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9HEAT STORING EFFECTIVENESS WITH THE USE OF A RECUPERATOR IN THE LIQUID TYPE BATTERY*

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ABSTRACT

The paper presents results of the analysis concerning the process of storing and discharging the liquid type battery. A system comprising a recuperator, a battery tank, a circulating pump and a ventilator, was analysed. Hot air obtained from the perforated conduits system from the laboratory tunnel was pumped through a recuperator. The heat storing system in the analysed battery cooperated strictly with a stone battery and its priority was to charge it. Tests were carried out from June to August. A detailed analysis included measurement cycles covering both the storing process as well as the process of discharging. Based on the obtained results, thermal power of the exchanger was determined as a function of air temperature difference between the flowing air and water stored in the battery and its flow velocity. Furthermore, quantity relations between the efficiency of work of the exchanger and independent variables of the process: air temperature and water stored in the battery, air flow velocity, process duration and the stream of heat transfer fluid which flows through a recuperator, were determined. Non-linear estimation with the use of quasi-Newton method was applied for determination of these relations. Moreover, the amount of the heat stored in the battery and the heat transferred to the inside of the object were defined. A total coefficient of heat supply with this system was introduced in the analysis. Based on the obtained values of the process performance, it was found out that despite favourable ecological effects, such system of heating support cannot be recommended for horticultural practice on account of a low value of the coefficient. Whereas the use of the storing system for heating process water is justified.

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The list of symbols:

m_{ak} – water mass in a battery, (kg)
c_w – proper heat of water, ($kJ \cdot kg^{-1} \cdot K^{-1}$)
Δt_{ak} – mean temperature of water in a battery, (^{o}C)
τ, τ_1 – initial (τ) and final time of a cycle respectively (τ_1), (s)
i_{WY}, i_{WE} – enthalpy of inlet air (i_{WE}) and outlet air from the exchanger (i_{WY}), ($kJ \cdot kg^{-1}$)
c_{pow} – specific heat of air, ($kJ \cdot kg^{-1} \cdot K^{-1}$)
t_{WE},t_{WY} – temperature of inlet air (t_{WE}) and air flowing out of the battery (t_{WY}), (°C)
q_{pow} – stream of air flowing through the exchanger, ($m^3 \cdot s^{-1}$)
q_{wym} – stream of liquid flowing through the exchanger circuit ($l \cdot s^{-1}$)
P_{el} – electric power for drive of devices, (kW)

