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Modeling and parametric studies for convective heat transfer in large, long and rough circular cross-sectional underground tunnels

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ABSTRACT

With the increasing scarcity of fossil fuel, developing hydropower becomes one of the most important energy strategies. Underground tunnel ventilating has been used in many hydropower stations to save energy by precooling air. This study describes a measurement of heat transfer characteristics in the tunnel model. Based on the test results, the air temperature variation from inlets to outlets and the cooling capacity of the underground tunnel are discussed. Experimental results show that the surface roughness and air velocity both have influence on the heat transfer of the underground tunnels. With the relative roughness increasing, the temperature drop and cooling efficiency increase gradually. And the temperature drop and cooling efficiency increase sharply with the air velocity decreasing. Meanwhile, the effect of air velocity on the temperature drop and cooling efficiency is more significant than that of the relative roughness. In addition, the air temperature decreased rapidly with the increase of length. After a certain length, the air temperature and cooling efficiency almost change no more. And cooling efficiency reaches a stable value at 90%–95%. Therefore, using underground tunnel as a giant natural "air conditioner" is an energy-saving ventilation method; it has significant economic and environmental benefits.

1. Introduction

With the demand for greenhouse gas reduction and environmental protection all over the world, developing hydropower becomes one of the most important energy strategies [1]. Hydropower is clean and renewable. Technically, it is the only clean energy source that can be commercially developed on a large scale at present [2]. Many countries all over the world have begun to develop the hydropower industry. China has an exploitable hydropower of 542 million kWh, which ranks the first place all over the world. According to the Aggregate of Confirmed China's Hydropower Resources issued by the National Development and Reform Commission (NDRC) in 2005, there are 3886 rivers with theoretical hydropower storage of more than 10 MW in the mainland of China [3,4]. With the development of large-scale hydropower resources in China, it will increase to 420 million kW in 2020 according to the plan of NDRC [5]. The control of thermal and humidity environment is necessary for the safety of personnel and the normal operation of electrical and mechanical equipment, so the ventilation and air conditioning system of the hydropower station are very important. Therefore, the tunnel ventilation and air conditioning technology of the hydropower station has been greatly developed to save energy by precooling air [6–8]. The air treatment process is relating to heat transfer and dynamic characteristic [6,9]. Most of the hydropower stations are underground structures, and the underground structures are different from the ground due to the soil thermal effect. Compared with the ground building, the underground construction is in a relatively stable thermal environment of the soil. According to this characteristic, the use of heat transfer between supply air and underground tunnel for cooling during the summer was known since ancient times.

In order to describe the performance of the buried underground tunnel system experimental study had been done [10], and theoretical and numerical models were developed at present [11–15]. With appropriate assumptions, Liu et al. [16] present a set of discrete numerical equations and its solution of heat transfer between air and the underground tunnel surface. Yu et al. [17] studied a detailed quasi-three-dimensional mathematical model of heat and mass transfer of tailrace tunnel ventilation based on the analysis of heat and moisture transfer during the air flowing through the underground tunnel. The model is used for performance simulation of tunnel ventilation for a real great hydropower station. de Jesus Freire et al. [18] studied and developed passive methods of heat transfer including heat exchange through buried pipes.

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Nomenclature

k	Relative roughness
d	Particle size of river sand (mm)
l	Dimensionless length
t_x	Air temperature at measuring point (°C)
G	Air volume per hour through the tube (kg/h)
t_T	Temperature of the sand in rectangle groove (°C)
U	Cross-section circumference of the tube (m)
x	The horizontal distance away from the inlet (m)
L	The total length of the underground tunnel (m)
ρ	Density (kg/m3)
$t_{x,\tau}$	Air temperature in the tube (°C)
q	Heat flux (W/m2)
t_{inlet}	Air temperature of the inlet (°C)
c_p	Heat capacity of air (kJ/(kg °C))
t_1	Taking the place of $-\frac{C_pG}{qU}$
v	Air velocity (m/s)
ϕ	Diameter of test tube (mm)
θ	Dimensionless temperature
η	Cooling efficiency of ventilation
λ	Thermal conductivity (W/(m °C))

Hollmuller and Lachal [19] examine the fundamental difference between winter preheating and summer cooling potential of buried pipe systems. Based on numerical heat transfer and computational fluid dynamics, Wu et al. [20] developed a transient and implicit model to evaluate the effects of the operating parameters (i.e. the pipe length, radius, depth and air flow rate) on the cooling capacity of earth–air–pipe systems. Mihalakakou et al. [21] studied four variables influencing the thermal performance of the earth to air heat exchangers: pipe length, pipe radius, air velocity of the tube and depth of the buried pipe. The developed algorithm is suitable for the calculation of the outlet air temperature and the cooling potential of the system. Kumar et al. [22] developed a numerical model to predict energy conservation potential of earth–air heat exchanger system. This model improves upon previous studies by incorporating effects of ground temperature gradient, surface conditions, moisture content and various design aspects of earth–air–tunnel.

