Energy saving analysis on mine-water source heat pump in a residential district of Henan province, central China

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Abstract. In this paper, the mine-water source heat pump system is proposed in residential buildings of a mining community. The coefficient of performance (COP) and the efficiency of exergy are analyzed. The results show that the COP and exergy efficiency of the mine-water source heat pump are improved, the exergy efficiency of mine-water source heat pump is more than 10% higher than that of the air source heat pump. The electric power conservation measure of “peak load shifting” is also emphasized in this article. It shows that it is a very considerable cost in the electric saving by adopting the trough period electricity to produce hot water. Due to the proper temperature of mine water, the mine-watersource heat pump unit is more efficient and stable in performance, which further shows the advantage of mine-water source heat pump in energy saving and environmental protection. It provides reference to the design of similar heat pump system as well.

1. Introduction

With the rapid development of economy and the people’s ever growing demand for comfort of indoor environment, the heating supply and air-conditioning has become common requirements for public buildings and housing buildings. This results in sharp rising of energy consumption in buildings. The problem of energy consumption has attracted more and more attention of governments from all over the world. The modern building energy saving is to perform scientific configuration to the resources that the construction needs to improve resource utilization rate and reduce unnecessary resource waste under the precondition of guaranteeing the using and living comfort of the buildings [1-3]. That is to use more renewable resources to reduce energy consumption of hot water supply, air-conditioning, heating, and illumination under the precondition of guaranteeing the indoor thermal and humid environment quality [4-6]. During recent years, as a kind of energy saving technology gradually applied widely, more and more people have focused concerns on the water source heat pump [7-14].

It is well known that the water source heat pump is featured in energy saving, high efficiency, flexibility, comfort, and high reliability [15-17]. Like any other water source heat pump: in winter the mine-water source heat pump “takes out” the heat from mine-water for indoor heating, and “takes out” the heat from the building and release it into the mine-water in summer. Therefore, the mine-water source heat pump is the use of renewable energy technologies using the solar energy resources stored in the mine-water as the cold and heat source; it is environmentally friendly with no pollution as well.
2. Background of the mine-water source heat pump system

This project is located in a residential area of high-rise housing buildings in a mining area in Pingdingshan City of Henan province. As a city in the central area of China, it is located within east longitude 112°14’–131°45’ and north latitude 30°45’–35°20’.

This residential area totally has a total of 14 buildings, among which, Building 14 is a three-floor public building (Mine Hospital Hotel), Building 2 to 8 are 11-floor housing buildings, Building 1 and 9 to 13 are 21-floor housing buildings; the total floor area is approximately 98,000 m². This residential area requires heating supply in winter and cooling supply in summer, as well as hot water supply all year round. In this project, the air conditioning system of water source heat pump would be applied to make full use of the abandoned mine water as natural water source of the water source heat pump air conditioning system. The mine-water comes from underground water system belonging to water resources. It is the water that comes out of the coal formation during the mining process and is clean water before it is polluted. The mine-water was tested by the experts of Henan water resources Management Office. The testing result indicates that: the temperature of the mine-water remains at 12-22 °C all the year round; the temperature is 12-18 °C in winter and 16-22 °C in summer; the temperature of water is around 15 °C located about the depth of 60m. Therefore, the mine water is a good natural water source for water source heat pump units. The water abstraction from the abandon mine pit is shown figure 1. However, the report related to the application of the heat pump system with mine-water as the source has not been found yet.

Figure 1. The diagram of the water abstraction from the mine pit.

The cooling load of the residential area is 9140 kW in summer, and the heating load is 6540 kW in winter, adopting 5 screw compressor water source heat pumps. The design parameters for each unit are shown in table 1.

