Verification of Method for Predicting Thermal Environment in Tunnels by Model Experimentation

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To verify the accuracy of the current method for predicting thermal environments in tunnels, a model experimental device was developed. This experimental device was designed to be able to investigate heat transfer in tunnels and heat conduction in the rock and soil surrounding the tunnel by blowing hot air into a thick pipe made of acrylic plastic. Temperature detectors were placed in various positions along the experimental device. The difference in temperatures measured in the model experiment and those obtained through calculation was about 1°C showing that numerical calculations obtained through the current method satisfy accuracy requirements.

Keywords: tunnel, ventilation, thermal environment, simulation, model experiment, verification

1. Introduction

It is more difficult to remove heat from underground railway tunnels in urban areas through natural ventilation, compared to mountain tunnels. To date, various investigations have been conducted and manifold measures have been implemented to counter this problem. At present, in the case of subway tunnels, it is standard practice to install mechanical ventilation equipment as a cooling measure. At the same time, transportation agencies, including railways, are more than ever compelled to reduce energy consumption. It is therefore important to be able to estimate the capacity of mechanical ventilation equipment in tunnels and cooling equipment in subway stations, accurately. Obtaining accurate estimation depends on being able to predict thermal environments inside tunnels. The Subway Environment Simulation (SES) computer program [1], developed by the US Department of Transportation, is a well-known estimation tool. In Japan, a NewSEAS was developed so that it could be used during the design of Line 12 on the Toei Subway, operated by the Tokyo Metropolitan Government. Because flow and thermal environment simulation programs deal with relatively low train speeds, such as those found on subways, SES uses incompressible flow equations whereas NewSEAS uses two-fluid piston model equations [2] for calculating the speed of airflow induced by trains running in tunnels. RTRI, at the same time, developed a method which could be applied to high-speed rail, such as Shinkansen. In order to take into consideration the propagation of the compression wave generated by a high-speed train entering a tunnel, this method calculates the speed of airflow in the tunnel using a numerical simulation program of pressure transients in railway tunnels [3], [4], which carries out calculations based on the method of characteristics. The obtained wind speed is then used as the input for carrying out heat transfer calculations in railway tunnels using the numerical simulation program for thermal environments in railway tunnels [5].

The first step in examining the calculation accuracy of the numerical simulation program for thermal environments in railway tunnels was to verify that the calculation results from the simulation mostly matched the theoretical values by steady state theory, with the set boundary condition that air flowing into the tunnel had a temporally constant temperature. However, in an actual subway tunnel, the temperature of outside air brought into the tunnel for ventilation would reflect changes caused by overlapping of diurnal and annual variations. The outside air causes the temperature inside the tunnel to vary over time by heat transfer. The second step in verification required examination of the temporal change in temperature in the tunnel. For that purpose, an experimental device was developed to simulate the basic aspects of heat transfer inside a subway tunnel and attempted to verify the calculation accuracy of the simulation program in the scenario where temperature in the tunnel changes over time.

2. Simulation verification method

When research is conducted using numerical simulations, it becomes important to assess the accuracy of the simulation calculations. This evaluation requires results from the simulation to be compared with field test results (full-scale test), where details of the boundary conditions are made clear. However, due to the length of actual railway tunnels—which form the target of these simulations—ranging from several kilometers to several tens of kilometers, and because they are buried deep in the ground, accurate assessment of boundary conditions for the field tests, such as soil temperature, is difficult. It is also difficult to investigate in detail the spatial distribution of the thermodynamic properties of the ground, such as soil and rock surrounding the tunnel, which is composed of a complex overlap of layers with different characteristics. For these reasons, before comparing results from simulation with prior field test or new field test results, it was decided that a model should be used, made of materials with clear thermodynamic properties and with simple shape and boundary conditions, to carry out precise experiments to verify the calculation results of the simulation.