Introduction

In the times of modern price relations, care for environment, searching for solutions, which would reduce heat demand in manufacturing facilities is a crucial issue. These challenges stimulate searching for solutions which aim at rationalization of energy consumption in facilities under covers, since according to detailed studies, energy costs reach even 60% of all operational costs in our country. Heat costs prevail in the energy costs. The issues concerning implementation of technical solutions, which minimize energy consumption, deal with modification of the facility structure, its technical equipment, optimal control of micro-climate parameters and the use of energy saving technologies. Subject to the obtained results of research, commercial solutions dedicated for production under cover were introduced. Numerous scientific centres carry out studies concerning the scope of use of heat surplus from the inside of the facility in the form of storing in energy batteries and then using the heat for heating demands of a facility in the process of battery discharging. Heat may be stored in bodies which use the heat volume and the heat from phase transformations of the battery bed. One of the solutions which use the heat volume of a bed is storing in the liquid type battery. A recuperator is an integral part of such system. Scientific experiments on this subject are carried out in various scientific centres. Thus, Attar et al., (2014) analysed the storing and heat collection efficiency in the system, where hot water heated in collectors was supplied to recuperators placed in a laboratory greenhouse. Sheikholeslami et al., (2015) studied the issues of heat exchange in an innovative liquid-air exchanger where plastic conduits were washed with air: there was a copper conduit supplied with circulating water, which was moved to the heating system. Similarity numbers and conditions at which heat transfer reaches the highest value, were defined. Grupta and Tiwari (2002) presented results of research on the passive heat storing from the inside of a laboratory greenhouse in the water accumulator. They formulated a heat exchange model between a tank and surroundings and they determined water temperature stratification in a tank for representative days in particular months. Ntinas et al., (2011) analysed savings of energy consumed for heating a greenhouse, where heat was stored in polyethyl conduits located under cultivation gutters to which perforated conduits adjusted. Air, flowing through these conduits through openings, was sucked into and directed directly to the inside of the facility. Haltiwanger and Davidson (2009) investigated stratification of liquid temperature which was in a tank which stored hot water. The second tank was placed inside the storing tank, outside which a recuperator was installed. The authors determined a temporary temperature fluctuation in a tank during cold water flow through a recuperator whereas based on experimental results, they described the intensity of heat transfer with the use of the similarity number (Reynold's, Prandtl's and Nuselt's). On the other hand, Ozenger (2011) presented results of scientific research carried out in various scientific centres, where such systems were used for greenhouse facilities: both for the open and closed ventilation system. Sethi and Sharma (2007) presented results of analysis carried out with regard to energy and economy for the system, where hot air from the inside of the facility was stored in the aquifier. In the period of heat demand by the greenhouse facility, air was pumped through the exchanger. The change of air temperature inside the facility and the basic economic indices of the system were defined (financial flows and internal period of return). Li et al., (2014) analysed the process of charging and discharging of the liquid type battery, where a recuperator was installed. Heat transfer liquid was heated with a resistance heater. The authors determined the intensity of heat exchange in relation to the velocity of water flowing inside the exchanger. Moreover, with the use of TRNSYS energy simulation software they presented results of energy efficiency of this tank which cooperates with solar collectors. Results of the research, which were carried out in scientific centres of the University of Agriculture in Krakow and the Institute of Horticulture in Skierniewice, where effects formed during heat storing in a stone battery were analysed, have been presented inter alia in the papers by Kurpaska and Latała 2011, Kurpaska et al., 2014.

The literature review shows that the issues of storing heat surplus from the inside of the horticultural facility are still carried out in various scientific centres in varied (on account of bed) energy batteries.

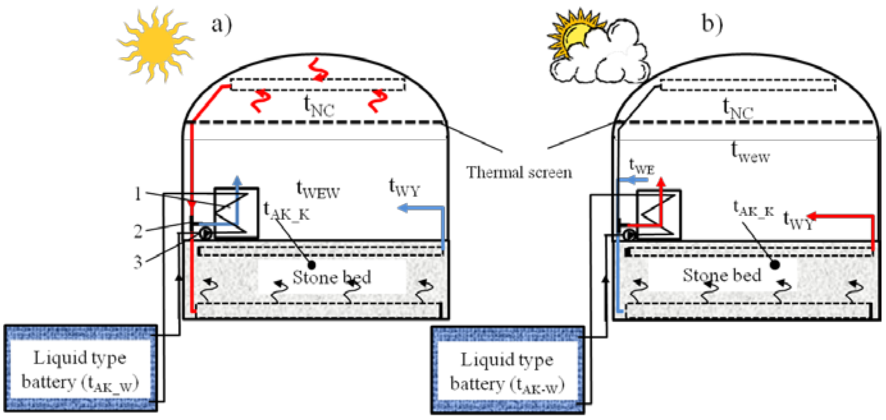
Water is one of storing mediums. Both non-control factors and those that depend on the system operator affect the efficiency of such system. Analysis of such manner of heat storing will be the main objective of the paper.

Material and method

Description of experiments

The tests were carried out in June-August in a laboratory tunnel with two heat storing systems: a stone battery and water battery. A liquid type battery was placed in the ground (below its level) whereas insulation of the structural wall was carried out with the use of 10 cm thick Styrofoam of 10. Fig. 1 presents a scheme of the discussed system.

