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AUTOMATED DISTRIBUTED SYSTEM FOR UTILIZATION OF LOW-TEMPERATURE ENERGY OF MINE WATER AND VENTILATION AIR ON THE BASIS OF THE TECHNOLOGY OF HEAT PUMPS

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Abstract. The energy crisis and the need to reduce greenhouse gas emissions require research in the practical development of energy systems based on alternative energy sources. The article discusses the possibility of using heat pumps for heat utilization of mine water and ventilation air. Application of the large number of pumps requires automatic control of the operation parameters in order to optimize the whole system.Control issues of an individual heat pump were well reviewed by researchers in many sources. At the same time there are much less works devoted to analysis of the operation issues and control regimes of groups of heat pumps. And very small number of works is devoted to the questions of supervisory control of groups of heat pumps, which consist of heat pumps "water - water" and "air - water".The aim of the study is to validate the feasibility of using heat pumps for heat utilization of mine waters and ventilation air, and development of algorithms for supervisory control of distributed system for utilization of heat from these sources, as well as formation of optimum modes of teamwork of heat pumps, both on the surface and in the deep horizons of the mine.

In the article the classical methods of analysis parameters of the particular system at one of the mines of Kryvyi Rih Basin and methods of the modern theory of automatic supervisory control of distributed systems were used. The processes visualization techniques considering a human perception and decision-making had also been applied when creating the human-machine interface of automated distributed system for utilization of low-temperature energy of mine water and ventilation air.

Keywords. Non-conventional sources of energy, mine water, ventilation air, heat pump, microclimate in the mine, automated distributed system, SCADA.

Introduction. Nowadays much attention is paid to sources of the low-potential heat energy (LPHE). A total of more than 6,7 million heat pump units were installed since 1994 [1]. This amounts to an installed thermal capacity of nearly 224 GW. All installed heat pumps produce 120,8 TW·h of useful energy, 77,8 TW·h of which being renewable. Their use saved 99,1 TW·h of final and 47,1 TW·h of primary energy [1].

In this regard, in recent years a large number of studies and analytical materials have been published, which highlight heat pumping solutions and their potential for household and industrial usage [2–8].

One promising direction of heat pumps application is the using of low-temperature renewable energy sources of mines [9, 10]. The use of mine water for space heating or cooling purposes has been demonstrated to be feasible and economic in applications in Scotland, Canada, Norway, and the USA [11].

In mines the sources of low-potential heat energy (LPHE) areas are follows:

- a fan with the capacity of 500 m^3/sec produces $3.8 \cdot 10^8$ kJ of heat annually.
- mine drainage with the flow rate of 150 m^3/h produces up to $2.9 \cdot 10^9$ kJ heat annually.

Compressor stations, high power electric drives of hoisting facilities are also sources of LPHE.

Mines annually release this tremendous amount of heat into the atmosphere or water in the form of mine water and ventilation air. With a heat pump we can reuse this heat for heating, production of hot water/steam for industrial processes and so on. Also there are options of converting heat into the cold. Users, which are situated near the mines, can use active ventilation and air-to-water heat exchangers for obtaining a huge number of low potential heat.

Distributed systems of thermal power generation based on heat pumps require coordination of the work due to changing the flow of mine water as a source of low-potential heat energy. In addition the heat consumption (and consumption of cooling in summer) of buildings is changing, as well as consumption of hot water depending on the work of showers in domestic housing of mine. At the same time in order to avoid overspending of power it is necessary to control the amount of operating pumps and the heat output in the range 75-100% of nominal.This led to the use of SCADA system for monitoring and control of operating modes of separate heat pumps on the common system of hot water and heat supply in the cold season and cooling systems in the warm season.

