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Modeling of a transient low-temperature waste heat recovery in the plate heat exchanger in Flownex Simulation Environment

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Modeling of a transient low-temperature waste heat recovery in the plate heat exchanger in Flownex Simulation Environment

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Abstract The paper analyses the feasibility of determining the parameters of a heat exchanger operating in the crop production and realising low-temperature heat recovery from biological processes. For the first time, the Flownex 8.7 Simulation Environment has been used for this purpose. The temperature of the waste water was between 20 and 30°C. On the basis of the simulations, the power of the heat exchanger is determined to be 1 MW. The heat exchanger can efficiently heat up cold water from a deep well (7-10°C) to an assumed temperature of 19.7°C. The results from the simulation calculations correspond to the results obtained under actual conditions within a range of up to 2%.

1. Introduction

The European Union's climate strategy by 2050 indicates the necessity to decarbonise the power industry and reduce greenhouse gas emissions [1]. These targets can contribute to limiting climate change [2]. Most attention is drawn to renewable energy sources for this purpose. However, this goal can be achieved not only by renewable energy sources. The efficiency of energy conversion facilities should also be increased. One possibility is to reuse the waste heat associated with almost each energy process. The amount of waste energy is significant. It comprises more than 50% of the world's total energy demand [3]. The industry is one of the most energy-intensive parts of the economy, so the possibility of waste heat recovery (WHR) in this sector should be considered [4]. Waste heat is approximately 30% of the industry's total primary energy needs, and its reuse can significantly increase the energy efficiency of production processes [3].

The most industrial waste heat is low-temperature heat, where the temperature of the energy carrier reaches up to 230°C [5]. The low-quality parameters of this energy make WHR difficult. Low parameters cause the problem of matching heat sources with their consumers [6,7]. The problems can also be caused by technological limitations and a lack of appropriate installation for heat recovery. The solutions can be utilizing of heat pumps [5], Organic Rankine Cycle (ORC) [8–11] or cryogenic energy stores [12–14]. It is also worth pointing out that as the temperature of the heat carrier decreases, the investment costs of WHR installations increase. Therefore, it is crucial to properly parameterise such a system and adjust it to the heat sources to avoid oversizing the installation and additional costs. On the other hand, insufficient equipment capacity will result in low WHR efficiency.

The technologies used to recover low-temperature waste heat include economisers, recuperators, rotary regenerators and plate heat exchangers [15]. An economiser consists of finned tubes which are placed in the exhaust duct. Fluid is contained in the tubes and is heated by the flowing fluid. This type of device is typically used for heat recovery from gas, e.g. in coal-fired power stations [16,17] or factories [18]. In recuperators, heat exchange occurs between fluids separated by a wall (ceramic or metal). They can be divided into co-current, counter-current and cross-current, depending on the direction of the fluid flow [19]. They are widely used in ventilation systems [20–23] but also in other industrial applications, e.g. in industrial textile [24] or central heating plants [25]. A rotary regenerator is also used for low-temperature WHR. The hot stream flows through a device and heats it. The energy is then transferred to the inlet fluid [26]. Another group of appliances are direct electrical conversion devices. These systems generate electricity directly from waste heat, but their use is not widely established [15].

The plate heat exchanger comprises thin metal plates. They are stacked on top of each other and form flow channels. These plates can have a smooth surface or be specially shaped to increase the heat transfer surface [27]. The large heat transfer surface per unit volume and the high heat transfer coefficient make plate heat exchangers widely used in low-temperature WHR installations [28]. Another advantage is the unit's tightness, preventing fluid mixing and contamination [15].

The aim of this paper is the feasibility of using the Flownex 8.7 Simulation Environment to determine the parameters of a heat exchanger used for low-temperature heat recovery in a crop production process. Section 2 describes the simulated system and Section 3 explains the research methodology. Section 4 details the simulation results and compares them with the actual data obtained during the waste heat recovery. The final section presents the conclusions of the research.

