Energy efficiency of ground heat exchangers co-operating with a compressor heat pump

Sławomir Kurpaska, Hubert Latała

University of Agriculture in Kraków, Institute of Agricultural Engineering and Computer Science,
University of Agriculture in Kraków, Poland Balicka 116B, 30-149 Krakow, Poland

Summary. The work presents results of an analysis of the coefficient of performance of a heat pump co-operating with ground heat exchangers. Three types of exchangers were examined: horizontal, vertical- made at the depth of 20 m (type I) and at the depth of 100 m (type II). It was proved that the highest value of the coefficient of performance (the COP) occurs for vertical exchangers (type I), slightly lower for horizontal exchangers and the lowest for vertical exchangers (type II). The statistical analysis, which was carried out, proved that the type of an exchanger significantly influences the value of the coefficient of performance; its average values are also statistically significant. Significance of the influence of temperature inside a facility on the value of the coefficient of performance was not proved.

K e y   w o r d s : compressor heat pump, vertical, horizontal ground heat exchanger.

INTRODUCTION

Constant search for methods of reducing energy outlays and alternative and more effective heat sources in technological processes and heating of facilities results from increased costs of obtaining heat from traditional carriers and from the care for the natural environment. Such activities are also influenced by policy of the European Community countries, which stimulates the use of renewable sources of energy. One of the methods of realization of this purpose is a heat pump, which co-operates with ground heat exchangers. Issues concerning the analysis of the effectiveness of the system, in which heat pumps are used, were the subject of the research in many scientific centres. Thus, [13] analysed operation effectiveness of the heat pump co-operating with vertical ground heat exchangers located in vertical poles, which constitute a foundation of housing estates. As a result of the research which they carried out, they determined usefulness of such a construction, they calculated a temporal and seasonal coefficient of energy efficiency of the system (calculated by means of the relation of the obtained thermal power with the supplied electric power). Kim et al. [4] presented a work containing results of the researched compressor heat pumps varied according to thermal efficiency and the applied thermal-dynamic factor. Air, water and soil were used as a lower heat source. In the constructed models, they included particular cycles of thermal-dynamic transformation of the circulation factor. On the basis of the tests which they carried out, they determined a percentage share of particular electric energy receivers (a compressor, a circulating pump) in shaping the value of the coefficient of energy efficiency of the system. Congedo et al. [1] using the CFD technology analysed the thermal issues in the ground, in which the ground heat exchangers co-operating with the heat pump were installed. As a result of the simulation which was carried out, influence of depth, ground conductivity and the flow speed of the circulation factor on the amount of heat obtained by the exchangers located in a flat and loop arrangement were determined. Temperature of ground at random depth and in random time was described by an equation of heat conductivity at the assumed periodical change of temperature of its outer layer. It was found that from among the analysed independent variables moisture of the ground influences the amount of the obtained heat the most, whereas from among the researched geometrical arrangements the loop system is recommended. Yang et al. [14] carried out a review of models used for describing phenomena occurring in the ground with the vertical heat exchangers. They concluded that there is a need to verify these models and the issues related to underwater flow which influence a change of central temperature should be added. Florides and Kalogiro S. [2] presented construction solutions of the ground heat exchangers and they characterised mathematical models used to describe phenomena in the ground. As a result of the analysis which they carried out, they stated that thermal-physical