In many field tests of underground tunnels in the hydropower stations, we found that tunnel structure has a variety of forms, for example, plain brick masonry, rubble masonry, cement mortar or concrete masonry. Therefore, the internal surface roughnesses of different tunnels are quite different (see Fig. 3). The previous research studied the many influencing factors on heat transfer between air and soil (or rock) in tunnel ventilation. But up to now, the actual influence on heat transfer of air velocity and surface roughness in the underground tunnels is still unknown. In this study, the aim is to analyze the changes of the air temperature and find out the heat exchange effect in the large, long and rough underground tunnels. In order to make certain of how the inlet air velocity and surface roughness influence the cooling effect of an underground long tunnel, a simple tunnel model is built to do laboratory tests. Through continuous laboratory test, the results of the laboratory tests provide the reference data for designing and operating the HVAC system in the same type hydroelectric power plants.

2. Experimental setup

2.1. Physical model

According to the actual situation of large, long and rough underground tunnels, such as large hydropower station, a rectangle groove was built with external size of 10 m × 0.6 m × 0.3 m by building bricks. In the middle of rectangle groove, a circular groove with the diameter of 0.05 m was reserved from the bottom of 0.13 m. And the circular groove was located in the same horizontal plane to bury the tube. The thermal conductivity of rock stratum around the underground tunnels is 1.0–3.2 W/(m·°C). In order to simulate the real underground tunnels, the rock stratum was replaced by the sands which thermal conductivity is in the same range and the rectangle groove was filled with the sands except of the circular groove. In many previous studies about underground structures [25–27], the scale models were usually made of transparent organic glass. Therefore, the tunnel model was made by the organic glass tube (external diameter: 100 mm, length: 10 m) in this paper. And in order to avoid affecting heat transfer, the thickness of the tube was about 3 mm. The experimental rigs are shown in Fig. 1.

2.2. Experimental system and measuring point distribution

The experimental system includes four parts: air supply equipment (axial flow fan), heating apparatus, measuring equipment of air velocity and temperature acquisition system. The experimental system appearance was shown in Fig. 1.

There are 23 measuring points were set in the medial axis of the test tube to measure the air temperature, the other 23 measuring points were set on the external face of the test tube to test the temperature of the sand. And all the measuring points were set about 400 mm from each other (see Fig. 1). The air temperature was measured by thermocouple, and thermocouple probes were

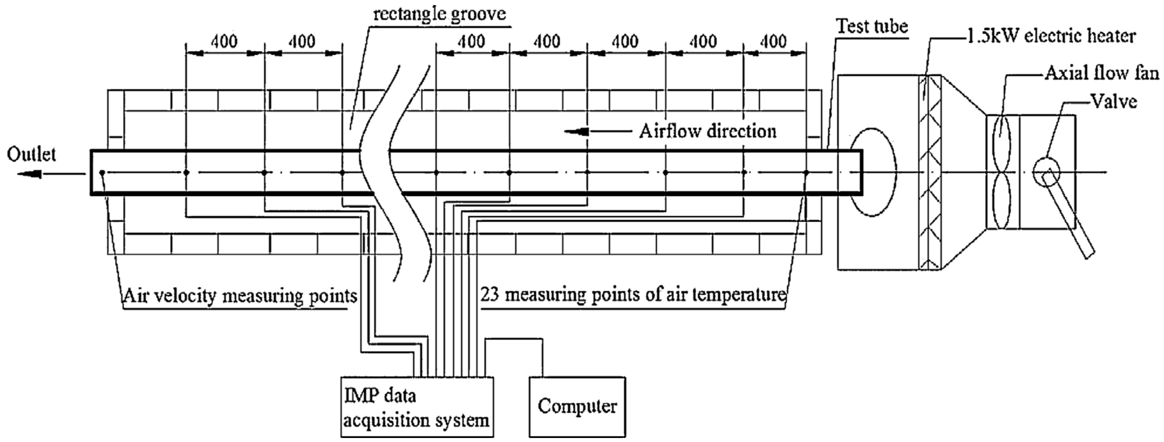

Fig. 1. The experimental system and measuring points distribution.