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ANALYSIS OF THE SELECTED FACTORS IMPACT ON THE AMOUNT OF THE STORED HEAT AND THE MASS CHANGE IN THE ROCK-BED STORAGE PLACED IN THE LABORATORY TUNNEL[1]

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ABSTRACT

The paper presents results of analysis of the air flow through the rock - bed storage. Air was collected from the inside of the plastic tunnel and pressed to the segments of the storage with area was 18.7m^2 and volume was almost 13.1 m^3. The research was carried out from March to October 2013. The cycle of the storage work (charging or discharging) was controlled based on the algorithm, in which a controlling signal was based on the difference in the temperature between the average temperature of the bed and the temperature inside a tunnel. 318 measurement cycles were selected for a detailed analysis. In those cycles, based on the measured parameters of air pressed into and flowing out of the storage, the amount of the stored heat in the storage and the change in the concentration of steam included in air was determined. For the obtained results multiple regression equations, describing a unitary heat stream and mass exchanged during the air flow through the storage, were found. Moreover, the quantity relations between a unitary heat and the mass stream exchanged during the air flow through the storage including two sets of independent variables, were determined. The first one includes: velocity of the pressed air (measured in the air pressing conduit for particular segments), initial temperature of the storage and the pressed heat stream. The second set of independent variables includes: temperature of the pressed air, deficiency of steam pressure inside the facility and the stream of the pressed air. Non-linear estimation with the use of quasi-Newton method was applied for determination of these relations.

The list of symbols:

q_{pow} – pressed air stream (m^3·s^{-1}),
ρ_{pow} – air density (kg·m^{-3}),
τ_1, τ – respectively initial time (τ_1) duration of a cycle (τ) (s),

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i_{WY}, i_{WE} – enthalpy of air which is flowing out (i_{WY}) and pressed into (i_{WE}) the storage, (J·kg^{-1})

f_{WE}, f_{WY} – absolute moisture of the air which is flowing out (f_{WY}) and pressed into (f_{WE}) the storage, (g·m^{-3})

Introduction

Searching for technical solutions used in the production processes should be integrally related to the improvement of the product quality and reduction of its costs. Undoubtedly, reduction of production costs in roofed facilities may be performed inter alia by using the excess of heat from the inside of the facility for heating the object. This issue, for crops under covers, concerns both the type of the object structure and its equipment. Research, concerning the impact of the object structure, efficiency of heat storage in the storage bed including aspects of the heat demand, was carried out in many scientific centres. From the point of view of the facility structure, Abreu et al, (2001) analysed the impact of its structure (single tunnel, blocked) on the effect of cultivated tomatoes. In the conclusion it was determined that in the blocked objects, it is easier to maintain the required parameters of the internal microclimate, which was seen with the improvement of the quality of tomatoes as well as limitation of use of plant protection substances. Volkaerts et al. (2012) analysed the answer of temperature and air humidity changes during natural ventilation in the facility, where precise control of the ventilator location was applied. Authors developed a mathematical model of the heat and mass exchange process and its validation was carried out in the blocked greenhouse. Kittas and Bartzanas (2007) in the analysis of the issue of the greenhouse ventilation (with various geometry of a ventilator) used the CFD programme and upon recognition of a satisfactory compliance, they carried out simulation experiments. Impact of the wind direction and velocity on the distribution of air velocity inside the facility in the aspect of temperature changes and concentration of steam was analysed. Boulard et al. (2004) carried out a series of research on the impact of ventilation intensity (through change of location ventilation openings) on the process of mass exchange during transpiration of tomatoes cultivated in the plastic tunnel. Impact of location of ventilators both on parameters describing intensity of transpiration (physiological resistance of mass conduct inside a leaf and on the leaf- surrounding air border) which in consequence affects microclimate in the facility, was reported. Researchers recognized a great usefulness of the obtained results for biological plant protection and controlling their growth. On the other hand, from the scope of use of waste heat from a greenhouse, Condori et al. (2001) presented results of their research related to the use of heat from the inside of the prototype greenhouse for drying vegetables (sweet pepper, garlic). Authors determined changes of water content in products dried with air obtained from the inside of the object and determined relation between temperature of dried air and intensity of solar radiation, recognizing usefulness of such system in a conclusion. Moreover, a similar issues concerning the use of waste heat from the inside of the facility were analysed by Fuller and Charters (1997) determining possibilities of using this heat from a production plastic tunnel for drying grapes. In the construed system, air sucked from the inside was moved to a heater. Authors developed an algorithm for controlling the operation of this system and its usefulness for practice was confirmed during test research. From the scope of storing heat surplus from the inside of the facility (Ozgener and Ozgener 2010) carried out a series of experiments in the storage, where the system of steel conduits was installed (placed in the loop shape) placed in soil. Conduits were supplied with hot air obtained from the inside of a greenhouse. Authors determined a coefficient of heat transfer between conduits and soil and determined efficiency of the heat storing process recognizing its usefulness in the region with high sun exposure (Mediterranean Sea region). Kurklu (1998) in his review paper presented constructional solutions of heat storages which use phase changes of material (salt hydrate, paraffin and polyethylene glycol) along with determination of potential heat effects at their use in a greenhouse. Boniecki (1999) presented assumptions for construction of the simulation model of the charging process of a rock-bed storage of thermal energy at including a random distribution of temperature of air pressed inside it. Thus in the paper (Muller and Maćkowiak 2010) presented and verified an alternative to the existing, a probable mathematical model of heat transfer, which more fully in comparison to previous models includes a stochastic nature of the bed structure and additionally reflects an uneven air flow through the storage during a charging phase. The presented review of research works shows clearly that the use of heat surplus from the inside of the facility, which was formed from solar radiation, in the process of heating a horticultural facility is one of the solutions which are used for the microclimate change. This issue is an object for the research carried out in the plastic tunnels located in the University of Agriculture facilities and the Institute of Horticulture in Skierniewice (Kurpaska et al., 2012; Hołownicki et al., 2012). In the process of heat storing, both thermal processes as well as mass exchange processes occur (condensation, evaporation) through changes of steam concentration in air. Therefore, determination of these effects which were formed during pressing air to the rock-bed storage is an essential problem. It will be a main objective of the paper.

