Prediction model of vertical shaft air temperature and its application

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Abstract. In order to obtain the distribution law of the temperature field of the vertical airflow, a theoretical model of the wind temperature forecasting of the vertical well is established and simplified on the basis of considering the convective heat transfer and the exchange moisture. The measured error of the theoretical model is between -3.1% and 2% by measuring the variation of air and surrounding rock parameters in a shaft. The theoretical model is used to analyse the effects of surface climate on the deep environment in vertical shaft. The temperature of the airflow is affected by the seasonal climate, and the influence is weakened with the increase of the ventilation distance. The greater the relative humidity change in the vertical well, the smaller the variation of the airflow temperature value, and the decrease of the temperature is affected by the enthalpy. When the shaft deep humidity environment is certain, the greater the humidity, the greater the temperature change.

1. Introduction

The heat damage exists in the deep mine, the wind is the media of heat transfer [1-2]. When the fresh air flow into the shaft, the heat exchange between the air flow and rock occurs, and the air temperature in deep shaft determines the severity of heat damage [3-4]. Accurately predicting the deep air temperature in a vertical shaft is important for preventing and controlling heat damage [5].

The airflow has a heat exchange with rock in the shaft, and the air humidity increases gradually with depth. The evaporation and condensation occur on the roadway wall, and a great deal of latent heat is produced, so the variation of heat and humidity parameters change at the same time [6-7]. As the vertical depth of mine is increased by 100m, the air pressure can increase by 1.2-1.3kPa. When the mining depth is 1000m, the air pressure will increase by more than 10% compared with the standard atmospheric pressure, so the influence from compressed air cannot be ignored [8-9]. In the traditional prediction model of vertical air temperature, the heat transfer is calculated through the unsteady heat transfer coefficient. For the thermal environment of the surrounding rock of the vertical shaft is affected by seasonal climate, the relationship between the unsteady heat transfer coefficient and the humidity change has not yet been grasped. In fact, the seasonal climate leads to great changes in the air temperature and humidity in the well, and the change of the borehole temperature may be above 20°C, which will bring uncertain effects on the deep environment of the shaft [10-11]. The prediction of air temperature in vertical mine must consider all the above factors [12].
Considering the convection and the exchange of heat with moisture, a simplified prediction model is established. The influence of different surface climate conditions on thermal environment of vertical shaft is analyzed according to the model. This paper can provide important reference for heat damage prevention and control in vertical mine.

2. Prediction model of air temperature in the vertical shaft

There is a shaft as shown in Figure 1. At the inlet and outlet sections, the air temperatures are $t_1$ and $t_2$ respectively, the relative humidity are $d_1$ and $d_2$ respectively, and the air pressure are $P_1$ and $P_2$ respectively.

![Figure 1. Vertical shaft cross section.](image)

According to the energy equation, the total energy flowing into the vertical shaft is equal to the energy flowing out of the vertical shaft.

$$u_1 + P_1v_1 + \frac{1}{2} \omega_1^2 + g z_1 + q = u_2 + P_2v_2 + \frac{1}{2} \omega_2^2 + g z_2$$  \hspace{1cm} (1)

Where: $u_1$ and $u_2$ are the internal energy from the inflow section and outflow section respectively (J/kg); $P_1$ and $P_2$ are the air pressures from the inflow section and outflow section respectively (Pa); $v_1$ and $v_2$ are the specific volume from the inflow section and outflow section respectively (m$^3$/kg); $\omega_1$ and $\omega_2$ are the wind speeds from the inflow section and outflow section respectively (m/s); $z_1$ and $z_2$ are the heights from the inflow section and outflow section respectively (m); $q$ is the thermal increment of airflow from the inflow section to the outflow section (J/kg);

According to the definition of specific enthalpy:

$$i = P v + u$$  \hspace{1cm} (2)

The formula (1) is changed to:

$$i_1 + \frac{1}{2} \omega_1^2 + g z_1 + q = i_2 + \frac{1}{2} \omega_2^2 + g z_2$$  \hspace{1cm} (3)

The wind speed of the cross section cannot be changed because the air volume is constant, the formula (3) can be changed to:

$$i_2 - i_1 = g(z_1 - z_2) + q$$  \hspace{1cm} (4)

The flow of mass is $M$, so:

$$M(i_2 - i_1) = Mg(z_1 - z_2) + Q$$  \hspace{1cm} (5)
Where: $M$ is the mass flow through the cross section (kg/s); $Q$ is the air heating quantity in mine thermal environment (W).