Table 1. The technical parameters of the mine-water source heat pump.

| Condition          | Refrigerating Capacity (kW) | Heating Capacity (kW) | Input Power (kW) | Inlet and Outlet of Air-conditioning Water (°C) | Inlet and Outlet of Mine-water (°C) | COP |
|--------------------|------------------------------|-----------------------|------------------|-----------------------------------------------|--------------------------------------|-----|
| Cooling condition  | 2034.3                       | 355.6                 | 12/7             | 15/30                                         |                                      | 5.72|
| Heating condition  | 2184.6                       | 480.5                 | 40/45            | 15/6                                          |                                      | 4.55|

In this community, according to the local conditions, the waste natural mine-water is used as the source of the water source heat pump. The heat energy reserved in the natural-mine-water is applied in the heat pump technology. It is more energy saving and environmental protective expanding the scope of application of the water source heat pump.

Figure 2 is the schematic diagram of mine-water source heat pump system. The working principle of the mine-water source heat pump system is: with the help of water source heat pump compressor system, a small amount of electric energy is consumed simultaneously. In winter, the mine-water...
source heat pump unit extracts the heat from the mine-water to heat the building (in the side of condenser); during the summer, the mine-water is used as the cooling water of the air-conditioning system, taking heat from the buildings efficiently and supply cold water to the buildings (in the side of the evaporator).

![Diagram of mine-water source heat pump system](image)

**Figure 2.** The schematic diagram of mine-water source heat pump system.

3. **Energy saving analysis on the mine water source heat pump**

The energy saving of the water source heat pump is mainly related to the water temperature of the hot water source (heating) or the cooling water (cooling). From this perspective, the energy saving characteristics of mine-water source heat pump is analyzed as follow.

3.1. **Performance coefficient (COP)**

The operation principle of heat pump is reverse Carnot cycle. Figure 3 shows the tephigram of reverse Carnot cycle of the ideal working substance between high temperature $T_1$ and low temperature $T_0(T_2)$.

![Reverse Carnot Cycle (T-S Chart)](image)

**Figure 3.** Reverse Carnot Cycle (T-S Chart).

In figure 3, Area ABCD represents net input power; Area DAFE represents the heat absorbed by the system from low temperature heat source; Area BCEF represents the heat released by the system to high temperature heat source. Generally, COP (coefficient of performance) is taken as the performance index weighing heat pump.

The COP calculation formula is as follow:

$$COP = \frac{Q}{W}$$

(1)

In the formula (1), $COP$ - coefficient of performance of heat pump; $Q$ - energy output by heat pump to environment, kW; $W$ - useful work input to the heat pump, kW.
The COP calculation formula of heat pump under cooling working condition:

\[ COP = \frac{Q_c}{W} \]  \hspace{1cm} (2)

In the formula (2), \( Q_c \) - heat absorbed by the system from low temperature heat source, kW.

The COP calculation formula of heat pump under heating working condition:

\[ COP = \frac{W + Q_c}{W} \]  \hspace{1cm} (3)

In Formula (3), since \( \frac{Q_c}{W} > 0 \), the COP of heat pump system under heating working condition is constantly over 1, namely, the output heat energy is larger than the input heat energy. And for traditional heating ways, such as: coal-fired, natural gas fired, and electric heating, the COPs are all less than 1. The higher COP, the better energy saving effect of the system.

From the angle view of mathematics, analysis on the effect of temperature of heat and cold sources on COP, it can be seen from figure 1 that, the COP calculation formula at the time of heating is:

\[ COP = \frac{T}{T - T_0} \]  \hspace{1cm} (4)

Formula (4) derivation of \( T_0 \):

\[ \frac{\partial COP}{\partial T_0} = \left( \frac{T}{T - T_0} \right)^2 \]  \hspace{1cm} (5)

It can be seen from Formula (5) that, \( \frac{\partial COP}{\partial T_0} \) is constantly greater than 0. It shows that COP would become greater as rising of \( T_0 \) (cold source temperature), and would become smaller as reduction of \( T_0 \).

Formula (4) derivation of \( T \) [18]:

\[ \frac{\partial COP}{\partial T} = \frac{T_0}{(T - T_0)^2} \]  \hspace{1cm} (6)

It can be seen from Formula (6) that, \( \frac{\partial COP}{\partial T} \) is constantly smaller than 0. It shows that COP would become smaller as rising of \( T \) (heat source temperature), and would become greater as reduction of \( T \).

