Effect of Temperature Change and Contact-wire Wear on Current Collection Performance

Mizuki TSUNEMOTO
Contact Line Structures Laboratory, Power Supply Technology Division

Masatoshi SHIMIZU
Contact Line Structures Laboratory, Power Supply Technology Division

Hiroyuki SAITO
Heat and Air Flow Analysis Laboratory, Environmental Engineering Division

Hiroshi KAJIYAMA
Heat and Air Flow Analysis Laboratory, Environmental Engineering Division

For electric railways, it is preferable for the tension and height of overhead contact lines to be constant to maintain satisfactory current collection performance. Since overhead contact lines expand and contract according to temperature change, an automatic tension balancer is generally installed at the terminations. However, the tension of overhead contact lines is not always constant because of tension fluctuations in automatic tension balancers and the gradient of the yokes. In addition, contact wire wear causes its mass to decrease. This also affects the contact wire tension and height. The authors performed a theoretical study and a simulation. As the results of them, we clarified the effect of temperature change and contact-wire wear on current collection performance.

Keywords: current collection, temperature, contact wire, wear, tunnel, simulation

1. Introduction

For electric railways, it is preferable for the tension of overhead contact lines to be constant to maintain satisfactory current collection performance. Since overhead contact lines expand and contract according to temperature change, tension changes sharply at fixed terminations. An automatic tension balancer is generally installed at the termination points, and the supporting point has a line-movable structure, such as a hinged cantilever or a pulley. However, the tension of overhead contact lines is not always constant because of tension fluctuations in the automatic tension balancer and the gradient of the yokes. The height of contact wires changes too. In addition, contact wires are subject to mechanical and electrical wear as moving pantographs run along them. Contact-wire wear causes its mass to decrease and also affects current collection performance. At high running speeds in particular, of 300 km/h or over, these effects on current collection performance will be amplified.

The speed of the wind towards the pantograph which also affects current collection performance is higher in tunnels than in open sections on Shinkansen lines. The value of the wind speed in the tunnel was identified through on-site measurements [1]. However, no studies have been conducted to measure concomitant temperature ranges.

Field tests were thus performed on commercial lines along with the thermal environmental simulation [2] to investigate air temperature distribution in tunnels. In addition, a theoretical study was conducted for overhead contact line - pantograph simulation to verify the effects of temperature variation and contact-wire wear on current collection performance.

2. Effect of temperature change and contact-wire wear on current collection performance

As shown in Fig. 1, overhead contact lines expand and contract according to temperature change and contact-wire wear. Therefore, an automatic tension balancer is generally installed at the termination points. The tension of the balancer changes with the displacement of its position. As shown in Fig. 2, tension is given by plural wires using yokes on the compound catenary equipment on Shinkansen lines. As each wire is made of a different kind of material with a different cross-section, yokes incline according to the differences in wire expansion and contraction. This changes the ratio among tensions of each wire. Therefore,
displacement of the balancer and the gradient of yokes change so that the tensions of each wire are balanced. The height of contact wires also fluctuates with tension change. Since the tension of each wire and height of contact wire influence current collection performance, it is important to verify quantitatively the effect of temperature change and contact-wire wear on current collection performance. However, detailed quantitative evaluations were not performed.

3. Thermal environment in railway tunnels

3.1 Heat transfer in railway tunnels with passing trains

When a train runs at a high speed, in order to overcome running resistance, such as rolling resistance and air resistance, it is always necessary to ensure a continuous energy supply. When a train runs through a tunnel, the supplied energy is transformed eventually into thermal energy raising the air temperature in the tunnel. Some of this thermal energy is then propagated to the ground from the surface of the tunnel wall, while the rest is discharged outside the tunnel with the train draft.

3.2 Field tests on a commercial line

3.2.1 Measurement conditions

In order to research the temperature characteristics in tunnels, temperature measurements were taken over a period of 12 months in the following two tunnels on a commercial line (Tohoku Shinkansen line – KuriKoma-Kogen station):
(a) Ichinoseki Tunnel (Tunnel A, length 9.730 km)
(b) Kuroishi Tunnel (Tunnel B, length 2.013 km)

Figure 3 shows the intervals at which temperature-measuring equipment was installed, i.e. at several tens of meters or hundred meters apart within 1 km of each tunnel entrance, and then every 1 km, in between. Since the distance between the two tunnels is approximately 1 km, it can be considered that the outside air temperatures around the tunnels were same and train operation conditions were almost the same for both tunnels.