The sensible heat of water vapor, which is smaller than that of latent heat can be neglected, so the specific enthalpy of air flow can be written as:

$$\dot{h} = c_p t + \gamma d$$  \hspace{1cm} (6)

Where: $c_p$ is the specific heat capacity at constant pressure (1.005 kJ·kg$^{-1}$·K$^{-1}$); $t$ is the air temperature (℃); $\gamma$ is the steam vaporization latent heat at 0℃ (kJ/kg); $d$ is the moisture content (quality of water steam/quality of dry air).

Substituting equation (6) into equation (5):

$$M(c_p(t_2 - t_1) + \gamma(d_2 - d_1)) = M\gamma(z_1 - z_2) + Q$$  \hspace{1cm} (7)

The above equation is the thermodynamic equation of the existence of heat and moisture exchange from the thermodynamic point of view. The heat increment $Q$ in the equation (7) mainly comes from the heat dissipation of the surrounding rock (ignore the oxidation heat of ore, heat release of equipment, etc.) and heat transfer in the form of heat convection. The heat convection is:

$$Q = hUL(t_1 - t_2)$$  \hspace{1cm} (8)

Where: $h$ is the convection heat transfer coefficient (W·m$^{-2}$·K$^{-1}$); $U$ is the circumference of section (m); $L$ is the length of roadway (m); $t_w$ is the average temperature of roadway wall (℃); $t_1$ is the air temperature of inlet section (℃); $t_2$ is the air temperature of outlet section (℃);

The rock wall is affected by different ground climate conditions in the vertical shaft, and the rock temperature changes seasonally. It is difficult to solve the problem directly by the formula. On the whole, the rock is basically stable in a longer ventilated shaft, approximately equal to the heat flux from the rock interior to the surface and then to the airflow.

$$q = \frac{\lambda_y(t_1 - t_w)}{R_0} = h(t_1 + t_2)$$  \hspace{1cm} (9)

Where: $q$ is the heat flow density (W/m); $\lambda_y$ is the rock thermal conductivity (W·m$^{-1}$·K$^{-1}$); $t_1$ is the average temperature of original rock (℃); $t_w$ is the average wall temperature (℃); $R_0$ is the thickness of vertical heat transfer ring (m).

After a long period of ventilation, the thickness of the heat transfer ring along the tunnel has only a little change, so $R_0$ can be considered as a constant value. The formula (9) is substituted into the formula (8), a conclusion can be drawn:

$$Q = \frac{hUL\lambda_y}{\lambda_y + hR_0} (t_1 + t_2)$$  \hspace{1cm} (10)

The formula of $h$ [13] is:

$$h = \frac{\lambda}{D}Nu = \frac{\lambda}{D} \times 0.023 \times Re^{0.8} Pr^n$$  \hspace{1cm} (11)

Where: $\lambda$ is the thermal conductivity of air (0.025 W·M$^{-1}$·K$^{-1}$); $D$ is the feature length (m); $Nu$ is the Nusselt number; $Pr$ is the Prandtl number (0.7); the number of $n$ is 0.4 when the air is heated, and the number is 0.3 when the air is cooled.

The $Re$ may be calculated by reference to the following formula:
\[ Re = \frac{\rho \omega D}{\mu} \]  

(12)

Where: \( \rho \) is the air density (kg/m\(^3\)); \( \omega \) is the air velocity (m/s); \( \mu \) is the viscosity coefficient (Pa·s).

According to the concept of geothermal warming rate, the original rock temperature increases linearly with depth, so \( R_0 \) can be got by consulting the geological data. When the wind parameters of the inlet section are known, other parameters can be directly obtained or calculated, only the \( t_2 \) and \( d_2 \) is not determined from the formula (7).