Material and method

Experimental research was carried out in the facility composed of a 4-segment rock-bed storage (with the area of 18.7 m^2 and the volume close to 13.1 m^3 each), which is placed in the experimental tunnel (without plant cultivation) in the facilities of the Department of Production Engineering and Power Industry of the University of Agriculture in Cracow. A schematic representation of the test bench with marked measurement points were presented in figure 1.

During the experiments, the following parameters were measured:

a) air pressed and flowing out of the rock-bed storage: speed, temperature, relative humidity,
b) temperature and humidity of air which flows through the rock-bed storage,
c) of the external air: temperature, humidity, intensity of solar radiation and the wind velocity.

All measured sizes along with determination of the location of electric gate valves were controlled with the use of the original measurement system with the time of sampling equal to 120 s.

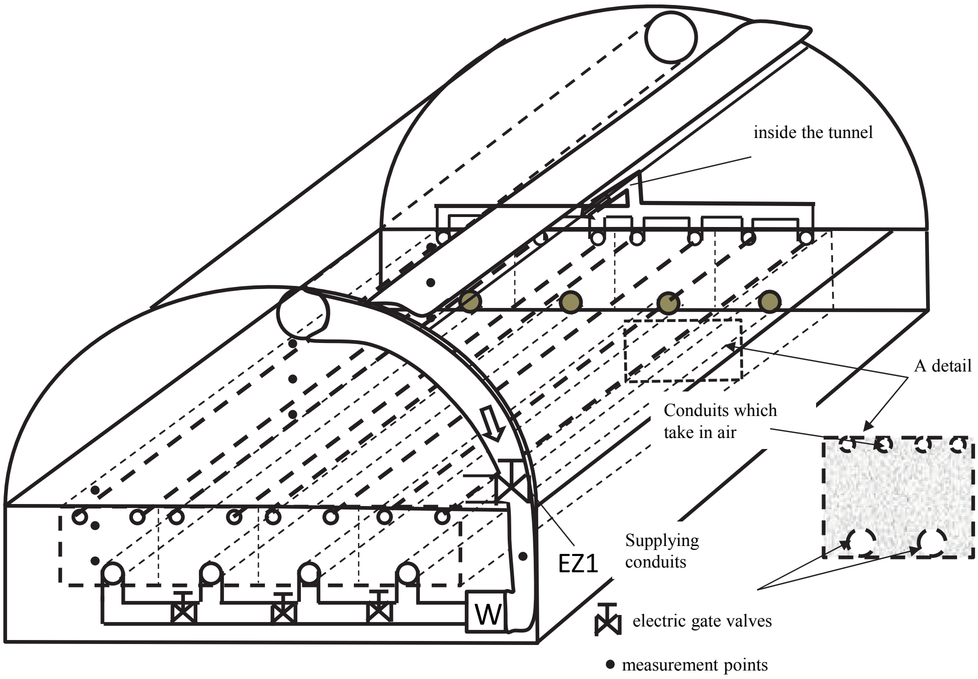

Figure 1. Schematic representation of the measurement stand

Change of a location of electric gate valves was performed with the use of the alogorithm presented in fig.2.