properties of the ground centre influences the amount of the heat taken up by the ground exchangers whereas, span and spatial sitting of exchangers and thermal conductivity of the ground are decisive factors in the vertical exchanger. Partenay et al. [10] worked out a mathematical model of phenomena, which take place in the flowing circulation factor in the vertical ground exchangers. The compiled model was resolved with a numeric method (of definite elements) while a change of ground temperature during operation of the heat pump was the analysed issue. On the basis of the experimental tests which were carried out (a system of six vertical heat exchangers), correctness of this model was reported and a relation of the heat pump operation efficiency to temperature in the heat exchangers of the system (a steamer, a condenser) were found. Lee and Lam [6] carried out a computer simulation for the system composed of vertical exchangers co-operating with the heat pump. In the isolated space of the ground, relations of heat exchange with loops of particular meshes were worked out (with the method of definite differences). As a result of the analysis, they determined a periodical variability of the ground temperature as well as the value of the coefficient of heat transfer for the ground heat exchangers. Trillat et al. [12] presented results of experimental research in which the heat pump co-operated with solar collectors forming the so-called hybrid system. Energy effects of such a system along with its energy efficiency (the coefficient of performance) and calorific effect of the ground exchangers were determined whereas the authors recommended the considered system for heating facilities. On the basis of a long-term research, Huang and Lee [3] determined the consumption of electric energy used for driving a heat pump. Calculations were carried out in relation to a unitary growth of temperature of liquid stored in the buffer tanks of the heat pump. Ozgener and Hepbasli [9] analysed energy issues and financial outlays incurred on the use of the heat pump (co-operating with the vertical ground heat exchangers) for heating purposes. The authors worked out a simulation model, which may be used for an analysis of financial inputs at using the heat pump for heating facilities. Ozgener and Hepbasli [9] presented results of experimental research on using a heat pump for heating a greenhouse. They described thermal efficiency of vertical ground heat exchangers and temperature of air inside a greenhouse at supplying heat only from a heat pump. They also determined values of the coefficient of work efficiency of the system divided into days of various weather conditions. Ozgener and Hepbasli [7, 8] in the experimental research determined the work efficiency of the heat pump with the vertical heat exchangers used for heating a greenhouse. Moreover, they determined a value of the coefficient of work efficiency of the system (the COP), which they related with total energy supplied from the heat pump and to this part of energy, which was used for heating purposes of the above assumed temperature inside a greenhouse. Kurpaska's work [5] presents nomograms for determining construction and operation parameters in which the heat pump was working in a monovalent and hybrid system.

The monovalent system constituted a co-operation of the heat pump with the grounded exchangers (both horizontal and vertical) whereas in the hybrid system a cumulative tank in which collected water was heated with solar collectors was the lower source of the pump.

The presented review of the literature explicitly results in actual analysis of the research issue, as the use of the heat pump in heating installations of facilities is one of future technical solutions. It is a consequence of the fact that the heat pump co-operating with a co-generative system (joint generation of heat and electric energy) is an ideal receiver of electric energy generated in this system. However, the system of obtaining heat from the bottom source, next to a type of the used pump decides on efficiency of using electric energy. Analysis of these issues is a main purpose of the presented work.

MATERIAL AND METHODS

Energy efficiency of the system the heat pump co-operating with the system of heat consumption and reception) decides on its economic cost-effectiveness.

Thus, this issue was analysed for a laboratory stand constructed in facilities of the Department of Production Engineering and Power Industry of the University of Agriculture in Kraków.

This stand (fig. 1) is composed of: a compressor heat pump, vertical ground exchangers: depth approx. 20 m (two U type exchangers and 2x U), depth 100 m (one U type exchanger and the other 2U type, horizontal exchangers in a geometric system: a single loop, a double loop and spiral arrangement. Two heat-air exchangers mounted in a laboratory foil tunnel constituted the system of heat reception.
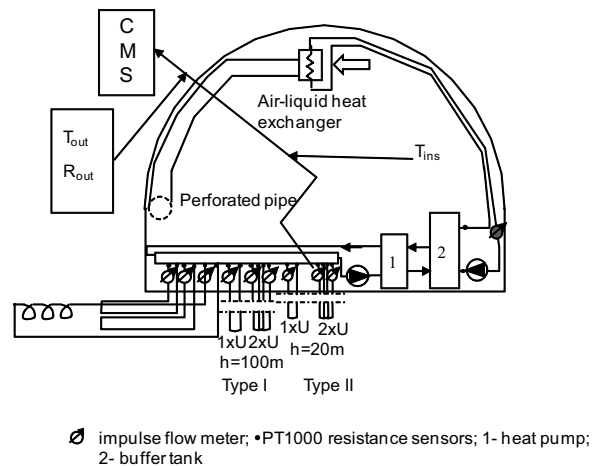

Fig. 1. Scheme of the laboratory stand

During the experiments, necessary measurement amounts were monitored and recorded using an original Computer Measurement System. A stream of the flowing factor was measured with an impulse flowmeter, while temperature (of supply and return of the circulation factor) in particular exchangers as well as air temperature

(outside t_{out} and inside a facility t_{ins}) with a resistance sensor PT1000. Additionally, during the research, a demand for electric power used for driving elements of the researched system (a compressor, a circulating pump and circulation pumps of exchangers of the upper heat source) was determined and radiation intensity Rs was measured (with a pyranometer).