On the assumption that "the temperature of the
ground surrounding the tunnel is constant temporally and spatially at a distance of 10 m or more away from the tunnel wall,” an experimental device consisting mainly of a cylindrical tunnel model was developed, that simulates the ground within 10 meters of the tunnel wall. The heat transfer inside the actual tunnel was too complex to be simulated in the model. Therefore, the focus was placed on the basic heat transfer phenomena, such as heat transfer due to airflow, heat transfer between the air and the ground, and heat conduction within the ground, and an experimental device was developed to simulate these. The experimental device designed to simulate the ground surrounding the tunnel was made with homogeneous material with known thermodynamic property values. In addition, the device was not designed to simulate heat transfer from water inside the tunnel and in the surrounding ground. Through experiments using this tunnel model, the temporal change in tunnel temperature was measured (dynamic response) when the temperature of the air supplied to the tunnel was changed over time (Fig. 1). By comparing this to the temporal change in temperature calculated through simulation, it was possible to verify the basic calculation techniques for heat transfer used in the simulation of thermal environments in tunnels. This experiment was conducted using a high measurement accuracy temperature sensor, to be able to gauge the accuracy of calculations through simulation to within approximately a 1°C (±0.5°C) margin of error.

3. Model experiment to verify the simulation of thermal environments in tunnels

3.1 Experimental device

The model experiment to investigate thermal environments in tunnels, works by blowing air - simulating air from the outside - into a thick acrylic cylinder simulating the tunnel (referred to hereafter as the ‘tunnel model’), using a hot air generator (Figs. 2 and 3). The tunnel model is an acrylic cylinder with an outer diameter of 150 mm, an inner diameter of 27 mm, and a length of 5000 mm. It is assumed that the tunnel wall and ground surrounding sections between two stations (assuming a length of 800 m) with small cross-sections (assuming an internal diameter of 4.3 m) in single-track subway tunnels are homogeneous. A reproduction was made of an area at approximately 10 m in depth from the inside surface of the wall on a 1/160 scale. Air was heated and regulated to a set temperature in the generator, and blown by a fan at a constant wind speed. The mouth of the hot air generator was connected to the opening of the tunnel model with a hose to blow the heated air inside the tunnel. Simultaneously, the air surrounding the tunnel model was circulated using another fan. The surface temperature of the outside of the tunnel model varied over time, influenced by the outside air temperature. However, circulation of the surrounding air made it possible to contain fluctuation of the outside surface temperature in the longitudinal direction of the tunnel model to within 2°C or less. By measuring this temporally-varying boundary condition and using it as the input to the simulation for comparative verification, it was possible to match experimental and simulation conditions.

3.2 Measurement method

A high-accuracy and very stable class A 4-wire resistance temperature detector (Pt 100) was used, to measure the air temperature in the tunnel, the surface temperature outside the tunnel model, and the temperature of the acrylic inside the tunnel model. For example, for a measured temperature of 30°C, the sensor had a tolerance level of ±0.2°C, which meets measurement accuracy requirements for this experiment (±0.5°C margin of error). The air temperature in tunnel was measured at seven points in the longitudinal direction of the tunnel using pipe-style resistance temperature detectors (RTDs) with a diameter of 1.6 mm. The acrylic temperature inside the tunnel model was measured using embedded, film-type RTDs at five points on two cross sections (X=750 and 2250 mm) in the longitudinal direction of the tunnel: three points (r=17.5, 27, and 46 mm) on one cross section and two points (r=17.5 and 27 mm) on the other cross section respectively, in the radial direction of the tunnel. The surface temperature outside the tunnel model was measured at eight points in the longitudinal direction of the tunnel using film-type RTDs. Figure 4 shows the measurement positions of these temperature sensors. An easy-to-use hot wire anemometer was installed at the center of the tunnel on the cross section at a distance X=4250 mm from the upstream edge of the tunnel model, to measure the speed of airflow in the tunnel (Fig. 5). In addition, the wind speed surrounding the tunnel model, circulated using a blower, was measured using a three-dimensional ultrasonic anemometer, because wind direction is influenced by the tunnel model and changes locally and three-dimensionally (Fig. 5).
3.3 Experimental procedure