Both the charging and discharging process of batteries is carried out with the use of algorithms, which control the position of flap valves. The algorithm scheme for the charging process was presented in fig. 2. The idea of heat storage consisted in priority charging of the stone battery and then (after charging) charging of a liquid type battery. As it can be seen, in the process of charging the stone battery, information on the values of temperature gradient between temperature over the protection screen and temperature in the battery (Δt_1), temperature flowing out of the battery and temperature inside the facility (Δt_2), and the difference between the stone battery temperature and the liquid type battery temperature (Δt_3) is necessary.



1- Recuperator; 2- Electric valve; 3- Circulating pump

Figure 1. Schematic representation of heat storing (a) and discharging (b) systems

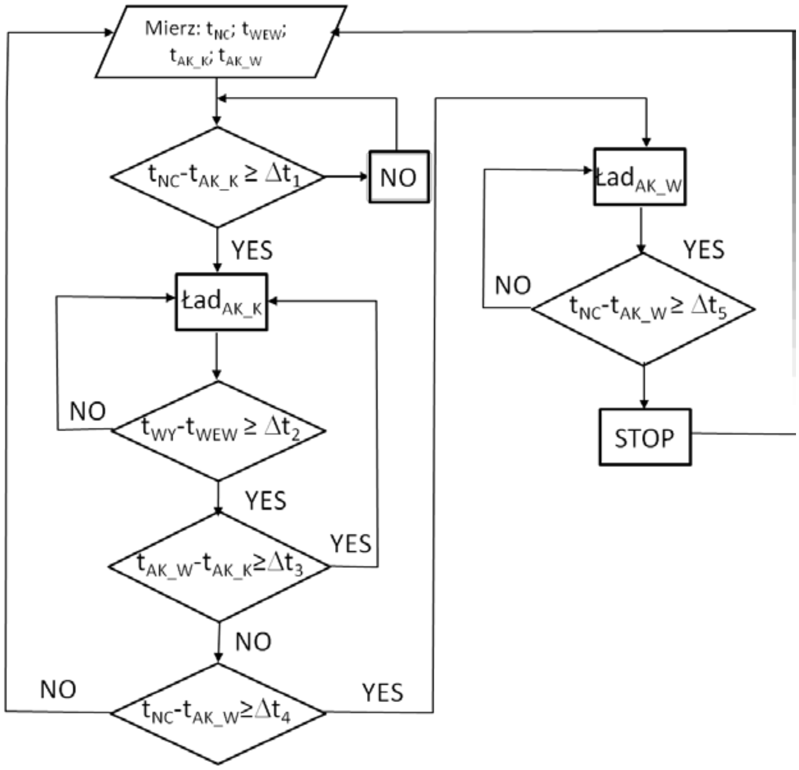


Figure 2. Algorithm of controlling the process of charging energy batteries

Whereas, during charging the liquid type battery, the knowledge of the gradient between temperature over the protection screen and temperature of liquid stored in the liquid type battery at the beginning (Δt_4) and at the end of the charging process is needed (Δt_5). Tests were performed at the following values of gradients respectively: $\Delta t_1 = \Delta t_3 = \Delta t_3 = 4K$; $\Delta t_2 = \Delta t_3 = 2K$.

After the loading process, the process of discharging the liquid type battery was performed in the night time. It consisted in pressing in air sucked from the inside of the facility by the analysed recuperator. The discharging process was carried out according to the control algorithm, where air temperature on the inlet and outlet from the exchanger was included.

Tests of the process of discharging batteries were carried out for the case when temperature inside the facility will be lower than 18ºC, whereas the temperature gradient of the stone battery and the temperature of air flowing out of the battery will be 4K and the gradient of liquid temperature in the liquid type battery and the stone one is 2K. It was also assumed that the temperature gradient in the liquid type battery and inside the facility is 4K.

Theoretical analysis

The subject of the analysis of efficiency (calculated as energy obtained in comparison to energy placed) is the system presented schematically in fig. 3.

