Investigation on the new design method of heat source for reducing the energy consumption in the shaft antifreeze system

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Abstract. In order to suppress the heat consumption for shaft antifreeze in coal mines, this study first analyzed the meteorological data required for shaft antifreeze in typical five cities (Harbin, Yulin, Hefei, Guiyang, and Nanning) located in different climate zones in China. The analysis results explain why some shaft heating measures must be taken in severely cold regions. So, in this study, Harbin is taken as the case city for research to show that the traditional heat load design methods have the problem of mismatching between the actual heat load and the designed heat load. Next, the annual temperature change analysis in Harbin reveals that the occurrence frequency of the extremely low temperature in a year is small and its continuation time is short. According to this finding, a new heat load design method is proposed based on the dual heat source usage. In this new method, the main heat source will be designed for flat-peak heat load compensation and the standby heat source will be designed for peak heat load compensation. The main heat source should be selected based on the outdoor calculated temperature for the shaft antifreeze system. The standby heat source should be selected based on the mean value between the average of the year-over-year lowest temperature and the outdoor design temperature for the adit system and on the average of the year-over-year lowest temperature for the vertical/inclined shaft system. The standby heat source accounts for 13% of the total heat load and the main heat source accounts for 87% of the total heat load in the adit system. On the other hand, the standby heat source accounts for 23% of the total heat load and the main heat source accounts for 77% of the total heat load in the vertical/inclined shaft system.

1. Introduction

According to the relevant data reported on the official website of the National Energy Administration (February 13, 2020), China has 996 coal mines in total with a production capacity of 2.65 billion tons per year. As coal production occupies an important position in the national production and life, the notion “scientific production capacity” has been gradually popularized, and the energy consumption associated with coal production has been lowered year by year [1]. However, the average energy consumption in coal mining in China is nearly 4 times higher than that in developed countries (with an average energy consumption of 2.5kg standard coal for mining 1 ton of coal). So China has a great potential in energy saving in coal mines [2]. According to the requirements of “Design standard for heating ventilation and air conditioning of coal industry”, some air-heating measures need to be taken as proved by mine production practices in severely cold or cold regions. In such regions, without...
appropriate air-heating measures, the freeze of wellheads, road surfaces, or water pipes may occur which affects the safe coal production. In this case, the mine air-intake shaft should be equipped with shaft antifreeze equipment [3]. The shaft antifreeze heat load accounts for a large proportion of the heating load in mines, so it has always been taken the top share in the energy consumption for heating in mines. Therefore, it is of great significance to study the reasonable method for designing the heat source in coal mines to lower the energy consumption associated with the operation of the coal mine heating system.

According to Ref.[3], the outdoor design temperature of the antifreeze air heating in the shaft should satisfy the following requirements. The local average of the year-over-year lowest temperature (the average of the lowest temperature of the coldest month in each year in the period of consecutive years selected for statistics such as 30 years) should be utilized for designing the heating system for the vertical and inclined shafts, and the mean value of the average of the year-over-year lowest temperature and the outdoor design temperature should be used for designing the heating system for the adit. As clearly stipulated in the “Coal Mine Safety Regulations”, the air-mixing temperature in the shaft must be kept above 2°C where no icing is allowed. Therefore, the relevant meteorological parameters should be selected stricter than the outdoor temperature of the ordinary heating system which does not guarantee the 5-days averaged daily temperature [4].

Traditional heat sources in coal mines mainly refer to boiler rooms where the coal-fired boiler rooms are most commonly used. Due to the tonnage limitation of coal consumption for heating, it is impossible to allocate all the heat loads in designing coal-fired boiler rooms. The additional heat loads usually need to be considered according to the factors such as the heat loss in the pipe network, the terminal heat loss, and deterioration of the heat source. In particular, steam boiler rooms are used to replace coal-fired boiler rooms. Coal-fired boiler rooms have the advantage of guaranteeing the water balance in desert regions and providing a high-temperature heating medium, while it also has the disadvantage of serious losses of steam and heat [5-7]. For this reason, relevant requirements must be satisfied in the calculation of the heat load in mines, especially in the antifreeze shaft. If the calculated heat load is lower than the required one, it would cause irreversible losses of the system. If the traditional heat source design methods are still used to design the shaft antifreeze system, the heating capacity of the heat source shall be allocated considering the most unfavorable working condition, which will inevitably result in high energy consumption in the operation of coal mines [8-10]. With the implementation of the strict national energy-saving and emission-reducing policies, most of the coal-fired boiler rooms shall be abandoned.

