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Analysis of the Potential for Reducing the Energy Consumption of a Vegetable Sprouts Production Using Flownex Simulation Software

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ABSTRACT

Using the waste energy generated in any production process is the one of possible ways of increasing energy efficiency. In the industrial cultivation of vegetable sprouts for food purposes, significant amounts of low-temperature waste heat are released, the source of which is the metabolic processes taking place inside the seeds. In typical installations, this energy is lost to the environment, while it could be utilised, for example, to heating the water used to irrigate the plants. This paper presents a concept of utilizing waste heat generated during the germination process of seeds using plate heat exchangers and the analysis of the potential for reducing the energy consumption of installations for vegetable sprout production. For this purpose, transient simulations were conducted using a developed simulation model of the technological line in Flownex Simulation Environment. In order to formulate a reliable simulation model, relevant device parameters and process data were collected. After building the model and calibrating it appropriately, an analysis of the variability of the values of all process parameters was performed, and the potential for recovering waste heat was determined. The results obtained from numerical modelling were verified against the results obtained from the production line and shows, that the amount of recoverable waste heat in the entire production cycle was about 5 GJ.

Keywords: industrial waste heat, waste heat recovery, low-temperature heat, transient simulation

INTRODUCTION

Enhancing energy efficiency plays a crucial role in the European Union's climate and energy policy, as it constitutes one of the primary objectives set forth by the European Green Deal. By increasing energy efficiency, it is possible to decrease primary energy consumption derived from traditional sources, reduce greenhouse gas emissions, and promote the decarbonization of the economy. A variety of measures can be adopted to achieve these efficiency improvements, including reducing energy consumption in existing facilities and processes, enhancing energy conversion efficiency, improving control systems for machines and devices, as well as utilizing existing and developing new technologies for energy recovery from low-quality sources. Waste energy is the energy portion discharged into the environment as part of the conversions carried out and that is irretrievably lost, despite the potential for further use resulting from the relatively high exergy [1, 2]. One type of waste energy is its temperature form, also referred to as waste heat [3]. Waste heat accompanies most energy transformations and is very often treated as a by-product. Waste heat sources can be classified as high-temperature (650°C and above), medium-temperature (230–650°C), and low-temperature (below 230°C) sources [4]. Waste heat recovery (WHR) has the potential to significantly contribute to rational energy policy due to its abundant global resources. It is estimated that waste heat resulting from conversion processes (e.g., combustion) accounts for up to 52% of total global energy consumption [5]. However, the usefulness of waste heat is limited by various economic and technical factors, and thus its potential is categorized into three subsets:

theoretical, economic, and technical. The theoretical potential refers to heat that can be recovered, given physical constraints (e.g., the energy should be associated with a medium whose temperature is higher than ambient temperature). For technical potential, the technological feasibility of recovering and utilizing the carrier's energy is considered, whereas the economic potential takes into account factors such as energy prices, interest rates, and payback periods to determine the profitability of WHR investments [6-8]. Theoretical and economic potentials are estimated to be approximately 12% and 9%, respectively, of the world's total energy demand (equivalent to approximately 22% and 16% of total waste heat) [6]. Information on the size of the global technical potential is currently unavailable in the literature.

The industrial sector is widely recognized as one of the most energy-intensive industries, with its energy consumption accounting for roughly 25% of total global energy consumption [9]. Waste heat generated in this sector is estimated to account for approximately 30% of the total energy demand [5], with the theoretical potential and economic potential for waste heat recovery being estimated at 12.4% and 10.6% of total primary energy consumption, respectively [6]. With the abundant reserves of waste heat, the increasing costs of electricity, heat, and conventional fuels, as well as the high energy efficiency targets, waste energy management has emerged as an attractive approach to reduce the energy intensity and operating costs of industrial facilities. In this context, the utilization of low-temperature heat, which accounts for up to 40% of the total waste energy generated by industrial processes, is of particular importance [10].

Low-temperature waste heat sources are found in various industrial subsectors. The petrochemical subsector is characterized by high energy consumption, with almost 30% of the industry's final energy consumption being attributed to this sector [11]. Waste heat in this industry takes various forms, such as waste gases from the vacuum distillation column of the waste processing unit in oil refinery [12], as well as wastewater at 110°C, which is typically cooled through water-based cooling systems and subsequently discharged into the environment through cooling towers [13]. Additionally, waste products generated during processes in the catalytic reforming unit, which operate at different temperature levels ranging from 98 to 215°C, contribute to waste heat generation in this sector [14]. Glass factories have flue gases from furnaces where glass is melted (about 140–200°C) or glass fibers (about 140–160°C) [15] as low-temperature waste energy sources. In the textile industry, the source of waste heat is mainly wastewater from processes such as garment dyeing (96°C), hot fabric rinsing (70°C), or bleaching (96°C) [16]. Cement plants have waste energy sources such as air at about 100°C from clinker cooling or wastewater from the production process [4], [17]. During iron and steel production, low-temperature heat medium is waste gases from the coke oven (200°C) [18] or water used to cool slag (50–90°C) [19]. The paper industry has a low-temperature energy source in the paper drying process (up to 50°C) [20]. The food industry also shows potential for recovering low-temperature waste heat from processes such as roasting [21], drying [22], freezing [23], hot oils [22], steam from evaporation and distillation [23], or refrigeration [24].