First, a blower was used to circulate the air surrounding the tunnel model, and the temperature of the hot air generator was set to 30°C. Air was blown continually for 5 or more hours. When it was deemed that the tunnel model had reached a thermal equilibrium state, the set temperature was raised to 45°C, and air was blown for another hour or more. The reason for blowing air continually for 5 hours from the start of the experiment was based on results from preliminary simulations and experiments which showed that the temperature in the tunnel model reached a steady state if hot air was blown continuously for approximately 5 hours. During this time, the air temperature in the tunnel model, the surface temperature outside the tunnel model, the acrylic temperature inside the tunnel model, and the speed of airflow in the tunnel model were measured at a sampling rate of 5 Hz. The wind speed surrounding the tunnel model was measured separately at a sampling rate of 10 Hz.

4. Results from the model experiment

4.1 Wind speed measurement results

Figure 6 shows wind speed measurements from inside the tunnel model, taken at the center of the tunnel. It can be said that the speed of airflow in the tunnel model was controlled and almost constant. The speed of airflow in the tunnel model time-averaged for the duration of the experiment was 7.3 m/s. Figure 7 shows wind speed measurements surrounding the tunnel model (average horizontal wind speed per minute). The wind speed surrounding the tunnel model time-averaged for the duration of the experiment was 0.9 m/s.
air temperature changed. This revealed a tendency indicating that the more distant the measured point was from the upstream end of the tunnel model, the longer it took to reach a thermal equilibrium state. Figure 10 shows the measured acrylic temperature inside the tunnel model at the cross section where X=750 mm. As the set temperature of the hot air from the generator was increased from 30 °C to 45 °C, 5.56 hours after the start of the measurement, the acrylic temperature at each measured point increased. This revealed a tendency indicating that the further the measurement point was from the center, the longer it took for the acrylic temperature to reach a thermal equilibrium state. In addition, compared to the air temperature in the tunnel model, there was a more gradual temporal change in the acrylic temperature when the set temperature was changed.

5. Simulation method

5.1 Overview of the simulation

In the simulation of the thermal environment in the tunnel, it was assumed that the air flow in the tunnel to be one-dimensional (Fig. 11) and that the ground surrounding the tunnel was a two-dimensional axisymmetric shape (Fig. 12), based on the method for predicting the thermal environment [6] in underwater tunnels mechanically ventilated at a constant wind speed. The temporal change in temperature in the tunnel was calculated by simultaneously solving the fundamental equation for air temperature in the tunnel (1) and for the ground surrounding the tunnel (2).

\[
c_{a} \rho_{a} A \left( \frac{\partial \theta_a}{\partial t} + U \frac{\partial \theta_a}{\partial x} \right) = h_{w} S (\theta_{w} - \theta_a) + A \lambda_{a} \frac{\partial^{2} \theta_a}{\partial x^{2}}
\]

\[
c_{c} \rho_{c} \frac{\partial \theta_a}{\partial r} = \frac{\lambda_{c}}{r} \frac{\partial}{\partial r} \left( r \frac{\partial \theta_a}{\partial r} \right) + \lambda_{c} \frac{\partial^{2} \theta_a}{\partial r^{2}}
\]

Here, the symbols represent the following:

\( A \): tunnel cross section, \( c_{c} \): constant-pressure specific heat of air, \( \lambda_{c} \): thermal conductivity of air, \( h_{w} \): heat transfer coefficient between the air and wall surface, \( S \): perimeter of the tunnel cross section, \( t \): time, \( U \): speed of airflow in the tunnel, \( x \): distance in the longitudinal direction of the tunnel, \( \theta_a \): air temperature, \( \theta_{w} \): temperature of the wall surface, \( \rho_{c} \): air density, \( c_{c} \): specific heat of the ground, \( r \): radial distance from the tunnel center, \( \theta_{g} \): ground temperature, \( \lambda_{c} \): thermal conductivity of the ground, and \( \rho_{g} \): ground density.