The presented schematic representation of signals flow shows clearly that the process of both charging the storage (left part of the algorithm) as well as its discharging (right part of the algorithm) takes place in case of excceding the temperature difference (Δt_1, Δt_2) between the bed temperature (t_I, t_{II}, t_{III} i t_{IV}) a temperature above shadowing (t_{NC}) or inside the facility (t_{wew}). Value of this difference was determined in the research in order to maintain stability of this system operation. As a result of complex temperature difference, change of the control of location of the guide valve in EZ1 device took place.

In the analysis of the storage charging process, two mutually related sizes (parameters of the pressed air and air in the storage) may be distinguished i.e. the amount of the stored air in each measurement cycle and the change of the mass content (counted as a difference in the steam concentration in air between air pressed to the storage and air flowing inside the tunnel).

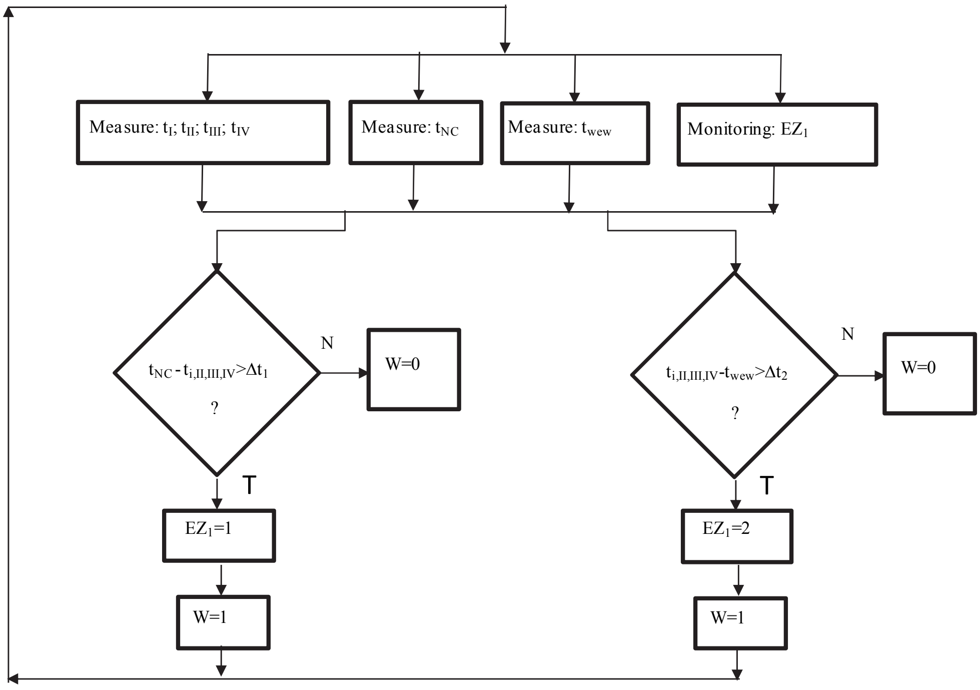

Figure 2. Schematic representation of the control of the charging/discharging process of the rock-bed storage

Thus, the amount of the stored heat in the storage (dQ_{ak}) in the differential time $d\tau$ was calculated from the relation:

$$dQ_{ak} = q_{pow} \cdot \rho_{pow} \cdot \int_{\tau_1}^{\tau_1+\tau} (i_{WE} - i_{WY}) d\tau \tag{1}$$

while the change of the mass amount with the steam concentration change in the air pressed by the storage from the formula:

$$dm_{H2O} = q_{pow} \cdot \int_{\tau_1}^{\tau_1+\tau} (f_{WE} - f_{WY}) d\tau \tag{2}$$

For generalization of the obtained results average values of parameters were calculated (W_{avg}) which determine changes in the scope of the stored heat amount and the change in the amount of the absorbed/ moistened water in the storage. These values were calculated using their actual values from the relation:

$$W_{avg} = \frac{1}{\tau} \cdot \int_{\tau_1}^{\tau_1+\tau} w(\tau) d\tau \qquad (3)$$

All parameters indispensable for determination of these relations were determined for each cycle using the standard psychometric relations.

