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Thermal effects of the stone battery depending on the bed volumes

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Abstract. The search restrictions energy consumption in horticultural production there are in progress continually. They concern on the one hand reduce heat loss and, second, better use of available energy. Greenhouse efect in the greenhouse forced ventilation process especially in the surplus heat. The paper presents the manner of management of excess heat in the stone battery. Its structure included four segments with a volume of 13.1 m^3 each. Segments of the battery were fed a stream of air in an independent manner. This enabled the work of individual segments or a few at a time. The battery can work in two stages: charging and discharging. Selecting the stage took place automatically according to the developed algorithm. This decision was dependent on the parameters of air flowing through the bed and the thermal state of the battery. During the process of charging and discharging monitored changes in air enthalpy at the inlet and outlet of the battery, and the temperature and relative humidity of air in the bed of battery. For different bed volumes increases its temperature, heat storage capacity and the ability to absorb water vapoure was determined.

1 Introduction

Environmental control in horticultural crops plays an important role. Possibility of adjusting the relevant parameters for plant growth conducive to intensification of production and achieving a good quality crop. To achieve this purpose, a number of technical solutions are applied. These include, inter alia, various types of coverage, modern heating systems and systems of accumulating heat.

The heat production under cover plays a key role especially in times of its deficiency in total production costs can reach up to 70%. One of the solutions to reduce these expenditures is the development of excess heat in the plastic tunnel caused by the greenhouse effect. Normally, excess heat is removed by ventilation. It is the heat flux lost forever. Reasonable, therefore, it is to use a system that accumulated excess heat. However, the differences in access of energy and heat demand affect the dispatch ability and performance [1].

In principle, the heat can be stored using the specific heat, heat of fusion and solidification. It depends on the type of materials and, more specifically whether during heating/cooling undergo a phase transition. The ability of the heat storage material in terms of the specific heat is highly dependent on the heat capacity. In addition to this criterion must be considered also good thermal conductivity and cost material [2].

In literature different types of media are used to heat accumulation. Using only the specific heat of these materials should be characterized by low cost of utilisable heat, high heat transfer coefficient in the process of charging and discharging the battery, ease of use and be friendly to the environment [3-6].

Storage of excess heat in the battery water for energy needs in the greenhouse or plastic tunnel is not very effective. Only such a solution is useful for the preparation of process water [7]. A better solution to this is to use a base stone. Ease of obtaining heat and supplying it to the battery on one side and on the other hand, heat distribution for the rows on the existing cultivation gutters provide a simple solution. Presented in articles [8-12] results indicate that the storage of surplus heat brings tangible results.

Due to varying environmental conditions available flow of surplus heat possible to the development needs of different size battery. Similarly, the use of its potential to meet the needs of heat resulting from the impact of climate outside. This is evidenced by searching multiple authors presented above. Therefore, in operation seeks to provide determination of the increase in temperature, the heat accumulation capacity and the absorption of water vapour in the battery depending on its volume.

2 Materials and methods

The experiment was conducted in a plastic tunnel, which was a four-segment battery stone. It was built below the level of cultivation area. All the walls and interior partitions were isolated 10 cm insulating material. Each segment contains 12.23 m^3 of stone (porphyry) of grain size of 30 - 63 mm. Jobs individual segments in both process of charging and discharging was supervised by the measurement system. This system also archived all the

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parameters monitored battery working conditions and the data associated with its surroundings.

The all segments of battery was supplied by stream of hot air during charging process. The stream of warm air from the upper layers of plastic tunnel was powered segments of stone battery. During this process was observed in the bed of battery changes of temperature, the quantity of accumulated heat and moisture content (Fig.1.). At the output from the battery to be monitored the same parameters as was the case at the entrance. Comparison of the state of the air inlet and outlet was the basis for the calculation of heat that has accumulated by battery.

The stone battery worked in two cycles. The first concerned the charge process, and the second discharge process. In the process of charging the system supplied to the battery the stream of warm air from the upper part of the tunnel film during the day. In the discharging process the system supplied to the battery the stream of cooled air came from the lower part of the tunnel film during night. In both cycles of the air flow coming out of the battery was directed to the interior of the object.

During the experiment the parameters of work of battery and the parameters of air flow were monitored. During the experiment monitored parameters regarding battery mining and parameters of air flow.