Using a definition of the heat pump operation, an equation of energy balance (including amount of heat obtained in a condenser of the analysed pump - Q) may by written down in the following form:

$$Q = W_{PC} + Q_{GZ}. \tag{1}$$

Operation efficiency of the heat pump in the system may be described with the coefficient of performance (coefficient of energy efficiency), which was defined pursuant to the standard PN-EN 255 in the following form:

$$COP_{grz} = \frac{Q_{GZ} + W_{PC}}{W_{PC}} = 1 + \frac{Q_{GZ}}{W_{PC}}. \tag{2}$$

In a differentiable time dτ, parameters necessary to describe the amount of heat obtained by the analysed ground heat exchangers, electric energy consumption (W_{PC}) and amount of heat obtained by exchangers located in the heated facility (Q_{GZ}) were measured.

Moreover, in the said time dτ the amount of heat obtained by the analysed ground exchangers was determined in relation to:

$$Q_{DZ} = \sum_{i=1}^{9}\left(\sum_{i=1}^{n} m_{cDZ,i} \cdot c_c \cdot \left(T_{z-DZ,i} - T_{p-DZ,i}\right)\right)d\tau_{PC}, \tag{3}$$

whereas for the system of heat reception in analogical time this relation takes the following form:

$$Q_{GZ} = \sum_{i=1}^{2}\left(\sum_{i=1}^{n} m_{cGZ,i} \cdot c_p \cdot \left(T_{z-GZ,i} - T_{p-GZ,i}\right)\right)d\tau_{PC+GZ}, \tag{4}$$

where: Q_{GZ} - heat supplied to the inside of the facility [J]; Q_{DZ} - heat obtained form the outside of the ground [J]; W_{PC} - electric power obtained by elements of the system [W]; τ_{PC}, τ_{GZ} -operation time of the heat pump (τ_{PC}) and of the upper source(τ_{GZ}) [s]; m_c - stream of the lower circulation factor (m_{cDZ}) and of the upper (m_{cGZ}) source [kg·s⁻¹], c_c - specific heat of the circulation factor [J·kg⁻¹·K⁻¹], T_{z-DZ} and T_{p-DZ}- temperature of supply and return of the circulation factor of the lower heat source, T_{z-GZ} and T_{p-GZ}- temperature of supply and return of the circulation factor of the bottom heat source [ºC].

RESULTS AND A DISCUSSION

The research was carried out in 2012. Fig. 2 presents an exemplary course of some measured values. Assuming pointlessness of all possible courses, visualisations of the measured parameters were limited to parameters of the liquid -air exchangers, which constitute an upper heat source in a tunnel, temperature inside and outside of the facility, difference between temperature of supply and return of the circulation factor and the state of work of the heat pump. Selected symbols include:

T_{z-DZ1}, T_{z-DZ2}- difference in temperature of the circulation factor, R_s- intensity of solar radiation outside the facility; V_{DZ1}, V_{DZ2}- indications of a water meter presenting amount of the factor flowing through exchangers supplying heat to the inside of the facility:, t_{ins}, t_{out} - respectively temperature inside and outside the facility, HP- operation state of the heat pump (value above zero means operation state of the heat pump).

According to what has been presented, in the period of 48 hours, the heat pump was working through 37 cycles of operation of the length within 11.5 to 32 minutes. Within this time, for driving technical devices of the system (a pump compressor, circulation pumps) almost 86 kWh of electric energy were used and 85.4 kWh of this amount was used for driving elements of the heat pump (a compressor, a circulating pump) whereas, approx. 0.6 kWh were used for circulation pumps obtaining heat from a buffer tank of the pump. In the presented period of time 460 MJ of heat where delivered to the facility.

