AN EXPERIMENTAL INVESTIGATION OF TRANSIENT HEAT TRANSFER IN SURROUNDING ROCK MASS OF HIGH GEOTHERMAL ROADWAY

by

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A self-designed experimental installation for transient heat transfer in the modelling surrounding rock mass of high geothermal roadways was elaborated in this paper. By utilizing the new installation, the temperature variation rules in surrounding rock mass of the high geothermal roadway during mechanical ventilation were studied. The results show that the roadway wall temperature decreases dramatically at the early stage of ventilation, and the temperature at every position of the surrounding rock mass is decreasing constantly with time passing by. From roadway wall to deep area, the temperature gradually increases until reaching original rock temperature. The relationship between dimensionless temperature and dimensionless radius demonstrates approximately exponential function. Meanwhile, the temperature disturbance range in the simulated surrounding rock mass. Besides, as the air velocity increases, heat loss in the surrounding rock mass rises and the ratio of temperature reduction becomes larger, the speed of disturbance range expansion also gets faster.

Key words: high geothermal temperature, transient heat transfer, modeling experiment, similarity experiment

Introduction

As a common obstacle in the construction of deep-buried roadways and long tunnels, high geothermal temperature can lower the efficiency of project construction, affect the performance of support structure and increase the project investment. It may also harm workers' physical and mental health, and cause accidents like roof falling, fire and gas explosion, *etc.* [1, 2]. Advancement and maintenance of tunnels in alpine regions also faced with the extreme temperature challenge [3-6], because frigid ground temperature can result in cracks of lining and freeze of pavements that would endanger the train operation. Due to the previous harm listed, high geothermal environment has often been considered as a natural disaster. As one of the major components of roadways and tunnels insulation technical studies, research on high geothermal temperature field has become more and more significant.

The natural temperature in rock strata which is not disturbed by human engineering activity is called original rock temperature [7, 8]. Once the roadway is excavated, the origin rock temperature equilibrium is disturbed, and heat in the deep surrounding rock mass contin-

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uously transfers to air stream, the surrounding rock mass temperature also continues to change during the process. Site investigation and numerical calculation are usually applied to study the temperature field. Although, *in-situ* observation data are relatively true, only a few data has been obtained so far because of its complicated and costly process [9, 10]. Compared with site investigation method, finite element method and finite difference method are more commonly used to study the temperature field in the roadway rock mass. More research results were found by the numerical calculation method concerning the rock mass temperature field prediction [3, 11], influence factors of temperature distribution in the rock mass [12-15], and the disturbed domain of the temperature in the surrounding rock mass [16]. Most of the existing researches on the rock mass temperature distribution of the roadway, however, were not validated in laboratory. With the knowledge of limited site observation data about the rock mass temperature of the roadway or tunnel drawn from previous studies, and the strong dependence of numerical computation method on the rationality of mathematical model, Zhang et al. [2] established a mathematical model by using cylindrical co-ordinate system and its unsteady modularization test method on the basis of analyzing heat conductive characteristics of surrounding rock mass, which provides possibility of carrying out modeling experiments in laboratory.

Modeling experiment is widely used in researches of hydromechanics and heat transfer. When applied to temperature field studies, not only the process of heat transfer can be intuitively and truly acquired, but also more credible data can be collected. In light of analogical rules between physical model and prototype, the test results can be easily generalized to practice. Furthermore, factors affecting the temperature field such as air velocity, humidity, temperature and thermo-physical property parameters of surrounding rock mass can be systematically controlled. Restricted by analogical conditions of geometry, time, physics and boundary, and considering the experimental error and test environment, the modeling experiment equipment demands rigorous test conditions and high costs in development and application. As a result, experimental system for high temperature environment of roadways is rarely found both at home and abroad. In 2008, scholars in Tianjin University [17] established a simulation system for heat and moisture transfer between roadway and airflow. At about the same time, researchers in China University of Mining and Technology developed a set of unsteady airflow heat transfer experiment system for roadway. A number of experiments were carried out by these two systems, and valuable experimental data has been acquired [18]. However, both systems have some disadvantages, such as small model size with imbalance boundary temperatures and less experimental function, etc. The longer simulated roadway is only 1200 mm long with the largest radius of 200 mm, and a small-size model would result in complex boundary conditions, shorter cylinder for effective simulation and greater test error. Besides, both test systems adopt thermostatic water bath circulation system that would slower adjusting temperature and maldistribution of water temperature. To make up these drawbacks, an experimental installation for heat transfer (EIHT) in the modelling surrounding rock mass of roadway was designed and developed, aiming to develop a system for research on coupled heat transfer between surrounding rock mass and airflow. In this paper, the temperature variation rules in surrounding rock mass of high geothermal roadway during mechanical ventilation were studied by utilizing the new installation.