New alternative heat sources such as water source heat pumps, air-source heat pumps, and mine waste heat recovery heat pumps are being popularized and applied. Due to flexible load allocation, free combination, and convenient operation and adjustment of heat pump units, the mine heat source is no longer limited to coal-fired boiler rooms. In fact, many mines are designed to have dual or multiple heat sources.

In this paper, a novel heat source selection method based on the meteorological data analysis is proposed to realize an applicable and reliable shaft antifreeze system.

2. Analysis of traditional heat load design conditions

2.1. Data source

The most important two sets of meteorological data used in the shaft antifreeze design are the average of the year-over-year lowest temperature and the outdoor design temperature for heating. These two sets of data are available in Appendix A of “Design specifications for heating ventilation and air conditioning of industrial buildings”. The data given in these specifications are the static design data, that is, the outdoor design parameters required for calculating the shaft antifreeze heat load. This calculated heat load is set to ensure that the shaft antifreeze heat load demand is satisfied under the most unfavorable conditions. However, in the real project implementation, the outdoor meteorological parameters frequently change dynamically. So the problem of mismatching between the shaft-
demanding heat load and the heat source-providing heat load may occur. In this part, five representative cities from typical climatic zones in China are analyzed.

2.2. Analysis of meteorological parameters in typical climatic zones

This research selected five cities located in different climatic regions and different altitudes. They are Harbin in Heilongjiang Province located in a severe cold region, Yulin in Shaanxi Province located in a cold region, Hefei in Anhui Province located in a region which is extremely hot in summer and extremely cold in winter, Guiyang in Guizhou Province located in a region with a mild climate, and Nanning in Guangxi Province located in a region which is hot in summer and warm in winter. The meteorological parameters of these five representative cities are shown in Table 1 [11].

| No. | City          | Altitude/m | Average of the year-over-year lowest temperature/°C | Outdoor design temperature/℃ | The mean value between the average of the year-over-year lowest temperature and the outdoor design temperature/°C |
|-----|---------------|------------|---------------------------------------------------|-------------------------------|----------------------------------------------------------------------------------------------------------------|
| 1   | Harbin (Ha)   | 142.3      | -32.2                                             | -24.2                         | -28.2                                                                                                           |
| 2   | Yulin (Yu)    | 1057.5     | -24.2                                             | -15.1                         | -19.7                                                                                                           |
| 3   | Hefei (He)    | 37.2       | -7.7                                              | -1.7                          | -4.7                                                                                                            |
| 4   | Guiyang (Gui)| 1223.8     | -3.7                                              | -0.3                          | -2.0                                                                                                            |
| 5   | Nanning (Nan)| 121.6      | 2.7                                               | 7.6                           | 5.2                                                                                                             |

The average of the year-over-year lowest temperature should be used in calculating the heat load in the vertical and inclined shafts, and the mean value between the average of the year-over-year lowest temperature and the outdoor design temperature should be used in calculating the heat load in the adit. To ensure the shaft wellbore antifreeze, the shaft intake air temperature must be kept above 2°C. Assuming that the air intake rate is 1kg/s, the calculation results of the heat loads in the vertical and inclined shafts and those in the adit are shown in Figures 1 and 2, respectively. As shown in these figures, the heat loads in Harbin and Yulin located in severe cold and cold regions are much higher than those in cities located in other warmer regions. In the case of Nanning located in a hot region, the heat load is negative indicating that no heat load or heat source is needed to guarantee the heat supply for the shaft. Since the outdoor design temperature is 2°C higher than the required temperature in the shaft, heating in the shaft is not needed. On the other hand, the heat load in Harbin located in a severely cold region is much higher than those in the cities located in other regions. This explains why the specifications explicitly stipulate that some shaft heating measures must be taken in severely cold regions. The colder a region is, the higher the calculated heat load is and the larger the capacity of the selected heat source equipment shall be. These specifications shall be applied to both the adit and the vertical/inclined shafts, where there is a minor difference that the heat load in the adit is lower than those in the vertical/inclined shafts in the same region under the same working conditions.