In the study were monitored and recorded the following data:

- Temperature of stone battery,
- The operating status of individual segments,
- Temperature and relative humidity over heat screens and inside the tunnel,
- Temperature and relative humidity on the output of the battery,
- The mass of air flowed through the battery was calculated on the basis of measuring the speed of air stream.

These values were used to determine the amount of heat and mass of the steam during simultaneous operation of I, II, III or IV of the battery segments. In the charging process was specified amount of accumulated heat and the mass of water vapour which was absorbed by each segment of the bed according to formulas 1 and 2. Similarly, in the discharge process the characteristics were defined above. To differentiate the processes of charging and discharging the heat accumulated in the accumulator is positive, and the heat comes from battery (discharge process) and put into the tunnel is negative. Similarly, the sign associated with the mass of water vapour - is positive absorption (dehumidify the air passing through the bed) of water vapour in the bed. While a negative sign indicates moistened air leaving the battery (evaporation of water accumulated in the deposit).

The quantity of heat accumulated in the battery (dQ_{batt}) was defined as the change in enthalpy of air at the inlet and outlet of the battery as result the flowing air stream in the time interval (dτ).

$$dQ_{batt} = m_{air} \cdot \int_{\tau_1}^{\tau_1+\tau} \left(i_{in} - i_{out}\right) d\tau \qquad (1)$$

The quantity of water vapour (dm_{water}) stored in the stone accumulator was calculated as the difference of concentration of water vapour at the inlet and outlet of the battery as result the flowing air stream in the time interval (dτ).

$$dm_{water} = V_{air} \cdot \int_{\tau_1}^{\tau_1+\tau} \left(x_{in} - x_{out}\right) d\tau \qquad (2)$$

where: m_{air} - air mass, kg; i_{in}, i_{out} - enthalpy of inlet (i_{in}) and outlet (i_{out}) from a battery, kJ/kg; V_{air} - air volume, m^3; x - concentration of water vapour (kg$_{\mathrm{vapour}}$/m^3) inlet (x_{in}) and outlet (x_{out}).

Enthalpy and concentration of water vapour of the air stream input and output have been calculated according to the psychometric formulas for the process of charging and discharging battery.

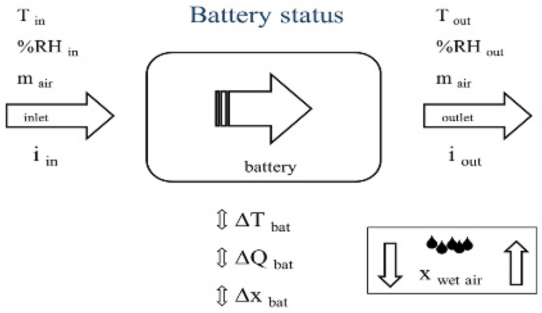

Figure 1. Scheme of process for charge and discharge the stone battery.

3 Results and discussion

For the analysis was selected cycles of charging and discharging the stone battery operating in same time for four configurations: I - one segment, II - two segments, III - three segments, IV - four segments.

This meant monitoring battery for four different volumes. The research took place in the conditions of a real object which was the plastic tunnel.

Figures 2 and 3 show the comparison of the time of charging and discharging for individual segments of the battery. About twice longer the discharge time of segments was resulted of a lower temperature differential inputs and outputs compared to the charging process. Energy accumulated in the battery (Fig.2.) was calculated based on the difference in enthalpy of the air at the entry and exit of individual segments of the battery. This energy was also dependent on the mass of air flowing through the stone bed during the charging cycle.

Discharge cycle of individual segments of the battery (Fig.3.) shows the amount of useful energy. Heat is supplied to the interior of the tunnel. Negative values shown in the graph was used to distinguish the stored energy from useful energy.

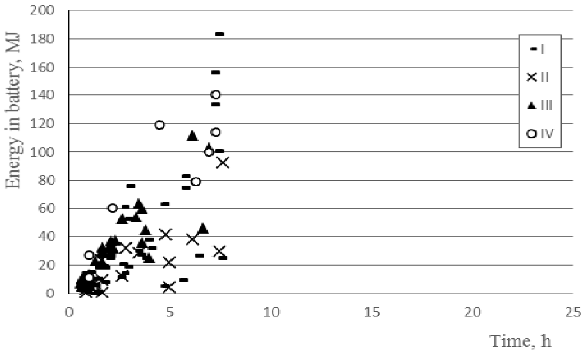

Figure 2. Storage energy in the battery depending on charging time for various bed volume.