The sources of waste heat mentioned above belong to the category of anthropogenic sources resulting from human activity. In addition to these, natural sources can also be identified, which are associated with biological processes, among others. Specific conditions for plant cultivation are required to recover and utilize the energy generated by plants, including a sufficiently large biological mass accumulated in one place and a watering process organized to receive the generated heat. Such conditions are provided during the production of sprouts for food purposes, which are defined as the product obtained as a result of the germination of seeds and their development in water or other medium, harvested before the development of proper leaves and intended for consumption in their entirety, including the seed [25]. Germinating plants generate a stream of low-temperature heat (20–40°C) during their growth, which is typically discharged into the environment and lost in traditional production systems [26]. The main source of heat is metabolic processes, particularly cellular respiration occurring in plant cells. The amount of heat generated depends on the seed species, its structure, condition, and microclimatic conditions during germination. Under natural conditions, the heat generated during germination is dissipated into the environment as a byproduct. In controlled cultivation, this heat can be recovered and used in the plant growing process. Since the energy from germinating plants is low-quality energy, the profitability of such a procedure mainly depends on the size of the heat resource and the technical feasibility of its recovery. Utilization of waste heat generated by sprouting plants is a scarcely explored topic in the literature, mainly due to the low exergy of the heat carrier and the need for on-site processing and utilization. The objective of this article is to analyze the feasibility of reducing energy intensity and the reliance on conventional fuels in a food plant specializing in vegetable sprout production by harnessing the waste heat generated by the plants. Novel method has been proposed to effectively utilize the waste heat produced during the growth phase of vegetable sprouts, which are extensively utilized for food purposes.

SYSTEM DESCRIPTION

The growth chamber is the main component of a sprout cultivation plant, where the cultivation of sprouts takes place. As shown in Figure 1a, in conventional systems without heat recovery, fresh water is supplied to the growth chamber, typically from a well, and heated to the appropriate temperature in a solid fuel boiler. The prepared fresh water is then used to irrigate the growing sprouts, while the used water is considered as dirty water and discharged as waste water. Therefore, in traditional sprout plants, dirty water is treated as a waste product. However, it is possible to utilize the energy stored in the dirty water to produce fresh water for watering, which can help reduce the energy consumption of the production process. The concept of utilizing waste heat, generated by biological processes during sprout growth, to produce fresh water for crop watering is illustrated in the plant block diagram in Figure 1b. The proposed concept for preparing fresh water using waste heat is implemented in two stages. The use of a two-stage heat recovery system is necessary due to the low temperature of the waste heat carrier, which makes it impossible to achieve adequate water heating in a single-stage process and limits the flexibility in forming the target temperature. In the first heating stage, fresh water from a deep well is preheated in a heat exchanger using dirty water at a higher temperature from watering the sprouts. Part of the preheated water is then directed to the cold water tank, while the remainder moves to the second stage. In the second heating stage, a compressor heat pump, a glycol reservoir, and a heat exchanger are used to further heat the fresh water to a temperature higher than that required for watering. This heated water goes to the hot water tank, and both hot and cold water are mixed in the appropriate proportions to provide the desired temperature for watering the

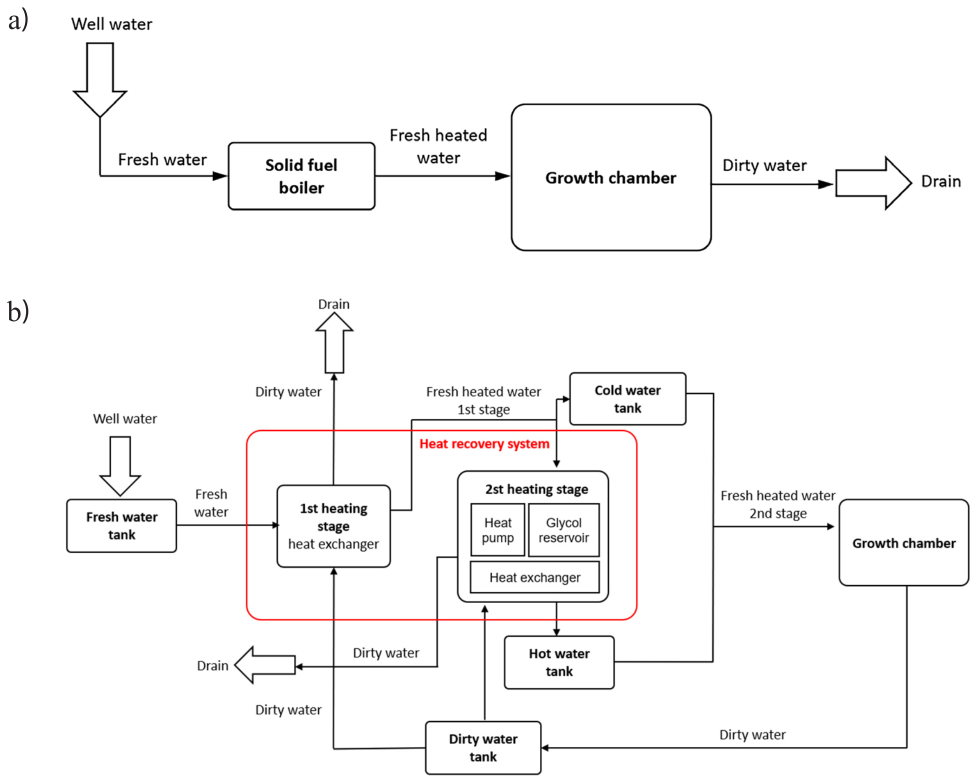

Figure 1. Schematic block diagram of a plant for producing vegetable sprouts without (a) and with (b) heat recovery

sprouts. After watering, the dirty water goes into the dirty water tank, where it is used in a heat recovery system to heat fresh water from the well. By using this configuration, the heat stored in the water after watering the plants can be maximally utilized.