2.3. Analysis of design conditions and operating conditions

Figures 1 and 2 show the calculation results obtained under the design conditions, so the effect of the heating operation based on the monthly averaged temperature requires further analysis.
Figure 1. Calculated heat load in the vertical and inclined shafts.

Figure 2. Calculated heat load in the adit.

The monthly averaged temperature of each city is available in the “Typical meteorological database handbook for buildings”. Since this research mainly focuses on the heat source for shaft antifreeze in winter, the monthly averaged temperatures in each city in December, January, and February are shown in Figure 3.

As can be seen from this figure, the monthly averaged temperatures in Harbin and Yulin in winter are lower than 2°C, while those in other cities are higher than 2°C. As discussed above, it is unnecessary to consider the issue of the shaft antifreeze in Nanning, because the monthly averaged temperature in Nanning in winter is higher than 10°C. Also, the monthly averaged temperatures in Hefei and Guiyang in winter are higher than 4°C. This indicates that in these two cities with a similar climate, the shaft antifreeze system shall be designed to run just for some periods in winter because heating is needed just for few hours in a day. Therefore, in the heating system design for such climatic regions, temporary heat sources such as electric heaters, air-source heat pumps, and so on can be selected for satisfying the heating demand with a short running time [12-13].

As shown in Figure 3, the monthly averaged temperatures in Harbin and Yulin in winter are lower than -2°C, so the shaft antifreeze system in these regions shall be designed to run all the time. However, there is a big gap between the monthly averaged temperature and the outdoor design temperature specified by the design conditions. As the design and operating conditions in Harbin and Yulin are similar, Harbin is now selected as the research object. The hourly average temperature of the standard day in Harbin in January is compared with the two outdoor design temperatures specified under the design conditions. The comparison results are shown in Figure 4.

In this figure, the actual outdoor temperature during the day is shown by the curve, and it is constantly changing 24 hours a day. This indicates that the shaft heat load demand is variable under the actual operating conditions. To be specific, the shaft heat load demand changes linearly in direct proportion with the outdoor air temperature. The average heat load demand in a day corresponds to the hourly averaged temperature shown by the curve in Figure 4. Figure 4 shows that maximum load demand in a day is 8.2°C deviating from the outdoor design temperature required for adit working conditions, and 12.2°C deviating from the outdoor design temperature required for the working conditions of the vertical/inclined shaft. In the actual heat source design, the heating equipment should be selected according to the outdoor design temperature to ensure that the antifreeze heat load demand can be satisfied even under the extremely cold conditions. And this can explain the reason why the average value of the year-over-year lowest temperature is used as an important parameter in relevant specifications, handbooks, and regulations.
Figure 3. Monthly averaged temperature in each city in winter.

Figure 4. Comparison among the hourly averaged temperature and the two outdoor design temperatures in the standard day (Harbin, January).

Figure 5. Comparison between the actual and the designed heat loads under the adit condition.

Figure 6. Comparison between the actual and the designed heat loads under the vertical/inclined shaft condition.

