

Numerical simulation and optimization design for ceiling supply air of an underground main workshop in hydropower station*

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Abstract: The indoor air distribution of an underground main workshop in hydropower station with different number, location and size of inlets and velocity of supply air were simulated by using the way of computational fluid dynamics (CFD). The air velocity, temperature and their standard deviation of 18 kinds of supply air schemes in the occupied region of the main workshop were obtained. By comparing to these schemes, it is shown that the air distribution with 60 inlets of two lines of symmetry location and supplying velocity of 7.8 m/s is preferable. In addition, a reasonable design method is proposed according to the large volume of supply air and duct of cross-section size in the underground main workshop. Valuable scheme is given for ventilation and air conditioning design of the hydropower station in inviting bids stage.

Keywords: numerical simulation; air distribution; manifold duct; resistance calculation

1. Introduction

The hydropower station was planed to develop the second ladder power station situated on middle and downstream of Nancang river, its main workshop where 6 generator groups with capacity 4200 MW installed will reach 18.99 billion kW·h is located in the underground 300~500m. Main and auxiliary workshop, bus cave, main transformer cave, inlets and outlets of ventilation etc are compose of large underground cave groups. The main workshop is 268.5 m long, 29 m wide and 23.5 m high. Cool load of air conditioning in the main workshop is 635.0 kW. Six ZK air conditioning units with $10^5 \text{ m}^3/\text{h}$ volume of air and another one with $8 \times 10^4 \text{ m}^3/\text{h}$ were initially selected, their total volume of air reach $6.8 \times 10^5 \text{ m}^3/\text{h}$. Temperature and velocity in high and large main workshop directly effect to working condition, operating normally, maintain and management of the power station. It takes much more investment and time if we study it with model test. There are many advantages including faster velocity, lower cost, abundant data, capable of simulating reality condition etc as developing of computer technology, therefore, we can achieve the same results as model test and save cost and time by the means of simulation calculation.

On the other hand, there are so large volumes of supply air that need too big size of ducts to arrange on two sides of the plant, the ducts usually were fixed up on the ceiling, obviously it is difficult to make the large

size of ducts [1]. It is necessary to make approximately equal air rate of each vents, namely air manifold duct, in order to ensure air distribution effect, even if the number and arrangement of vents is reasonable. We have clearly known the difficulty before to make and install so large size of wedge ducts. Therefore it is very important to design the section of ducts in order to ensure the same air volume of each inlets, to make and install easily, to induce investment.

2. Physical and Mathematical Models of Airflow

Boussinesq hypothesis is usually used because airflow in the main workshop is nonisothermal and properties of fluid aren't obviously affected by a little variety of air density. Thereby inertia and viscous force, pressure difference terms in equation for conservation of momentum are affected by air density is negligible, only can we consider the influence of mass term. Turbulence model of numerical simulation of indoor airflow is almost eddy viscosity model that is based on Boussinesq's Reynolds stress hypothesis [2]. The key of eddy viscosity model is how to solve turbulence viscosity coefficients μ_t . Eddy viscosity model according to the number of additional differential equation can be classified into zero, one and two equations model etc. The $k-\varepsilon$ two equation model is usually used to solve the mixture convection with initial momentum of nonisothermal supply air [3].

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Controlled differential equation of convection heat transfer for compressible fluid using the k - ε turbulence model in three-dimensional Cartesian coordinates are as follows.