This simulation takes into account the heat transfer from water inside the tunnel and in the ground surrounding the tunnel. In this paper, the functionality of the simulation is restricted to make it match with the conditions of the experiment, and the influence of water is ignored (equations (1) and (2) represent scenarios where water influence is ignored). Since it is assumed that the ground temperature reaches a ‘deep sink’ temperature (depth at which ground temperature does not change) at a 10 m (62.5 mm at 1/160 scale) distance from the inner wall of the tun-
nel, the boundary condition of the outer surface of the cylindrical region—which simulates the ground surrounding the tunnel—is set up so that the temperature is temporally and spatially constant. However, the surface temperature of the device developed for this model experiment changed over time, while its spatial variation was within 2 ℃. To meet the experimental conditions, the simulation for comparison with the model experiment used, as the input value, the time series data which were measured in the experiment as the boundary condition for the ground surrounding the tunnel. The tunnel diameter (inner diameter of the cylindrical region) was set to 27 mm; the outer diameter of the cylindrical region, to 150 mm; and the tunnel length, to 5000 mm in accordance with the model experiment device. With regards to the boundary condition of the inner surface of the tunnel cylinder, the transfer of heat to and from the air flowing inside the tunnel was calculated with the heat transfer coefficient \( h_a \) given by the Petukhov-Popov equation [7] ((3) - (7)).

\[
h_a = (\lambda_{efd} / d)N_a
\]  
(3)

\[
N_a = \left( \frac{f}{8} \right) R_{es} P_r \left[ K_1 + K_2 \left( \frac{f}{8} \right)^2 \left( \frac{2}{P_r^2} - 1 \right) \right]
\]  
(4)

where,

\[
K_1 = 1 + 3.4 f
\]  
(5)

\[
K_2 = 11.7 + 1.8 P_r^2
\]  
(6)

\[
f = (1.82 \log R_{es} - 1.64)^2
\]  
(7)

Here, the symbols represent the following: 
\( d \): the inner diameter of the tunnel model, \( R_{es} \) the Reynolds number based on the inner diameter of the tunnel model and the speed of airflow in the tunnel, and \( P_r \): the Prandtl number of air.

5.2 Speed of airflow in the tunnel

In the simulation, the airflow in the tunnel is regarded as being one-dimensional, but the actual wind speed in the tunnel model changes in a radial direction. For this reason, the averaged wind speed over the cross-section was determined from the temporally averaged value of the speed of the airflow through the tunnel center, measured in the experiment (Section 4.1) and the wind speed distribution inside the tunnel model measured in the preliminary experiment, and input the obtained result into the simulation as the speed of airflow in the tunnel.

According to the literature [8], in the case of turbulent flows, wind speed \( U(r) \), positioned at a distance of \( r \) away from the center of a cylindrical tube with inner radius \( R \) and a smooth inner surface, can be approximated by the following power law equation (8).

\[
U(r) = U_{max} \left( 1 - \frac{r}{R} \right)^{\frac{1}{13.5}}
\]  
(8)

Here, \( U_{max} \) represents the wind speed at the center of the tunnel.

In the turbulent pipe flow, \( n \) is generally 7, but in reality, it is dependent on the Reynolds number, \( R_e = (Ud) / \nu \), where the pipe diameter \( d \) (\( = 2R \)) is taken as the reference length and the wind speed averaged over the pipe cross section \( U \), as the reference velocity. Through experimentation, J. Nikuradse obtained values of the exponent \( n \) for a very wide range of Reynolds numbers [8]. From the interpolation of those experimental values, with \( U_{max} = 4.6 \) m/s and 10.1 m/s in the preliminary experiment by which the wind speed distribution was measured, the values of \( n \) were found to be 6.26 and 6.50, respectively. As shown in Fig. 13, the results of the preliminary experiment are generally consistent with the empirical formula (8).

Assuming that the wind speed inside the tunnel model follows the power law, the relationship between the wind speed averaged over the cross section \( U \), and the wind speed at the center of the tunnel model cross section \( U_{max} \) can be obtained by integrating the function (8) over the cylindrical pipe cross section, as shown by the following equation [9].

\[
\frac{U}{U_{max}} = \frac{2n^2}{(n+1)(2n+1)}
\]  
(9)

Fig. 13  Wind speed distribution within the tunnel model

5.3 Surface temperature of the tunnel model

Surface temperatures of the tunnel model measured at 8 points in the experiment (Fig. 8) were used as the surface temperatures for the simulated tunnel model (boundary condition). Boundary conditions for the points lying outside the measured points were obtained by interpolation of data.

