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ANALYSIS OF EFFECTIVENESS OF STORING WASTE HEAT IN THE WATER ACCUMULATOR[1]

Kazimierz Rutkowski[a*], Jan Vogelgesang[a], Pavol Findura[b]

[a]Institute of Agricultural Engineering and Informatics at the University of Agriculture in Krakow
[b]Department of Machines and Production Systems, Slovak University of Agriculture in Nitra
[*]*Contact details: ul. Balicka 116B, 30-149 Kraków, e-mail: kazimierz.rutkowski@ur.krakow.pl*

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ABSTRACT

The paper presents analysis of the ways in which waste heat collected from the upper space of the plastic tunnel may be used. Warm air sucked from the upper space was pumped to a diffuser located in the process water tank. The assumed method was theoretically analysed and then tests were carried out in a real facility. Air bubbles moving in the liquid layer transferred heat, which they contained. The initial research, carried out according to the assumed method, did not bring satisfactory results. Nonetheless, some relations and possibilities of improvement of the described method by increasing the degree of complexity and the system costs were reported.

Introduction

The organic and economic factors as well as the threat resulting from the lack of energy resources, enforce new trends in searching for energy sources. Popular, the so-called renewable energy sources not always completely satisfy our expectations. The use is completely justified if we carry out a multi-criteria assessment of their obtaining and use (Rutkowski, 2008; 2009). Sometimes, we should think how to improve energy effectiveness of the existing systems and how to carry out analysis on the existence of sources and possibilities of using the waste energy.

In the horticultural production in crop cultivation under cover considerable heat consumption is reported in the winter season but in the period of early spring and later, the greenhouse effect causes production of great amount of heat, which is wasted in most cases. On the other hand, within the same period, the production process requires heat even for heating the process water or for short-term storage in order to use it at night. We should also remember that the present level of technology allows transformation of energy parameters, which in a new form will find wider application. For example, heat pumps supplied from the source, which has higher temperature, reach high efficiency (Rubik, 2011). Taking

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into account high prices of heat pumps, one should carry out an extended economic analysis on the production activity when making an investment decision. However, before we make investment decisions, we should analyse one of the manners of using waste energy, which is heating the process water with the use of a diffuser.

The object of the research is a plastic tunnel with dimensions 9x16 m, which has a double plastic cover, filled in with air. In the upper part of a tunnel (fig.1) two intakes made of spiro pipes are located. Openings of 35 mm diameter were made in the spiro pipes of 300 mm diameter. The total surface area of openings constitutes 270% of the cross-section of a suction pipe. A suction pipe was connected to a fan, which pumps air to the diffuser located in the process water tank. Performance of the fan could have been arbitrarily changed during the tests. Measurement of the energy parameters was carried out with the use of the available apparatus used for another tests in the analysed facility. Figure 1 presents distribution of the measurement points.