Continuity equation:

$$\frac{\partial u_i}{\partial x_i} = 0$$

Momentum equation:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = \frac{\partial}{\partial x_j} \left[\left(\nu + \nu_t \right) \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{\partial p}{\partial x_i} + \rho g \beta \nabla T \delta_i$$

The turbulent kinetic energy equation (equation for k)

$$\frac{\partial}{\partial x_i}(\rho u_i k) = \frac{\partial}{\partial x_i} \left[\left(\nu + \frac{\nu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_i} \right] + G - \rho \varepsilon$$

The dissipation rate equation (equation for ε):

$$\frac{\partial}{\partial x_i}(\rho u_i \varepsilon) = \frac{\partial}{\partial x_i} \left[\left(\nu + \frac{\nu_t}{\sigma_\varepsilon} \right) \frac{\partial \varepsilon}{\partial x_i} \right] + \frac{\varepsilon}{k} (c_1 G - c_2 \rho \varepsilon)$$

The turbulent energy equation:

$$\frac{\partial}{\partial x_i}(\rho u_i T) = \frac{\partial}{\partial x_i} \left(\frac{\nu}{Pr} + \frac{\nu_t}{\sigma_T} \right) \frac{\partial T}{\partial x_i} + \frac{q_i}{c_p}$$

where $G = \nu_t \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right] \frac{\partial u_i}{\partial x_j}$ and $\nu_t = \frac{c_\mu k^2}{\varepsilon}$.

Empirical coefficient μ , c_1 , c_2 , σ_k , σ_ε , σ_T are given in reference [4]. Numerical simulation applying computational fluid dynamics software based on the real main workshop had been completed. The physical model of simulation including geometry, size, arrangement (Fig. 1) and heat emitting from illuminates, outer casing of generators, controlling panels (Table 1) are completely same as the generator floor.

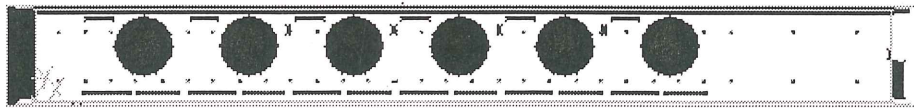


Fig 1 Physical model of main workshop

Table 1 Heat sources of the main workshop in kW

casing of generator/ set	lighting above generators	lighting installment site	controlling panels
38.53	205.92	73.32	125.40

Designing parameters in underground main workshop are $T_n=23.0$ °C, $\phi_n=74$ %; The volume of supply air are 680000 m³/h, difference temperature of supply air is $\Delta t=3.5$ °C, temperature of supply air is $t_o=19.5$ °C. Supplying vents are velocity inlet, exit of stairs and transportation cave at the side of installment site are all pressure opening. All walls are assumed to be adiabatic because the premises is located at underground, lighting heat is handled into uniform heat emitting from unit area of ceiling, boundary conditions at the floor surface are looked into convection, air temperatures on two sides of the floor are indoor temperature of the generator and turbine casing, respectively 23 °C and 28 °C. Eddy viscosity

coefficients in the flow field adjacent to walls are solved applying standard function method with logarithms distribution. Initial indoor temperature in the main workshop indoors is assumed to be 30 °C [5].

3. Simulation of airflow field in main workshop

Schemes of 18 kinds of air distribution of circle nozzle supply air in ceiling were simulated in this research. The simulated schemes of supply air involve to varying number of inlets, patterns of vent arrangement and velocity of supplying air etc among 60 inlets of two lines of symmetry location to be illustrated in Fig.2.

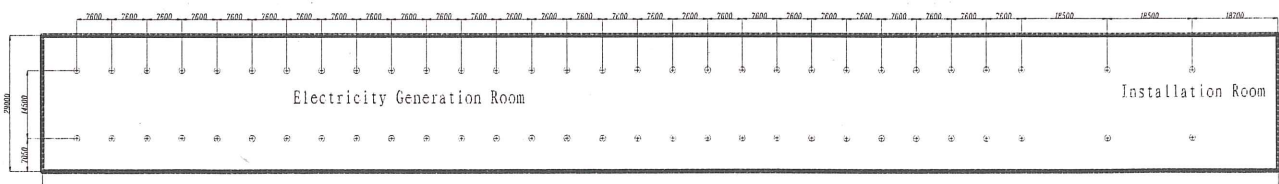


Fig. 2 Inlets arrangement in main workshop

Divide meshes of indoors airflow in the main workshop, the diffusion, convection, pressure and

source items in the differential equation of controlled cell are dispersed using different forms and then solved.