In this paper, Harbin is taken as the case city for research. The calculated values of the required heat load per unit air intake (1kg/s) under different working conditions are shown in Figures 5 and 6. Figure 5 compares the actual and the designed heat loads for antifreeze under the adit working conditions. Here, as shown in Table 1, the mean value (-28.2°C) of the average of the year-over-year lowest temperature in Harbin (-32.2°C) and the outdoor design temperature for heating (-24.2°C) is used to calculate the designed heat load. The actual heat load shown by the curve is calculated using the hourly averaged temperature of the standard day in January shown in Figure 4 and the daily averaged temperature on that day (-16.7°C). Figure 6 compares the actual and designed heat loads for antifreeze under the vertical/inclined shaft working conditions. The average of the year-over-year lowest temperature in Harbin (-32.2°C) is used to calculate the designed heat load. The actual heat load shown by the curve in Figure 6 is the same as that in Figure 5. As clearly shown in Figures 5 and 6, the calculated heat load value under the design temperature condition is larger than the actual heat load value and the daily averaged heat load value. The actual heat load values in these two figures are compared with the daily averaged heat load values to take the smaller heat load values. We put vertical lines connecting the smaller heat load values and the designed heat load values as shown in these figures. Theoretically, this marked area is the range of the heat load for flexible real-time adjustment. This marked area of the heat load shall be considered in the heat load design, and the adjustable range of the heat source is quite limited in the actual equipment running. This part of the heat load ranges between the hourly load and the average load, and the variance value is 2.5. Under the design conditions, the difference between the daily averaged heat load value and the designed heat load value under the adit condition is 11.6kW, and that under the vertical/inclined shaft condition is 15.6kW. The
traditional heat load design methods have the problem of mismatching between the actual heat load and the designed heat load. So we can conclude that the traditional heat load design methods are somewhat imperfect and unreasonable.

3. New design method and working condition analysis

3.1. Heat load analysis
There is a cyclical change of four seasons, so the outdoor meteorological parameters are constantly changing throughout the year. Statistical methods are used to find out that the change law for the outdoor meteorological parameters conforms to the normal distribution law. The standard daily temperatures in January, March, May, July, September, and November in Harbin are recorded for the statistical analysis. According to this analysis, the annual change of this temperature is shown in Figure 7. As can be seen from this figure, the occurrence frequency of the extremely low temperature in a year is small and its continuation time is short. Based on the meteorological data obtained from the literature [11], a statistical analysis is performed on the number of average hours when the outdoor temperature of Harbin is continuously equal to or lower than a certain value. The analysis results are shown in Figure 8. The heat load for the extremely low temperature is huge, but this figure shows that such a huge heat load cannot last for a long time. Moreover, Table 2 also shows that there are only 87 hours when the temperature was continuously lower than -26°C, and 200 hours when the temperature was continuously lower than -24°C.

3.2. New heat load design method
In order to deal with the extremely low temperature, despite of its low occurrence frequency and short continuation time, the heat supply equipment should be designed to provide a huge heat load resulting in an inevitable increase in energy consumption. Figure 9 schematically shows the daily change of the outdoor design temperature for shaft antifreeze, the design temperature for heating, and the hourly averaged temperature in a typical day. The corresponding heat load is represented by the area graph which includes the three curves showing the above three temperatures. According to the new heat load design method, the oblique shaded part below the hourly averaged temperature curve represents the hourly averaged demanded heat load and the part under the curve of the design temperature for heating (cross shaded + oblique shaded) is the designed heat load of the main heat source. According to the relevant specifications, the heat load gap between the outdoor design temperature and the design temperature for heating shall be fulfilled by the standby heat source.
Table 2. Statistics for the number of hours when the temperature was continuously lower than each value.

| $\leq T (^\circ C)$ | Duration of hours (h) |
|----------------------|-----------------------|
| +5                   | 4296                  |
| +3                   | 3935                  |
| 0                    | 3483                  |
| -2                   | 3198                  |
| -4                   | 2960                  |
| -6                   | 2727                  |
| -8                   | 2509                  |
| -10                  | 2268                  |
| -12                  | 1997                  |
| -14                  | 1689                  |
| -16                  | 1331                  |
| -18                  | 998                   |
| -20                  | 682                   |
| -22                  | 389                   |
| -24                  | 200                   |
| -26                  | 82                    |

Figure 9. A schematic daily change of the outdoor design temperature, the design temperature for heating, and the hourly averaged temperature.

