Improving a water treatment and a heating performance of the water-to-water heat pump: misallocation and available solutions

L. R. Junussova 1, S. V. Chicherin 2

1 Non-profit JSC Almaty University of Power Engineering and Telecommunications, Almaty, Kazakhstan.
2 Omsk State Transport University (OSTU), Omsk, Russia
man_csv@hotmail.com

The object of our experimental investigation is a heat pump system operating at low temperatures of a low-grade heat source. The purpose of experimental research of the heat pump installation is to increase the efficiency and reliability of heat pump unit by adjusting compressor performance. To carry out the experiment we connected the reciprocating compressor with Variable Frequency Drive of AC 0..650 Hz, designed for rated capacity of 2.2 kW, as well as electricity meter. The dependence of heat load of pump condenser on the speed (rpm) is approximated by the formula and will be used to design a heat pump unit. The proposed experimental unit allowed us to determine the correlation between basic characteristics and the compressor shaft speed and determine the possible range of its regulation (50..180%). The obtained results allow us to design the water treatment plant with using heat pump unit with quality regulation systems as well.

Introduction

The most important objectives of current development of power engineering sector in the country is the increase of thermal and economic efficiency, reliability and sustainability of power engineering complex. A special place in the solution of these objectives is assigned to further development of district heating plants and distribution systems [1, 2].

One of the most effective ways of the development of heat supply sources and systems is the use of combined heat supply systems based on large and small heat power and boiler plants, matching the operation of traditional sources of heat and renewable energy sources for heat pumps, as well as autonomous power supply systems based on heat pump systems [3].

The recent research revealed the possibilities for further improving compressor characteristics by providing smooth control of their efficiency [4], improving reliability [5], reducing noise and energy consumption [6-8], as well as decreasing cost, weight and size [9]. Promising methods of regulating thermal power of air conditioning in the heat pump were proposed. The possibilities of using scroll compressors were analyzed [10]. The objectives of coordination of the evaporator and compressor

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operation by applying auxiliary gas cooler for simultaneous production of heat and cold by means of a heat pump were considered in our research [11, 12].

Heat pumps are used as converters of heat energy from an energy source with low temperature [13] to an energy source with higher temperature. As it follows from the description of the processes in heat pumps, its main elements are a compressor, condenser, evaporator and throttle (regulation valve) connected by a piping system for circulation of a working fluid. The combination of a heat pump and auxiliary equipment such as hydraulic machines, pipelines for supply and removal of transfer fluids (cooled and heated), power supply, control and regulation systems is a heat pump unit.

Consequently, the object of our experimental investigation is a heat pump system, operating at low temperatures of a low-grade heat source. The purpose of experimental research of the heat pump installation is to increase the efficiency and reliability of heat pump unit by adjusting compressor performance.

Materials and methods

A heat pump system with water as the lower source is proposed as the most effective one from the point of view of running costs for heating. The following conditions should be completed for this:

- water should have an appropriate quality, in terms of chemical composition - it should not cause corrosion of the evaporator of heat pump; it is necessary to obtain reliable results of its chemical and biological analysis;
- water should not contain mechanical impurities, which can increase the flow hydraulic resistance through the evaporator;
- water temperature should not be below 7°C [13];
- encroachment line should be closed to avoid the contact with air.

Ground water containing a lot of iron is used most of all as a low-grade heat source for heat pumps. When contacting with oxygen, iron comes down in the water resulting in mineral deposits in the pipes and heat pump evaporator, which increases the flow hydraulic resistance. The increase of hydrodynamic resistance of the system reduces the efficiency of a transporting pump and, consequently, leads to malfunction of the heat pump. Ground water undergoes preliminary cleaning in an ultrafiltration module before going into the evaporator of the heat pump, according to the scheme presented in fig. 1 [11, 12].

![Fig. 1 Technological bloc-diagram of the water treatment plants (WTP)](image)

We perform all experiments on a verification and calibration test bench in the flow laboratory of Almaty University of Power Engineering and Telecommunications, Kazakhstan using plastic pipes of inner diameter D = 5.0 mm (DN5) and D = 10.0 mm (DN10). Preliminary water softening is done in the ultrafiltration unit (fig. 1, UFP). Setup of the experiment is in fig. 2.

The plate pack is assembled between a fix frame plate and a movable pressure plate and compressed by tightening bolts. The plates are installed with a gasket which seals the inter plate channel and directs the fluids into alternate channels. Table 1 shows the testing conditions.
Table 1. Data about the setup and the elements

| Outline of the test site                                      | UFP |
|--------------------------------------------------------------|-----|
| Water flow rate (litre per hour)                             | 100 |
| Number of cells                                              | 6   |
| Machine mass, including a valve assembly filled with water   | 35  |
| Dimension XxYxZ (millimeter)                                 | 330x330x450 |
| Pump power (kW)                                               | 0.5-2.5 |

To adjust the Total Dissolved Substances (TDS) setup was used and pH was controlled (Table 2).