The software is performed and relaxation factors are moderated in accordance with inputted parameters, determined boundary conditions, given initial flow field and number of iteration until pressure, speed, temperature and the other flow field variables of the sum of residues are reduced by at least three orders of magnitude [6]. The converged solution of each supplying air schemes can be obtained, only are part of diagram results of 60 inlets of two line of symmetry location and incoming air velocity 7.8 m/s given here because the limited space in this paper, as shown in Figs. 3 and 4.

The data that we are interested according to output document in every kind of scheme were handled, the results are listed in Tables 2 to 4. where n stands for the number of inlets; v_s is incoming air velocity (m/s); v_{su} , v_{sd} are supply air velocity of the single row upstream

and downstream arrangement (m/s); v_{p1} , v_{p2} are mean velocity of horizontal plane at a height of 1m, 2m (m/s); t_{p1} , t_{p2} stand for mean temperature of horizontal plane at a height of 1 m, 2 m (°C); σ_{v1} , σ_{v2} are velocity distribution standard deviation of horizontal plane at a height of 1 m, 2 m (m/s); σ_{t1} , σ_{t2} are temperature distribution standard deviation of horizontal plane at a height of 1 m, 2 m (°C). When the number of inlets is changed and supply air velocity is approximately same, the characteristic data are given in Table 2.

When the number of inlets and supply air velocity are same and patterns of vents arrangement are varied, the typical data are listed in Table 3.

When the number of inlets and patterns of vent arrangement are same and supply air velocity is changed, the typical data are showed in Table 4.

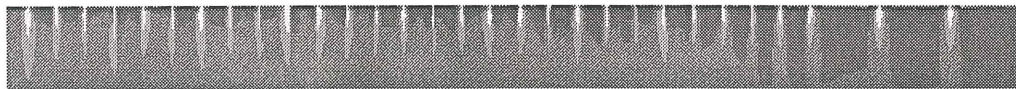


Fig 3 Vertical plane air temperatures distribution at 7m from main workshop downstream

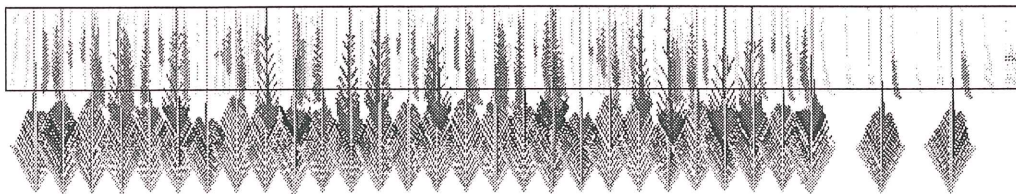


Fig 4 Vertical plane velocity vector at 7m from main workshop downstream

Table 2 Mean velocity, temperature and standard deviation in the occupied region

n	v_s	v_{p1}	σ_{v1}	v_{p2}	σ_{v2}	t_{p1}	σ_{t1}	t_{p2}	σ_{t2}
6	8.0	0.754	0.46	0.555	0.43	21.23	0.17	21.30	0.19
15	8.0	0.666	0.45	0.464	0.40	21.45	0.14	21.52	0.17
30	7.9	0.554	0.34	0.425	0.37	21.60	0.19	21.63	0.26
60	7.8	0.451	0.32	0.393	0.37	21.50	0.22	21.53	0.26

Table 3 Mean velocity, temperature and standard deviation in the occupied region

n	v_s	v_{p1}	σ_{v1}	v_{p2}	σ_{v2}	t_{p1}	σ_{t1}	t_{p2}	σ_{t2}
30	$v_{su}=7.9$	0.677	0.47	0.551	0.51	21.53	0.25	21.57	0.25
30	$v_{sd}=7.9$	0.624	0.42	0.523	0.45	21.51	0.19	21.54	0.20
30	$v_s=7.9$	0.554	0.34	0.425	0.36	21.60	0.19	21.63	0.26