The amount of stored energy in the battery during charging cycle also affects the temperature of the bed in each segment (Fig.4.). In the course of the experiment the temperature of a single segment increased from 0.1 to 19.2 ^{0}C with an average value of stored energy at 30.8 MJ. For the two segments change in temperature of the bed contains from 0.1 to 6.8 ^{0}C. For the three and the four segments of these changes ranged from 0 to 3.7 ^{0}C and 0.2 to 2.9 ^{0}C respectively.

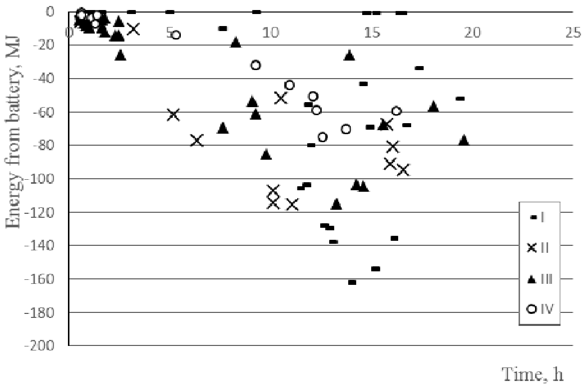

Figure 3. Useful energy of the battery depending on discharging time for various bed volume.

Simultaneous increase an amount of concurrent segments, and thus the volume of the bed caused heating of the battery (segments) to a lower temperature. The average amount per unit of energy stored in the individual segments of the battery for the above temperature ranges were as follows: II-segments - 19.4 MJ, III-segments - 30.7 MJ, IV-segments - 81.4 MJ.

The process of charging the different segments of stone battery was conducted under the conditions which were the following: battery volume (V_{ak}), 12.3≤ V_{ak} ≤48.9 m^3; air temperature of the inlet (t_{NC}), 10.1 ≤ t_{NC} ≤ 38.2 ^{0}C; air relative humidity (ϕ_{NC}), 10.7≤ϕ_{NC} ≤ 67.2%; mass of air flowing through the bed (m_{air}), 0.1 ≤ m_{air} ≤ 1658.7 kg, cycle time (τ) 0.5≤ τ≤7.6 hours.

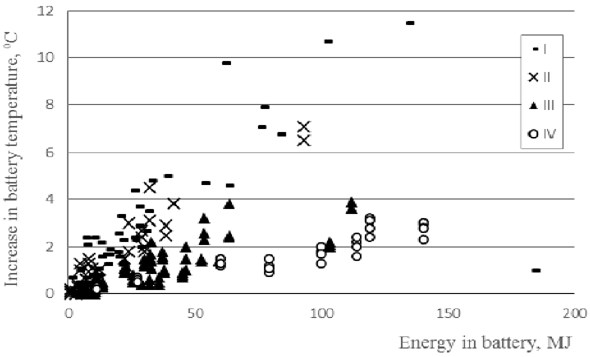

Figure 4. Increase the temperature of the battery depending on stored energy for various bed volume.

Figure 5 shows the dependence of the energy stored in the battery at different temperatures in the bed, depending on the number of segments working simultaneously.

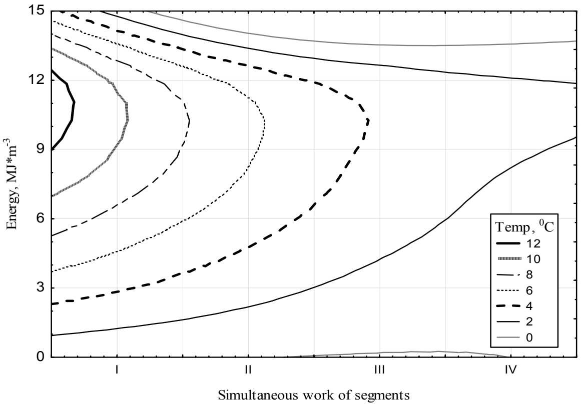

Figure 5. Accumulated energy in the battery depending on its temperature for various bed volume.

Next figure (6) describes how the absorption of water in the battery depending on the temperature and the amount of concurrent segments. Positive values indicate the absorption of condensation of water vapour in the bed and also the drying air leaving the battery. This is particularly noticeable during the charging cycle if the battery temperature rises above 2 ^{0}C Negative values concern to the process of evaporation of water from the battery. Then the air at the output of the battery becomes moist.