It shall be noted that the hourly averaged temperature shown in this figure is taken based on the typical daily actual temperature curve obtained in the above analysis. The maximum hourly averaged temperature in this figure is not higher than the design temperature for heating. However, since the maximum hourly averaged temperature is determined to represent the statistical data on the average temperature, some extremely low temperatures are not considered. Therefore, the actual hourly averaged temperature may exceed the design temperature for heating, or even exceed the outdoor design temperature. As was discussed above, the extremely low temperature causing such a situation has a small occurrence frequency with a short-lasting time.

3.3. Heat source arrangement and scientific analysis

The occurrence frequency of the extremely low temperature is low. However, as revealed in the above analysis, it is stipulated by the specifications that a sufficient heat load must be guaranteed for shaft antifreeze even under the extremely low-temperature working conditions. Therefore, in the new heat load design method, a standby heat source is used to supply the additional heat load required at the extremely low temperature. Since the standby heat source just accounts for about 1/4 of the heat source of the entire system, the standby heat source can be arranged in the following two options.

The first option is to arrange electric heaters or small low-temperature air source heat pumps and other equipment with an easy start-up directly in the air heating room near the shaft or properly arranged around the air intake vent. Only when the actual outdoor temperature becomes lower than the outdoor design temperature, the standby heat source shall be operated for shaft antifreeze. Therefore, there is no need to lay down pipes for the standby heat source equipment. This reduces the pipeline-laying cost and saves the investment cost as well as the capacity of the main heat source. The standby heat source just needs to satisfy the demand of a small heat load and the installation of it is quite simple. The cost increase by the standby heat source is much lower than the cost-saving by lowering the capacity of the main heat source. The occurrence frequency of the extremely large heat load is quite low and the operating time of the standby heat source is short, so the energy consumption for operating the heating system can be reduced significantly.
The second option is to arrange the standby heat source in the same room as the main heat source. In this case, the standby heat source can be an electric boiler or similar equipment with a smaller heating capacity compared with the main heat source. Once the extremely cold temperature occurring, the extremely high heat load can be handled in two ways. One way is to perform the quantity-based adjustments to deal with the extremely high heat load. After occurring the extremely low temperature, the water coming from the standby heat supply network is heated by the standby heat source and then mixed with the water coming from the pipe network of the main heat source and eventually delivered to the end heat load target to meet the demand of the heat load. Under this working condition, some hot water coming from the standby heat source is mixed into the water coming from the main heat source, so both the pipeline water flow rate and the operating energy consumption increase. In the implementation of such heating design under this working condition, we should consider the hydraulic imbalance in the pipe network caused by the series and parallel connection of pumps, so this arrangement method is more complicated than the first option. Another way is to perform the quality-based adjustments to deal with the extremely high load. The standby heat source directly raises the temperature of the water delivered from the main heat source to meet the end heat load demand. In this case, the water should be heated by the main heat source first, and then heated by the standby heat source, and eventually delivered to the end heat load target. In this second way, it is essential to consider the water-saving working condition that meets the demand for the series connection of water pumps.

The outdoor design temperature for heating is taken as a basis for selecting the main heat source equipment. The advantage of this method is in the fact that the average value of the year-over-year lowest temperature is used as an important parameter in the design of the shaft antifreeze system. The year-over-year parameter refers to its value in each year of the previous consecutive years selected for statistics when making meteorological data. When the statistical period is 30 years, the 151st value of the 30-years’ daily average temperature in the descending order is used as the final calculation parameter. Here, the year-over-year lowest temperature refers to the lowest temperature in the coldest month in each year in the period of consecutive 30 years selected for statistics, and the average value of it is used as the final calculation parameter. Therefore, this parameter can realize the heating system matching with the extremely high heat load when applied to actual projects. In this way, the parameters that do not guarantee the outdoor design temperature for heating are excluded. The unsatisfied working condition refers to the condition under which the demanded heat load is not satisfied only in 5 years one year [14-15]. In severely cold regions, the traditional heating design method cannot guarantee the heat load matching for the extremely cold days whose occurrence rate is less than 4%. If the outdoor design temperature is used as a basis for selecting the main heat source of the shaft antifreeze system, the standby heat source is needed just for about 4% of the entire cold season in most regions.