Results and a discussion

Research was carried out between March and October 2013. The scope of the temperature difference used in the control of the air flow process was determined in the initial research in 2012. Figure 3 presents temperature changes in the storage bed and the facility with no working ventilator.

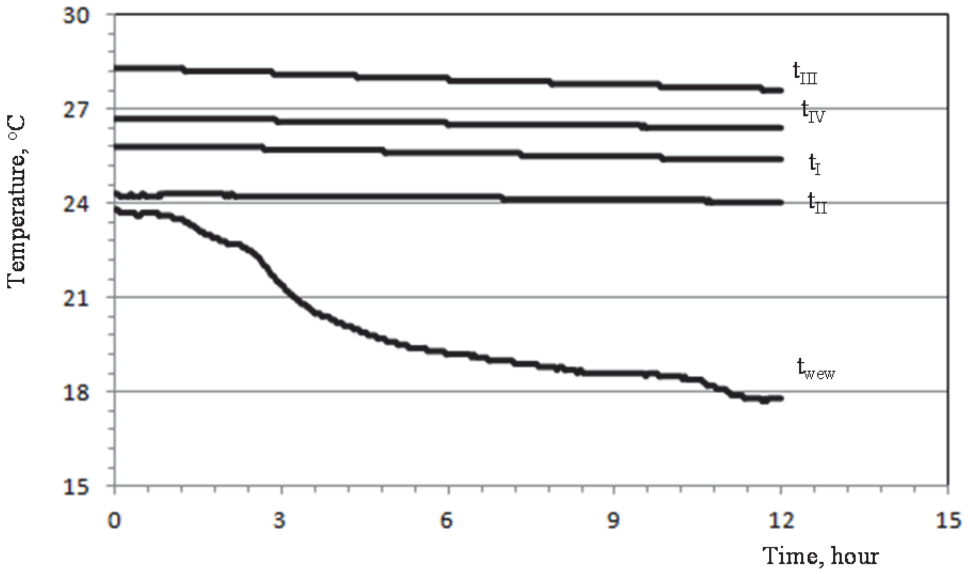

Figure 3. Temperature changes in the bed segments and inside the tunnel

One may notice that for conditions of surrounding, difference between the initial and final temperature of the bed is within 0.3 to 0.8 K. Higher value were reported for the bed segment, which was characterized with a higher value of initial temperature. It proves a good insulation of segments, whereas as a result of narrow scope of temperature changes temperature difference between a final and initial temperature (from 1.1 to 2.9%) towards the initial values, it was assumed in the nomogram that the difference between temperature values used in the control algorithm will be 2K.

During the research, as a result of selection 318 measurement cycles were selected from all possible states of accumulator operation.

Table 1 presents measured and calculated average values of the measured parameters during the measurement cycles along with the detailed duration of experiments.

Table 1

Values of parameters in the analysed cycles during the experiments which were carried out R – intensification of the solar radiation, t – air temperature, RH – relative humidity, V_{wiatr}- wind velocity

Specification	Time, (s)	Surrounding climate				Input		Output		Bed temperature	Air stream
		R ($W \cdot m^{-2}$)	t (^oC)	RH (-)	V_{wiatr} ($m \cdot s^{-1}$)	t (^oC)	RH (-)	t (^oC)	RH (-)	$t_{I,II,III,IV}$ (^oC)	q_{pow}, ($m^3 \cdot cykl^{-1}$)
Minimum value	689	23.3	-6.2	0.261	0.01	10.8	0.155	6.4	0.296	6.7	65.1
Maximum value	53673	891.1	37.1	0.975	3.47	48.7	0.706	33.1	0.944	39.7	6370.2

The course of changes in the amount of the stored heat and changes in the water mass content in air flowing out from the storage was presented graphically in fig. 5 and 6.