5.4 Physical property values used in the simulation

The physical properties of both the air inside the tunnel model and of the material used to make acrylic tunnel model used in the simulation, are shown in Tables 1 and 2.

| Table 1 Physical property values of air used in the simulation |
|---------------------------------------------------------------|
| Constant-pressure specific heat (J/(kg K)) | Density (kg/m³) | Thermal conductivity (W/(m K)) |
| 1006 | 1.275 | 0.0272 |
5.5 Grid spacing of the simulation

Numerical calculations were made through discretization of equations (1) and (2). Grid points in the X direction of the airflow in the tunnel model and the acrylic portion inside the tunnel model were spaced at equal intervals of 19 mm and the tunnel model was divided into 270 parts in the X direction. The grid point intervals in the r direction of the acrylic temperature inside the tunnel model were generally set to be shorter for the grid points closer to the center and the tunnel model was divided into 16 parts at unequal intervals of 0.2 mm to 8.7 mm in the r direction. The time increments in the calculation were set to 0.2 s.

6. Verification of the simulation of thermal environments in tunnels

To verify the simulation of thermal environments in tunnels, a comparison was made of calculation results from the simulation with the results from the model experiment. Figures 14 to 16 show the comparison between simulation results and experimental results with respect to air temperatures inside the tunnel model taken at cross sections at distance X from the upstream edge of the tunnel model, where X was 750 mm, 2250 mm, and 3750 mm, respectively. Figures 17 and 18 show a similar comparison with respect to the acrylic temperature inside the tunnel model at distances r=17.5 mm and 27 mm from the tunnel center, at the cross section at a distance of 750 mm from the upstream edge of the tunnel model. The data used for comparison were obtained from about 30 minutes before the set temperature of the hot air generator was raised from 30 °C to 45 °C to about 1 hour following the increase.

The difference in air temperature in the tunnel model, and acrylic temperature inside the tunnel, obtained in the model experiments and through simulation was within 1 °C. This confirmed the calculation accuracy of the simulation. Additionally, this 1 °C margin of error is thought to include the effects of ignoring the impact of temperature

Table 2  Physical property values of the acrylic used in the simulation

| Specific heat (J/(kg K)) | Density (kg/m³) | Thermal conductivity (W/(m K)) |
|-------------------------|----------------|-----------------------------|
| 1400                    | 1190           | 0.21                        |

Fig. 14  Comparison of model experiment results and simulation results
(Air temperature in tunnel model, X=750 mm)

Fig. 15  Comparison of model experiment results and simulation results
(Air temperature in tunnel model, X=2250 mm)

Fig. 16  Comparison of model experiment results and simulation results
(Air temperature in tunnel model, X=3750 mm)

Fig. 17  Comparison of model experiment results and simulation results
(Acrylic temperature inside the tunnel model, X=750 mm, r=17.5 mm)

Fig. 18  Comparison of model experiment results and simulation results
(Acrylic temperature inside the tunnel model, X=750 mm, r=27 mm)
changes due to the thermodynamic properties of air.

7. Conclusion

A model experimental device was developed to verify the essential parts in calculations for the simulation of thermal environments in the tunnels—in other words to verify heat transfer through airflow and ground surrounding the tunnel, and the heat exchange between them. The following became clear from the comparison of experimental results and calculation results simulation replicating the model experiment.

The difference between the calculation results from the simulation of thermal environment in the tunnel and the results from the model experiment is approximately 1 °C. From this, we see that the margin of error of the numerical analysis by the simulation is about 1 °C.

For the future, we must examine the factors that could not be verified by the model experiment, such as the influence of ground water and the margin of error owed to prediction accuracy of wind speed within the main tunnel and the tunnel’s ventilation shaft.

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