METHODOLOGY

A simulation model of a vegetable sprout production line with a heat recovery system is developed to determine the possibility of recovering and utilizing waste heat generated by seeds during germination and growth. The model is developed using FLOWNEX® Simulation Environment software and includes the entire production cycle, including all watering and plant growth cycles. To formulate a reliable simulation model, relevant technical and process data of the modeled sprout plant are collected. Technical data used to formulate the model includes nominal values of equipment parameters, piping dimensions, and operating characteristics of pumps and valves, such as the dependence of efficiency or energy demand on load. To validate the developed model, data on process parameters, such as the temperature and flow rate of water from the deep well, temperature and flow rate of water used for soaking and watering the sprouts, and temperature and flow rate of water after leaving the growth chamber after watering, are used. Once the model is constructed and validated, a range of transient simulation experiments is carried out to investigate different production scenarios, including various conditions such as different watering times, time periods between successive waterings, and temperature levels of fresh water used for watering. In this study, simulation results are presented for a selected production scenario consisting of 32 watering cycles, lasting for almost 6 days (5 days 22 h 22 min). Due to the secrecy of process parameters (protected property of Uniflora Sp. z o.o.), detailed process data cannot be presented, and the simulation results are presented in the form of normalized values.

Estimation of available waste heat

The simulations do not consider the phenomena taking place within the growth chamber. However, the heat produced by the biological mass is incorporated through an approximate model that is developed based on experimental measurements conducted during actual sprout production. The measurement results have been used in formulating the approximation model are illustrated in Figure 2, while the model is explained by the Equation 1.

$$\dot{Q}_k = A_1 + A_2 \cdot \left[\frac{A_3}{1+10^{A_4 - t \cdot A_6}} + \frac{(A_3 - A_1)}{1+10^{A_5 - t \cdot A_7}}\right] \quad (1)$$

$$T_0 = 168 \cdot 3600$$
$$A_1 = -10.1$$
$$A_2 = 27.3$$
$$A_3 = 25.6$$
$$A_4 = 0.234$$
$$A_5 = 0.235$$
$$A_6 = 2.655$$
$$A_7 = 1.714$$

where: $\dot{Q}_k$ – heat flux generated by the biological mass [kW], t – dimensionless growth time [-], T_0 – time-scale referring to the maximum duration of the experiment.

Model

The model's complexity necessitates its division into several subsystems that are subsequently integrated into a single model. The subsystems that are the most critical include the HE1 heat exchanger subsystem, the cold water tank subsystem, the second stage heat recovery subsystem, and the hot water tank subsystem. The HE1 heat exchanger subsystem's primary component is the HE1 plate surface counterflow heat exchanger, which utilizes heat stored in the dirty water tank to warm the cold water drawn from the well. Figure 3 presents a schematic diagram of this component, which represents the first stage of waste heat recovery. Figure 3 depicts the PID controller (PID-1), responsible for regulating the operation of pump P1 within the dirty water storage and supply subsystem. The controller adjusts the output of the P1 pump based on the instantaneous flow rate and temperature of cold water from the well at the outlet of the HE1 exchanger to maintain the desired temperature of fresh water downstream.

The second stage heat recovery subsystem consists of heat exchanger HE2, an intermediate heat buffer with higher energy potential, and a compressor heat pump. A glycol reservoir serves as the intermediate buffer and is supplied with waste heat from dirty water via a heat pump. It also provides a source of energy for fresh water heating in the HE2 exchanger. A PID-3 controller is responsible for controlling the system by determining the flow rate of glycol required to achieve the desired water temperature at the outlet of HE2.

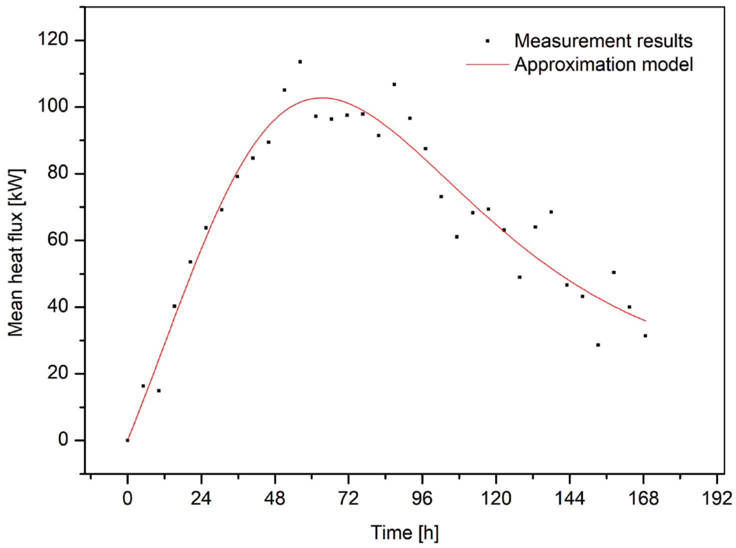

Figure 2. Measurement results for determining the heat generation model by sprouts