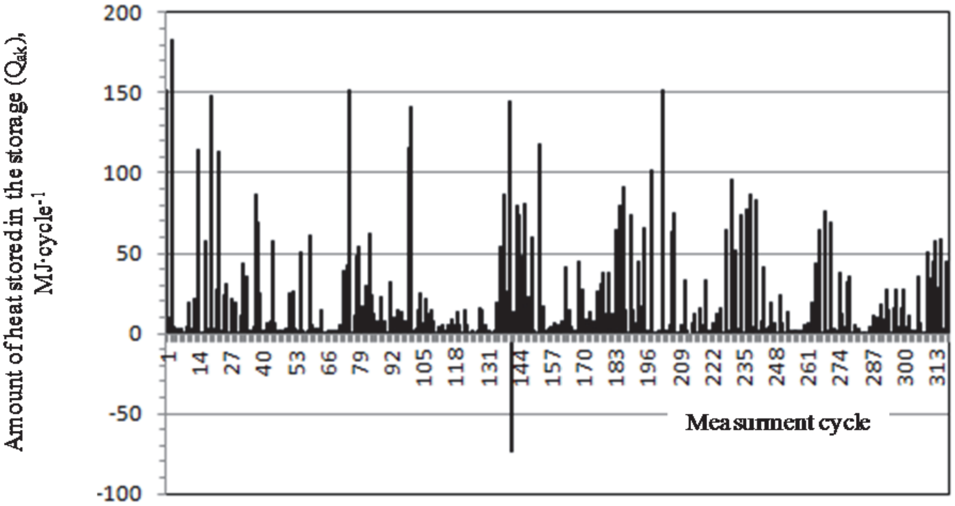

Figure 5. The course of the amount of heat stored in the rock storage

Positive values mean that the heat was stored in the storage whereas, the negative value (cycle 141) shows that in the condition of the performed cycle the amount of the heat obtained from the storage is lower than the amount of the supplied heat. When analysing these data one may assume that the amount of the stored heat in the storage is within -74 to over 182 MJ.

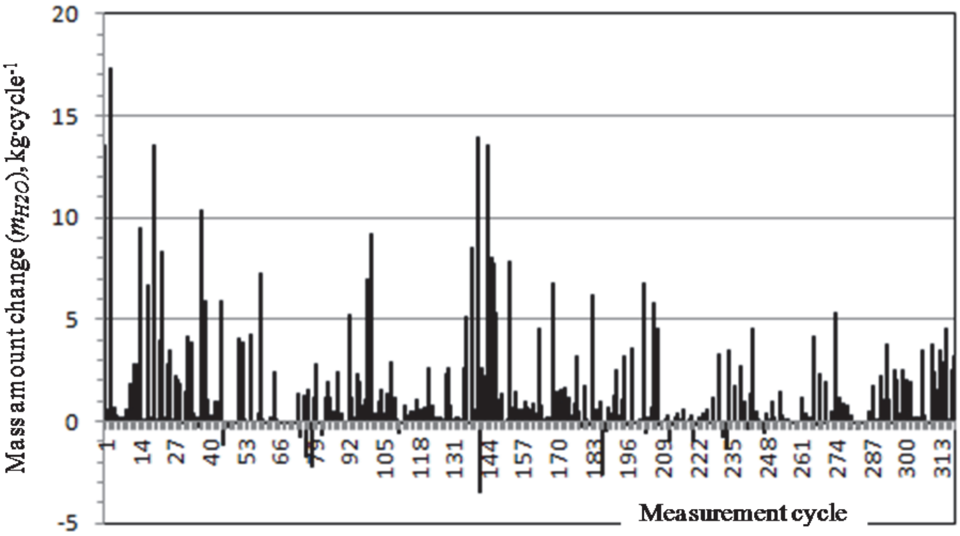

Figure 6. The course of water mass changes in the air flowing out from the storage bed in particular measurement cycles

When analysing the data presented in fig. 6 (positive values mean that the air was dried, the negative, on the other hand mean that it was moistened); similarly to the previous situation, one may report that during experiments, such cycles occurred, as a result of which, evaporation of water from the bed took place and as a result the increase of absolute moisture in air, which was supplied to the inside of the tunnel. In the measurement cycles, which were carried out, the scope of changes was within -3.5 to 17.5 kg·cykl^{-1}.

In order to generalize the obtained results and their application to similar systems which use the rock bed as a heat storage, two approaches were applied. In the first on, the heat stream and the change of the mass stream were determined as dependent variables from velocity (V_{pow}) of the pressed in air (measured in the conduit with diameter 300 mm which presses air to particular segments), initial temperature of the storage (t_{0ak}) and the pressed heat stream (q_{WE}). For the obtained results, the found equation which includes this relation (the form of the power model based on the highest value of coefficient of determination; this relation has been determined with non-linear estimation with quasi-Newton method at maintaining the convergence factor 0.001) takes the following form:

a) for the heat stream (q_{ak})

$$q_{ak} = -295{,}2 \cdot V_{pow}^{0{,}508} + 51{,}18 \cdot q_{WE}^{0{,}43} - 6{,}21 \cdot t_{0ak}^{1{,}16} + 10{,}5 \quad (\mathrm{W \cdot m^{-2}})$$

b) for the heat mass (m_{H2O})

$$m_{H_2O} = -12{,}71 \cdot V_{pow}^{0{,}19} + 5{,}79 \cdot q_{WE}^{0{,}17} - 0{,}0182 \cdot t_{0ak}^{1{,}49} \quad (\mathrm{g \cdot m^{-2} \cdot min^{-1}})$$

Within the scope of use:

$$1.34 \leq V_{pow} \leq 3.25\ \text{m}\cdot\text{s}^{-1};\ 185.5 \leq q_{we} \leq 1064.8\ \text{W}\cdot\text{m}^{-2};\ 2 \leq t_{0ak} \leq 37.7\ (^{o}\text{C})$$

These formulas have been developed including duration of experiments (table 1).