Almost 500 cycles of pump operation were analysed (for all conditions of the experiment). For every cycle from the equation (2) a coefficient of performance was calculated.
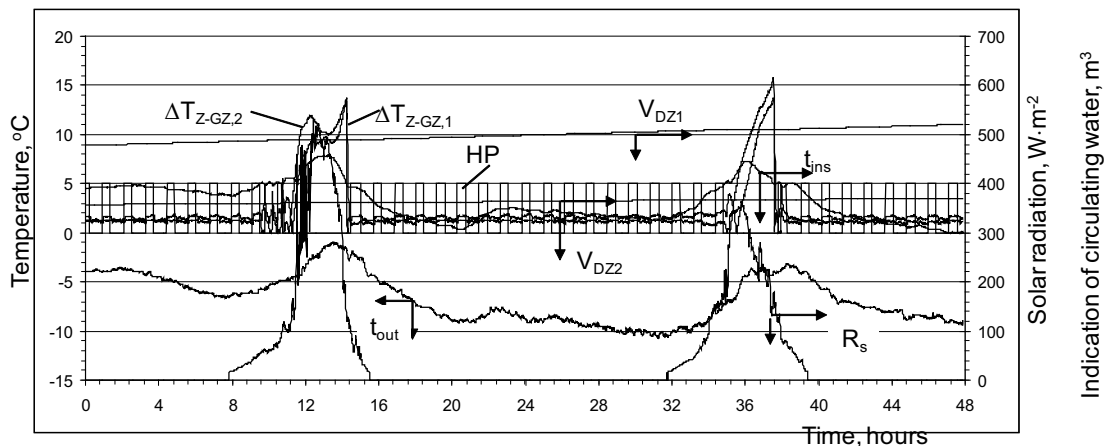

Fig. 2. Temporary course of some measured parameters in the expriment

Fig. 3 and 5 presents a calculated coefficient of operation efficiency of the pump co-operating with the analysed ground heat exchangers. Type I of vertical ground heat exchangers means exchangers located at the depth of 18 m while the type II means ground exchangers of 100 m depth.
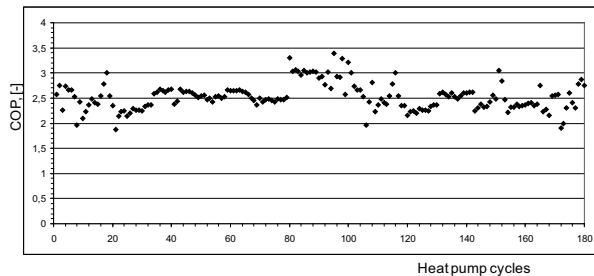

Fig. 3. Course of changes in energy efficiency of the heat pump co-operating with horizontal exchangers
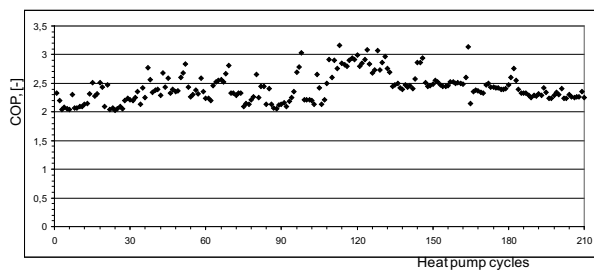

Fig. 4. Course of changes in energy efficiency of the heat pump co-operating with vertical ground exchangers of approx. 20 m depth
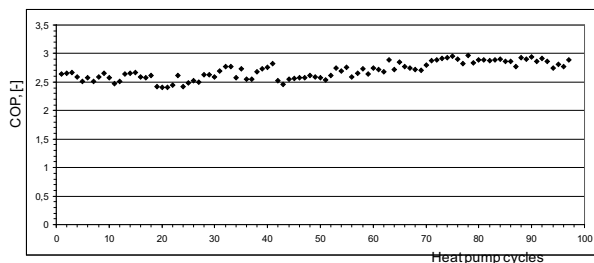

Fig. 5. Course of changes in energy efficiency of the heat pump co-operating with ground vertical exchangers at 100 m depth

When analysing the obtained courses, one may notice that the highest average value of the coefficient COP (the COP = 2.69) was obtained for the case when the heat pump was co-operating with the vertical ground exchangers located at 100 m depth. Whereas, when the pump co-operates with the horizontal exchangers, an average value of COP was 2.53, while for the vertical exchangers of approx. 20 m depth, the COP was 2.42. Comparable values of the surrounding climate were selected for the analysis. Thus, vertical exchangers made at the depth of 100 m are recommended as the lower heat source of the pump.

While analysing these relations, one may find that the co-operation of the heat pump with the vertical exchangers of 100 m depth is characterised also by a lower variability of the value of the coefficient of performance.