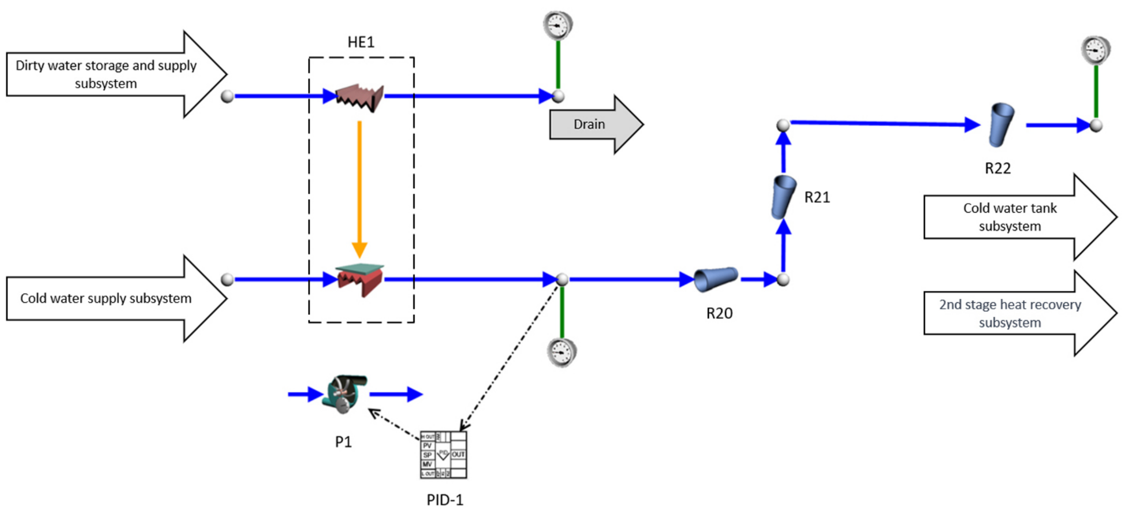

Figure 3. Schematic diagram of the model of the HE1 heat exchanger subsystem (HE1 – heat exchanger, P1 – fresh water pump, R20-R22 - pipelines)

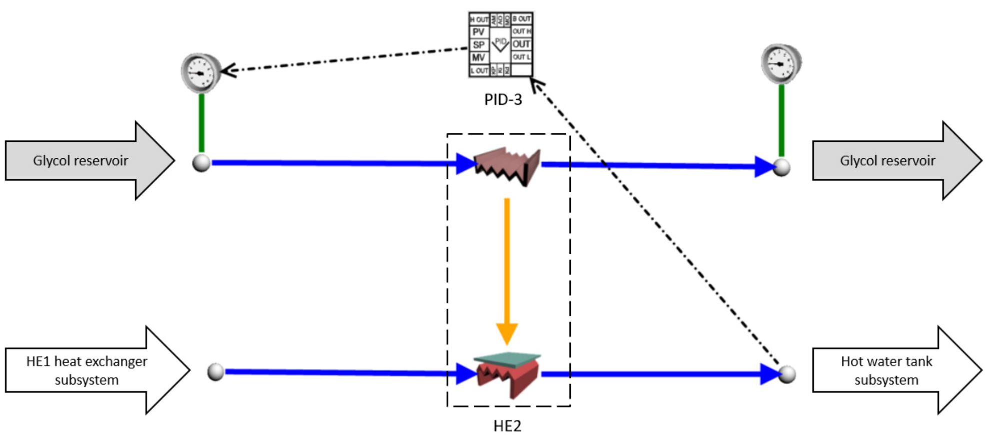

Figure 4. Schematic diagram of the model of the second stage heat recovery subsystem (HE2 – heat exchanger, PID-3 – PID controller)

Figure 4 shows a schematic diagram of the HE2 exchanger in the heat recovery subsystem model.

Subsystems including a cold water tank and a hot water tank are part of the system responsible for watering the sprouts. The subsystems consist of water tanks (ZWZ for cold water and ZWC for hot water), valves (ZA1 and ZA2) controlled by PID controllers (PID-2 and PID-4) that regulate the water flow into the tank, pumps (P2, P21, P3, and P31), and pipelines. The primary objective of the cold water tank subsystem is to store fresh water from the well that has been preheated in the HE1 heat exchanger. The hot water tank subsystem is responsible for storing hot water that enters the tank after being heated in the HE2 heat exchanger. A schematic diagram of the cold water tank subsystem model is shown in Figure 5, while the hot water tank subsystem is depicted in Figure 6.

The PID-2 and PID-3 controllers are responsible for regulating the opening and closing of valves ZA1 and ZA2 to maintain the liquid level in the cold or hot water tank within the specified limits. When the liquid level falls below the minimum set value, the controller opens the valve, and if it exceeds the maximum value, it closes it. ZWZ and ZWC tanks have a closed water circulation system to equalize the temperature of water in the entire volume of the tank. This circuit comprises circulation pumps P21 and P31, which are controlled by the PID-21 and PID-31 controller, respectively, such that they start when the valves open. In this manner, the water stored in the tanks mixes with the water supplied to these tanks from the corresponding heat exchanger.

Aside from the aforementioned subsystems, the heat recovery plant model comprises a cold water supply subsystem, a dirty water storage and supply subsystem, and a mixer subsystem for preparing water for watering.