The correlation equations for the flow of heat and mass were determined on the basis of the monitored operating parameters of the individual segments in the course of the experiment . The values of these streams are dependent on the parameter input and output, taking into account their interdependence. The significance of the parameters determining the value stream was set at a significance level of less than 0.05 as linear estimation using the quasi-Newton's method.

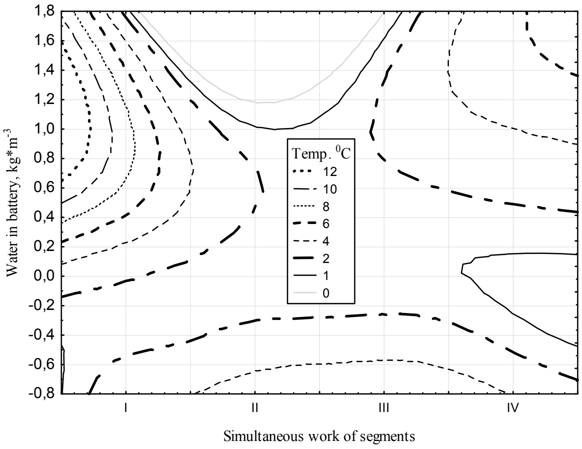

Figure 6. Absorbed water in the battery depending on its temperature for various bed volume - charging process.

Charging process of stone battery (**one segment**):
Heat accumulated in the battery (MJ/m^3):

$$q_{LOAD} = 0.563 \cdot t_{batt} + 0.051 \cdot t_{NC} - 0.038 \cdot \phi_{NC} + 0.83 \cdot m_{vapour}$$

R^2=0.68

Mass of water vapour absorbed in the battery (g/m^3):

$$m_{Lwater} = 126.861 \cdot q_{LOAD} - 50.548 \cdot t_{batt} - 5.762 \cdot t_{NC} + 3.271 \cdot \phi_{NC}$$

R^2=0.82

Charging process of stone battery (**two segments**):
Heat accumulated in the battery (MJ/m^3):

$$q_{LOAD} = 0.006 \cdot m_{air} + 0.256 \cdot t_{NC} - 0.06 \cdot \phi_{NC} - 9.662$$

R^2=0.96

Mass of water vapour absorbed in the battery (g/m^3):

$$m_{Lwater} = -1.238 \cdot m_{air} - 20.428 \cdot t_{NC} + 26.567 \cdot \phi_{NC}$$

R^2=0.80

Charging process of stone battery (**three segments**):
Heat accumulated in the battery (MJ/m^3):

$$q_{LOAD} = 0.006 \cdot m_{air} + 0.256 \cdot t_{NC} + 0.06 \cdot \phi_{NC} - 9.662$$

R^2=0.96

Mass of water vapour absorbed in the battery (g/m^3):

$$m_{Lwater} = -159.872 \cdot t_{batt} + 0.539 \cdot m_{air} - 7.757 \cdot t_{NC} + 10.581 \cdot \phi_{NC}$$

R^2=0.43

Charging process of stone battery (**four segments**):
Heat accumulated in the battery (MJ/m^3):

$$q_{LOAD} = 3.251 \cdot t_{batt} - 0.148 \cdot t_{NC} - 0.176 \cdot \phi_{wew}$$

R^2=0.96

Mass of water vapour absorbed in the battery (g/m^3):

$$m_{Lwater} = 79{,}826 \cdot q_{LOAD} - 23.915 \cdot t_{NC} + 31.245 \cdot \phi_{wew} +$$

R^2=0.89

The process of charging the individual segments of the battery showed two phenomena inside. The first is the rise of temperature of the battery with the supplied energy. The carrier is a stream of warm air from inside the tunnel. The second phenomenon is more complex because it relates to the transformation of water vapour in to the battery. A stream of warm air, which supplies the battery also provides a certain amount of water vapour. This pair in contact with a cool bed may condense. This means that absorption of water vapour by the accumulator. Analysing the accumulation of water vapour in the segments turned out that the segments I, II and III followed by condensation and evaporation of water. The extent of these changes were in the range from -741.5 to 1,877.4 g/m^3 bed. Only the work of four segments characterized by only a process of condensing level of 42.9 to 754.2 g/m^3.