3.2.2 Measurement results

Examples of temperature measurement waveform are shown in Fig. 4. At five places in Fig. 4, the maximum value, the minimum value, and the range in variation (difference between the maximum and the minimum temperature) of annual temperature are as follows:

(1) Outside of the entrance (south of Tunnel A)
Max. 35 °C, Min. -10 °C, Range in variation 45 °C

(2) Tunnel A 1 km from south entrance
Max. 26 °C, Min. 0 °C, Range in variation 26 °C

(3) Tunnel A at center (5 km from entrance)
Max. 24 °C, Min. 12 °C, Range in variation 12 °C

(4) Tunnel B at center (1 km from entrance)
Max. 26 °C, Min. -1 °C, Range in variation 27 °C

(5) Outside of the entrance (north of Tunnel B)
Max. 35 °C, Min. -10 °C, Range in variation 45 °C

Air temperature of (1) and (5) is almost identical. The range in variation of annual temperature in tunnels is smaller than that of outside. The range in variation of annual temperature in Tunnel A becomes small as to go inward the tunnel. And, the range in variation of annual temperature in Tunnels A and B of 1 km from entrance is almost identical.

Figure 5 shows examples of the temperature measurement waveform for daily variation. The daily variation of temperature adjacent to the center of the tunnel remained

![Fig. 3 Conditions for temperature measurements in tunnels](image-url)
unchanged. 1 km away from the south entrance of Tunnel A, the temperature changed at 30 minute intervals. Since the temperature changed during train operating hours (6:00 to 24:00), the temperature change appears to have been the result of train draft.

3.2.3 Range in variation and average of annual temperature in the tunnels

The relation between the distance from the south entrance and range in variation of annual temperature is shown in Fig. 6. The range in variation of the annual temperature in both Tunnels A and B fell in line with distance from the tunnel entrance. The relation between the distance from the south entrance and average annual temperature is shown in Fig. 7. The average annual temperature in both Tunnels A and B rose in line with distance from the tunnel entrances.

The relation between the distance between side entrances close to the measurement points and range in variation of annual temperature is shown in Fig. 8. The relation between the distance from the entrance and the range in variation of the annual temperature in Tunnel A and that in Tunnel B are almost identical. Therefore, the difference in tunnel length has no effect on the range in variation of its annual temperature. The approximated curve of the measured points as an exponential function is expressed by the following equation.
3.3 Calculation of temperature using simulation

In order to verify the possibility of the prediction of the thermal characteristics in tunnels, the results of the thermal environmental simulation [2] were compared with the measured results.

3.3.1 Calculation conditions

The thermal environmental simulation in the tunnel is a calculation method for predicting the air temperature change in a tunnel, on the basis of the outside air temperature change, the cross-sectional area of the tunnel, the wind speed of the train draft, and the amount of heat generated by the train.

The seasonal and daily variations of the outside air temperature are given by approximating the obtained observational data from the nearest weather stations using sine wave synthesis. Table 1 shows the input conditions for the outside air temperature. The earth temperature at a depth from the tunnel wall greater than or equal to a certain threshold (here, more than 10 m) is assumed to be the same as the annual average of the outside air temperature: 11.4 ℃.

Velocity of the train draft in the tunnel is determined using the simulation of pressure transients in a tunnel [3].

Only the running resistance in the tunnel (horizontal- and straight-line, constant speed) is considered as a calorific value of the train. Running resistance is assumed to be the total of air resistance and rolling resistance. Air resistance is calculated using the simulation of pressure transients in the tunnel. Rolling resistance \( R_{M} \) is then calculated by the following equation [4].

\[
R_{M} = \frac{(1.2 + 0.0792 \times V)}{1000} \times W \times g \tag{3}
\]

where 
- \( V \) : Train speed [m/s]
- \( W \) : Gross weight of the car [kg]
- \( g \) : Acceleration of gravity [m/s²]

3.3.2 Comparison of the measured results and calculated results

Figure 10 shows examples of the measured results and the calculated results from the thermal environmental simulation. The calculation results for the thermal environmental simulation indicate a similar tendency to the measurement results. Figure 11 shows the relation between the distance from the entrance and the range in variation of the annual temperature. The calculated results were almost identical to the measured results. Therefore, it is conceivable that the thermal characteristics in the tunnel can be predicted from the thermal environmental simulation.

3.4 Predictable temperature in the tunnel

The measured results and calculated results revealed that the distance from the entrance had an effect on the range in variation of the annual temperature and average annual temperature in the tunnel, regardless of tunnel length. Then, provided that such conditions as outside air temperature, earth temperature and train driving pattern are equivalent among the tunnels in question as is often the case with the same railway section, it is conceivable that the temperature range which should be taken into consideration in the evaluation of current collection performance can be determined solely according to the distance from the entrance regardless of the tunnel length.