RESULTS AND DISCUSSION

1st stage waste heat recovery

The first stage of heating fresh water from a deep well is done through the HE1 heat exchanger subsystem. The flow rate of fresh water through this device is dependent on the state of the cold and hot water tanks. When the liquid level in the tanks drops below a certain threshold, the corresponding valve (ZA1 and/or ZA2) is opened, allowing fresh water to flow through the HE1 heat exchanger. Figure 7 illustrates the normalized

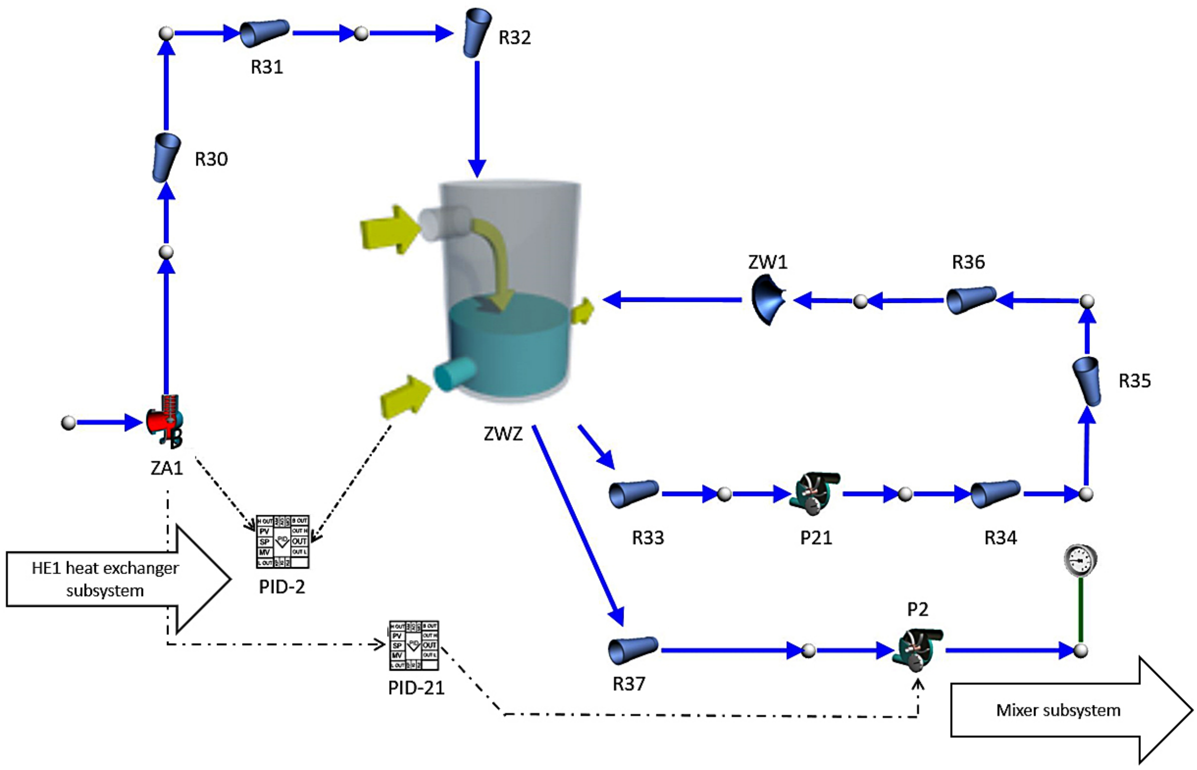

Figure 5. Schematic diagram of the model of the cold tank subsystem (ZWZ – cold water tank; ZA1, ZW1 – valves; P2, P21 – water pumps; PID-2, PID-21 – PID controllers, R30-R37 - pipelines)

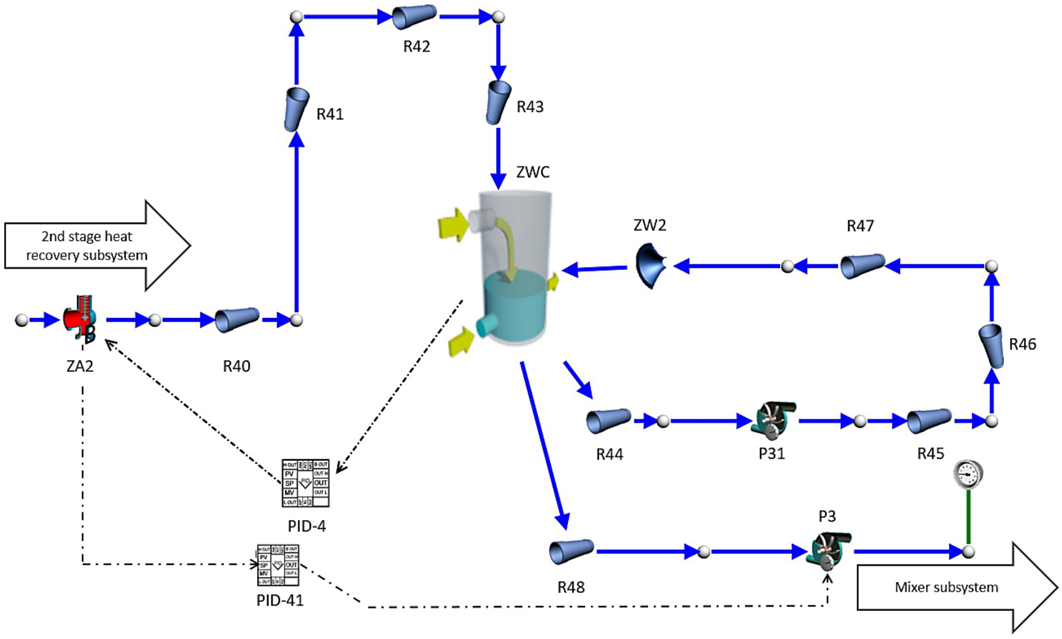

Figure 6. Schematic diagram of the model of the hot tank subsystem (ZWC – hot water tank; ZA2, ZW2 – valves; P3, P31 – water pumps; PID-4, PID-41 – PID controllers, R40-R48 - pipelines)

