Applied Thermal Engineering 105 (2016) 151–158

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Numerical simulation and experimental study on ventilation system for powerhouses of deep underground hydropower stations

Yicai Liu, Shouchuan Wang, Yangbing Deng, Weiwu Ma *, Ying Ma

School of Energy Science and Engineering, Central South University, Changsha 410083, China

HIGHLIGHTS

- A reformed RNG k–ε model was proposed and applied in the simulation study.
- The arch crest air supply system was taken as an independent research object.
- We verify the reliability of simulation by a comparison with experimental results.
- Some feasible optimization advices were given to realize evenness of cooling effect.

ARTICLE INFO

Article history:
Received 9 August 2015
Revised 16 March 2016
Accepted 17 May 2016
Available online 27 May 2016

Keywords:
Underground hydropower station
Ventilation systems
Simulations
Experimental study
Powerhouse
Arch crest

ABSTRACT

Maintaining a steady and proper indoor thermal and humidity environment in deep underground powerhouses has a significant effect on human safety and the steady operation of power-generation systems. A quick and accurate numerical method to predict and evaluate the ventilation system is seriously needed. After reviewing and summarizing the current researches, as well as research on the heat or cold source conditions of underground hydropower stations, a reformed RNG k–ε model is proposed, and then applied to simulation study conducted on the ventilation system of powerhouses in Xiluodu. The actual temperature and velocity of ventilated air in different areas were also measured and compared with the simulation results, some notable differences were further discussed to improve the model. On the basis of simulation results, some feasible optimization advices for the ventilation system were given. In conclusion, the accuracy and reliability of CFD for prediction and evaluation of ventilation system in big space deep-underground is verified.

1. Introduction

Deep underground hydropower stations consist of main buildings or facilities, such as water-derivation tunnels, surge shafts, pressure conduit, main powerhouse, and tailrace tunnel, all of which are located deep underground. A generator floor of underground power stations has tall building envelopes called powerhouse, with a huge cross-sectional area and up to thousands of square meters in floor area, the powerhouse is considered a "large space" in the ventilation system design. Given that the walls of the buildings mainly use native rock as their support structure, the heat or mass transfer from rocks and groundwater seepage can affect the characteristics of supplied air like temperature and humidity. Furthermore, the meters and instruments demand a steady atmospheric working condition. The heat and mass transfer during ventilation must therefore be studied, given their importance in the adjustment of ventilation systems, steady operation, and the health of workers.

In most cases, arch crest system and outlets in the surrounding walls are adopted as air supply and exhaust systems for ventilation system design of powerhouses, respectively. After cooling process, the cold air is mechanically ventilated into the powerhouses through the air distributors in the arch crest, and finally returned through the exhaust systems. In which, the backflow phenomenon tends to occur in some areas and results in dead zones of temperature and humidity control.

2. Brief review of current researches

In recent years, whether or not the even distribution of ventilated air can be ensured is an important standard for valuating ventilation systems in large spaces. Such standard has gradually led to the formation of a valuation system that consists

---

* Corresponding author.
E-mail address: lyc0301@163.com (W. Ma).

http://dx.doi.org/10.1016/j.applthermaleng.2016.05.101
1359-4311/

Nomenclature

$\boldsymbol{u}$	vectorial velocity, m/s
u	velocity, m/s
Z	compressibility factor of gas
h	convective heat transfer coefficient, W/m^2 K
m	mass, kg
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
Re	Reynolds number
t	temperature, °C
X, Y, Z	rectangular coordinate, m

Greek symbols

v	specific volume, m^3/kg
ρ	density, kg/m^3
μ	turbulent viscosity, Pa s

Subscripts

c	convection
e	efficient
ε	dissipation rate
tunnel	exit surface of tunnel

of professional indexes, such as age of air, effective draft temperature, and air diffusion performance index [1].