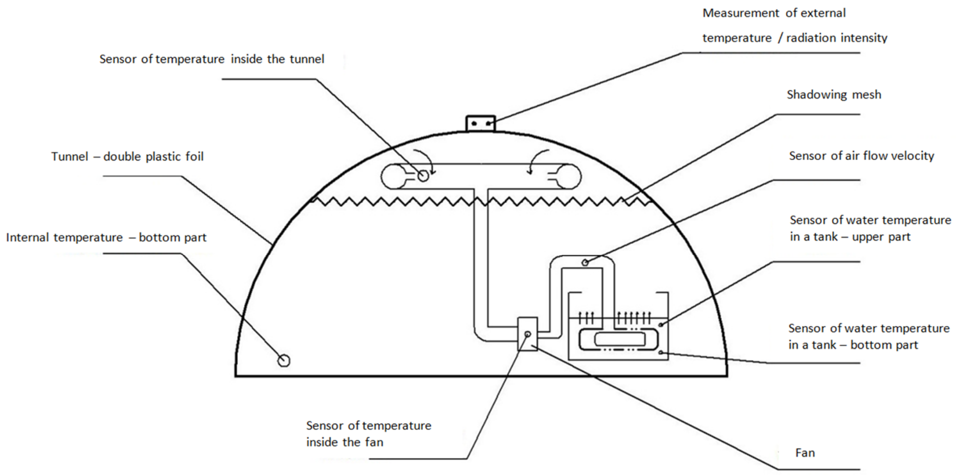

Figure. 1 Schematic representation of the test rigs

In the facilities under cover, as a result of solar radiation a great variability of temperatures occurs in the vertical arrangement. When analysing the temperature course inside the facility in the period of research presented in figure 4, we will notice that the temperature in the upper zone of the plastic tunnel in the afternoon is three times higher than in the plant vegetation zone. When using a shadowing mesh in the upper part of the tunnel, we separate this zone, thus obtaining in the system of heat recovery more even, high temperature. Excess of heat, which is collected during the day over the shadowing mesh, may be successfully stored in order to secure heat deficiencies at night in facilities which do not have a continuously operating heating system, or for heating e.g. the process water or supplying the bottom source of the heat pump. In order to find the simplest, economical solution, the system presented in figure 2 was taken into consideration.

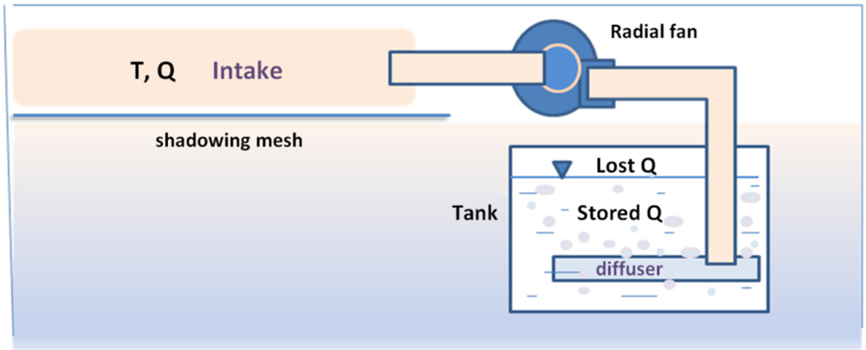

Figure. 2 Schematic representation of the technical system for recovery of heat waste concentrating over shadowing mesh

The objective of the paper was to determine effectiveness of the direct heat exchange in the diffused flow in the above-presented technical system

Total energy intake of this system is defined by the fan operation L_w.

$$L_w = L_p + L_b$$

where:

L_p – work of shaping the inflow stream to diffuser

L_b – work of forming bubbles in the diffuser openings for performance of ballott (free inflow)

Effectiveness condition requires that:

$$L_w < Q_{mag}$$

where:

Q_{mag} – supply of the collected heat in the accumulator tank

Although the initial theoretical assumptions indicated restrictions related with this method in the aspect of heat exchange, the above method may be taken into consideration and may be improved in case of the recovery of waste energy. Since there are no documented literature assessments in this scope therefore basic research should be carried out. A simple structure of the system did not require financial expenditures and enabled realization of experimental research with the use of standard laboratory equipment.

A simplified theoretical analysis of the system had, in this case, a nature of a simple application of the relation of airing systems generally popular in the field of environmental protection, water physics, floatation etc. The paper includes mainly the patterns and methods provided by (Podgórski, 2012; Kowal et al., 1997; Szyszka, 2004; Weinerowska et al., 2004).

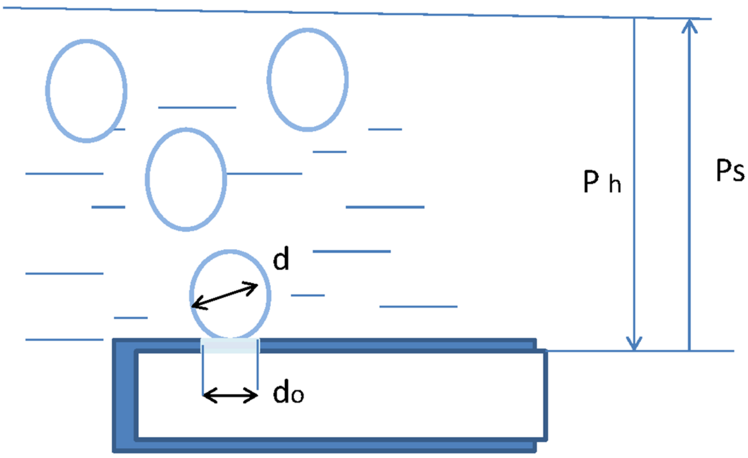

Figure. 3 Air bubble formation

According to these relations, the following assumptions were made:

1. Free ballotage or free beading effect begins from the balance state $p_h = p_s$ namely, from the state of pressure balance from the column of liquid over the diffuser and pressure of the supplied air (fig. 3).
2. Diameter of bubbles d depends on the diameter d_o and the surface tension σ. Bubbles do not absorb gases dissolved in water, they do not merge thus they do not considerably change their diameter during the outflow (there is an impact of small pressure decrease along with ascending but simultaneously bubbles are chilled).
3. Velocity of outflow in free ballotage is mainly a function of bubbles diameter d and liquid viscosity. As a result of the buoyant force as well as the viscosity force, air bubbles move along the considerable part of a trajectory with a uniform motion.
4. The number of bubbles in the free ballotage per a time unit is determined by the air flow intensity in $m^3 \cdot s^{-1}$ in connection to the total area of outflow openings.
5. Bubbles with diameter of ≈ 2 mm maintain a rounded shape in water, their velocity in water fluctuates within 0.2 to 0.3 $m \cdot s^{-1}$ (above this diameter, the flow resistance may cause shape deformation).

Initial selection of the input parameters of the suggested system was based on the following assumptions:

1. The set volume of the heated air intake was approx. 60 m^3. It was assumed that an hourly average number of exchanges in the investigated period corresponding to the average sun exposure was 6 (in reality from 4 to 8 exchanges due to variable conditions of sun exposure).
2. The height of water surface over the diffuser should not be too low so that a bubble has enough time to give back heat, but it was also too big for the fan to balance pressure.
3. Time of bubble ouflow should enable effective heat exchange. Since "the heat stock" in a bubble is proportional to d^3 and the surface area of heat exchange to d^2. Shortening the exchange time requires decrease of the bubble diameter.

The above shows that the bubble diameter and the height of the water column over a diffuser decide in this case on the length of the bubble route and the time of heat exchange. These assumptions determined difficulties in the performance of research on the selection of a fan and an appropriate diffuser. According to the recommendations (Gondek, 2000) a fan with low efficiency but good pile-up properties, high-pressure (up to 10, 000 Pa) should be applied. A radial fan with the maximum power of 1.5 kW, efficiency of 300 $m^3 \cdot h^{-1}$, Δp = 8,000 Pa, the rotational speed of which was regulated with the use of the electronic system (HPB-F-200-150), ensured similar parameters to the required conditions.

Selection of a diffuser required the following conditions to be met.

1. The area of outlet openings of diffusers should correspond to the cross section of the outlet channel of the fan suggested above with a 100 mm diameter.
2. A diffuser should ensure possibly the lowest diameter of bubbles.

In this case due to the costs of the experiment, minimization of the outlet openings diameter was attempted by wrapping a perforated pipe made of plastic with a high-density cloth. A 2.5 m long diffuser with a cross-section diameter d=50 mm was used. In order to check the condition 1 of the compliance of the area, the measurement of the air speed flow in the outlet channel of the fan was carried out before and after the diffuser was mounted. The applied diffuser did not show suppression of flow. Nonetheless, no bubbles, formed this way, with diameters below 1 mm, were obtained. Diameters remained within 1 to several millimeters.

A tank with volume V=9001, where heat was stored, was made of polyamid and was thermally insulated. The maximum height of water surface from the diffuser axis was 700 mm and corresponded to the possibilities of balancing pressure of the applied fan. For such assumed technical system, initial calculations were made. Calculations were carried out including typical conditions in the possessed experimental greenhouse. Moreover, the author's own computer program, which carried out calculation of the heat exchange, was used in a simulation. This program was created as a part of another research work.