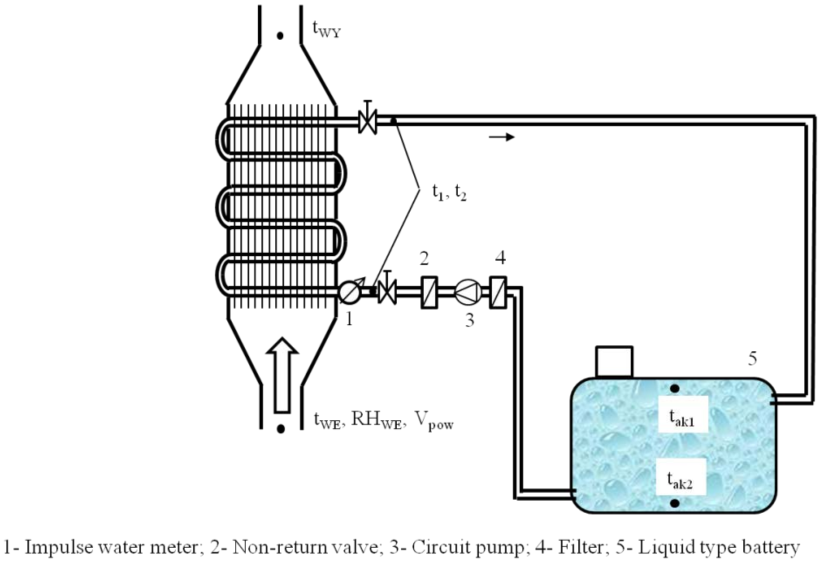


Figure 3. Schematic representation of heat storing in liquid type battery

Based on the available literature, the surface area of heat exchange and the power of an exchanger were designed. Having physical parameters of air, a decision was taken that it will be: a plate fin heat exchanger which operates in the countercurrent with the total area of heat exchange which is 47.5 m^2 and the maximum heating power equal to 8.27 kW.

Using standard relations, the amount of the stored heat (including average temperature of water in a tank – Δt_{ak} – calculated as an arithmetic mean from the value t_{ak1} and t_{ak2}) in the water battery (dQ_{ak}) in the differential time $d\tau$ was calculated from the formula:

$$dQ_{ak} = m_{ak} \cdot c_w \cdot \int_{\tau_1}^{\tau_1+\tau} \Delta t_{ak} d\tau \tag{1}$$

Air enthalpy after heating in the exchanger in the process of discharging the battery was determined from the relation:

$$i_{WY} = \int_{\tau_1}^{\tau_1+\tau} \left[i_{WE} + c_{pow} \cdot (t_{WY} - t_{WE}) \right] \cdot d\tau \tag{2}$$

Therefore, the amount of heat supplied from the liquid type battery in the process of discharging is described by the formula in the form of:

$$dQ_{ob} = q_{pow} \cdot \rho_{pow} \int_{\tau_1}^{\tau_1+\tau} (i_{WY} - i_{WE}) d\tau \tag{3}$$

Based on the obtained results, the coefficient of performance of transferring heat on the route: a recuperator – flowing air, was defined. Efficiency was described from the formula:

$$COP = \frac{di_{WE,WY}}{P_{el} \cdot \tau_{lad,rozł}} \tag{4}$$

Performance of the entire process decides on the usefulness of the considered system. Performance includes the obtained effect (calculated as the amount of supplied heat to the inside of the facility) in comparison to the inputs incurred on the process of storing and discharging a stone battery.

Thus, the total performance of the heat supply process to the inside of the facility from the battery including the charging time (τ_{lad}) and discharging time of a battery (τ_{rozl}) is described by the relation:

$$\eta = \frac{dQ_{ob}}{P_{el} \cdot (\tau_{lad} + \tau_{rozl})} \tag{5}$$

Thus, the applied equations (particularly 4 and 5) include the amount of heat supplied to the facility including the incurred energy for the charging process (equation 4) and the entire cycle (equation 5).