It can be seen from the research that the water source temperature of the mine water source heat pump system is maintained 12~22 °C all the year round. This is great for improving heat pump unit COP. In the summer, the heat pump unit has lower condensation temperature and better cooling capacity; and in winter, the heat pump unit has higher evaporation temperature and better heating capacity. Thus, whether in winter or in summer, the COP of mine water source heat pump system can both be improved to realize better energy utilization efficiency. It can be concluded that, under the same cooling capacity and the same operating conditions, the mine-water source heat pump can save energy greatly than the air source heat pump. Furthermore, the temperature of mine-water source heat pump is stable and reliable, avoiding the serious problems of frost in air source heat pump in the cold winter. Meanwhile, the cooling tower can be saved at the same time.

3.2. Analysis of exergy

Some texor energy, its “quality” and “quantity” are called “Exergy” in unified manner. Therefore, it is scientific to analyze energy by “exergy”. Theoretically, it is hoped the smaller exergy loss, the better exergy efficiency, for it can effectively use the provided energy.

The design parameters of the project as follow. The indoor design temperature in summer is 26 °C, in winter is 20 °C; adopting mine-water source heat pump units producing cold water 7/12 °C in summer and hot water 45/40 °C in winter; the outdoor environment design parameters: summer 34 °C, relative humidity 65%; winter -6 °C, relative humidity 55%. The mine water temperature: summer 15 °C, winter 15 °C. In summer, the evaporation temperature is 4 °C, the condensing temperature is 25 °C, the
super-cooling degree is 2 ℃, the superheating temperature is 2 ℃; In winter, the evaporation temperatureis 4 ℃, the condensing temperature is 50 ℃, the super-cooling degree 3 ℃, the superheating temperature is 3 ℃. The R134a is the cooling working substance; and the cooling theoretical circulation process is as shown in figure 4, ignoring pipeline resistance, condenser and evaporator resistance, as well as compressor suction and exhaust resistance.

![Figure 4: Compressor Theoretical Circulation P-h Chart.](image)

The exergy of unit mass at steady flowing can be expressed:

\[ e_x = h - \bar{h}_0 - T_0(s - s_0) \]  

where, \( T_0 \) is the ambient temperature; \( h \) is the specific enthalpy of working medium; \( \bar{h}_0 \) is the specific enthalpy of ambient; \( s \) is the specific entropy of working medium; \( s_0 \) is the specific entropy of ambient.

The cooling capacity exergy of unit mass can be express:

\[ e_{c, q} = q_l \left(1 - \frac{T_0}{T_e} \right) \]  

where, \( q_l \) the refrigeration capacity of unit working medium, \( T_e \) is the average temperature in water side.

The consumption of the compressor is:

\[ e_{x, w} = w_c = h_2 - h_1 \]  

The exergy loss of the compressor is:

\[ e_{x, c} = w_c + e_{x,1} - e_{x,2} \]  

The exergy loss of the condenser is :

\[ e_{x, l, con} = e_{x,2} - e_{x,3} \]  

The exergy loss of the evaporator is

\[ e_{x, l, ev} = e_{x,4} - e_{x,1} - e_{x,ql} \]  

The exergy loss of the throttling element is:

\[ e_{x,t} = e_{x,3} - e_{x,4} \]  

The total exergy efficiency is:

\[ \eta_e = \frac{e_{x, q}}{w_c} \]  

In table 2, the parameters of mine-water source heat pump and air source heat pump are calculated under the same outdoor conditions by taking parameters under environment state as benchmark.

As seen in the table 1and the figure5, the exergy loss of compressor is the largest among the exergyloss of the main components of the system because of the irreversible adiabatic compression process causing the irreversible exergy loss.
Table 2. Exergy analysis of refrigeration cycle in summer.

| Name                          | Mine-water source heat pump | Air source heat pump |
|-------------------------------|----------------------------|---------------------|
|                               | Summer | Winter | Summer | Winter |
| Consumption of the compressor | 26.6   | 38     | 32     | 63     |
| Exergy loss of the compressor | 4.95   | 7.1    | 7.75   | 13.4   |
| Exergy loss of the condenser  | 3.24   | 4.07   | 6.45   | 6.8    |
| Exergy loss of the evaporator | 2.65   | 4.11   | 3.42   | 8.24   |
| Exergy loss of the throttling element | 3.57 | 3.5    | 3.34   | 10.1   |
| The cooling capacity exergy of system | 12.19 | 19.22  | 11.04  | 24.46  |

Figure 5. Comparison of exergy efficiency between mine-water source heat pump and air-source heat pump.