The air flow of 0.1 $m^3 \cdot s^{-1}$ with temperature 30ºC was assumed for calculations. During the beading effect, this stream occurs in the form of $2.4 \cdot 10^7$ bubbles with the total area of 312 m^2 and heats a water tank with a complex initial temperature of 15ºC . The simulation proved that the flow process is accompanied by small heat exchange. The temperature increase was estimated as 1ºC after approx. 1 hour of exchange. Despite rather unfavourable results of simulation for verification, a decision was taken to carry out an experiment in the real facility. Since, for the accepted model, the greatest uncertainty was brought along with a thermal transfer coefficient *U* taken from thermodynamic tables Engineering ToolBox. This coefficient is calculated according to the following formula:

$$U = (h_1^{-1} + l\,\lambda^{-1} + h_2^{-1})^{-1}$$

where:

- h_1 – coefficient of heat transfer by water from the external side of a buble, $(W \cdot (m^2 \cdot K)^{-1})$
- l – thickness of a membrane which is around a bubble, (m)
- λ – heat transfer coefficient of the surface surrounding a bubble, $(W \cdot (m \cdot K)^{-1})$
- h_2 – coefficient of heat transfer by air from the inside, $(W \cdot (m^2 \cdot K)^{-1})$

A partition, namely a water layer with specific directed tensions, which surrounds the air bubble, is characterised by uncertainty (but not only the partition). The second factor is an impact of the bubble velocity and the related phenomena (turbulences) on the heat exchange. The obtained results of experiments are presented in figure 4.

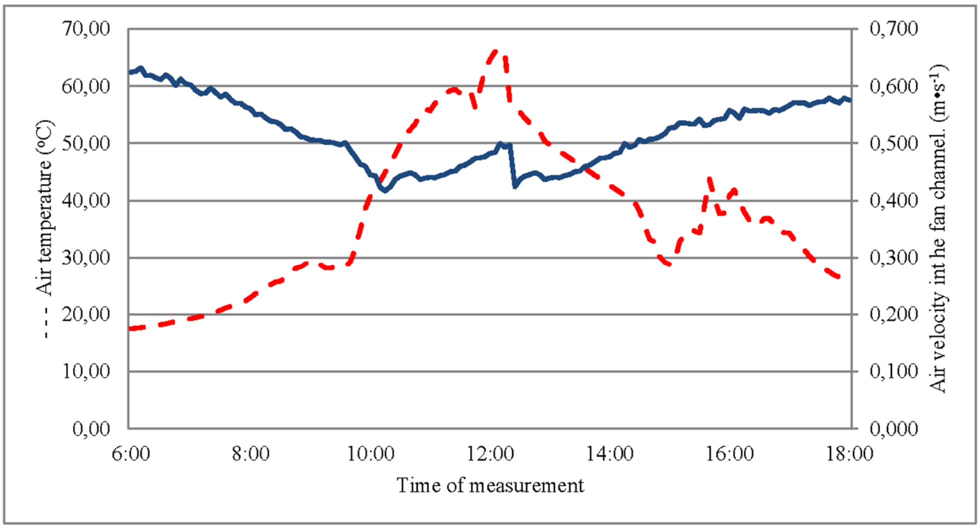

Figure. 4 Physical parameters of air over the shadowing mesh (exemplary day of research)

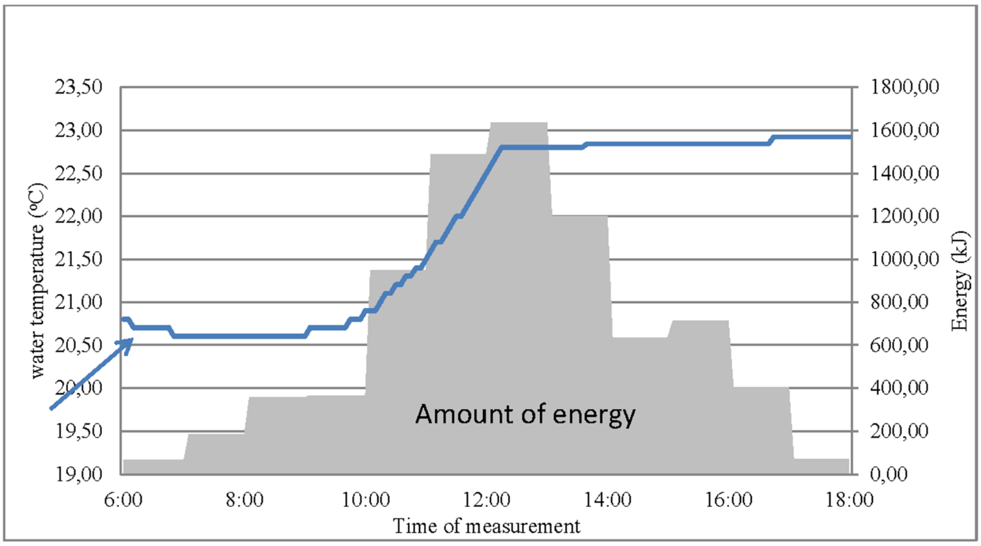

Figure. 5 Dynamics of heating the process water (exemplary day of research)