Lowering the temperature of the individual segments of the battery and the amount of useful energy obtained by a discharge process were marked as the negative values (Fig. 7.). The average amount of energy supplied from the individual segments of battery was as follows: I-segment - 48.2 MJ, II-segments - 31.7 MJ, III-segments - 9.8 MJ, IV-segments - 28.1 MJ. Delivery the heat to the inside tunnel lowered the temperature of the individual segments. The average values of decreasing temperature were respectively: I-segment - 2.6 ^{0}C, II-segments - 0.9 ^{0}C, III-segments - 0.1 ^{0}C, IV-segments - 0.5 ^{0}C.

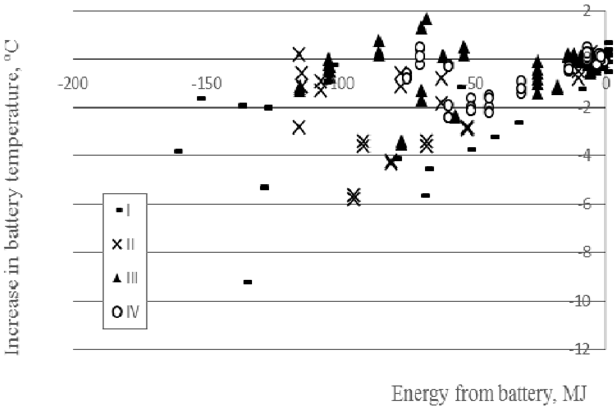

Figure 7. Decrease the temperature of the battery depending on downloaded energy for various bed volume.

Discharging cycle: battery volume (V_{ak}), 12.3≤ V_{ak} ≤48.9 m^3; air temperature of the inlet (t_{wew}), -3.6 ≤ t_{wew} ≤ 21.2 ^{0}C; air relative humidity (ϕ_{wew}), 42.0≤ϕ_{wew} ≤ 90.2%; mass of air flowing through the bed (m_{air}), 0.1 ≤ m_{air} ≤ 625.1 kg, cycle time (τ) 0.5≤ τ≤19.6 hours.

Figure 8 shows the dependence of the energy supplied from the battery at different temperatures in the bed, depending on the number of segments working simultaneously. For the analysis of the available energy from the battery in the process of discharge (useful energy) assumed negative values. This assumption is made to quickly identify the processes of charging and discharging of the battery.

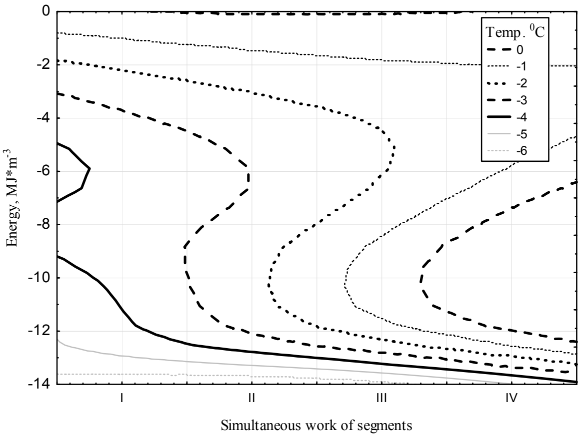

Figure 8. Downloaded energy from the battery depending on its temperature for various bed volume.

The absorption of water in the battery depending on the temperature and the amount of concurrent segments in the process of discharge (Fig. 9) has a negative value. That is, in this cycle, the water contained in the bed evaporates and humidified air leaving the battery. This is particularly evident during the operation of a single segment, for cooling the bed which contributes to a smaller evaporation of water. The work of two or three segments had little effect on humidification air heated from the battery in comparison to the work of one or four segments. The lack of air humidification in the process of discharging the battery is vital for plants grown in plastic tunnel. This is important because of the need to remove excess water formed in the process of plant growth.

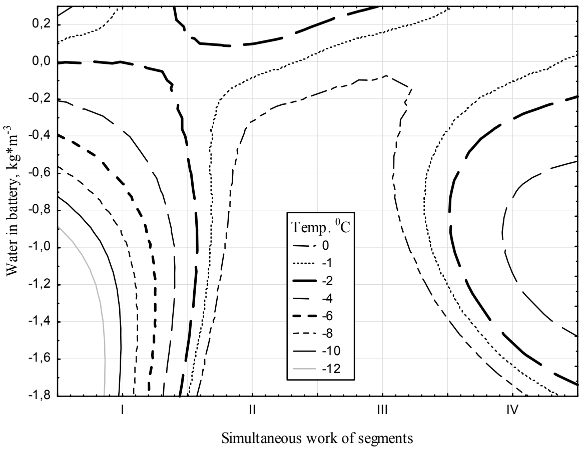

Figure 9. Absorbed water in the battery depending on its temperature for various bed volume - discharging process.