It can be seen from the above analysis that, combined with air source heat pump, exergy losses of all components of the mine water source heat pump reduce. The exergy efficiency of mine-water source heat pump is more than 10% higher than that of the air source heat pump. This shows that the energy utilization rate of the mine water source heat pump is high. And the energy conservation effect of the system is obvious.

4. Electric power energy saving

On the way of energy storage, the electric power energy saving measures can be taken in the residential community due to the hot water obtained by the mine-water source heat pump adopting the industrial electricity. The hot water can be produced by using off-peak electricity in the night. This is one of the characteristics of this project. The hot water produced by mine-water source heat pump unit in the night can be stored in hot water storage tank. And in daytime, the hot water unit is stop working, and the users can be supplied hot water by the storage tank.

The hot-water unit of mine-water source heat pump produces hot water all the year round. The unit needs work 8 hours (00:00-8:00) a day to meet the requirement of hot-water load. In this way, it makes full use of off-peak electricity in the night to accumulate heat and releases heat in daytime peak hours of electricity use, thus to realize “peak load shifting” to take use of the electricity price difference to greatly reduce electric running fees. The heat produced by the heat pump unit could be great due to suing the mine water source; furthermore, the unit can run in high efficient state for a long time. According to the State Grid Henan Electric Power Company, the peak hour price and off-peak hour
price of electric power at this stage is as shown in table 3. In order to fully illustrate the energy-saving effect of the mine-water source heat pump unit, the electric cost of the unit are compared with that which is not used the off-peak electricity under the same working conditions and the same working time. The comparison results are shown in the table 4.

| Start and finish time | Electric price (yuan/kW·h) |
|-----------------------|-----------------------------|
| apex period           | 18:00-22:00                 | 1.03 |
| peak period           | 8:00-12:00                  | 0.92 |
| flat period           | 22:00-24:00                 | 0.60 |
|                       | 12:00-18:00                 |     |
| trough period         | 0:00-8:00                   | 0.32 |

Table 3. Peak and valley time-of-use electricity price of Henan province.

| Input power of the unit for hot-water (kW) | Trough period electricity | Non-trough period electricity |
|-------------------------------------------|---------------------------|-------------------------------|
| Time                                      | 00:00-8:00                | 8:00-12:00                   |
| Electric price(yuan/kW·h)                 | 0.32                      | 0.92                         |
| Daily electric cost (yuan)                | 1,298.43                  | 3,083.78                     |
| Yearly electric cost(yuan)                | 473,927.68                | 1,125,579.7                  |

Table 4. Comparison of the electric cost between the trough period and non-trough period electricity.

It can be seen from the table 4, adopting the trough period electricity to produce hot water is a very considerable energy saving measure.

5. Conclusions

The conclusions are as follows:

(1) In this paper, the abandoned mine water is taken as the water source of the heat pump system. It combines heat energy reserved in natural mine water with heat pump technology and indoor air-conditioning and heating water system to not only take full use of abandoned mine water, but also save high-grade energy of coal and electricity. Moreover, the exhaust of urban residual heat and pollutants of CO2, NOx, SOx, and dust also can be reduced. It is a kind of technical measure featured in capacity of comprehensive use of low-grade energy and environmental protection value. It is better performance in energy conservation and environmental protection and expands scope of application of water source heat pump system.

(2) Natural mine water is featured in high temperature and small change. For water source heat pump, in summer, it has lower condensing temperature; and in winter, it has higher evaporation temperature. Therefore, the COP of mine water source heat pump unit is much more efficient, steady, and of lower running cost.