Methodologies

Experimental installation

The composition sketch map of EIHT is illustrated in fig. 1. As indicated in fig.1, the installation is composed by simulated cylinder, constant temperature, and humidity machine

(CTHM), silicon controlled rectifier (SCR), and data acquisition system (DAS). The simulated cylinder simulates the surrounding rock mass of the roadway: CTHM blows air to the simulated roadway or tunnel with certain temperature and humidity, SCR power heats the simulated surrounding rock mass, and DAS monitors and collects data such as real-time temperature and air velocity, temperature, humidity, and air pressure.

The self-designed EIHT picture is shown in fig. 2. Apart from exploring coupling heat transfer and mass transfer between surrounding rock and airflow in high geothermal roadway and alpine regions, the installation can also provide basic experimental conditions for ventilation parameters design, spouting thermal insulation materials cooling, and heat preservation design in alpine tunnels. The major technical parameters are:



Figure 1. Composition of EIHT



Figure 2. The EIHT for the modelling roadway

The simulated cylinder as shown in fig. 2 is consisted of six barrels. Each barrel is 1.0 m long with inner diameter of 0.8 m and external diameter of 1.0 m.



Figure 3. Cross-section diagram of the simulated cylinder

The heating mode has constant current, voltage and power, with iron chromium aluminium alloy mesh as heating element, low voltage and high current as heating method. The highest heating current is 1000 A, and the highest voltage is 30 V. An environment of

Ventilation is carried out by constant temperature and humidity machine, with the assistance of an axial flow fan and a small air blower. Maximum airflow rate is 5000 m³/h,

the temperature is 5-45 °C, with fluctuation range of ± 1 °C, the humidity range is 20-90%

pump station and oil cylinder, which enables the inclination angle of simulation roadway

The experimental installation is autocontrolled by microcomputer. The data of airflow temperature, humidity, velocity, and gas pressure are also collected automatically. Temperature sensors were placed in simulat-

ed roadway and its surrounding rock mass in

RH, and the fluctuation range is $\pm 2\%$ RH. The pedestal of physical simulated roadway is tower structure with hydraulic regulating

to be adjusted from 0 $\,^{\circ}$ C to 45 $\,^{\circ}$ C.

steady original temperature field can be set up with temperature ranging from indoor temperature to 60 °C. The heating precision is ± 0.1 °C.



Figure 4. Temperature sensors arrangement

each cylinder, as shown in fig. 4. *Material of simulated surrounding rock mass*

According to the requirements of simulated surrounding rock, and the impossibility of adopting original structure material in such large-size and large-scale modeling experiment, Portland cement-based material was chosen for the equipment. The thermal conductivity of cement mortar is basically under 1.0 W/mK, thus a certain proportion of heat-conducting powder is necessarily added to promote the heat-conducting property. High-purity quartz sand has favorable heat-conducting performance, and its thermal conductivity is several or tens of times of that of river sand. Contrasted with coarse aggregates such as marble and granite, the heat conducting capacity of iron powder or Fe_2O_3 is beyond compare because their particle sizes are small and easy to dissolve into grout, so a small amount is sufficient. Based on the previous analysis, small proportion of high purity quartz sand and river sand are included as fine aggregates, and Fe_2O_3 powder is added to increase its heat-conducting property. The composition proportion of each material is listed in tab. 1.

