Simulation optimization research of anti-freezing heat pipe for preheating fresh air in wellbore

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Abstract: In order to solve the icing phenomenon of mine wind gap, a physical model of L-type gravity heat pipe was designed in combination with calculation of shaft operating condition, which based on the new idea that geothermal energy of thermostatic formation is used as driving heat source of heat pipe for shaft antifreeze. The numerical simulation showed that the condensation end temperature of the heat pipe could reach 275K. The heat pipe optimization simulation was carried out for the length of the condensation and insulation section of the heat pipe. When the condensing section is 5 m, the effect is the best. The results showed that the temperature at the condenser end of the heat pipe was increased by 275.6K after optimization. The optimized scheme for extracting heat energy from thermostat by heat pipe has a good effect.

1. Introduction

At present, the research on heat pipe technology mainly focuses on the optimization of structural parameters, while the two-phase flow environment and other heat transfer limit problems in heat pipe need to be further studied. Chuanzhou Xu[1] found that the key technical problem affecting the anti-freezing effect of shaft is the imperfect anti-freezing treatment of shaft. In actual engineering design, the problem of strengthening the mixing of hot and cold air system in shaft has not been solved, which seriously hinders the wide application of this mixed heating method in construction shaft. There are few literatures on shaft antifreeze, which mainly focus on the study of mine ventilation system [2-4]. Walker et al. carried out field experiments and proposed a new device for recovering residual heat of mine air return. Walker et al. carried out field experiments and put forward a new device which could recover residual heat of mine air by vegetation. Experiments showed that dust and other harmful substances contained in return air could not be absorbed and utilized by vegetation[5]. Yongsheng Niu has designed a system that can provide heat to buildings on the ground by recycling heat from mines[6]. Shouquan Hu et al. suggested that residual heat from mine inrush water be used for shaft heating to prevent frozen water from being extracted by heat pump unit, and the heat load required for heating system was calculated in detail [7]. Lin simulated the miniature oscillating heat pipe and compared the simulation results with the experiments. It was found that heat transfer length, inside diameter and heat input had significant influence on the overall heat transfer characteristics [8]. Fangming Jiang et al. put forward the technical
scheme of extracting heat energy from dry hot rock by using heat pipe, and carried out numerical simulation and theoretical analysis[9].

In this paper, a new idea of using geothermal energy of thermostatic formation as driving heat source of gravity heat pipe for shaft antifreeze was proposed. An L-type gravity heat pipe was designed based on Calculation of well bore operating conditions. Reasonable retrofit measures for extracting thermostatic layer geothermal system device by heat pipe were put forward, based on the analysis of simulation results of working fluid in heat pipe. According to the numerical simulation results, the heat pipe system structure was optimized and the feasibility of the optimized structure was verified. The total length of heat pipe is 80m, the length of evaporation end is 10m, the length of condensation section is 5m, and the remaining sections are insulating sections with an internal diameter of 52mm.

2. Materials and methods

2.1 Physical model

Taking Qing-shui-ying mine as the background, it is one of the super large mines with annual output of 10 million tons in Ningxia. According to literature [10], the depth of isothermal zone in Qing-shui-ying well field is 70m and the temperature is 14℃. The gravity heat pipe studied in this paper is a slender L-shaped cylindrical pipe. L-type gravity heat pipe is installed in the thermostatic layer, and geothermal heat of the thermostatic layer is extracted to preheat the air inlet at the shaft head so as to achieve the anti-freezing effect of the shaft. The installation schematic is shown in Fig.1.

![Fig.1 Installation schematic diagram](image)

2.2 Mathematical model

The new heat pipe studied in this paper is a L-shaped thin straight cylindrical pipe. If a three-dimensional physical model is established for the heat pipe, the grid is divided by Gambit, the number of grids is large and the calculation is complicated, which requires high computer configuration and running speed. Therefore, this paper comprehensively considers the symmetry of heat pipe and ignores the thickness of heat pipe wall. Two-dimensional model is built by any section of the axis and two-dimensional object model is built by using Gambit. The motion of each phase in each phase of gas-liquid two-phase flow in a heat pipe can be determined by VOF model and the results of the motion based on the two-phase interface can be derived.

The governing equation of VOF model consists of continuity equation, momentum equation and energy equation. Describe as follows:

\[
\frac{1}{\rho_a} \frac{\partial}{\partial t} \left( \alpha_a \rho_a \right) + \nabla \cdot \left( \alpha_a \rho_a \bar{v}_a \right) = S_{\alpha_a} + \sum_{b=1}^{n} \left( \dot{m}_{ba} - \dot{m}_{ab} \right) \tag{1}
\]

\[
\frac{\partial}{\partial t} \left( \rho \bar{v} \right) + \nabla \cdot \left( \rho \bar{v} \bar{v} \right) = -\nabla p + \nabla \cdot \left[ \mu (\nabla \bar{v} + \nabla \bar{v}^T) \right] + \rho \ddot{g} + \ddot{F} \tag{2}
\]

\[
\frac{\partial}{\partial t} \left( \rho E \right) + \nabla \cdot \left[ \bar{v} (\rho E + p) \right] = \nabla \cdot \left( k_{\text{eff}} \nabla T \right) + S_h \tag{3}
\]
3. Analysis of numerical simulation results

3.1. Temperature field distribution

According to the numerical simulation results of the heat pipe, the temperature distribution cloud in the heat pipe at different times is recorded. Through the analysis of the process of cloud image change, the representative time nodes in the graph are extracted for curve fitting and the data change curve of each node is analyzed. Over time, the heat transfer per unit time decreases gradually due to the decrease of the temperature difference inside and outside the heat pipe, which results in the decrease of heat transfer. It can be seen from the temperature distribution in the heat pipe at each time that the temperature change in the heat pipe gradually decreases along the pipe length.