A formula for calculating the moisture content of \( d \) [14]:

\[ d = 0.622 \frac{P_v}{P - P_v} \]  

(13)

Where: \( d \) is the moisture content; \( P_v \) is the water vapor pressure in the air (kPa); \( P \) is the atmospheric pressure (kPa);

The formula for calculating the partial pressure of water steam is:

\[ P_s = \psi P \]  

(14)

Where: \( \psi \) is the relative humidity (%); \( P_s \) is the saturated partial pressure of saturated air (kPa);

The calculation formula of \( P_s \) [15]:

\[ P_s = \frac{2}{15} \exp[18.5916 - \frac{3991.11}{(t_1)_c + 233.84}] \]  

(15)

Substituting equation (10) into equation (7), and \( L=\gamma t_1-z_2 \).

\[ \frac{gL}{\gamma} + hUL\gamma t_1 + t_1 \left[ \frac{c_p}{\gamma} - \frac{hUL\gamma}{2M(\lambda + hR)} \right] - t_2 \left[ \frac{c_p}{\gamma} + \frac{hUL\gamma}{2M(\lambda + hR)} \right] + d_1 = d_2 \]  

(16)

When the following relationship exists:

\[ A = \frac{gL}{\gamma} \]

\[ B = \frac{hUL\gamma}{M(\lambda + hR)} \]

\[ C = \frac{c_p}{\gamma} \]

The equation (16) can be simplified to equation (17):

\[ A + t_1B + t_1(C + \frac{B}{2}) - t_2(C + \frac{B}{2}) + d_1 = d_2 \]  

(17)

When the parameters of the roadway and inlet air flow are set from the equation (17), so \( A, B, C, t_1, ti, di \) are the contant values, and the \( t_2 \) and \( d_2 \) from the outlet section will affect each other. The equations of (13) and (15) are substituted into equation (17):

\[ \frac{15P_v}{2\psi \exp[18.5916 - \frac{3991.11}{(t_2)_c + 233.84}]} = \frac{0.622}{A + t_1B + t_1(C + \frac{B}{2}) - t_2(C + \frac{B}{2}) + d_1} + 1 \]  

(18)
The formula intuitively reflects that the temperature, relative humidity and air pressure can affect each other when they arrive at the exit section. The $P_2$ can be determined according to mine depth or $Z_2$ in the formula, and the $\psi_2$ can also be set according to actual conditions. The equation (18) is a prediction formula of wind temperature at outlet section. The formula is complex and it is difficult to obtain analytic solution directly, but it can be solved by the iterative method.

3. Verification of air temperature prediction model

The air flow parameters of a shaft from +164m to -652m are measured to validate the model. The vertical section area of the shaft is 23.7m$^2$, diameter 5.5m, perimeter 17.3m, wind speed 3.7m/s, air volume 88m$^3$/s, the wind speed and air volume are constants. The depth of the constant temperature zone is 30m, and the local average temperature of 11.6°C. In order to eliminate the influence of the ground climate on the temperature of the original rock, the vertical inlet section is set to +134m. The original rock temperature of the inlet section is 11.6°C and the atmospheric pressure is 101kPa. After testing, it is found that the thickness of the transfer ring is 15 meters. Due to the increase in depth, the outlet atmospheric pressure is 110kpa at -652m. The formula for calculating the original rock temperature is: $t = 11.6 + 0.024L$ (where L is calculated as +134m as the starting point), and the average original rock temperature of the tunnel is 21°C. The temperature and humidity parameters of the inlet and outlet sections of the shaft are measured as shown in Table 1.