temperature values of the media flowing through the HE1, before and after the heat exchanger, throughout the entire production cycle. Additionally, the opening and closing times of the valves are indicated for a selected portion of the HE1 operation. The temperature of fresh water in the deep well remains constant throughout the calculation cycle, with slight fluctuations observed in the second half of the production cycle due to the interaction of the dirty water stream, which is warmer, with the fresh water stream during valve opening and closing processes. Conversely, the dirty water temperature in front of the exchanger shows variation both globally and instantaneously. The global variation results from the temperature of the dirty water in the waste energy storage (ZWB) tanks, which is related to the amount of waste heat generated by the sprouts (refer to Figure 2) and the variation in the temperature of water used for watering over the entire production cycle. Despite

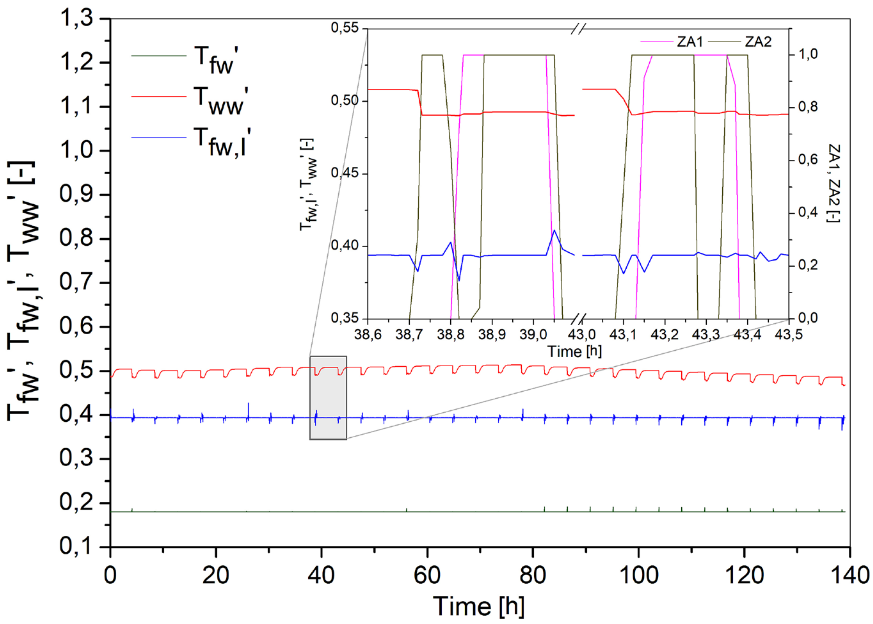

Figure 7. The fresh water temperature after ($T_{fw,l}'$) and before (T_{fw}') the HE1 heat exchanger and the dirty water temperature (T_{ww}') throughout the production cycle and the opening stage of the ZA1 and ZA2 valve

this, the large thermal capacity of the dirty water tanks restricts the temperature variation of waste water in the ZWB tanks. The average temperature difference between fresh water after ($T_{fw,I}$') and before (T_{fw}') the HE1 heat exchanger is about 9°C, and between dirty water (T_{ww}') and fresh water (T_{fw}') is about 13°C. When analyzing a single cycle of the heat exchanger's operation, significant fluctuations in the temperature of fresh water downstream of HE1 can be observed. These are related to the variable flow rate of water from the deep well due to the opening and closing of valves ZA1 and ZA2. The observed temperature peaks are due to the system's inertia, specifically the time constants of each of the system components.

Figure 8 presents the instantaneous power output of the HE1 heat exchanger throughout the production cycle, where the maximum power output of 583 kW is achieved with little deviation from the maximum value in the individual cycles of the exchanger's operation. The power output slightly decreases only towards the end of the sprout production cycle due to the lower temperature of the dirty water in the ZWB tanks during this period. The liquid level in ZWZ and ZWC, the opening of valves ZA1 and ZA2, and the fresh water flow rate determine the nature of the instantaneous power of the HE1 heat exchanger, which is mainly dependent on the mass fluxes of the heat-exchanging media and their temperatures. As the temperatures of the two mediums remain relatively constant, the power output of the exchanger is solely a function of the mass fluxes.