For generalization of the obtained results average values of parameters (W_{avg}) which define changes in the scope of the amount of stored heat were calculated. These values were calculated using their actual values from the relation:

$$W_{avg} = \frac{1}{\tau} \cdot \int_{\tau_1}^{\tau_1+\tau} w(\tau) d\tau \tag{6}$$

All parameters necessary to define these relations were determined for each cycle with the use of standard psychometric relations. All parameters were controlled and archived by a computer measurement system.

Results and discussion

Tests were carried out in a laboratory plastic tunnel located in the buildings of the Department of Production Engineering and Power Energy of the University of Agriculture in Kraków. During research (in both analysed cycles) the scope of changes of input parameters was within: electric power of devices (P_{el}) used for the system operation: 1,12 to 4.18kW; air velocity (V_{pow}) in the measured distance (a conduit with a diameter 300 mm): 2.45 to 4.85 m·s^{-1}; system operation time (τ): 892 to 54930 s; water temperature in a battery (t_{ak}): 23.1 to 37.2ºC; temperature (t_{WE}) of air flowing through an exchanger: 13.1 to 47.2ºC; stream of the heat transfer liquid in the exchanger circuit (q_{wym}): 0.08 to 0.44 l·s^{-1}.

Fig.4 shows the obtained power of the applied plate fin heat exchanger in the function of two independent variables: air flow velocity and the difference in temperature calculated as a difference between the flowing air and water temperature in the battery. Power was calculated as a ratio of the heat amount (calculated from formula no. 3) in comparison to the duration of an experiment. It is noticeable that the higher the air velocity and temperature difference the higher the exchanger power. It results directly from heat transfer conditions since along with the growth of this size, the increased intensification in heat transfer between both mediums takes place. Calculated average power of the heat exchanger for the experiments which were carried out (both processes was 3.12 kW.

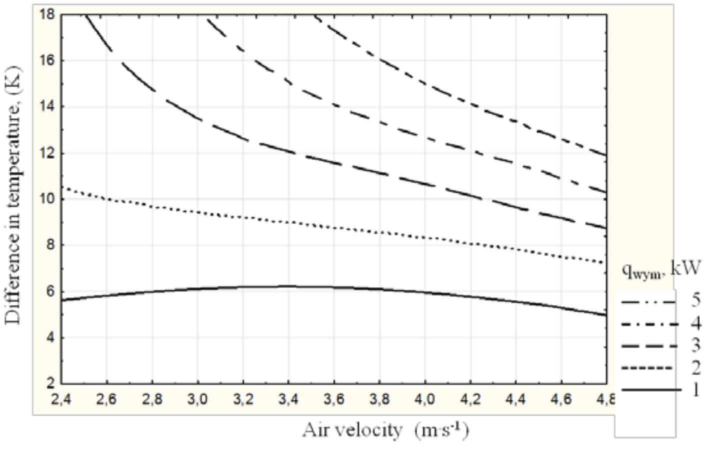


Figure 4. The power of the recuperator during experiments

For the calculated COP, the equation which was found and which includes the relation between this variable and independent variables (the form of a power model was selected based on the highest value of determination coefficient; this relation was determined with non-linear estimation with quasi-Newton method at the retained coefficient of convergence of 0.001) takes the following form:

$$COP_{\mathrm{mod}} = \left| 23{,}63 \cdot t_{WE}^{-0{,}65} - 30{,}37 \cdot t_{ak}^{-0{,}137} + 9{,}66 \cdot V_{pow}^{-1{,}67} + 14{,}26 \cdot \tau^{0{,}0036} + 2{,}25 \cdot q_{wym}^{0{,}373} \right|$$

This equation is obligatory within the scope given in the introduction of input variables values. One may notice that only with the growth of the process duration and the velocity of pressed air, the performance decreases: in case of the remaining input variables the growth of this coefficient rises.