When tracing the amount of energy obtained from the upper space of the investigated plastic tunnel, one may notice that it is not too high; however, in the aspect of the crop technology, the value of the process water temperature has a significant impact on the production efficiency. Raising water temperature in the existing conditions of research by 2-3ºC is not much but it should be emphasised that in relation to the type of the cultivated plants on the investigated surface of the tunnel, demand for process water is as much as 8 times lower in comparison to the tank volume.

In the accepted weekly period of research (3rd decade of February) average values of the obtained results are as follows;

1. In the accepted conditions of research at the average value of the intensity of solar radiation at the level of 185 $W \cdot m^2$ (within 10 hours) in the tank of volume of 900 l water temperature raises at the average by 3.5ºC.
2. In the accepted conditions of research, heat stored in the process water constitutes approx. 50% of the electric energy consumption which serves as the fan drive
3. The obtained value of the heat transfer coefficient (air bubbles - water) is two times lower than the one assumed in simulation calculations (assumed: 0.6 $W \cdot m^{-2} \cdot K^{-1}$, obtained: 0.3 $W \cdot m^{-2} \cdot K^{-1}$)
4. In order to improve the efficiency of heat recovery, the research conditions should be verified.

Raising the average value of air temperature by 17ºC in the intake during a day in comparison to the heated water temperature resulted in raising the water temperature by 3ºC in the accepted research conditions (60 litres of air intake per 1 litre of water in the heater tank).

The above experiments show that the simulation calculations were too optimistic. Compliance of results may be obtained if heat transfer coefficient is corrected. At the beginning the assumed value was U=0.6 $W \cdot (m^2 \cdot K)^{-1}$, corrected 0.2 $W \cdot (m^2 \cdot K)^{-1}$. Thus, heat transfer coefficient values of the air bubble - water are disputable and require specification of the flow conditions.

Conclusion

The method of direct supply of heat by the air diffuser proved to be ineffective in the considered simple, cheap technical system. In particular, operation of a fan, which maintains proper static pressure, exceeded 3 times the yield of energy which came from the heat exchange.

Facilitation of operation of the heat recovery system according to the described method is possible but through the increase of its complexity and thus costs. One should aim at decreasing diameters of air bubbles and at prolonging the heat exchange time e.g. by prolonging the passage of outflow but at the same time reducing the height of the water column over a diffuser. Orientatively, a diffuser should ensure the beading effect of diameters equal or smaller than a tenth part of a milimeter at the unchanged flow efficiency. Reduction of the particles size causes also reduction of the outflow speed enabling effective heat exchange. However, these solutions bring new technological issues which are theoretically related to the electro-static phenomena, balance of phases and other which are not subject to simple estimations (Takahashi, 2005). It is not known whether in a general balance of costs they will prove effective for production under cover.

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ANALIZA EFEKTYWNOŚCI MAGAZYNOWANIA CIEPŁA ODPADOWEGO W AKUMULATORZE WODNYM

Streszczenie. W pracy przeprowadzono analizę metody zagospodarowania ciepła odpadowego pobieranego z górnej przestrzeni tunelu foliowego. Ciepłe powietrze zasysane z górnej przestrzeni wtłaczano do dyfuzora umieszczonego w zbiorniku z wodę technologiczną. Przyjętą metodę przeanalizowano teoretycznie a następnie przeprowadzono badania w obiekcie rzeczywistym. Unoszące się pęcherzyki powietrza przemieszczając się w warstwie cieczy przekazywały zawarte w nich ciepło. Badania wstępne realizowane według przyjętej metody nie przyniosły zadawalających wyników. Niemniej zaobserwowano pewne zależności i możliwości doskonalenia opisanej metody na drodze zwiększenia stopnia złożoności i kosztów układu.

Słowa kluczowe: obiekty pod osłonami, wymiana ciepła powietrze-woda, balotaż, dyfuzor