air flow is lower thanks to the gates. As a result, the total heat loss averaged with respect to train travel time is 2 times lower in the tunnel with gates than in the tunnel without gates.

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