Comparison of COP values calculated from the model and measurements together with the calculated mean square error was presented in fig.5. It can be seen that the value of the coefficient calculated from the suggested model has great convergence with values determined from the measurement.

Fig. 6 presents the obtained effects (in the form of the stored and supplied heat) during performance of full 29 days of measurement cycles. The process of charging and discharging the battery and moving the stored heat to the inside of the facility was assumed as a full cycle.

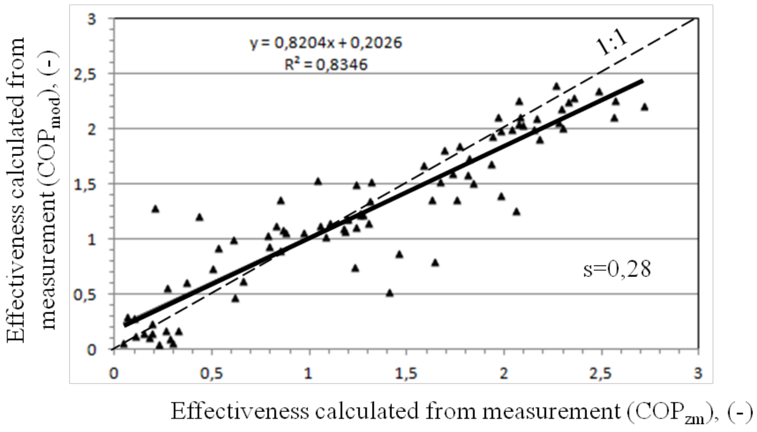


Figure 5. Comparison between the calculated and measured values of COP

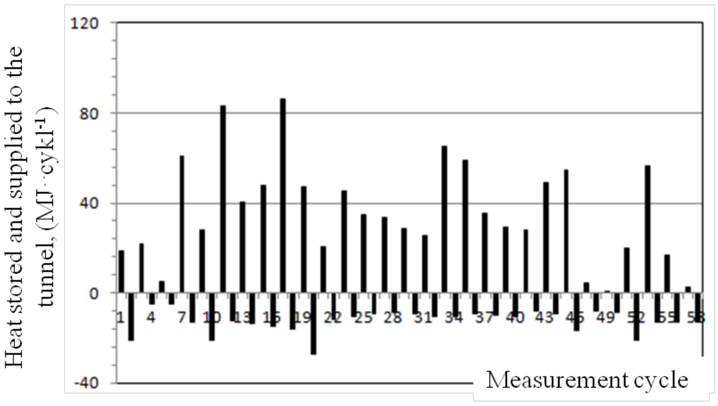


Figure 6. The amount of stored and supplied heat to the inside of the facility during experiments

The amount of stored heat in the liquid type battery is almost 1020 MJ whereas approx. 360 MJ of heat was supplied to the inside of the facility. The change in the amount of stored and supplied heat may be justified with heat losses from the liquid type battery to the surrounding ground and almost 10K growth of the final temperature of liquid between the experiment.

Fig. 7 presents the calculation of the efficient of transferring stored heat to the inside of the facility.

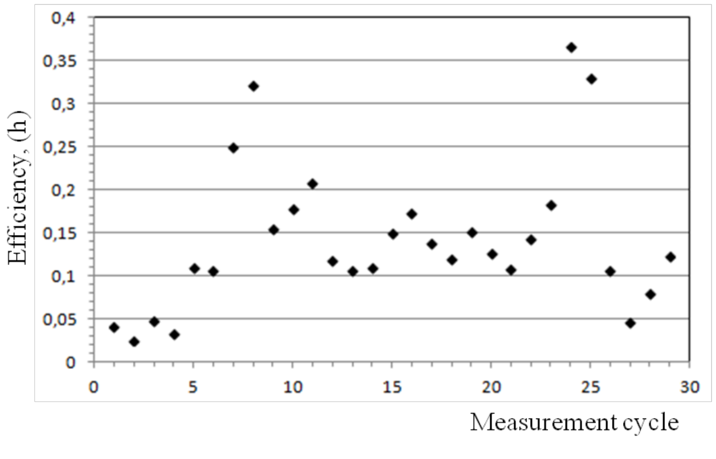


Figure 7. Total efficiency of the system which supplies the heat stored in the battery to the inside of the facility