2nd stage waste heat recovery

A portion of fresh water from HE1 heat exchanger is directed to the second heating stage only when the ZA2 valve is open. Figure 9 presents the normalized temperature values of the media flowing through HE2, before and after the heat exchanger, along with a selected section of HE2 operation correlated with the opening and closing of valve ZA2. In the simulation, the temperature in the glycol reservoir is assumed to be constant, maintained by a compressor heat pump using water from the dirty water tanks as the lower energy source. The average temperature difference between fresh water after ($T_{fw,II}$') and before (T_{fw}') the HE2 heat exchanger is about 5°C, and between glycol (T_{ww}') and fresh water ($T_{fw,I}$') is about 13°C. Similar to the operation of HE1 exchanger, Figure 9 depicts fluctuations in the temperature of fresh water at the inlet and outlet of the unit. These are a result of the measurement location (directly at the inlet and outlet of HE2) and are associated with the varying flow rate of the heat-exchanging media and the inertia of the system components. The maximum power output of the HE2 heat exchanger is 227.5 kW, as shown in Figure 10. The average power output of the HE2 heat exchanger is more than half of the HE1 heat exchanger, which can be attributed to the lower fresh water flow rate and its lower degree of heating. The power output of the HE2 heat exchanger increases in the second half of the production cycle due to the decreasing temperature of fresh water downstream of the HE1

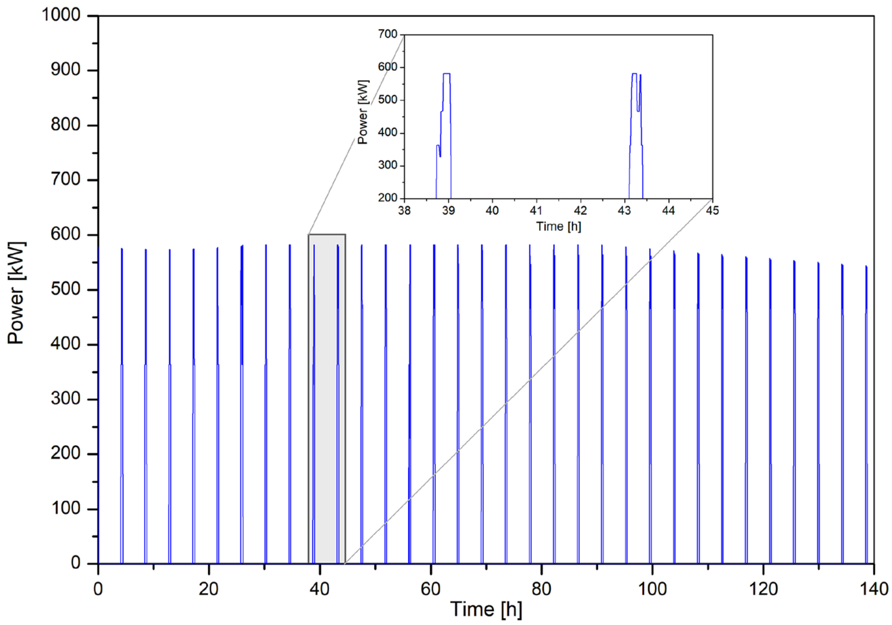

Figure 8. Instantaneous power output of the HE1 heat exchanger throughout the production cycle

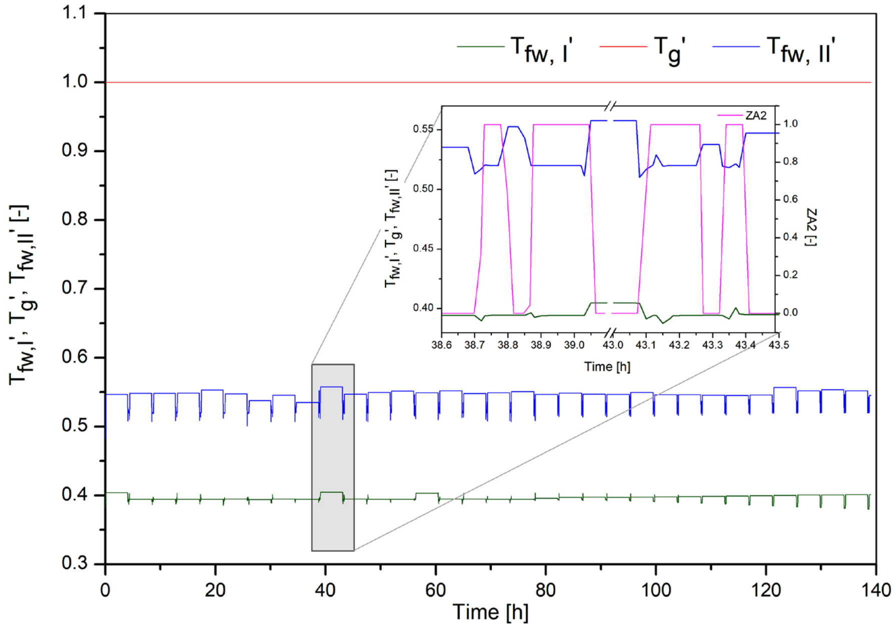

Figure 9. The fresh water temperature before ($T_{fw,I}$') and after ($T_{fw,II}$') the HE2 heat exchanger and the glycol temperature (T_g') throughout the production cycle and the opening stage of the ZA2 valve

exchanger, which is caused by the decreasing temperature of dirty water in the ZWB.

