Experimental investigation of the refrigeration cycle of water-to-water heat pump

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Abstract. The refrigeration cycle of a reversible water-to-water heat pump has been investigated at different operation parameters of a laboratory installation. The investigation has been accomplished in cooling working conditions. The real operation cycles of the pump have been plotted in "logp-h" diagram by determination of definite thermodynamic parameters of the refrigerant. For this purpose, COOL PACK software has been used. The investigated refrigeration cycles are characterized by different switch off temperature of the heat pump. Based on the obtained results, the following parameters characterizing the heat pump’s efficiency have been determined: specific heat of vaporization, specific compression work, specific heat of condensation, and coefficient of performance.

1. Introduction
Nowadays, due to the energy and environmental crisis, the use of renewable energy requires reduction of the environmental pollution. The increasing environmental pollution and its influence on people’s lives has led to design of systems that are environment-friendly as well as paying attention to energy consumption. One of these systems, which is environment-friendly and low energy consumption, is the heat pump system [1].

Currently, renewable energy resources are becoming alternative options due to their special advantages; especially biomass and geothermal energy require attention in the worldwide for their abundant and widely distributed features [2,3].

In the context of sustainable development, the use of underground water source heat pump air conditioning system is a major feature of nowadays air conditioning applications. The energy saving effect of the ground water heat pump air conditioning installations is obvious, and this type of systems have the advantages of small environmental pollution, cover the requirements of cooling and heating, require low investment and operation cost, simple operation of the system and high water temperature. As well they are with high operating stability, and that is a new developing area in the environmental protection field [4].

Through the heat pump technology, natural low-grade energy stored in the soil, water, air or waste heat energy from industries and daily lives, is supplied for building of cooling/heating and hot water serving [5].

As presented in study [6], heat pumps are also applied in systems of greenhouses cooling. Greenhouse cooling systems are with three different types of heat pumps: air source-air supply, water source-air supply and water source-water supply types, are assessed by hourly calculations related to a
simple heat balance model. Nowadays, heat pumps are used worldwide in various applications, both commercial and residential buildings, or in industrial applications. On the other hand, on the market can be found units from small size (3-5 kW) up to large size (>200 kW) [7,8,9].

One of the important parameters for cooling systems is the type of refrigerant. Principally, refrigerants used in cooling systems damage the atmosphere and cause global warming. For these purpose, alternative refrigerants which are not harmful to the environment and atmosphere must be used [10].

Different protocols and regulations lead to using refrigerants with both zero Ozone Depletion Potential and low Global Warming Potential. These new limitations cause the progressive phase-out of HFC and to their replacement by the 4th generation of refrigerants based on HFO mixtures. Alternative refrigerants with low Global Warming Potential are in development process for residential heat pumps, air-conditioners and heat pump water heaters, since R410A, R407C and R134a have Global Warming Potential of 2088, 1650 and 1430, respectively [11].

In study [12] a novel cycle is regulated by the average density, is investigated based on cycle simulation. The used refrigerants are: pseudo azeotropic mixture R410A and zeotropic mixture R407C.

The ever-increasing energy consumption of buildings has caused a great interest in improving the seasonal characteristics of heat pumps [13,14].

The aim of the research is to investigate experimentally the refrigeration cycle of a water-to-water heat pump installation.

2. Methodology

2.1. Laboratory installation
The investigation has been realized by a laboratory heat pump installation of water-to-water type, presented in figure 1.

![Figure 1. Principal scheme of the laboratory installation.](image)

In the cooling regime of the system, the working of the heat pump is regulated with set of shutting down temperature of the heat pump. This is the temperature of the water coming from the heat consumer and entering the evaporator of the heat pump.

In order to ensure a constant temperature of the fluid coming from the buffer into the heat pump, the conditions for stratification in the buffer are met.

The heat pump is reversible, which allows to be studied in summer and winter modes. Water buffer is used as the heat source. The heat consumer is a two-stage water-to-air heat exchanger.
2.2. Building of the refrigeration heat pump cycle
The refrigeration cycle is built on the basis of measured temperatures and pressures of the refrigerant in the laboratory system in figure 1. Figure 2 presents the theoretical refrigeration cycle of heat pump in "log-p-h" diagram.

![Figure 2. Theoretical heat pump cycle.](image)

The vaporization pressure is $p_0$ and the pressure of condensation is $p_c$.

The processes building the refrigeration cycle are:

1-1’ – process of preheating of the vapours at constant pressure;
1’-2 – adiabatic process of vapours compression;
2-2’ – process of vapours cooling;
2’-3 – process of condensation at constant pressure and at constant temperature;
3-3’ – precooling process of the liquid at constant pressure;
3’-4 – throttling process at constant enthalpy;
4-1 – process of vaporisation at constant pressure and at constant temperature.

2.3. Determination of the heat pump parameters
The parameters determining the efficiency of the heat pump can be calculated by equation 1÷4. The reported enthalpy values at the respective intersection points in the cycle are used (figure 2).