Materials and Methods. The annual volume of water with the constant year-round temperature of 14-17 °C pumped out of 12 Kryvyi Rih mines is assessed to be about 12 mln m^3, its energy potential being 200 mln kWh per year. Along with the energy potential of mine ventilation air added this figure will double and can be compared with the potential of 3% of annual oil production by the PJSC Ukrnafta. These figures can be considered true if the whole potential of LPHE is used, but this is not always possible, e.g. due to lack of heat pipelines or because of the general tendency to decentralized power supply of housing objects.

Heat pumps that use low potential heat of mine waters and mine ventilation air will allow modernization of the municipal (centralized) heating of Kryvyi Rih and significant reduction of gas consumption. Then, some payback periodit is possible to greatly cut heating rates.

The feasibility study of the initial project that can be implemented in Kryvyi Rih is presented to demonstrate the above said.

In the city with the population of 655,000 people centralized heating boiler stations produce over 4200 thousand Gcal a year.

The suggested pilot project can provide heat for a mine and partly for one of Kryvyi Rih wards and produce 58008,5583 Gcal annually that makes nearly 1,4% of heat consumption of the city.

On average, when using the whole potential of low-temperature sources, it is possible to install heat pumps with total power of 13000 kW each of 12 mines of Kryvyi Rih .Half of this power can be used for mine's own needs, and the other half can go to the city's heating system. The total amount of heat from the 12 mines makes nearly 15% of the city's heat consumption. But, as heat pipeline systems of some mines are not connected with the city's heating system, it will be necessary to invest into pipeline building.

Before selecting a heat pump, it is necessary to calculate the minimum heat power necessary for certain premises and determine the possibleheat power from mine waters and air.

Calculation of required heat power is based on the information about volume of heated premises, difference between air temperature outside and required temperature inside the premises and dispersion coefficient (depends on the type of design and heat insulation of the premises). For the conditions of administration and service building of one of the Kryvyi Rih's mine the calculation gives a value 1264 kW. The production buildings of the mine's crushing section and workshops require approximately the same amount of heat power as the above mentioned administration and service building, i.e. 1264 kW. Without heat consumption for hot water supply, the total calculated power for heating will make 2528 kW. The available statistics shows that the heat power for hot water supply is approximately equal to the power required for heating – 2600 kW. The total calculated heat power for hot water supply and heating will consequently equal 5128 kW.

In 2013 the mine's boiler station consumed 6361,95 thousand m^3 of gas, i.e. the necessary amount of heat made 51213,7 Gcal (gas caloricity of 8,05 Gcal/1000 m^3 was taken as the basis for the calculations). To fully refuse gas consumption for the mine it is necessary to install heat pumps with total power of 5846312,785 kcal·h (6798,04 kW).

The divergence of over 1500 kW of the required heat power testifies unpractical use of heat at the mine (bad heat insulation of buildings, heat pipeline system, low boiler station efficiency, etc.).

The next step is to determine the possible heat power from mine waters and air and select heat pumps.Heat pump power is determined from the mine water volume consumption:

$$Q_{t(water)} = L_{(w)} \cdot p_{(w)} \cdot c_{v(w)} \cdot \Delta t_{(w)}, \qquad (1)$$

where $L_{(w)}$ – water volume consumption, m^3/h; $c_{v(w)}$ – the specific heat of water, kW·h/kg K; $p_{(w)}$– water density, kg/m^3; $\Delta t_{(w)}$– difference between intake and returned water temperature, K. For the conditions of considered mine the calculation gives a value 3923 kW.

Air heat pump power is determined from volume consumption of mine ventilation air:

$$Q_{t(air)} = L_{(a)} \cdot p_{(a)} \cdot c_{v(a)} \cdot \Delta t_{(a)}, \quad (2)$$

where $L_{(a)}$ –air volume consumption, m^3/h; $c_{v(a)}$– specific heat of air, kW·h/kg K; $p_{(a)}$– air density, kg/m^3; $\Delta t_{(a)}$– intake and returned air temperature difference, 12K. For the conditions of considered mine the calculation gives a value 4700 kW.