Table 2. Chemical composition of the test solution

| Test solution          | Pure water characteristics (grams per litre) | Softened water characteristics (grams per litre) |
|------------------------|-----------------------------------------------|--------------------------------------------------|
|                        | TDS (grams per litre) | t (°C) | pH | TDS (grams per litre) | t (°C) | pH |
| Underground water      | 11.64 | 20 | 8.5..9.5 | 0.77 | 22 | 8.5..9.5 |

Prior to the testing, the solution was deaerated by purging ions (92..99%) for 2 h, because the underground water system is block with the outside, i.e., the closed system, so that the dissolved solids are very low. The unit for water pre-treatment at the ultrafiltration module allows the heat pump to operate with higher performance. When using clarified water heat pump equipment capital costs are reduced. One can get simultaneously higher quality of purified water. The ultrafiltration module can effectively collect suspended substances and the smallest particles of colloidal iron, due to the size of membrane pores 30..1000 Å. The particles up to 0.005E-06 m are removed at operating pressure of 0.2..1.0 MPa. A compressor is the most important and most expensive part of a heat pump. A heat pump ensures the thermodynamic cycle implementation and consumes a basic amount of electricity. It is impossible to achieve significant gains in efficiency and reliability of heat pumps without updating them. As for refrigerants hydrocarbons are today considered as promising alternatives to hydrofluorocarbons [10]. The reduction of pump noise impact is of great importance for consumers.

The most common type of compressor is currently the reciprocating one and its performance is studied thoroughly [9]. In recent years, the studies have identified the opportunities for further
improving the characteristics of reciprocating compressors by providing smooth control of performance, enhancing reliability, reducing noise and energy consumption, weight and size, as well as cost. Other types of compressors were not studied well, and from this point of view, the question of improvement of their energy characteristics is important nowadays. An exergy analysis of vapor compression heat pumps with reciprocating compressors also shows that the largest exergy losses occur in the compressor (about 20% of the exergy supplied to the pump) [6-8].

Capacity control of compressors is most often done systematically by periodic starting and stopping [5]. However, this leads to the reduction of their service lifetime and does not permit to use fully the energy saving potential of a heat pump because of operation in off-design transient conditions.

Compressor operation depends on the mode of operation of a heat pump system. Capacity control of heat pumps can be done by reducing pressure at the compressor exit or by reducing throttle passage section or bypass of a working fluid. At present, the most progressive method of compressor capacity control is the change of speed of shaft rotation by means of electronic microprocessor device [4], so called Variable Frequency Drive (VFD). Such regulation ensures heat pump operation in design mode and reduces the number of starts of the compressor to a minimum. We have conducted an experimental study of energy characteristics of a heat pump water-water using a VFD for regulating the compressor efficiency.

To carry out the experiment we connected the reciprocating compressor with VFD “Siemens micromaster 420” of AC in range of 0 to 650 Hz, designed for rated capacity of 2.2 kW, as well as electricity meter BFM 136, according to the schematic circuit in fig. 3.

Fig. 3 Schematic circuit of the water source heat pump: CP – compressor; FC – frequency converter (VFD); K – condenser; Tr – throttle valve; E – evaporator; W – electricity meter

The energy efficiency of the heat pump is characterized by Coefficient of Performance (COP):

\[
COP = \frac{Q_a}{N_{cp}},
\]

with \( Q_a \) – produced heat; \( N_{cp} \) – used electricity.

The compression ratio is determined by eq. 2:

\[
\pi_x = \frac{p_x}{p_u},
\]

with \( p_x \) - refrigerant vapor pressure at the compressor exit; \( p_u \) - vapor pressure at the evaporator exit.
The dependence of COP on compression degree of the compressor is obtained by processing the experimental data in Microsoft Office Excel by means of Scatter Chart, and adding a polynomial trendline of order 2 using the least square method [14].

Case study, results and discussions

The results of experimental research of quality indicators of softened water are shown in fig. 4, 5.

The ground water after preliminary treatment in the ultrafiltration unit by means of centrifugal pump is supplied to the evaporator of the heat pump.

![Fig. 4 Volume (m$^3$) profiles within a filtration cycle](image)

![Fig. 5 Efficiency of opposite of TDS](image)

![Fig. 6 COP in function of a speed (rpm)](image)

Measured energy characteristics of a circular process in the heat pump unit allowed determining the energy performance parameters presented in the graphs (fig. 6..9). The dependence of COP on the speed (rpm) showing effective values of COP 5.55..7.23 with speed in the range of 1400 to 2150 rpm is drawn in fig. 6 based on the results of the experiments.

Optimal values of compressor electromechanical $\eta_{em}$ and internal efficiency $\eta_i = f(n)$ (fig. 7) correspond to the interval of variation of speed in the range of 1400 to 2150 rpm, which is determined by the intersection of curves $\eta_{em}$=$f(n)$ and $\eta_i = f(n)$, which corresponds to $\eta_{em} = \eta_i$=0,95.
Thermal energy is transferred to the building from heat pump condenser because of condensation of a working fluid or refrigerant through heat exchange between the refrigerant and heat conductor of the heat consumer. In this case, while condensing some vapor of the refrigerant (R22) gives off heat to cold air of the room. Heated air is supplied into the condenser cavity by a fan. Fig. 8 shows the influence of changing the speed (rpm) drive on the heat capacity supply of the heat pump.

The decrease of refrigerant compression degree of the compressor $\pi_k$ by an average 1.3 times leads to the increase of COP by 1.6, and on the contrary, to the decrease of electrical capacity of the compressor needed to drive it. Fig. 9 shows the dependence of COP on compression ratio $\pi_k$. The dependence of COP on compression degree of the compressor shown in fig. 9.

Conclusions
The value of pump COP obtained during the experiment and the value determined by calculation conform to each other within experimental errors with the regulation of compressor capacity. The
dependence of heat load of pump condenser on the speed (rpm) is approximated by the formula and will be used to design a heat pump unit.

The proposed experimental unit allowed us to determine the correlation between basic characteristics and the compressor shaft speed (rpm) and determine the possible range of its regulation (50..180%). The obtained results allow us to design the water treatment plant with using heat pump unit with quality regulation systems as well. The results will also provide the deeper control of power and temperature regimes, better matching the changing parameters of heat supply systems and the environment, as well as high efficiency in operation.

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