### Table 1. The temperature and humidity data of inlet and outlet airflow.

| Numbers | +134m | -652m |
|---------|-------|-------|
|         | $t_1/\degree C$ | $\psi_1$ | $t_2/\degree C$ | $\psi_2$ |
| 1       | 6     | 40%   | 10.4           | 54%     |
| 2       | 14    | 55%   | 16.8           | 70%     |
| 3       | 15.6  | 53%   | 19             | 62%     |
| 4       | 16    | 65%   | 19.1           | 70%     |
| 5       | 16.8  | 37%   | 18.5           | 60%     |
| 6       | 22.1  | 85%   | 24.2           | 90%     |

The relative errors of $t_2$ and $t_{2r}$ are calculated as:

$$e = \frac{t_{2r} - t_2}{t_2} \times 100\%$$

The relative errors of the 6 sets of data is shown in the following figure:
It can be seen from Fig. 2 that the relative errors are between -3.1% and 2% according to the formula (16). From the table 1 and Table 2, the errors are always within 1°C that the result can be accepted. Therefore, the formula (16) can be used to predict the vertical air temperature of the shaft.

4. Influence of ground air on the thermal environment of shaft
In order to obtain the influence degree of the ground air on the deep thermal environment of the vertical shaft, the thermal physical data of the surrounding rock are analyzed.

4.1. Seasonal weather effects
In northern China, the ground temperature in winter is generally below 0°C, while the maximum temperature in summer is close to 40°C. The change of seasonal climate will affect the deep thermal environment of the vertical shaft. According to changes in the local seasonal temperature difference, the air temperature of inlet section are set as 0°C, 10°C, 20°C, 30°C, 40°C, the relative humidity of inlet section is set as 40%, and the relative humidity increased 2.5% per 100m, so the relative humidity is 60% at -652m after 786m distance. The change of air temperature in vertical shaft is shown in figure 3.
As shown in Figure 3, the inlet air temperature are 0°C, 10°C, 20°C, 30°C, 40°C. When the relative humidity changes the same, the outlet air temperature is 4.9°C, 12.9°C, 21°C, 29.2°C, 37.6°C. The shaft has an "air temperature balance" function from the figure, the high temperature air from inlet section is cooled, and the low temperature air is heated. The differences between the curve become smaller with the ventilation distance increases which can be found from the trend of the development trend of the temperature curve. It can be concluded that the temperature of the air is gradually reduced by the influence of seasonal seasonal climate in the shaft.

4.2. Humidity effects
In the dust weather conditions, the air relative humidity decreased rapidly, even close to 0%. Under conditions of rain, snow, fog and other weather, the air relative humidity of almost 90% or more, or even close to 100%. So the deep thermal environment of the shaft will be affected by different ground air. The air temperatures of inlet section are 10°C, the relative humidities of inlet section are 0%, 25%, 50%, 75% and 100%. The relative humidities of the outlet section are 100%, and the relative humidity increases linearly as shown in Figure 4.

![Figure 4. Variations in air temperature at different humidities.](image)

As shown in Figure 4, the relative humidities are 0%, 25%, 50%, 75%, 100% at the inlet section, and the air temperatures become 5.5°C, 7.7°C, 10°C, 12.1°C, 14.1°C at the outlet section. When the relative humidities are different, the maximum outlet temperature difference is 8.6°C, which is a big difference. It can be concluded that the greater the humidity of the inlet air, the more the temperature value increases. The greater the change in relative humidity, the smaller the change in temperature. When the relative humidity does not change, the temperature increases linearly. In the process of ventilation, the air temperature has been lower than the original rock temperature. Theoretically the wind has been in the heating process, but due to different changes in the wet environment, the temperature dropped once less than 10°C. This is because the air humidity changes, part of the heat will be consumed in the enthalpy increase. Therefore, when the ground air humidity is different, and the vertical well humidity environment is certain, the greater the humidity, the greater the change in outlet temperature.

5. Conclusion
The conclusions of this paper are as follows:
(1) Based on the convection heat transfer and the exchange moisture, a theoretical model of vertical air temperature prediction is established. The model shows that the air temperature, air pressure, relative humidity, ambient thermal conditions of the surrounding rock, inlet air parameters affect each other.
(2) The calculation errors of the theoretical model are between -3.1% and 2%, and the errors are within the acceptable range by measuring the variation of the air and surrounding rock parameters in a shaft of mine.

(3) The theoretical model is used to analyze the influence of the temperature and humidity of the ground air, and the general rule of the influence of seasonal wind and humidity is obtained.

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