For the process of discharging the correlation equations for the flow of heat and mass were determined on the same way as for process of charging.

Discharging process of stone battery (**one segment**):
Downloaded heat from the battery (MJ/m^3):

$$q_{unload} = 0{,}314 \cdot t_{batt} - 0{,}02 \cdot m_{air} + 0.106 \cdot t_{wew}$$
R^2=0.66

Mass of water vapour absorbed in the battery (g/m^3):

$$m_{Uwater} = 10.02 \cdot m_{air} + 115.25 \cdot t_{wew} + 58.49 \cdot \phi_{wew} - 4608.33$$
R^2=0.87

Discharging process of stone battery (**two segments**):
Downloaded heat from the battery (MJ/m^3):

$$q_{unload} = -0.016 \cdot t_{wew} - 0.023 \cdot m_{air} - 0.002 \cdot \phi_{wew} + 0.002 \cdot m_{vapour} + 0.359$$
R^2=0.99

Mass of water vapour absorbed in the battery (g/m^3):

$$m_{Uwater} = 406.67 \cdot q_{unload} + 9.427 \cdot m_{air} + 6.433 \cdot t_{wew} + 0.851 \cdot \phi_{wew} + -144.246$$
R^2=0,99

Discharging process of stone battery (**three segments**):
Downloaded heat from the battery (MJ/m^3):

$$q_{unload} = 0.067 \cdot t_{batt} - 0{,}023 \cdot m_{air}$$
R^2=0.99

Mass of water vapour absorbed in the battery (g/m^3):

$$m_{Uwater} = 410.392 \cdot q_{unload} + 9.623 \cdot m_{air} + 3.792 \cdot t_{wew} - 65.202$$
R^2=0.99

Discharging process of stone battery (**four segments**):
Downloaded heat from the battery (MJ/m^3):

$$q_{unload} = -0.023 \cdot m_{air} + 0.004 \cdot m_{vapour}$$
R^2=0.99

Mass of water vapour absorbed in the battery (g/m^3):

$$m_{Uwater} = 9.875 \cdot m_{air} + 5.021 \cdot t_{wew} - 1.183 \cdot \phi_{wew} + 421.347 \cdot q_{unload}$$
R^2=0,99

The process of discharging the individual segments of the battery showed that the most useful energy referred to the unit volume of deposits can be obtained with the single segment. The average value of this energy was 3.9 MJ/m^3. The energy obtained from the segment - double and quadruple was at the average level of 2.6 MJ/m^3 and 2.3 MJ/m^3 respectively. The smallest useful energy was in the triple segment. It was about 0.8 MJ/m^3.

In the process of discharging the most important role played the water vapour during operation of a single segment. On average, the amount of water which vapour exhausting out of the battery was at 133.8 g/m^3 bed with a maximum value of 1939.2 g/m^3. This meant that during the operation of this segment of the air coming out was mainly humidified. Better results achieved for the other segments. During their work followed by absorption of water vapour. The amount of vapour absorbed by these segments were contained on average from 10.0 to 59.0 g/m^3. Operating variables segments II, III and IV also cause evaporation of the water. `For single discharge cycles the amount of water vapour absorbed by the air stream didn't exceed, respectively for segments: II - 89.9 g/m^3, III - 66.1 g/m^3 and IV - 51.2 g/m^3.

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4 Conclusions

1. In the process of charging the highest average amount of accumulated heat (6.6 MJ/m^3) was recorded for the four operating segments simultaneously. While the lowest (1.6 MJ/m^3) for the two segments.
2. Only in the process of loading the four segments at the same time there were no evaporation of water from the reservoir. In other cases they occurred in both of evaporation and condensation.
3. The biggest average gain of useful heat was obtained in the process of discharging a single segment (3.9 MJ/m^3) and the lowest value 0.8 MJ/m^{3}for triple segment.
4. The dried air from the battery bed in the process of discharge is easier to achieve using more segments of the battery compare to the one.

Acknowledgements

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