Material composition proportion					Properties	
Portland cement River sand		High purity quartz sand	Fe ₂ O ₃	W/C	$\lambda [Wm^{-1}K^{-1}]$	$c [\mathrm{m}^2\mathrm{s}]$
1	4	0.1	0.07	0.6	1.2	$0.8 \cdot 10^{-6}$

Experimental program and procedure

Program

To study distribution rules and evolution laws of surrounding rock temperature field in high geothermal roadway and explore the spatial-temporal revolution rules of temperature field, the experimental original rock temperature is set as 37 °C, according to upper limit of first class heat hazard and lower limit of second class heat hazard of China Mine Engineering Standards [19]. To simplify the tests, the mass transfer process between airflow and surrounding rock mass is neglected. The air humidity is 20% RH invariably, and the airflow temperature is in two groups: 10 °C and 20 °C. The air velocity is classified into three sets including 5 m/s, 7 m/s, and 8 m/s, as presented in tab. 2.

Table 2. Experimental program

Tachnical parameters	Experimental program				
rechinear parameters	Scheme 1	Scheme 2	Scheme 3	Scheme 4	
Original rock temperature, t_0 [°C]	37	37	37	37	
Inlet air flow temperature, <i>t</i> _f [°C]	20	20	20	10	
Air flow velocity, $u [\text{ms}^{-1}]$	5	7	8	5	

Procedure

- (1) Install the simulation surrounding rock mass into the physical simulated roadway. Turn on the rectifier power after the heating alloy mesh and sensors are correctly connected, then test the working conditions of heating element to ensure that the total resistance of heating alloy mesh is no more than 0.03Ω .
- (2) Take the outer boundary of simulation roadway as the temperature control point and set the upper limit of temperature control point as original rock temperature (37 °C). The lower limit value is about 0.2 °C less than that of upper limit. If the temperature exceeds the upper limit, the heating will be automatically suspended, while, if the temperature is under the lower limit, the heating procedure will restart automatically.
- (3) Set the heating mode into auto-control steady current heating and the soft start time into 10 seconds. The output current stepwise decreases from 300 A to 100 A, with each step of 50 A and heating time of 2 hours.
- (4) Start heating procedure and adjust heating mode to manual-control steady current heating with electricity of 100 A until temperature of all measure points reach original rock temperature. Adjust the electricity within 20-100 A repeatedly by approximation method and find a particular voltaic value to ensure the steady temperature of outer boundary.
- (5) Keep warm for about 6-8 hours, and observe the temperature at each monitoring point, if the temperature fluctuates dramatically, repeat step 4 so as to obtain the heat dissipation power in laboratory environment.
- (6) After all the temperature values are steady, start the constant temperature and humidity machine, and set the airflow temperature to 20 °C, humidity to 20% RH, air velocity to 5 m/s (Scheme 1). Blow the fresh air to simulated cylinder until the temperature of outer boundary reaches 36.6 °C, which is 1% differ from original rock temperature.
- (7) Stop constant temperature and humidity machine and subsidiary axial flow fan. Save all the experimental data and move on to the heating procedure of next experiment.
- (8) Repeat from step 2 to step 7, conduct the experiments of Schemes 2, 3, and 4 with parameters shown in tab. 1.
- (9) Turn off the heating power, collate experiment data and finish the experiment.

Results and discussion

Method for data analysis

To acquire the common laws between surrounding rock temperature, time and space, dimensionless process for experimental data was conducted. The equations are:

$$\begin{cases} \Theta = (t - t_{\rm f})/(t_0 - t_{\rm f}) \\ R = r/r_0 \\ Fo = a\tau/r_0^2 \end{cases}$$
(1)

where Θ is the dimensionless temperature, R – the dimensionless radius, Fo – the dimensionless time, t – the surrounding rock real-time temperature, t_0 – the original rock temperature, t_f – the airflow temperature, r – the distance between monitoring point and axis of the simulated roadway, r_0 – the radius of the simulated roadway, a – the surrounding rock thermal diffusivity, and τ – the the ventilation time.

