Design and application of heat pipe heat exchange technology for supplying the anti-freeze heating in coal mines

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Abstract. For designing the heat exchanger to supply necessary anti-freeze heating in the inlet wellhead of a mine, the specific heat demand there and the state of the art of the heat pipe technologies for waste heat recovery are reviewed. According to the existing conditions in a mine located in a cold region, a heat pipe heat exchanger was designed, the feasibility of this heat pipe heat exchanger was theoretically investigated, and the influence of the heat exchange efficiency on the effect of the heat exchanger was analyzed. Then the necessary guarantee measures and the implementation scheme for sufficient heat supply under the extremely cold weather conditions were pointed out. Finally, the feasibility of this heat pipe heat exchange technology is verified by the actual preliminary operation performance and the key technical problems of its application are clarified.

1. Introduction
Heat pipes are called "superconducting conductors" which emerged in the 1940s. The heat pipes have been widely used in the aerospace field [1]. The principle of the standard heat pipe was first proposed by the American scientist, P.S. Gaugler, in 1942, and was applied to the space system by related scholars in 1962. Since then, the research and development of heat pipes have received great attention all over the world. In recent years, the application of gravity heat pipes has been rapidly developed. Gravity heat pipes have the advantages of simple operation, low cost, and good heat transfer performance. The disadvantage is that heat can only be transferred from their lower ends to the upper ends. But they can be used in waste heat recovery which overcomes their shortcomings well. For industrial heat pipe applications, especially large-scale development and utilization in the field of waste heat recovery, gravity heat pipes have received great attention. At present, researches on large-scale heat pipe applications have shifted from space applications to industrial and civil usage. So we can say that the heat pipe technologies have advanced from the theoretical exploration stage to the stage of popularization and application, and active developments of new heat pipes are progressing [2-5].

This article will analyze the successful application of the heat pipe technology for fulfilling the actual anti-freeze heating demand of a mining enterprise.

2. Project overview
The project belongs to a mine operated by a certain group company. The mine has a designed coal production capacity of 20.0Mt/year. It is located in a remote area and the site of the mine’s ventilation
shaft is far away from the main industrial square. The air shaft area is equipped with one exhaust air shaft with a volume flow rate of 20000m³/min and one inlet air shaft with a volume flow rate of 15000m³/min. Three 6t/h coal-fired hot blast stoves are used to provide the heat source for the original wellhead antifreeze. According to the local standard of Shaanxi Province DB61/1226-2018 "Boiler Air Pollutant Emission Standard", the air emission concentration limits of pollutants from coal-fired boilers to be fulfilled in northern Shaanxi are; particulate matter 10mg/m³, sulfur dioxide 35mg/m³, nitrogen oxide 50mg/m³, and mercury and its compounds 0.03mg/m³ [6]. The pollutant emissions from the existing boiler rooms at the mining site are seriously exceeding the above pollutant emission standards and must be rectified within a certain time limit. According to the "Notice of the People's Government of Yulin City on Printing and Distributing the Three-Year Action Plan (2018-2020) (Revised Edition) for Controlling Haze and Winning the Blue Sky Defense War with an Iron Fist" Yuzheng Fa [2018] No. 33 Document, Yulin city no longer permits to build new coal-fired boilers with a steam generation capacity of less than 35 tons per hour, and mandates to install all completed energy-saving and ultra-low emission equipment in coal-fired boilers with a steam generation capacity of more than 65 tons per hour [7]. Therefore, the mining sites must find a new alternative heat source meeting the above new environmental regulations to continue normal coal production in the mines.

3. Design of a new alternative heat source scheme

3.1. Scheme design assumption

According to "Industrial Building Heating Ventilation and Air Conditioning Design Code", the outdoor air parameters of this place for calculating the heat load for outdoor heating in winter is as follows. The calculated outdoor temperature is -15.1 °C, the calculated outdoor temperature for ventilation is -9.4 °C, the extremely low temperature is -30.0 °C, and the average of the extremely low temperatures over the years is -24.2 °C. In this heating system, the mining was designed by professional process designers with a volume flow rate of the intake air of 15000m³/min and a volume flow rate of the exhaust air of 20000m³/min. The exhaust air temperature is designed to be constant at 16 °C all year round and the intake air and exhaust air shafts are located at the same site.

According to the "Coal Safety Technical Regulations", the average value of the extremely lowest temperatures over the years is set at -24.2 °C to calculate the heat load required for the air intake in the mine. The temperature at the head of the air intake shaft is set at 2 °C, and the calculated heat demand for the air intake is 9301kW. On the other hand, based on the calculated outside temperature (-15.1 °C), it is estimated that the heat demand for the intake air is 6070kW. The exhaust air temperature is set at a constant value of 16 °C throughout the year. It is assumed that the temperature difference between the hot and cold air at the heat exchange ends is 2 °C. Since the volume flow rate of the exhaust air is larger than that of the intake air, the heat content of the exhaust air is about 8000kW. The schematic diagram of scheme layout is shown in Figure 1.