It may be stated that its average value is only 14% which means that this manner of supporting heating of the facility (despite the measurable effects in the amount of reducing emission of hazardous substances to atmosphere) may not be recommended for horticulture. However, due to the obtained effects this system may be used for heating technological water, since average increase of water temperature as a result of using the recuperator was almost 2.2K; in one of the measured cycles the temperature growth was over 5 K. Average efficiency of the heat storing process in the liquid type battery was 0.84.

Conclusions

1. The average power of the plate fin heat exchanger for the range of input parameters change in the measured cycles was 3.12 kW.
2. The amount of stored heat in the liquid type battery was almost 1020 MJ whereas approx. 360MJ of heat was supplied into the facility.
3. Based on the experimental results, equations which allowed, at known input parameters, determination of energy efficiency of the plate fin heat exchanger, were determined.
4. The average efficiency of the entire process of supplying heat into the facility is 14% which means that this manner of supplying heat may not be recommended for horticulture. This system may be successfully used for heating process water.

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EFEKTYWNOŚĆ MAGAZYNOWANIA CIEPŁA W AKUMULATORZE CIECZOWYM Z WYKORZYSTANIEM PRZEPONOWEGO WYMIENNIKA CIEPŁA

Streszczenie. W pracy przedstawiono wyniki analizy z zakresu procesu magazynowania i rozładowywania akumulatora cieczowego. Analizowano system składający się z: przeponowego wymiennika ciepła, zbiornika akumulatora, pompy obiegowej oraz wentylatora. Ciepłe powietrze, pozyskiwane systemem przewodów perforowanych z wnętrza tunelu laboratoryjnego, zatłaczano przez przeponowy wymiennik ciepła. System magazynowania ciepła w analizowanym akumulatorze współpracował ściśle z akumulatorem kamiennym z nadanym priorytetem ładowania akumulatora kamiennego. Badania przeprowadzono w okresie czerwiec- sierpień. Do szczegółowej analizy wyszczególniono cykle pomiarowe obejmujące zarówno proces magazynowania jak i rozładowania akumulatora. Na bazie uzyskanych wyników określono moc cieplną wymiennika, jako funkcję różnicy temperatury powietrza między przepływającym powietrzem a wodą zmagazynowaną w akumulatorze oraz jego prędkości przepływu. Wyznaczono także ilościowe zależności między efektywnością pracy wymiennika a zmiennymi niezależnymi procesu: temperatura powietrza oraz zmagazynowanej wody w akumulatorze, prędkość przepływu powietrza, czas trwania procesu oraz strumień czynnika obiegowego przepływającego przez wymiennik przeponowy. Do określenie zależności zastosowano estymację nieliniową z wykorzystaniem metody quasi-Newtona. Określono również ilość zmagazynowanego ciepła w akumulatorze oraz ciepło przekazane do wnętrza obiektu. W analizie wprowadzono całkowity współczynnik sprawności dostarczania ciepła tym systemem. Na podstawie uzyskanych wartości sprawności procesu stwierdzono, że pomimo korzystnych efektów ekologicznych, taki system wspomagania ogrzewania ze względu na niską wartość współczynnika nie można rekomendować do praktyki ogrodniczej. Uzasadnione zaś jest wykorzystanie systemu magazynowania do ogrzewania wody przeznaczonej na cele technologiczne.

Słowa kluczowe: magazynowanie ciepła, akumulator cieczowy, przeponowy wymiennik ciepła