In sections between the entrances and a point approximately 3 km away from the entrances, it is advisable to consider that the range in variation of annual temperature is equal to that in the open air because it is comparatively large: for example, 10 ± 30 ℃ at measurement points. And, in sections over 3 km away from the entrance, it can be assumed that the range in variation of annual temperature is narrower than in the open air. In this regard, since air temperature in a tunnel is affected by earth temperature, air temperature and the calorific values of trains, there is

![Fig. 9 Relation between the distance from side entrance close to measurement points and average annual temperature (average value in ten minutes)](image)

\[
t_{t_{a}} = 27.1 \exp(-0.62 \times x_{a}) + 10.3 \tag{1}
\]

where 
- \( t_{t_{a}} \) : Range in variation of annual temperature
- \( x_{a} \) : Distance from the entrance

The approximated curve of the measured points explains the tendency of the measurement results well.

The relation between the distance from the side entrance close to the measurement points and average annual temperature is shown in Fig. 9. The relation between the distance from the entrance and average annual temperature of Tunnel A and that of Tunnel B are almost identical. Therefore, the difference in tunnel length has no effect on average annual temperature. The approximated curve of the measured points as an exponential function is expressed by the following equation.

\[
t_{a} = -12.4 \exp(-1.76 \times x_{a}) + 23.4 \tag{2}
\]

where 
- \( t_{a} \) : Average annual temperature

The approximated curve of the measured points explains the tendency of the measurement results well.

| Item | Temperature [℃] |
|------|-----------------|
| Average | 11.4 |
| Variable amplitude of annual variation of daily average (half amplitude) | 15.0 |
| Variable amplitude of daily variation (half amplitude) | 5.0 |

Table 1   Input conditions of outside air temperature
4. Change in tension and height of wires

4.1 Calculation condition

The calculation model for the tension in overhead contact lines [5] is shown in Fig. 12. It is reported that the calculated values of the model and the measured values approximately coincide with each other [5]. Table 2 shows the calculation conditions. Figure 13 shows the characteristics of the tension balancer. The tension balancer was a Weight type Tension Balancer (WTB) in the open air, and is a Tunnel Tension Balancer (TTB) in the tunnel. The characteristics of the TTB are shown in consideration of the hysteresis at the time of movement by internal-friction resistance etc. In the open air, air temperature is 10 °C (Standard value) ± 30 °C. In addition, in the tunnel, the temperature range within which the TTBs are movable is taken into consider-

![Fig. 10](image1)

**Fig. 10 Comparison of temperature change between measured results and simulated results (Example of daily variation, average value of ten minutes)**

![Fig. 11](image2)

**Fig. 11 Calculated results - tension of the contact wire - a difference in average annual temperature between the open air and the tunnel. Accordingly, it is necessary to take into consideration not only the range in variation of annual temperature in tunnels but also average annual temperature.**

![Fig. 12](image3)

**Fig. 12 Calculation model for the tension in overhead contact lines**

| Table 2 Calculation conditions |
|---------------------------------|
| Area          | Open air | Tunnel |
| Messenger wire (standard Tension) | St180 (24.5 kN) | -- |
| Auxiliary messenger wire (standard tension) | PH150 (9.8 kN) | -- |
| Contact wire (standard tension) | GT-Sn170 (19.6 kN) | -- |
| Span length [m] | 50       | 45     |
| Stagger [mm] | ± 150    | ± 150  |
| (two span cycle) |         | (eight span cycle) |
| Drum length [m] | 1500     | 1100   |
| System height [mm] | 1600     | --     |
| Tension balancer | WTB      | TTB    |
| Variability rate of tension [%] | 5        | 3      |
| Movelsable length [mm] | 588      | 400    |
| Yoke size | θc:0.11  | θc:0.18 |
| Length of member \( l \) [m] | θc:0.13  | θc:0.22 |
| Angle of member (initial condition) \( \dot{\theta} \) [°] | θc:0.18  | θc:0.16 |
| Temperature °C | 10 ± 30   | --     |
| Diameter of contact wire [mm] | 15.49 (new wire) | 14.00, 12.50 |
that in the open air. The height of the contact wire in the tunnel will be larger than height of the contact wire in the open air is smaller than that in the tunnel. This is because the yokes incline by the difference of the linear expansion coefficient of the wires (contact wire and auxiliary messenger wire, 17 × 10⁻⁶ and messenger wire, 12 × 10⁻⁶).

The change in tension of the messenger wire in the open air is smaller than that in the tunnel. This is because the vertical length of No.2 yoke in the open air (550 mm) is greater than in the tunnel (330 mm). This means that the gradient of the yoke in the open air is smaller than in the tunnel. Since tension of the messenger wire affects the height of the contact wire, it is assumable that a change in height of the contact wire in the tunnel will be larger than that in the open air.