Figure 1. Schematic diagram of the heat exchange arrangement using heat pipes.
3.2. Feasibility analysis

There are two main calculation models based on the designing calculation methods of heat pipe heat exchangers; the equivalent continuous partition calculation model and the discrete partition calculation model [8-10]. In this research, the former model is employed.

The so-called equivalent continuous partition calculation model is to model the heat pipe heat exchanger as a dividing wall heat exchanger where the heat pipe heat transfer resistance is arranged in series on a continuous conversion heat transfer surface. So it can be considered as a conventional dividing wall heat exchanger. This calculation model is one of the engineering calculation methods and is based on the fact that the internal thermal resistance of a heat pipe is so small that it has almost no effect on the external convective heat transfer characteristics of that heat pipe. Actual calculations show that the internal thermal resistance of a heat pipe only accounts for about 10% of the total heat transfer resistance.

Assuming that the airflow outside the heat pipes is one-dimensional and ignoring the discrete distribution of the heat exchange surface as well as the change of the heat transfer coefficient along the heat exchange surface, the basic heat transfer equation of the heat exchanger can be obtained based on the energy balance of the entire heat transfer surface and the equivalent continuous partition calculation model:

\[ Q = K \times N \times A \times \Delta t_m \]  

(1)

Where \( Q \) is the total heat exchange capacity (kW), \( K \) is the heat transfer coefficient (kW/m²·℃), \( N \) is the number of heat pipes, \( A \) is the total heat transfer area of the heat exchange tubes (m²), and \( \Delta t_m \) is the logarithmic mean temperature difference between the hot air and the cold air (℃).

For the exhaust air heat recovery calculation, the average value of the inlet and outlet temperatures is taken as the qualitative temperature. \( Q \) can also be expressed as follows:

\[ Q = m_1c_{p1}\Delta t_1 - Q'_1 = m_2c_{p2}\Delta t_2 + Q_2' \]  

(2)

Where \( m_1 \) is the mass flow rate of the hot air (kg/s), \( m_2 \) is the mass flow rate of the cold air (kg/s), \( c_{p1} \) is the specific heat of the hot air at constant pressure (kJ/kg·℃), \( c_{p2} \) is the specific heat of the cold air at constant pressure (kJ/kg·℃), \( \Delta t_1 \) is the temperature difference between the inlet and outlet of the hot air (℃), \( \Delta t_2 \) is the temperature difference between the inlet and outlet of the cold air (℃), \( Q'_1 \) is the amount of heat loss from the hot air to the environment (kW), and \( Q_2' \) is the amount of heat loss from the cold air to the environment (kW).

The relationship between the released heat \( Q_1 \) from the hot air (mine exhaust) in the heat release side and the absorbed heat \( Q_2 \) by the cold air (outdoor air) in the heat absorption side is as follows:

\[ Q_2 = \eta \times Q_1 \]  

(3)

Where \( \eta \) is the designed heat transfer efficiency.

In order to analyze the feasibility of the heat pipe system, the relationship between \( Q_1 \) and \( Q_2 \) shown in Eq.3 is analyzed. The main problem now is to estimate the value of \( \eta \). The influence of the height on the heat exchange effect and the measures to ensure the amount of electric heating that need to be taken. Figure 2 shows the calculated \( Q_2 \) value as a function of the value of \( \eta \) and Figure 3 shows the heat load demand at different calculated outdoor temperatures. As stated above, the calculated outdoor temperature is -15.1℃ and the average value of the extremely lowest temperatures over the years is -24.2℃. So, from Figure 3, we can find that the required base heat load is 6071kW and the limit heat load is 9301kW. By referencing Figure 2, a comprehensive analysis considers the selection of a heat pipe heat exchanger with the designed \( \eta \) value of 0.85 to meet the base heat load requirement and ensure the base heat load operating conditions. For fulfilling the difference between the base heat load and the limit heat load, electric heaters are arranged to ensure the partial heat load demand in winter. The required electric heat load is 2501kW. The relationship among these heat loads is shown in Figure 4.

In the actual operation of the project, the fluctuation of the outdoor weather parameters leads to a change in the working conditions. According to the statistics of meteorological data, the occurrence frequency of the extremely low temperature in this area is low, and most of the heating time is within
the base heat load range. So the actual operating hours of the electric heating shall be relatively short. By incorporating a high-performance automatic control system to ensure that the operation of the electrical heater will start and stop automatically according to the outdoor temperature change, the project can be operated in an energy-saving way.