Table 4 Mean velocity, temperature and standard deviation in the occupied region

n	v_s	v_{p1}	σ_{v1}	v_{p2}	σ_{v2}	t_{p1}	σ_{t1}	t_{p2}	σ_{t2}
60	5.0	0.361	0.26	0.291	0.26	21.28	0.13	21.31	0.16
60	6.0	0.399	0.28	0.327	0.29	21.37	0.13	21.41	0.17
60	7.8	0.451	0.32	0.393	0.37	21.50	0.22	21.53	0.26
60	10.0	0.536	0.37	0.446	0.39	21.53	0.24	21.55	0.28

4. Results Analyze and Scheme Selection

There is essentially no discrepancy of temperature distribution in the occupied region in the computed results for different supplying air schemes that include to changed incoming air velocity, number of inlets, arrangement of vents, and all of temperature distribution in the occupied region can satisfy the design request.

Mean velocity in the occupied region increases as supplying air velocity increases for given patterns of vents arrangement and the number of inlets. In the generator floor, there is no appreciable difference about mean temperature of horizontal plane at a height of

1m and 2m for given scheme, however mean velocity of horizontal plane at a height of 1m is higher than the plane at a height of 2m. The reasons may be that airflows are stagnated near floor surface result in changing direction, part of the reverse flow near the floor ground cause higher of air velocity because development of the air supply jet were limited by the height of workshop.

Both mean velocity and standard deviation in the occupied region decrease gradually as the number of inlets increasing for given supplying air velocity. The results indicate that the more number of inlets are, the lower and the uniform air velocity in the occupied region.

When patterns of vent layout are varied and given the number of inlets and supply air velocity, both mean velocity and standard deviation in the occupied region are the least for the inlets of two lines of symmetry location, and then for the single row upstream arrangement are slightly larger than single row downstream. The results indicate the lower and the uniform air velocity in the occupied region for two lines of symmetry arrangement.

Given the number and location of inlets, both mean velocity and standard deviation in the occupied region increase as supply air velocity increasing gradually. The results indicated that the higher of incoming air velocity is, the poorer uniform of air velocity in the occupied region is.

From air distribution of all kinds of schemes, it is reasonable to select the scheme with more number of inlets, two lines of symmetry location and lower of supplying air velocity. Therefore, the scheme of 60 vents Fig 5 Ducts layout in ceiling of main workshop with two lines of symmetry layout and supply air

velocity 7.8 m/s is appropriate selection because mean velocity in the main workshop should be controlled by 0.2~0.8 m/s in design norm of hydropower station. Under the condition, diameter of vents is 710mm, mean air velocity in the occupied region is 0.42 m/s, velocity standard deviation is 0.35 m/s, mean temperature in the occupied region is 21.53 °C, temperature standard deviation is 0.25 °C.

5. The Method of Duct Design

Left side in the main workshop is site of 6 generators, right side is spot for installment as shown in figure 1. The ducts were designed in accordance with 60 inlets with two lines of symmetry arrangement. The way of using single main duct is obviously unreasonable because length of the main workshop is 268.5m and supply air volume of air conditioning are too large. In order to reduce the size of ducts, a method was proposed that one main duct serve for one air conditioning unit, two air conditioning units with 105 m³/h air volume provide cool load of two sections of generator units, and related to two main ducts are installed symmetry on two sides of ceiling in the workshop. Six ducts for the sections of generator units and one duct for the site of installment were fixed successively on horizontal ceiling (figure 5). Each duct open eight branches for corresponding sections of generator units to supply uniform air. An air conditioning unit with 8×104 m³/h air volume provide cool load of installment site, and related to the duct that open twelve branches to supply uniform air are installed in the middle of ceiling in the main workshop.