Temperature distribution in simulated surrounding rock mass

Results

Figure 5 illustrates the relation curve of dimensionless temperature, Θ , and dimensionless radius, R, of surrounding rock mass at the dimensionless time, Fo, from 0 to 0.8. As suggested in fig. 5, the experimental data from Scheme 1-4 have similar tendency on their relation curves between dimensionless temperature and dimensionless radius.

Take fig. 5(a) as an example, the temperature distribution characteristics in simulated surrounding rock mass are as follows.

- When Fo = 0.1, the excessive temperature $(t t_f)$ of the roadway wall decreases to about 0.73 times of the original excessive temperature $(t_0 t_f)$. However, the temperature decreasing amplitude of the simulated surrounding rock mass is also falling gradually. These phenomena show that the temperature of roadway wall decreases dramatically at the early stage of ventilation, and the decreasing rate declines continuously with the ventilation process proceed.
- From roadway wall to deeper area, the temperature of surrounding rock mass constantly rises until reaching original rock temperature ($\Theta = 1$), while the temperature at every position of the surrounding rock mass is decreasing gradually with time goes by.
- The temperature disturbance range in the simulated surrounding rock mass extends little by little, with its value of 2R at Fo = 0.1, compared with 3R and 4R when Fo = 0.3 and 0.8, respectively.
- At any time, the bigger the dimensionless radius is, the smoother the Θ -R curve becomes. The slope of the curves in fig. 5 is $\partial t/\partial r$, equal to the temperature gradient. It indicates that the heat flux gradually decreases because of the steady thermal physical properties of the simulated surrounding rock mass.

Discussions

OriginPro software was applied to fit the relation curves between Θ and *R* in fig. 5(a). The results show that the curves present high correlativity with exponential function. All the correlation coefficients are larger than 0.99. The fitting results are shown in tab. 3, where S_1 , S_2 , and S_3 are coefficients.

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Figure 5. Relation curve between dimensionless temperature and dimensionless radius

Fitting function		Correlation		
	S_1	<i>S</i> ₂	S_3	coefficient
Fo = 0.1	-8.4323	-3.4308	1.0001	1.0000
Fo = 0.2	-3.3037	-2.2631	1.0019	0.9999
Fo = 0.3	-2.4363	-1.8246	1.0053	0.9989
Fo = 0.4	-2.1407	-1.6191	1.0039	0.9934
Fo = 0.5	-1.8037	-1.3969	1.0066	0.9942
Fo = 0.6	-1.7686	-1.3489	1.0006	0.9929
Fo = 0.7	-1.6228	-1.2314	1.0031	0.9944
Fo = 0.8	-1.6346	-1.2002	0.9974	0.9932

|--|

When the scope of *Fo* falls between 0.8 and 1, the value of S_3 stays around 1. Here $\Theta = 1$ represents that the surrounding rock mass has initial temperature. When *R* is infinite, the value of $S_1 \exp(S_2 R)$ is close to 0 and Θ approaches 1. Actually, the temperature at positions of infinite distance is steadily approaching original rock temperature, *i. e.* the value of Θ is also close to 1. So it is reasonable that the fitting formula in table 3 can be written.

$$\Theta = 1 - S_1 \exp(S_2 R) \tag{2}$$

In the preliminary stage of ventilation, temperature changes dramatically in the surrounding rock mass, which is reflected by the great variation of parameter S_1 and S_2 in the fit-

ting formula in tab. 3. With the increase of ventilation time, the absolute value of S_1 and S_2 both present a decreasing trend, so does the changing amplitude. Thus, parameter S_1 and S_2 may have a correlation with dimensionless time.

Fan and Zhang [16] has established a mathematical model of heat conduction and adopted finite difference method to study the temperature field of roadway surrounding rock



Figure 6. Comparison between resolving and actual measurement results [16]

mass and conducted site investigation in a Pb-Zn-Au mine in China. The relation curve between temperature of surrounding rock mass and distance from axle center of the roadway derived from their research is displayed in fig. 6. It can be seen from the chart that the resolving results have a good consistency with the actual measurement results.