![Figure 2. Relationship between Q₂ and η.](image)

![Figure 3. Relationship between the heat load demand and the calculated outdoor temperature.](image)

![Figure 4. Heat load comparison diagram.](image)

4. Process of the heat exchanger selection
Considering the site conditions and the site occupancy, to facilitate the layout and later operation and management, the heat exchange room is arranged centrally, the heat pipe heat exchanger platform is located on the roof of the room, new ventilation channels are built, and the heat exchanger is designed and selected according to the performance requirements for heating. Then the heat exchanger and the ventilator are installed, and a 2501kW electric heater is arranged in the air duct. The mine exhaust air is discharged to the atmosphere after passing through the evaporation section of the heat pipe heat exchanger. The newly-built fresh air pipeline absorbs heat through the condensation section of the heat pipe heat exchanger and then the heated air is supplied to the air intake shaft using a blower. The system layout diagram of the heat exchanger room is shown in Figure 5. The detailed steps of the heat exchanger calculation and its selection are not repeated here but just outlined below:
The heat balance calculation is conducted to determine the heat transfer amount, the flow rate of the hot and cold air, and the temperatures of both air at the inlet and outlet of the heat exchanger;

- The structure, the size, the arrangement, and the basic parameters of heat pipes and heat pipe heat exchangers (including the expanded heat exchange surface arrangement, the flow rate, etc.) are selected and determined;
- The heat transfer coefficients of the hot and cold sides of the heat pipes are calculated;
- The sub-thermal resistance and the total thermal resistance of the heat pipes, as well as the heat transfer coefficient, are calculated;
- The size and layout of the heat pipes are verified and the numbers of the heat pipes and rows are decided;
- The highest working temperature in the heat pipes and the lowest pipe wall temperature are calculated and verified;
- The flow resistances of the hot and cold sides of the heat exchanger are calculated and verified;
- The safety check and economic analysis are conducted.

![System layout diagram of the heat exchanger room.](image)

**Figure 5.** System layout diagram of the heat exchanger room.

### 5. Conclusions

The actual operation of the project within one year during the operation period achieved good results and met the on-site needs. The combined arrangement of the actual heat pipe heat exchange method combined with electric heating played a very good role in energy saving. Since the electric auxiliary electric heating module is only designed to avoid frost and antifreeze of the evaporator under extreme climatic conditions, and to ensure the reliability of system operation, the electric auxiliary heating
module does not need to be turned on under normal circumstances. Even in extreme weather conditions, in order to achieve the purpose of energy saving and consumption reduction under the premise of ensuring the reliability of the system. Each electric auxiliary heating module is divided into multiple independent heating units, and each heating unit is controlled by a computer, and automatically starts and stops according to the signal returned by the wind temperature monitoring. The heat pipe has good thermal conductivity, ideal isothermality, irreversible heat transfer direction and adjustable thermal resistance on both sides. The length of the heating section and the heat release section can be flexibly selected and arranged. Therefore, the recovery of waste heat resources in mines and other similar places has a very good effect, and it is worthy of promotion and application in suitable places.

References
[1] Tu Chuanjing, Wang Pengju, Hong Ronghua 1989 Gravity heat pipe heat exchanger and its application in waste heat utilization[M] Zhejiang: Zhejiang University Press
[2] Yao Qiang 2012 Design and Applications of Heat Pipe Air Preheaters[D] Shanghai; East China University of Science and Technology
[3] Bai Yanbin, Jiao Chunlin,Huo Haihong 2017 Discussion Under the New Situation of Coal Mine HVAC Design[J] Refrigeration and Air Conditioning 31(3) 281-285
[4] DU Chun tao, ZHU Yuan zhong, MENG Guo ying, GAN Yan biao 2015 Mathematical Model of Heat Exchange Efficiency of Mine Return Air Spraying Heat Exchanger[J] COAL ENGINEERING 47(10) 104-107
[5] Cheng Ranran 2016 Analysis and Numerical Simulation of Heat Transfer of Gravity Heat Pipe Heat Exchanger[D] Jiangsu; Jiangsu University of Science and Technology
[6] Shaanxi Provincial Department of Ecology and Environment. Emission standard of air pollutants for boiler: DB61/1226-2018[S]. Shaanxi: Shaanxi Provincial Market Supervision Administration
[7] http://www.yl.gov.cn/P/C/45036.htm
[8] Chen Yanze 2013 Study on Heat Transfer Process and Nonlinear Characteristics of Two-phase Closed Thermosiphon[D] Dalian: Dalian University of Technology
[9] Liu Cunyu 2013 Analysis of Multifunctional Variable Condition Heat Pump System and Its Application Research in Wutongzhuang Mine[D] Beijing: China University of Mining
[10] Sun Yang 2015 Research on Heat Pipe Heat Exchanger Recovering Mine Return Air Heat Energy to Preheat Fresh Air in Yangdong Mine[D] Hebei: Hebei University