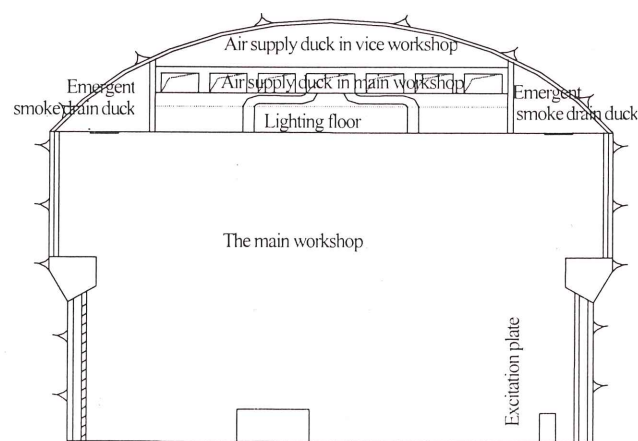


Fig.5 The layout of air supply in main workshop

The size of rectangle ducts should not be changed too many and equipped the short tubes of branch in view of difficultly making and installing the large size

of manifold duct so that it can be sure that direction of jets normal to wall of main ducts and circular nozzle can be connected conveniently. Firstly, it is necessary to keep constant static pressure to realize the rectangle ducts with short tubes to supply uniform air; secondly, only can the same of length, diameter and resistance feature of three-way branches make the roughly same volume of supply air of branches and more or less 7.8 m/s supply air velocity of each vents. Difference of static pressure at the three-way drives air to flow in the direction because static pressure normal to the ducts wall.

In the manifold duct of constant static pressure, static pressure of duct is used primarily to overcome the local resistance of three-way, bend and vent, friction drag of branch. So the static pressure of main duct at three-way is expressed [7]:

$$P_j = \left(\zeta_{\text{总}} + \frac{\lambda l}{D_{dl}} \right) \frac{\rho v_3^2}{2} = P_{jb} + P_{mc} \quad \text{Pa}$$

where P_j is the air static pressure of duct; ζ is the sum of resistance coefficient of short tube; λ is the friction drag coefficient of branch; v_3 is the air velocity of branch; D_{dl} , l are the equivalent diameter of branch, P_{jb} , P_m are the local resistance and friction drag of branch. For the local resistance coefficient of branch can be calculated as following relation

$$\zeta = 0.3 + (v_3/v_1)^{-2}$$

where v_1 , v_3 are the air velocity three-way main and branch, m/s. the expression is suitable for $0.3 \leq \frac{v_3}{v_1} \leq 2$, ζ

is the local resistance coefficient corresponding air velocity of branch.

$$P_{q1} = P_{j1} + P_{d1} = \frac{\rho v_{j1}^2}{2} + \frac{\rho v_{d1}^2}{2}$$

$$P_{qn} = P_{q1} - (Rl + Z)_{1-n}$$

where P_{q1} , P_{d1} are the air total pressure and kinetic pressure at the first tree-way, $(Rl + Z)_{1-n}$ is the sum the local resistance and friction drag of duct from tree-way 1 to n , Pa.

$$P_{jn} = P_{qn} - P_{dn}$$

$$L_1/L_n = \sqrt{P_{j1}/P_{jn}}$$

where L is the air volume of branch, m^3/h .

If there is no obvious discrepancy between L_1 and L_n , it is indicate the roughly same of air volume or velocity from tree-way 1 to n . Meanwhile, each of the cross-section of duct should obey the energy equation:

$$P_{j1} + P_{d1} = P_{dn} + P_{jn} + (Rl + Z)_{1-n}$$

Given $P_{jn} = P_{j1}$,

then,

$$P_{dn} = P_{d1} - (Rl + Z)_{1-n} = \rho v_{dn}^2 / 2$$

The varied size of duct can be calculated according to the air volume and velocity v_{dn} of main duct.