Figure 7 and 8 present graphical comparison between the values calculated from the suggested models and measured values.

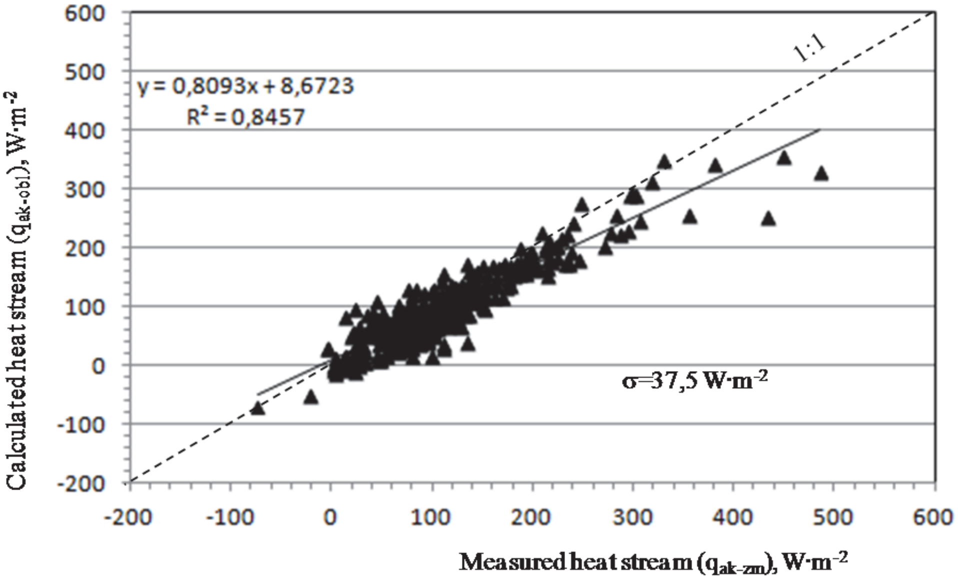

Figure 7. Comparison between the calculated and measured heat streams stored in the rock bed (independent variables: V_{pow}, q_{we}, t_{0ak})

While, in the second case, the values of the dependent variables (heat and mass streams) were made dependent from: supply temperature (t_{WE}), deficiency of steam pressure in the air inside the tunnel (*VPD*) and the stream of the pressed air (q_{pow}). Using, similarly as in the previous case, a procedure, the relation ,which describes the analysed values takes the following form:

– for the heat stream (q_{ak})

$$q_{ak} = 124{,}8 \cdot t_{WE}^{0{,}59} - 65{,}45 \cdot VPD^{0{,}3} - 12{,}92 \cdot q_{pow}^{-1{,}07} \quad (\text{W}\cdot\text{m}^{-2})$$

– for the heat mass (m_{H2O})

$$m_{H_2O} = -612{,}5 \cdot t_{WE}^{0{,}011} + 616{,}22 \cdot VPD^{0{,}0055} - 1{,}1 \cdot q_{pow}^{1{,}49} \quad (\text{g}\cdot\text{m}^{-2}\cdot\text{min}^{-1})$$

Within the scope of use:

$$49.4 \leq t_{WE} \leq 11.1\ \text{m}\cdot\text{s}^{-1};\ 364.4 \leq VPD \leq 8422.4\ \text{Pa};\ 0.09 \leq q_{pow} \leq 0.22\ (\text{m}\cdot\text{s}^{-3})$$