This power is utilized by heat pumps in ventilation shafts. Considering the fact that a heat pump is also placed in the cage shaft where air is intaken, the utilized power can double and then the total amount of power utilized by water and air pumps will make 13322,594 kW.

At the stage of a pilot project it is only reasonable to use part of the great amount of possible power to be obtained from ventilation flows, i.e. to install 2 heat pumps of 1000 kW each in a cage shaft airflow: one 400 kW pump – at the ventilation station 'Severnaya' (Northern) and one 1000 kW pump – at the ventilation station 'Flangovaya' (Flank). This is because of the fact that the ventilation stations are located far from the mine's infrastructure and heat energy use requires building pipelines for heat transfer.

The ventilation station 'Flangovaya' is located near a large greenhouse that is a potential heat consumer. Besides, the station is about a hundred meters away from the ward boiler station 'Leninskaya' and in the future, by arrangement with the city heating plant, the mine can sell heat to the city. Three heat pumps of 1000 kW (or 6 of 500 kW) each can be installed to utilize mine waters energy. At that, the total power of water and ventilation air heat pumps will make 6400 kW.

Calculations show that needs for heat power for heating the mine's surface buildings and supplying hot water can be satisfied in full measure. The potential of using LPHE is almost twice as big and can be realized after installing additional pumps. In case of building additional pipelines within the city heating system, bigger part of the power from LPHE sources can go for heating residential buildings or other objects within the service area of the boiler station 'Leninskaya' of the city's centralized heat supply system.

To satisfy needs for heating of the mine's buildings and neighboring buildings of the 'Leninskaya' boiler station service area, twelve 500 kW heat pumps and one 400 kW pump are installed. Territorial arrangement on sites with mine water and ventilation air carriers is made as mentioned above (see Fig. 1).

For realization of the described system can be used WaterkotteDSheat pumps (Germany), that are the most powerful on our market [12]. They are mostly used in powerful heating systems – for public buildings, shopping malls or large industrial premises. Pumps of these series are easily serviceable, operationally and environmentally safe, powerful and economical. The standard features and options, such as water heating system (a vertical accumulative tank on the heating side, a water heater, a temperature sensor, a three-way valve), the remote control, the software for visualization, the software for telemechanical devices, the sensor in the control premises, natural cooling ensure controlling the system conveniently.

It is also advisable pay attention to the products OilonChillHeat [13]. The range of their application is expanded through numerous options to adapt the same product for different applications. Modules for system extension structurally identical and allow you to add groups of pumps and valves to the base unit.

To ensure the effective functioning of described complex of equipment it is expedient to implement an automated process control system of utilization of low-temperature energy of mine water and ventilation air. Given the territorial distribution of control objects the system should be decentralized and realized on the basis of appropriate hardware. As shown in Fig. 1, the local PLCs are used for control the heat pumps installed on central cage station, ventilation stations 'Severnaya' and 'Flangovaya'. Information from local controllers is transferred to the controller hub, which solves the problem of optimizing control of the entire complex of equipment for heat power generation, depending on the current needs of the enterprise in heat energy.