In addition, the amount of fresh air calculated from the total load can hardly meet the actual needs because of the complex conditions of cold and heat sources in underground spaces, whereas setting excessive allowance in the heat or cold load results in a waste of energy. In recent years, the reasonable design of ventilation systems in underground hydropower stations based on large space ventilation technology has been a frontier study. A reasonable design should generally consider factors, such as geological conditions in underground buildings, operation conditions, locale's conditions of heat and cold sources (i.e., rock heat flow and groundwater), and efficiency of energy consumption [2].

At present, the major method of studying air distribution in underground hydropower stations mainly includes experimentation, physical model experiments, mathematical simulation, and some combinations of the three.

Before the breakthrough of CFD technology based on computer hardware, using trace elements or gas as a tool of determining the age of air was an important method of detecting air distribution in large spaces [3]. Thus far, the element tracing method remains an important method in the experimental study of the ventilation of underground spaces. Widiatmojo et al. used tracer gas SF6 to detect dead ends in the ventilation system of the Kushiro underground coal mine and conducted numerical simulation to predict air distribution [4]. The paper conducted good detection work to examine the dispersion characteristic of air, the method has great reference value in air safety, but due to limitation of trace gas method, other characteristics of the ventilated air cannot be offered.

The reduced-scale model is a convenient way to study the roof supply system for underground station powerhouses. The theories are firstly developed in 1996 by Fu [5], Angui Li et al. conducted a research project on a 1:20 reduced-scale model to investigate the air distribution in the generatrix floor of the Hohhot underground hydropower station [6]. A series of tests was performed under 48 various operating conditions. The air distribution was evaluated by calculating dimensionless temperature and dimensionless velocity. Given that the effective gravity is equal to the difference between gravity and buoyancy force, the Froude number was replaced with the Archimedes number as a similar dimensionless parameter in this study. This study has taken the buoyancy into consideration. But in the model, the actual distribution of heat source conditions and heat flux from the wall and was neglected.

In recent years, the technology of using CFD as a tool for airflow prediction in large spaces has been greatly developed. Liu proposed a prediction model about heat and moisture environment in underground hydropower station, the model has taken the material of building envelope into consideration, but air diffusion in the entire space cannot be given [7]. Li Xiao-dong et al. developed a method based on the study of the multi-zonal model, which established the mass and energy equilibrium equations for each macro "large control volume." The calculation results of the wall surface temperature and heat flux can be directly treated as the energy boundary conditions in the CFD model, which is regarded as a necessary auxiliary to CFD simulation [8]. But there's no experiment to verify the model, and the complex calculation process made the model less operable and practical.

3. Mathematical model

The establishment of appropriate mathematical models can have a significant effect on improving the accuracy of simulation and on reducing computational burdens. After blown into interior space of powerhouse through air distributors in the arch crest, the fresh air is fully developed in large spaces, which belong to free air jet. The buoyancy caused by temperature rises near the wall and the generator shields contribute to natural convection. In conclusion, the airflow in a powerhouse should belong to the combination of natural convection and forced convection.

3.1. Governing equations

The governing equations of the air flow are formed by the mass continuity Eq. (1), energy Eq. (2) and Navier–Stokes Eq. (3), which also determine the temperature field [9,10]:

$$\frac{D\rho}{Dt} + \rho\nabla \cdot u = 0, \tag{1}$$

$$\rho\frac{De}{Dt} = K_d\nabla^2 T - P\nabla \cdot u, \tag{2}$$

$$\rho\frac{Du_i}{Dt} = -\frac{\partial P}{\partial x_i} + \rho f_i + \mu\left[\frac{\partial^2 u_i}{\partial x_j x_j} + \frac{1}{3}\frac{\partial}{\partial x_i}(\nabla \cdot u)\right]. \tag{3}$$

3.2. Turbulence model

The most popular turbulence models today are the two-equation models. Among them, the standard k–ε models are widely used, given their good performance with fast convergence in simulations for isothermal flow. However, they produce large errors in non-isothermal and mixed convection conditions. The RNG k–ε turbulence model has great advantages in predicting near-wall flow and low Reynolds number flows and has a good performance in terms of accuracy and efficiency [11].

In this case, we use the RNG k–ε model to simulate the air ventilation in the powerhouse, and the transport equations for