For the obtained data, at the level of significance □=0.05 a statistical analysis was carried out using the Statistica® packet. Fig. 6 presents results of average values along with a standard deviation of analysis.
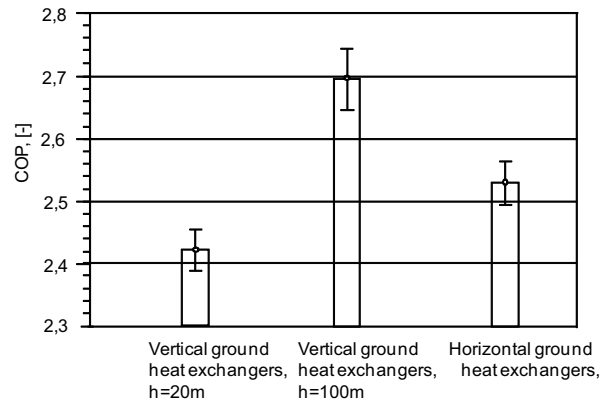

Fig. 6. Results of average values of the coefficient of performance with a standard deviation

The analysis of variance in a single classification, which was carried out proves that the assumed factors of the experiment (a type of the ground exchanger) significantly influence the analysed value of the coefficient of performance. Whereas, Duncan test proved that the average values of this coefficient differ in a statistically significant way.

Fig. 6 presents a graphic relation of the coefficient of efficiency of the heat pump (calculated from the equation 2) and temperature inside the facility.
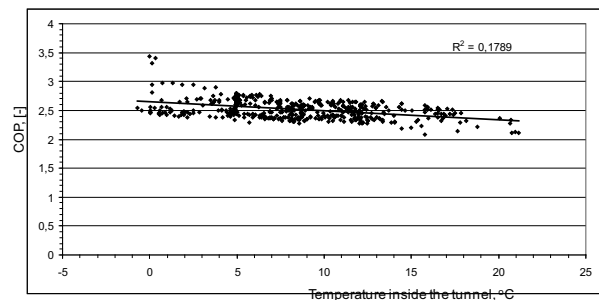

Fig. 7. Dependence of the heating efficiency coefficient on the temperature inside the object

One may notice that growth of temperature inside a foil tunnel means a slight decrease of the coefficient of efficiency of the heat pump. The statistical analysis did not prove significance of the regression coefficient. It means that there is no linear influence of temperature inside a foil tunnel on the value of the COP. Moreover, the value of the coefficient of determination (R^2=0.18) does not prove statistically significant relation of the COP with temperature inside a facility. It results from the relation of intensity of heat reception between exchangers and a surrounding air, since the higher temperature is around the heat exchangers, the lower value of the transfer coefficient gets. At the low difference of temperatures, the operation time of circulating pumps from the system

of heat reception increases. However, the power used for driving circulating pumps is many times lower than a demand for power by a compressor and a circulating pump of the lower heat source.

CONCLUSIONS

The highest average value of the COP was obtained for the vertical ground heat exchangers (type II), slightly lower for the horizontal exchangers and the lowest for vertical exchangers (type I). The analysis of variance proved that the assumed factors of the experiment (a type of the ground exchanger) considerably influence the analysed value of the COP and average values of this coefficient differ in a statistically significant way. Along with a temperature growth inside a foil tunnel, the value of the COP decreases slightly. However, the coefficient of regression is not statistically significant.

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EFEKTYWNOŚĆ ENERGETYCZNA WYMIENNIKÓW GRUNTOWYCH WSPÓŁPRACUJĄCYCH ZE SPRĘŻARKOWĄ POMPĄ CIEPŁA

Streszczenie. W pracy przedstawiono wyniki analizy wartości współczynnika efektywności pracy sprężarkowej pompy ciepła współpracującej z wymiennikami gruntowymi. Badano trzy typy wymienników: poziome, pionowe- wykonane na głębokość 20m (typ I) oraz na głębokość 100m (typ II). Wykazano, że największa wartość współczynnika COP występuje dla wymienników pionowych (typ I), nieco mniejsza dla wymienników poziomych i najmniejszą dla wymienników pionowych (typ II). Przeprowadzona analiza statystyczna wykazała, że rodzaj wymiennika wpływa istotnie na wartość COP; również średnie jego wartości są statystycznie istotne. Nie wykazano istotności wpływu temperatury wewnątrz obiektu na wartość współczynnika COP.

Key words: sprężarkowa pompa ciepła, pionowy, poziomy, wymiennik gruntowy.