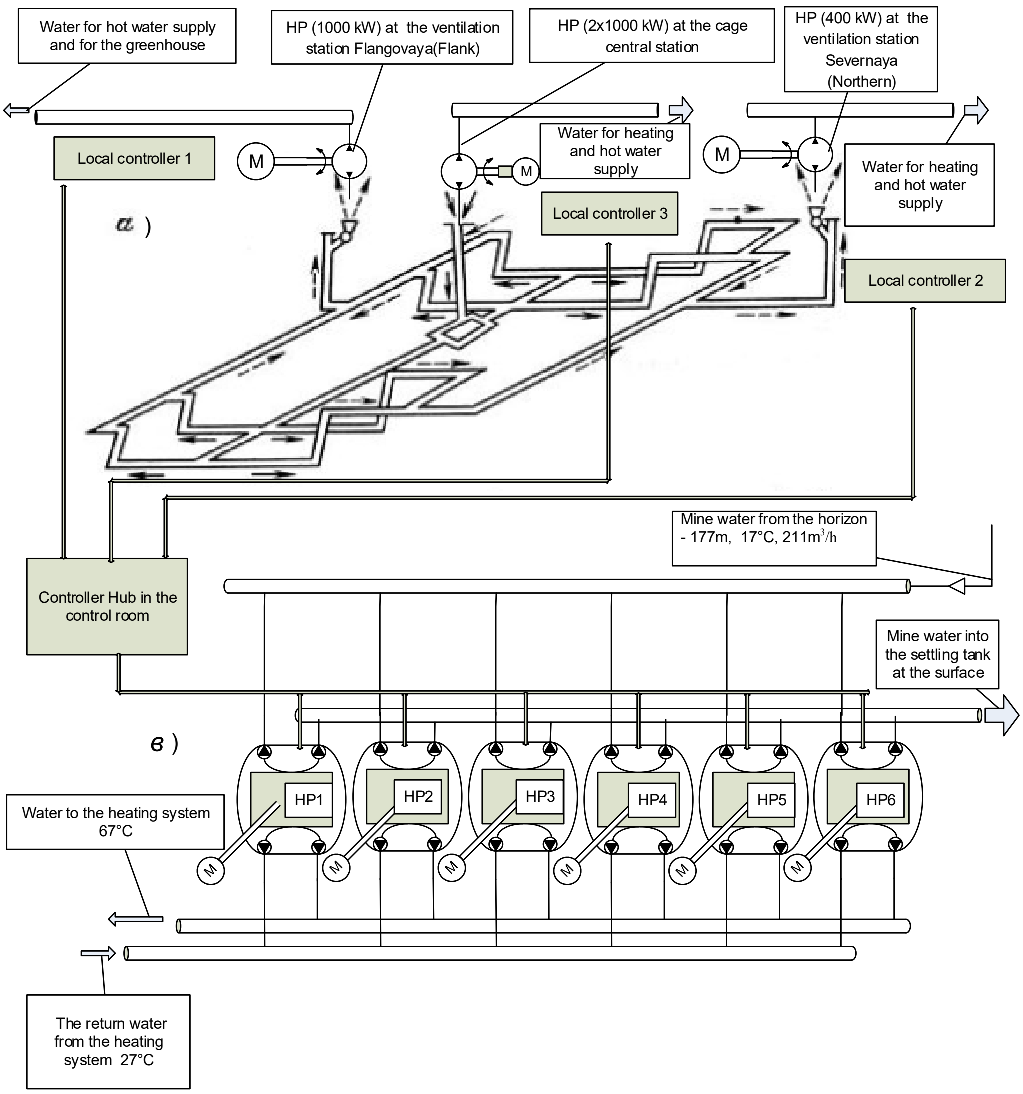

Figure 1.The diagram of installing heat pumps at an iron ore mine
a) air-water heat pumps in the mine's ventilation shafts;
b) water-water heat pumps in the mine's water pumping system.

The diagram does not show heat pumps that are installed at elevations below 1000 m in the mine and intended for local cooling of the ventilation air, which may have a temperature in this zone above 300 °C. These pumps are also included in the total distributed system for utilization of low-temperature energy and climate control in the mine.

In addition to the main heating system the project envisages the following solutions for heating and cooling buildings:

- water heating system (which includes: a vertical storage tank on the side of the heating, water heater, temperature sensor, three-way valve);
- remote control (external terminal);
- visualization software (PC connection to the RS 232);
- software for telemechanical devices (telephone modem, software with access protection);
- sensors in the control premises;
- supervisory control of the amount and mode of operation of the heat pumps of all complex for utilization of low-temperature energy of mine water and ventilation air.