In addition, when a contact wire becomes worn, its tension decreases. This is because yokes incline by elastic extension of the contact wire.

4.3 Height of the contact wire

Figure 15 shows the calculation result of the height of the contact wire. Since the tension of TTB has hysteresis characteristics, the height change, under relevant conditions from the initial condition, is large, and is shown for both the minimum temperature and maximum temperature (the minimum temperature is “D” point of Fig. 13, and the maximum temperature is “B” point of Fig. 13). As contact-wire wear progresses, the height of the contact wire will rise. When the temperature changes, the height of the contact wire hardly changes in the open air. On the other hand, in the tunnel, the height of the contact wire rises according to the rise in temperature. This is because of the hysteresis characteristics of the automatic tension balancer, and the size of the No.2 yoke. In the tunnel, provided that the temperature is at its maximum and the diameter of the contact wire is 12.5 mm, the height of the contact wire diverges most from the standard condition. The height of the contact wire rises by approximately 40 mm at the support point. Therefore, through temperature change and contact-wire wear, the margin of uplift at the support point diminishes in relation to the standard value.

5. Dynamic evaluation using computer simulation of current collection performance

5.1 Simulation conditions

A simulation was conducted of the overhead contact line - pantograph [6] to verify the effect of temperature change and contact-wire wear on current collection performance. The conditions for the calculation of overhead contact lines are shown in Table 2, and Fig. 15 shows the height of the contact wire. Figure 16 shows the dynamic models of the pantograph [7]. It is assumed that the aerodynamic lift force is proportional to the square of the running velocity. In addition, it is supposed that the wind speed in the tunnel is 1.5 times faster than that in the open air, and therefore, the aerodynamic lift force in the tunnel is 2.25 (= 1.5²) times larger than that in the open air.

5.2 Simulation result

Figure 17 shows the calculated results for contact-wire uplift and strain at the support point. Since the tension of the TTB has hysteresis characteristics, the results of the simulation are shown for both the minimum temperature and maximum temperature (the minimum temperature is “D” point of Fig. 13, and the maximum temperature is “G” point of Fig. 13). At the time of temperature change, contact-wire uplift and strain become larger as temperature becomes higher. Even if contact-wire wear progresses, contact-wire uplift and strain remain almost unchanged. However, the evaluation of contact-wire uplift in the simulation is performed based on change in height of the contact wire as shown in Fig. 15. Therefore, by temperature change and contact-wire wear,
the margin of uplift at the support point becomes small compared to the standard value.

6. Measures to suppress the effect of temperature variation and contact-wire wear

It has been clarified that the margin of uplift at the support point is smaller and the current collection performance deteriorates when temperature rises, because of temperature change and contact-wire wear. In consideration of these results, measures were investigated to suppress these effects.

At first, reduction of the tension hysteresis characteristics of the automatic tension balancer can be considered for the suppression of gross-tension change. And, for the suppression of change in height of the contact wire due to variation in tension of the messenger wire, change in size of No. 2 yoke can be also considered. The possibility and the effect of the suppressing tension change in the messenger wire were examined by adjusting the size of No. 2 yoke, and reported results show that this measure had a positive effect, especially in tunnels [8].

As other measures, reduction of the upward force of the pantograph was considered. Moreover, adoption of support equipment with a large margin for uplift at the support point, and a contact wire with high fatigue strength for strain at the support point were also considered.

7. Conclusions

With respect to the effect of temperature change and contact-wire wear on current collection performance, we conducted the temperature measurement in tunnels on a commercial line, the theoretical study, and the overhead contact line - pantograph simulation. The results can be summarized as follows:

1. With increasing inward distance from the tunnel entrance, the range in variation of the annual temperature in tunnels falls while the average annual temperature in tunnels increases.

2. The difference in tunnel length does not affect the range in variation nor the average of the annual temperature.

3. The simulation results were almost identical to the measured results. Therefore, the thermal characteristics in the tunnel can be predicted from the thermal environmental simulation.

4. When contact-wire wear progresses and the temperature changes, the height of the contact wire rises by approximately 40 mm at the support point. Therefore, the margin of uplift at the support point decreases in relation to the standard value.

5. When temperature rises, uplift at the support point, which is one of the current collection performance evaluation criteria, deteriorates.
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Authors

Mizuki TSUNEMOTO
Assistant Senior Researcher, Contact Line Structures Laboratory, Power Supply Technology Division
Research Areas: Dynamic Interaction between Pantograph and Catenary, Catenary Maintenance

Makoto KAJIYAMA, Dr. Eng.
Senior Researcher, Heat and Air Flow Analysis Laboratory, Environmental Engineering Division
Research Areas: Aerodynamics, Thermal Engineering