Waste heat recovery throughout the system

The total amount of energy transferred to fresh water in the two-stage waste heat recovery system for the complete production cycle of sprouts is approximately 22.18 GJ, as depicted in Figure 11. This value represents the heat requirement of the installation for the sprout production cycle. Of the total energy transferred, about 17.87 GJ is transferred on the HE1 heat exchanger, and the remaining 4.31 GJ on the second heating stage. Notably, the heat transferred to the fresh water in the first heating stage constitutes 80.6% of the total heat transferred. The graph of the amount of heat transferred on the HE2 exchanger levels off in the second half of the production cycle, which is linked to the reduction in the temperature of water required for watering plants. Consequently, the demand for hot water decreases, and the

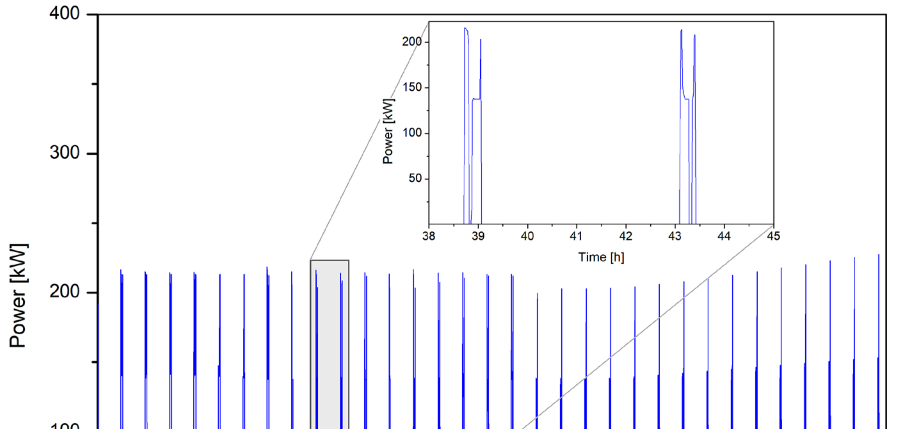

Figure 10. Instantaneous power output of the HE2 heat exchanger throughout the production cycle

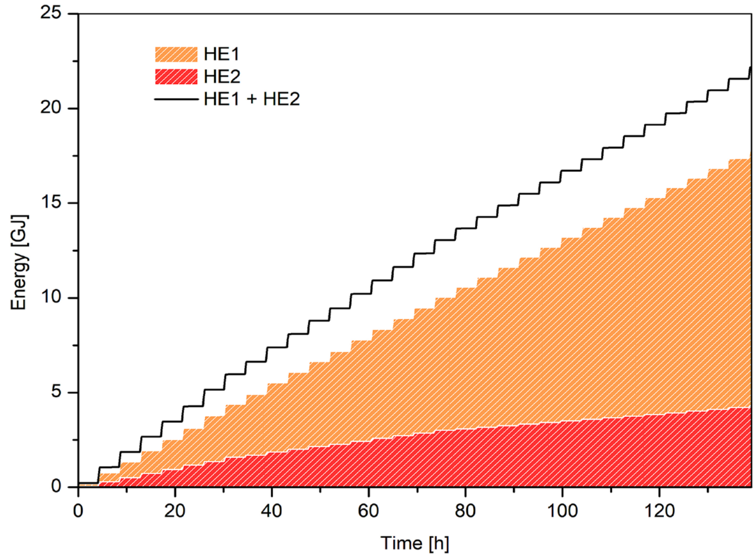

Figure 11. Accumulated amount of energy transferred to fresh water in heat exchanger HE1 and HE2

operating time of the HE2 exchanger decreases as well. Furthermore, it is important to mention that all the heat transferred in the HE2 exchanger to the fresh water is partly composed of the electricity utilized to operate the compressor heat pump. Assuming an average COP of 7.5 for the heat pump, according to the actual data, the amount of heat recovered from the dirty water at the second heating stage is approximately 3.73 GJ.

The proposed energy recovery system effectively utilizes all the waste heat generated during the growth of sprouts and stored in the water after watering the biological mass. This is evident from the temperature of the dirty water entering the drain after passing through the HE1 exchanger, which remains at around 9ºC on average. Remarkably, this temperature is comparable to that of the deep well water entering the first stage of heating. The warm medium in HE1, i.e., the dirty water, transfers sufficient energy to the fresh water, resulting in the latter equating the temperature of the colder medium at the outlet of the counterflow heat exchanger. When considering the required energy to heat the fresh water (22.18 GJ) and the actual recoverable energy from sprout production (measured at 4.942 GJ), it becomes evident that relying solely on waste heat is insufficient to heat water for plant watering. Thus, alternative heat sources, such as an oil boiler, are necessary. Nevertheless, the proposed heat recovery system considerably decreases the energy consumption of the vegetable sprout plant, resulting in a reduction of approximately 198 kg of coal and preventing the emission of roughly 1.24 Mg of CO_2 in a single production cycle.

CONCLUSIONS

The production of vegetable sprouts for consumption results in a considerable amount of low-temperature waste heat, which originates from the metabolic processes during seed germination. In traditional systems, this heat is released into the environment and lost irreversibly. On the other hand, recuperating the waste energy produced during seed germination can be an efficient means of decreasing the energy intensity of the production line.

The paper presented a waste heat management method for vegetable sprout production that utilizes plate heat exchangers. In the proposed heat recovery system, the total amount of energy to be supplied to fresh water for heating is 22.18 GJ, of which 22.3% is waste energy from sprouting seeds. While the plant-generated heat is insufficient to heat water for watering, it still results in savings of approximately 198 kg of hard coal and prevents the emission of about 1.24 Mg of carbon dioxide in a single production cycle.

The waste heat recovery system proposed in this paper comprises two stages of heating. In the first stage, the heat exchanger directly transfers 17.87 GJ of energy to fresh water from the water after watering the plants, which constitutes 80.6% of the total energy. The remaining 4.31 GJ is transferred to fresh water in the second heating stage, where dirty water acts as the bottom source of the heat pump. To further enhance the energy efficiency of the production line, it is recommended to consider utilizing renewable energy sources to operate a heat pump, or to partially substitute the use of an oil boiler.

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