In summary, in this new heat load design method, the outdoor design temperature is used to select the main heat source in the shaft antifreeze system, while the mean value between the average of the year-over-year lowest temperature and the outdoor design temperature is used to select the standby heat source in the adit system, and the average of the year-over-year lowest temperature is used to select the standby heat source in the vertical/inclined shaft system.

3.4. Working condition analysis of the new heat load design method
In this paper, a case study has been conducted for Harbin located in the severely cold region as an example. According to the new design method, loads of the outdoor design temperature, the outdoor design temperature for heating and the hour-by-hour temperature are calculated and analyzed. Figure 10 compares the actual and the designed heat loads under the adit condition, while Figure 11 compares the actual and the designed heat loads under the vertical/inclined shaft condition. In these figures, the heat loads per unit air intake (1kg/s) were shown.
Under the adit condition, the designed heat load is 30.5kW, the heat load at the outdoor design temperature is 26.5kW, and the maximum heat load at the hourly averaged actual temperature is 22.2kW. When the new heat load design method is applied, the designed heat load of the main heat source is 26.5kW, the designed heat load of the standby heat source is 4.0 kW, and the total heat load is 30.5kW. The standby heat source supplies 13% of the total heat load and the main heat source supplies 87% of the total heat load.

Under the vertical/inclined shaft condition, the design heat consumption is 34.5kW, the heat consumption at the outdoor design temperature for heating is 26.5kW, and the maximum heat load of the hourly averaged temperature is 22.2kW. When the new design method is applied, the designed heat load of the main heat source for unit air volume is 26.5kW, the designed heat load of the standby heat source is 8.0 kW, and the total heat load is 34.5kW. The standby heat source supplies 23% of the total heat load, and the main heat source supplies 77% of the total heat load. As the specified temperature for the vertical/inclined shafts is lower than that for the adit, the standby heat source equipment for the vertical/inclined shafts supplies a 10% higher proportion of the total heat load than that for the adit system. This makes the heating system for the adit system more energy-saving.

4. Conclusions

Through the analysis of this paper, it has been revealed that the traditional design method for the selection of the heat source in coal mines based on the outdoor extremely low-temperature conditions is not reasonable because of the dynamic fluctuation of the meteorological parameters throughout the year. In the heat source design for the shaft antifreeze system, if the boiler house in a large central heating area is not adapted to provide the demanded heat, it is appropriate to adopt the double heat source heating scheme. In normal times, the main heat source ensures the safe and reliable operation of the heating system. Only in very rare extremely low-temperature days, the standby heat source can be used, which not only saves investment but also meets the requirements of the actual operating conditions.

In the actual engineering design and operation, the main heat source and the standby heat source should be selected according to the following methods in combination with the meteorological data. The main heat source should be selected based on the outdoor calculated temperature for the shaft antifreeze system. The standby heat source should be selected based on the mean value between the average of the year-over-year lowest temperature and the outdoor design temperature for the adit system and on the average of the year-over-year lowest temperature for the vertical/inclined shaft system.

After the selection of the main heat source and the standby heat source, taking account of the working condition in the adit of Harbin city as an example, it has been determined that the heat load proportions of the standby heat source and the main heat source is 13% and 87%, respectively. When
taking account of the vertical/inclined shaft conditions as an example, the heat load proportions of the standby heat source and the main heat source is 23% and 77% respectively. In the case of the adit system, compared with the vertical/inclined shaft system, the heat load proportion of the standby heat source is 10% lower, which is more effective for energy-saving operation.

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