Control of heating system is carried out using the latest generation of microcontroller. With a few sensors, located in the heat pump circuit, the constant diagnostics of the contour is carried, so that the abnormal operating condition is detected in advance and the message about this situation is sent before the system fails. All tasks related to control (depending on the outside temperature with the control of control room), supervision and self-testing are performed. The system provides for the retention of data in the event of failure, etc. through the RS-485 interface for external terminal and RS 232 for remote control system, for example, using a telephone modem (for remote heat pump of mines ventilation system).

To solve the problems of optimal control of processes of utilization of low-temperature energy of mine water and ventilation air, the automation system consists of sensors for measuring evaporation pressure and condensation pressure, as well as sensors for measuring temperature in all contours, outside temperature, temperature in the control room and temperature of technical water. Adjusting the power of each pump separately is available either in a stepwise manner at two positions (75/100%) or smoothly, given that motors of compressors will be equipped by frequency converters .When you adjust power the limit of the operating range on the side of the heating can be reduced by 10 K.

Automation ensures energy efficiency and achieving maximum of coefficient of efficiency, optimization separate or combined production of heat and cold.

To ensure a reliable and versatile communication between different systems, hardware base of automation system must be selected for the conditions of maintaining the format of most common field buses (Modbus, Profibus, Profinet, Ethernet). Interfaces of field buses offer great opportunities for remote control, programming and acquisition of technological data, as well as provide a versatile reporting and high-quality monitoring of the processes dynamics.

The remote controlling and programming ensures reliable operation, reduces the cost of maintenance and support as well as facilitates subsequent modification of complex.

The whole set of equipment required for the processing of mine water and air streams, presents a distributed system that performs a common task of heating premises of the mine and hot water supply of domestic premises. Due to the fact that the flow of mine water is unstable, as well as the ambient temperature is changed, there arises the problem of adapting to these conditions. This problem lies in the discrete control of the amount of operating heat pumps, as well as in the smooth regulation of the generated thermal capacity of each machine. The reason is that heat pumps are limited in the control range without loss of efficiency. Similar problems are solved at different stages of the ore extraction and its processing [7, 13–15]. The most appropriate control system for this complex is a SCADA (supervisory control and data acquisition) system with displaying models of processes of the complex on a screen of the operator's station.

To solve the problem of optimal control of the process of generation and utilization of low-temperature energy of mine water and ventilation air is necessary to obtain an adequate mathematical model of the process. To do this, on the first stage of work is necessary to have tools to collect data about the functioning the system in different modes. From this point of view, the SCADA system is also the best solution.

For this purposes work is underway on develop a system of supervisory control and data acquisition, which will display the status of the process equipment and the values of regime parameters of heat pumps, as well as collect data for further analysis.

Fig. 2 shows one page of developed SCADA for visualization of the state of the heat pump for the utilization of low-temperature energy of mine water (air). The system displays values of the temperature of the heat pump, the evaporation pressure and the condensation pressure, the electric power consumed by the compressor, heat power generated by the heat pump, the state of the equipment (pumps, compressors, valves, tank).

Results. The pilot project implementation effect:

- reduction of gas consumption due to operation of heat pumps on 6000 thousand m^3 a year (at the cost of gas of 4,02 UAH/m^3 the annual amount for gas consumption at a boiler station will make UAH 24,12 mln or 1,5075 mln EUR);
- reduction of atmospheric emissions by over 100 t/year;
- reduction of thermal pollution of the atmosphere by over 20 thousand Gcal/year.

Figure 2. Visualization of the state of the heat pump for the utilization of low-temperature energy of mine water

The amount of financing (the project and implementation) will make about 1810 thousand EUR. Taking into account electric power costs increase (982094 EUR in a year), the annual effect from implementation of the project will amount over 427906 EUR.The payback period of the project is 4 years and 3 months.

Conclusion. The results of the development of initial materials for the conceptual design of the automated distributed system for utilization of low-temperature energy of mine water and ventilation air on the basis of the technology of heat pumps for hot water supplying of mining premises on the surface and improving the microclimate of working area miners in deep horizons of mines are presented.

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