3.2. Volume fraction distribution

Through the volume fraction cloud analysis, the mass distribution of the working fluid in the heat pipe at different times can be obtained, which reflects the flow state of the working fluid in the heat pipe. The volume fraction distribution nephogram of working fluid at different time is shown in Fig.3. It can be seen from the cloud chart that when $t = 3s$, the gravity heat pipe starts up, and most of the liquid working fluid still exists, and there is no phase change in the liquid pool. Natural convection occurs in liquid working fluid under the action of low heat flux. So, the start-up time of heat pipe is about $3s$.

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**Fig.2.** Temperature variation in gravity heat pipe at different times

**Fig.3.** 0.1s, 0.3s, 3s, 10s, 15s, 20s, 30s volume fraction distribution nephogram

**Fig.4.** Time dependence diagram of working fluid velocity in condensation end of heat pipe
3.3. Velocity field distribution
The representative data of the velocity distribution cloud of the condensate end of the heat pipe at different times are extracted for curve fitting and analyze by the data changes in the curve.

Fig. 4 shows the variation of the velocity of the working medium inside the condensation end of the heat pipe with time. The flow rate distribution of the gas phase working medium in the condensation end of the heat pipe can be seen more intuitively from the diagram. When the heat pipe is just started, the flow rate at the condensation end of the heat pipe is 0 m/s, which is due to the long section of the heat pipe in this paper. At this stage, the working fluid boiling in the liquid pool is transformed into an insulating section where the vapor flows to the heat pipe because it has not moved to the condensation end of the heat pipe for a short time. When the time is between 5s and 14s, with the passage of time, there is continuous vapor movement to the condensation end of the heat pipe, the flow rate of working substance in the condensation end of the heat pipe rises quickly, and the maximum flow rate reaches 1.8 m/s. The steam flow rate at the condensation end tends to stabilize after 20s.

3.4. Pressure field distribution
Fig. 5 shows the pressure curve inside the heat pipe. It can be seen from the figure that the pressure in the heat pipe gradually decreases along the tube rectangle at the same time. The pressure of the liquid part of the heat pipe is higher because of the liquid filling at the evaporation end of the heat pipe. The pressure inside the heat pipe decreases sharply with time at the position of 70m-40m along the tube. The reason is that the working fluid boils violently in the evaporation zone of the heat pipe, and a large amount of steam flows to the adiabatic section of the heat pipe. With the decrease of the mass fraction of the liquid phase in the evaporation section of the heat pipe, the pressure in the evaporation section of the heat pipe decreases.

![Pressure curve](image_url)

Fig. 5. Internal pressure curve of heat pipe

4. System optimization
In order to study the influence of length changes of condensation section and insulation section on heat transfer performance of heat pipe, the length of condensation section is increased by reducing the length of insulation section while the filling rate is 50% and the total length of heat pipe remains unchanged. The length of condensation section is L=5m, L=8m and L=10m.
It can be seen from Fig.6 that when the length of condensation end is L=5m, the short length of condensation section in the heat pipe results in insufficient heat transfer in phase transition. When L=8m at the condensation end, the heat transfer capacity of the heat pipe increases at the same evaporation end temperature. When L=10m, the temperature at the condensate end rises quickly in the first 15s and slows down after 15s, which cannot meet the requirements of well bore antifreeze.

It can be seen from Fig.7 that when the length of the condensation section of the heat pipe is increased, the speed of the working medium inside the condensation end of the heat pipe changes greatly. When T < 3s, the transient velocity at the condensate end of the heat pipe is basically the same in three scenarios. When t>10s, the speed at the condensation end of the 8m length heat pipe is greater than 5m and 10m. When T > 15s, the condensation end speed of 8m length heat pipe reaches the highest and tends to be stable, which is about 2.2m/s. It is concluded that increasing the length of condensation section of heat pipe properly can increase the temperature of condensation end of heat pipe.

5. Conclusion
This paper draws the following conclusions through research:

1. Through theoretical calculation, the designed L-type antifreeze gravity heat pipe has the total length of 80m, the evaporation end length of 10m, the condensation section length of 5m.

2. The gravity heat pipe is used to extract geothermal energy from the thermostat for shaft antifreeze by numerical simulation. It is found that the temperature of shaft antifreeze was 275K and the maximum flow rate was 1.8m/s under the design conditions. The feasibility of using heat pipe for anti-freeze in well bore was verified.

3. Compared with the original scheme, the optimization results are greatly improved, which can provide theoretical basis for applying gravity heat pipe to extract geothermal energy in the thermostatic layer for anti-freezing in well bore.

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