(3) Compared with COP, the utilization efficiency of the mine water source heat pump system is improved. The exergy losses of all components of the heat pump system reduce and the exergy efficiency is enhanced.

The project takes use of the abandoned natural mine water as cold and heat source of the heat pump to meet the building requirements of cooling supply in summer and heating supply in winter. It needs not to set cooling tower or boiler room, saving large area of space. And meanwhile, the pollution to environment is reduced greatly. It is very good low grade renewable clean energy, not only featured in high energy utilization rate, but also in great energy conservation degree. Under the serious tendency of energy shortage and environment pollution nowadays, such form of mine-water source heat pump system is significant in both energy conservation and environmental protection.
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References
[1] L Poruschi, CL Ambrey 2016 On the confluence of city living, energy saving behaviours and direct residential energy consumption. *Environmental Science & Policy*, 66 334–343
[2] X Luo, P Song, Y Wang, W Tian, Z Gu 2016 Design of an Energy-saving Environmental Control System for Relics Preservation in Archaeology Museum. *Energy Procedia*, 104 431-436
[3] L Li, H Huang, Zh Liu, X Li, et al 2016 An energy-saving method to solve the mismatch between installed and demanded power in hydraulic press. *Journal of Cleaner Production*, 139 636-645
[4] TS Jadhav, MM Lele 2015 Theoretical energy saving analysis of air conditioning system using heat pipe heat exchanger for Indian climatic zones. *Engineering Science & Technology an International Journal*, 18(4) 669-673
[5] A Thongtha, HY Chan, P Luangjok 2017 Influence of Phase Change Material Application on Photovoltaic Panel Performance. *Key Engineering Materials*, 730563-568
[6] T Hong 2014 A New Model to Simulate Energy Performance of VRF Systems. *Microbiology*, 150(8) 2609-17
[7] J Zhen, J Lu, G Huang, H Zhang 2017 Groundwater source heat pump application in the heating system of Tibet Plateau airport. *Energy and Buildings*, 136 33-42
[8] AD Carvalho, P Moura, GC Vaz, et al. Ground source heat pumps as high efficient solutions for building space conditioning and for integration in smart grids. *Energy Conversion & Management*, 103 991-1007
[9] A Michopoulos, V Voulgari, ATsikaloudaki, et al. 2016 Evaluation of ground source heat pump systems for residential buildings in warm Mediterranean regions: the example of Cyprus. *Energy Efficiency* 9(6) 1-16
[10] GP Vasilyev, NV Peskov, VA Lichman, et al. 2015 Simulating the thermal operating conditions in the thermal wells of ground-source heat-pump heat supply systems. Part I: Porous moisture freezing processes in soil. *Thermal Engineering*, 62(8) 547-552
[11] L Schibuola, M Scarpa. 2016 Experimental analysis of the performances of a surface water source heatpump. *Energy and Buildings*, 113 182-188
[12] K Allaerts, JA Koussa, J Desmedt, R Salenbien. 2017 Improving the energy efficiency of ground-source heat pump systems in heatingdominated school buildings: a case study in Belgium. *Energy & Building* 138 559-568
[13] R Lund, U Persson. 2016 Mapping of potential heat sources for heat pumps for district heating in Denmark. *Energy*, 110 129-138
[14] L Schibuola, M Scarpa. 2016 Ground source heat pumps in high humidity soils: An experimental analysis. *Applied Thermal Engineering*, 99 80-91
[15] S Oh, Y Cho, R Yun. 2014 Raw-water source heat pump for a vertical water treatment building. *Energy and Buildings*, 68 321-328
[16] N Zhu, P Hu, W Wang, J Yu, F Lei 2015 Performance analysis of ground water-source heat pump system with improved control strategies for building retrofit *Renewable Energy* 80 324-330
[17] L Schibuola, M Scarpa 2016 Ground source heat pumps in high humidity soils: An experimental analysis *Applied Thermal Engineering* 99 80-91
[18] G Yan 2007 Design and research of sewage source heat pump system and performance improve of sewage heat exchanger *Beijing University of Technology*