The actual measurement results were nondimensionalized with eq. (1), and listed in tab. 4. At the same time, the dimensionless data were presented in fig. 7. OriginPro software was used

to fit the relation curve between Θ and R. The result shows that the curve also presents high correlativity with exponential function, and the correlation coefficient is up to 0.9999.

Measurement site	-294 m below ground level, in Kangjiawan mine, Hunan Province, China						
Basic parameters	$a = 4.81 \cdot 10^{-7} \text{ [ms}^{-1]}, t_{\text{f}} = 20.5 \text{ [°C]}, t_0 = 31.0 \text{ [°C]}, r_0 = 2 \text{ [m]}, \tau = 9.4608 \cdot 10^7 \text{ [s]}$						
Actual measurement results	Temperature	24.9	29.2	30.9	31	31	
	Distance	5	10	20	26	30	
Non-dimensionalized results	Θ	0.42	0.83	0.99	1	1	
	R	3.5	6	11	14	16	
	Fo	11.38					

Table 4. The actual measurement results and their dimensionless values

The fitting formula in fig. 7 agrees well with the research results in tab. 3, suggesting that the research results in this paper have good consistency with previous numerical studies and site investigations, and the temperature distribution law in the surrounding rock mass of roadway is proved credible.

The influence of airflow temperature to surrounding rock temperature field can be grasped by comparison between Schemes 1 and 4, and the effect law of air velocity on temperature distribution can be obtained by comparison among Schemes 1, 2, and 3. To clearly reflect the influence of ventilation air velocity to roadway surrounding rock temperature distribution, relation curves between wall temperature ,and air velocity is illustrated in fig. 8 with roadway wall as the example.

- The variation of ventilation air velocity and temperature will not change the curve tendency of dimensionless temperature, radius, and time, but it will change the value of dimensionless temperature.
- Figures 5(a)-(c) indicate that, after the decreasing of airflow temperature, the temperature gradient along radius of surrounding rock becomes larger, the decreasing of surrounding

rock temperature obviously speed up, because the decline of air temperature enlarged the temperature gap between roadway wall and airflow and improved the heat flux ratio.



results

Figure 8. Relation curve between wall temperature and air velocity

Figures 5 and 8 suggest that under the same air temperature and ventilation time, the larger the air velocity, the lower the dimensionless temperature. The speed of disturbance range expansion also gets faster. With the increasing of air velocity, the heat loss in roadway surrounding rock rises, the ratio of temperature decrease become larger, and the temperature gradient inside the surrounding rock mass is widened.

Conclusions

On the basis of the newly designed system EIHT, an empirical experiment of transient heat transfer in surrounding rock mass of high geothermal roadway was conducted. Under given original rock temperature, airflow temperature and air velocity, the paper demonstrated the temperature evolution laws of surrounding rock mass. Following conclusions can be drawn from experiment and analysis results.

- The roadway wall temperature decreases dramatically at the early stage of ventilation, but the decreasing rate declines continuously with ventilation proceeds.
- From roadway wall to the deeper area, the temperature gradually increases to original rock temperature, while the temperature at every position of the surrounding rock mass decreases gradually with time passes by.
- The relationship between dimensionless temperature and dimensionless radius presents high correlativity with exponential function, and has good consistency with the previous numerical studies and site investigations.
- The temperature disturbance range in the simulated surrounding rock mass gradually extends from the roadway wall to deep area in the surrounding rock mass. As air velocity increases, the heat loss in surrounding rock mass rises, the ratio of temperature decrease becomes larger, and the speed of disturbance range expansion also gets faster.

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Nomenclature

- a surrounding rock thermal diffusivity, $[m^2 s^{-1}]$
- c specific heat capacity of surrounding rock
- Fo dimensionless time
- R dimensionless radius
- r the distance between monitoring point and axis of the simulated roadway, [m]
- r_0 radius of the simulated roadway, [m]
- t surrounding rock real-time temperature, [°C]
- t_0 original rock temperature, [°C]
- $t_{\rm f}$ airflow temperature, [°C]
- W/C water/cement ratio
- Greek symbols
- Θ dimensionless temperature
- λ thermal conductivity
- τ the ventilation time, [s]

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