The specific heat of the vaporization process is estimated by the equation:

$$q_0 = h_1 - h_4$$  

The equation for the specific compression work is:

$$l_a = h_2 - h_1'$$  

The specific heat of condensation process is calculated by:

$$q_c = h_2 - h_3$$

The equation for the coefficient of performance is:

$$COP = \frac{q_0}{l_a}$$

3. Results
Table 1 presents the values of the parameter for setting up the heat pump ($I_{\text{heat pump shutdown}}$), as well as the measured parameters ($I_{\text{f}}$, $p_c$), on the basis of which the refrigeration cycles are built. The investigated regimes are characterized by a different setting of the shutdown temperature of the heat pump.
Table 1. Setting up the heat pump and values of measured parameters.

| Regime   | $t_{\text{heat pump shutdown}}$ $^\circ\text{C}$ | $t_{1'}$ $^\circ\text{C}$ | $t_{2'}$ $^\circ\text{C}$ | $t_{3'}$ $^\circ\text{C}$ | $t_{4'}$ $^\circ\text{C}$ | $p_0$ bar | $p_c$ bar |
|----------|-----------------------------------------------|----------------------------|---------------------------|---------------------------|---------------------------|-----------|-----------|
| Regime A | 12.5                                          | 10.8                      | 71.0                      | 34.4                      | -0.6                      | 4.76      | 15.21     |
| Regime B | 14.0                                          | 11.7                      | 69.9                      | 34.7                      | 0.3                       | 4.92      | 15.30     |
| Regime C | 15.5                                          | 12.4                      | 68.4                      | 34.8                      | 1.4                       | 5.29      | 15.40     |
| Regime D | 17.0                                          | 13.2                      | 66.9                      | 34.8                      | 2.6                       | 5.44      | 15.40     |

The setting of the heat pump is according to the temperature of the water returning from the heat exchanger, at which temperature the heat pump is getting switched off. The presented values of the measured temperatures and pressures refer to the moment of switching off the heat pump.

Figure 3 presents the variation of the measured temperatures over time during the operation of the heat pump in Regime A. Temperatures values are measured at intervals of 1 s.

The presented graphical dependences for the alteration of the temperatures measured in the cycle cover the period of operation of the heat pump in the respective regimes. The measured temperatures in table 1 represent the endpoints of the graphical dependences.

Figure 4 presents the refrigeration cycles built in the "logp-h" diagram in the studied regimes. The cycles are built on the base of the temperatures and pressures measured at the time of shutting down the heat pump (table 1).

Since the refrigerator R407C is a zeotropic mixture, the isotherms in "logp-h" diagram have a slope, i.e. they are not parallel to the isobars. As shown in the diagram, the evaporation of the refrigerant at constant pressure, proceeds with an increase in the temperature while the process of condensation at constant pressure - with a decrease in the temperature.

The heat pump switch off temperature increases, and the curve of refrigeration cycle shifts upwards in the diagram. The relatively higher change in the evaporation pressure compared to the condensation pressure is because of the temperature range of the refrigerant evaporation is controlled by the respective setting of the switch off temperature of the heat pump.

Table 2 presents the enthalpy values of the specific enthalpy taken from the diagram at the respective intersection points in the cycle, and the calculated parameters presenting the efficiency of the heat pump.
Figure 4. Refrigeration cycles of heat pump in "logp-h" diagram.

Table 2. Specific enthalpies taken from the software, and calculated heat pump efficiency parameters.

| Regime  | $h_1$  | $h_1'$ | $h_2$  | $h_3$  | $h_4$  | $q_0$  | $l_a$  | $q_c$  | COP  |
|---------|--------|--------|--------|--------|--------|--------|--------|--------|------|
| A       | 414.54 | 422.15 | 464.35 | 244.73 | 254.74 | 159.80 | 42.20  | 219.62 | 3.79 |
| B       | 415.27 | 422.75 | 463.01 | 245.21 | 255.10 | 160.17 | 40.26  | 217.80 | 3.98 |
| C       | 416.23 | 422.69 | 461.37 | 245.42 | 255.59 | 160.64 | 38.68  | 215.95 | 4.15 |
| D       | 416.71 | 423.11 | 459.76 | 245.42 | 255.59 | 161.12 | 36.65  | 214.34 | 4.40 |

From the data observed from figure 4 and table 2 follows that with increase of the shutdown temperature, the increase of the coefficient of performance is due to the increase of the specific heat of vaporization, and the decrease of the specific compression work on the other hand.

The application of the results obtained in this study for real installations must be in accordance with the specific features of these installations, the temperature of the heat source and the temperature in the cooled buildings.

4. Conclusions

The refrigeration cycle of a reversible water-to-water heat pump is built at the end of four different regimes of operation of the laboratory installation, according to the presented methodology. The operation regimes have been realized at different settings of the heat pump.

The variation of the temperatures in time, used for building the refrigeration cycle in the respective periods of operation of the heat pump, has been studied.

According to the presented methodology the following parameters related to the efficiency of the heat pump, have been calculated: specific heat of vaporization, specific compression work, specific heat of condensation and coefficient of performance.

The vaporization and condensation processes in the refrigeration cycle have been realized with a change in temperature, since the refrigerant is a zeotropic mixture and the individual fractions in its composition have different temperature of change of the physical state, at constant pressure.

It has been found that when regulating the switch off temperature of the heat pump, the vaporization pressure changes significantly more compared to the condensation pressure.
It can be concluded that with the increase of the heat pump switch off temperature, the refrigeration cycle shifts upwards in the "logp-h" diagram.

Last but not least, based on the results can be generalized that with increasing the shutdown temperature of the heat pump, the efficiency of its operation increases.

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