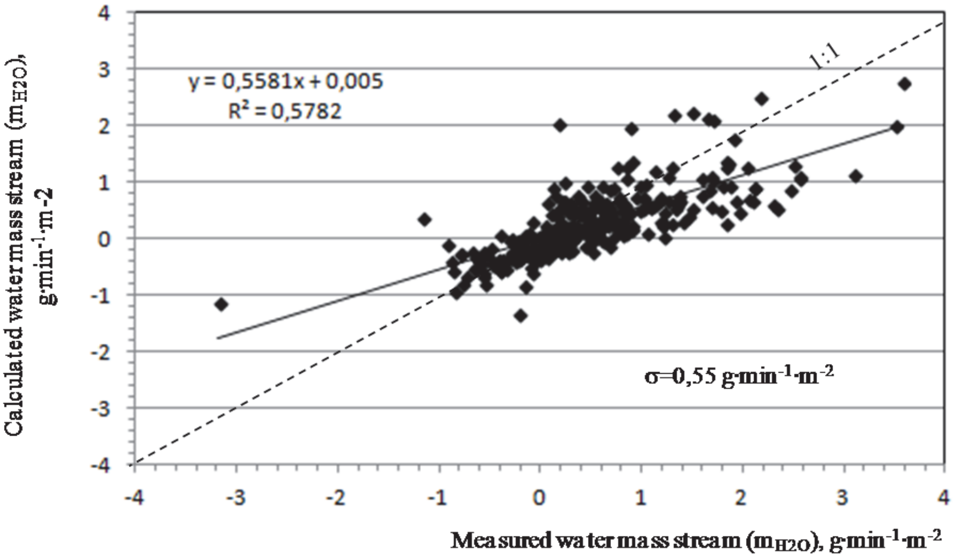

Figure 8. Comparison between the calculated and measured water mass streams in air flowing out from the rock storage (independent variables: V_{pow}, q_{we}, t_{0ak})

Both in the first case (equations a and b) and the other case, statistical analysis proved significance of the determined values of coefficient and exponents, which describe the impact of independent variables on the analysed dependent variables.

Fig. 9 and 10 presents the comparison between values calculated from the relation (c and d) and the measured ones.

Summing up the obtained relations one may conclude that they have (except for cognitive values) also application features. These formulas (within the provided scopes of use of initial variables and the duration of the process) allow determination of the heat and mass stream density. Thus, having a storage of the analysed area (18.7 m^2) and knowing the time of pressing air into it, it is simple to calculate the effects in the form of the amount of the stored heat and exchanged mass.

When analysing changes in the amount of heat stored in the storage and changes of steam content in air which flows out from the bed, one may also observe, that for some values of independent variables there are such cases, in which the storing process does not occur and air is moistened. A detailed analysis of such case will be a subject of further analyses.

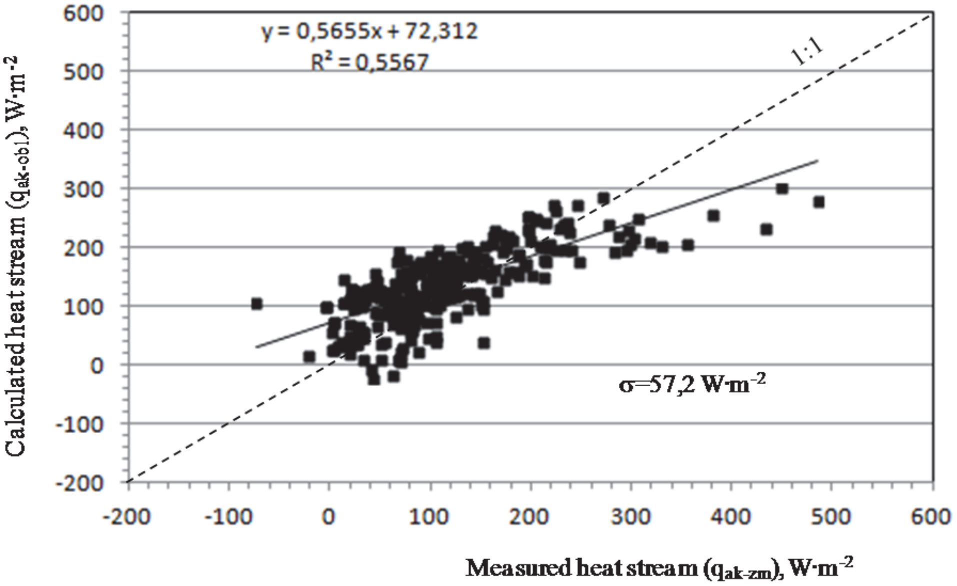

Figure 9. Comparison between the calculated and measured heat streams stored in the rock bed (independent variables: t_{WE}, VPD, q_{pow})