6. Duct design cases comparison

Case 1 is initially considered that the size of six mains for generator site is changed through every four branches, and one main for installment spot is changed through every six branches. Therefore, not only can the relatively large cross-section size of mains act the function of static box, but also installment of ducts is easier than the manifold ducts. There is less than 10% air volume difference at each three-way exit of each supply air duct when diameters of circular branches are 670mm. This indicates that case 1 is feasible.

In order to reduce the difficulty of installment, improve the quantity of installment and save the project cost case 2 is proposed. In the case, the air velocity of main is increased, and cross-section size of mains is decreased. Case 2 is considered that the size of six mains for generator site is changed through every two branches, and one main for installment spot is changed through every four branches. Therefore, air velocity of main in case 2 is higher than case 1 in the main workshop, on the other hand, the times of mains size varied is increased result in mains size can slightly decreased again. Diameters of circular branches are enlarged as 730mm to reduce air velocity of branches and total resistance of the circuit. There is less than 10% air volume difference at each three-way exit of each supply air duct in Case 2.

Results of duct resistance calculation of two kinds of cases indicated that circuit of largest resistance is not at the terminal branch but at the first branch. Largest value of resistance among seven ducts in case 1 is 627.14Pa, and in case 2 is 681.57Pa. Thereby air conditioning units with 900Pa pressure head enough to

satisfy the design request. There was no appreciable difference about duct resistance comparing with calculation results of two kinds of cases. It is more economic and reasonable to design and carry out construction in accordance with the second case because the size of ducts is smaller, making and installment of ducts are easier, and used material of ducts is less.

7. Conclusions

The physical and mathematical models of nonisothermal airflow in the underground main workshop of hydropower station with different number, layout and size of inlets and velocity of supply air were established in this paper, 18 kinds of air distribution of circular nozzle in ceiling were simulated. Air velocity and temperature fields, velocity vector and temperature distribution diagrams in the occupied region were obtained. The scheme with 60 inlets of two lines of symmetry location and 7.8m/s supply air velocity was finally determined by analyzing and comparing to these schemes. As a result, it is important significance that using the way of numerical analysis guide indoors air distribution designs of nonisothermal supply air in high and large spaces or complex building. In addition, duct design and resistance calculation for selected scheme were carried out in this paper because it is difficult to ensure approximately same volume of air from each

inlet in view of the large volume of supply air and duct of cross-section size in the underground main workshop. A kind of more economic and reasonable design scheme in which the size of duct is smaller, making and installment of ducts are easier, and costs of project are less was given. Great valuable the feasibility study report of simulation calculation and duct design was submitted for ventilation and air conditioning design of the hydropower station in inviting bids stage.

References

- 1 Fu Xiangzhao. Research of ceiling air supply in underground water powerhouse. *Heating Ventilation & Air conditioning*, 1996.1:59~62.
- 2 Murakami, S., S. Kato, and Y. Suyama. Three-dimensional numerical simulation of turbulent airflow in ventilated room by means of two-equation model. *ASHRAE Transactions* 93(2):621-642.
- 3 Zhao Bin, Li xianting and Yan Qisen. Influence of Turbulence Parameters at supply opening on Indoor Air Distribution. *Architecture Heat Energy Ventilation & Air conditioning*, 2000.1:1~4.
- 4 Tao Wenquan. *Numerical Heat Transfer*. Xian: Publishing house of Xian transportation university, 2001.
- 5 Zhao Rongyi, Fan cunyang. *Air Conditioning*. Peking: Publishing house of China construct industry, 1999.
- 6 Chen Caikan. *Computational fluid Dynamics*. Chongqing: Publishing house of Chongqing, 1992.
- 7 Sun Yijian. *Industrial Ventilation*. Peking: Publishing house of China construct industry, 1995.