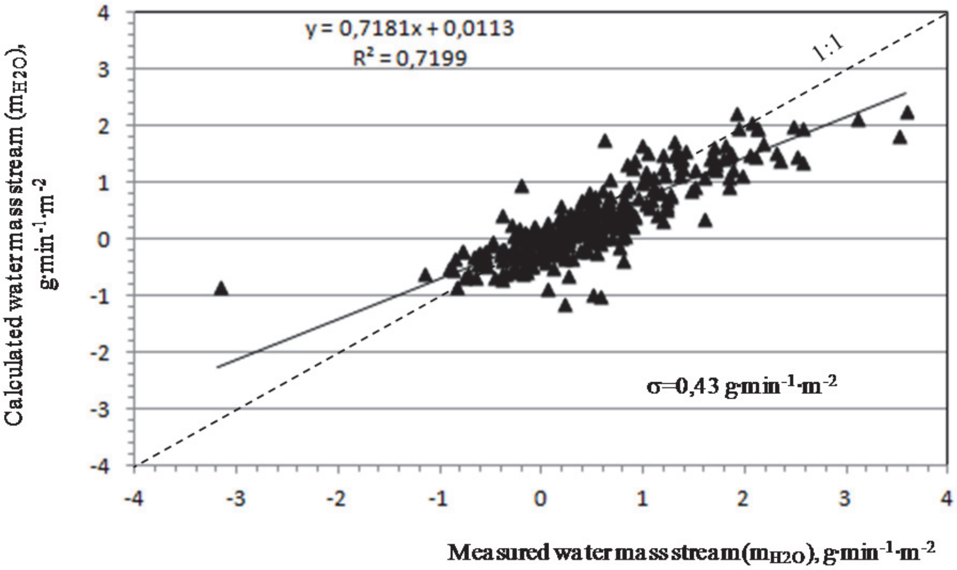

Figure 10. Comparison between the calculated and measured water mass streams in air flowing out from the rock storage (independent variables: t_{WE}, VPD, q_{pow})

Conclusions

1. The total scope of changes in the amount of stored heat in the considered rock storage in the investigated cycles is within -74 and 182 MJ.
2. In the investigated cycles of pressing air inside the rock storage, the scope of changes in the amount of water (calculated as a difference between the water content in the pressed air and flowing out the bed) is within -3.5 to 17.5 kg.
3. Based on the experimental results, equations were determined, which allow, at known input parameters, determination of the heat and mass stream density mentioned in the process of air flow through the rock - bed storage in the cycle of charging.

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ANALIZA WPŁYWU WYBRANYCH CZYNNIKÓW NA ILOŚĆ ZMAGAZYNOWANEGO CIEPŁA ORAZ ZMIANY MASY W AKUMULATORZE O ZŁOŻU KAMIENNYM ZLOKALIZOWANYM W TUNELU DOŚWIADCZALNYM

Streszczenie. W pracy przedstawiono wyniki analizy związanej z przepływem powietrza przez złoże akumulatora kamiennego. Powietrze pozyskiwano z wnętrza tunelu foliowego i tłoczono do segmentów akumulatora o powierzchni 18,7m^2 i objętości blisko 13,1m^3. Badania przeprowadzono w okresie od marca do października 2013r. Cyklem pracy akumulatora (ładowanie lub rozładowanie) sterowano w oparciu o algorytm, w którym sygnał sterujący opierał się o różnicę temperatury między średnią temperaturą złoża a temperaturą wewnątrz tunelu. Do szczegółowej analizy wyodrębniono 318 cykli pomiarowych, w których na bazie zmierzonych parametrów zatłaczanego i wypływającego z akumulatora powietrza określono ilość zmagazynowanego ciepła w akumulatorze oraz zmianę w koncentracji pary wodnej zawartej w powietrzu. Dla uzyskanych wyników znaleziono równania regresji wielokrotnej opisującej jednostkowy strumień ciepła i masy wymienianej podczas przepływu powietrza przez akumulator. Wyznaczono także ilościowe zależności między jednostkowym strumieniem ciepła i masy wymienianym podczas przepływu powietrza przez akumulator uwzględniających dwie grupy zmiennych niezależnych. W pierwszej grupie wykorzystano: prędkość zatłaczanego powietrza (zmierzoną w przewodzie tłoczącym powietrze do poszczególnych segmentów), temperaturę początkową akumulatora oraz strumienia ciepła zatłaczanego. Druga grupa zmiennych niezależnych obejmuje: temperaturę tłoczonego powietrza, deficyt ciśnienia pary wodnej wewnątrz obiektu oraz strumienia zatłaczanego powietrza. Do określenie tych zależności zastosowano estymację nieliniową z wykorzystaniem metody quasi-Newtona.

Słowa kluczowe: magazynowanie ciepła, akumulator kamienny, tunel foliowy