2. System description

In the crop production process, it is necessary to irrigate the plants with water at the right temperature periodically. During this phase, waste heat is generated by exoenergetic plants. In traditional installations, the water after irrigation is removed into the sewage. However, it is possible to use this hot water to heat fresh, cold water from a well. Fresh water then can be used in a new watering cycle.

Figure 1 shows the process diagram of an installation to recover low-temperature waste heat from the crop production process.

A counter-current plate HEAT EXCHANGER is used for heat recovery in this installation. After irrigation, the water is transferred to the DIRTY WATER TANK. The accumulated thermal energy is used to heat the WELL WATER. The dirty water has a significantly higher temperature than the fresh water drawn from the well and can therefore be used to heat up the fresh water. The DIRTY WATER PUMP and the WELL PUMP convey the water into the plate HEAT EXCHANGER, where energy is transferred between the media and heat is recovered. The heated fresh water is then transferred to the FRESH WATER TANK and used for irrigation purposes.

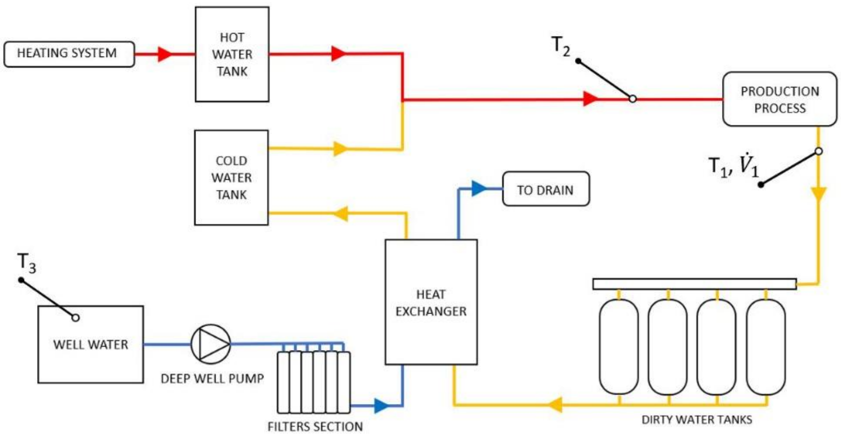

Figure 1. Block diagram of a system for the recovery of low-temperature industrial waste heat (T_1– temperature of water after irrigation (dirty water), $\dot{V}_1$– volumetric flow rate of water after irrigation (dirty water), T_2 – temperature of water for irrigation, T_3 – temperature of deep well water (fresh water)).

3. Methodology

Figure 2 shows the research methodology. The first step is to estimate the temperature and the quantity of waste heat available in the crop production process. Then, a model of the installation with a heat exchanger is built in the Flownex 8.7 Software Environment. Next, transient simulations are carried out to determine such power of heat exchanger and the principles of operating the device to obtain the assumed heat-flow conditions. Finally, the results of the numerical modelling are compared with the results obtained under real conditions.

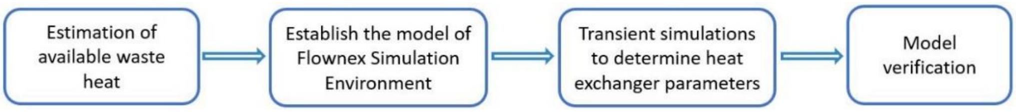

Figure 2. Flowchart of the methodology.

3.1. Estimation of available waste heat

To correctly determine the parameters of the heat exchanger for WHR, it is necessary to collect the data on the potential for waste heat. Therefore, an experimental study is conducted under actual operational conditions to determine this potential. The research consists of measuring process parameters such as the temperature and volumetric flow rate of the water after irrigation of the crop, the temperature of the water used for irrigation and the temperature of the fresh water from the deep well over the entire production cycle. Table 1 presents the results of these measurements, and the locations of the measurement points are marked in Figure 1.

Table 1. Results of the measurements carried out under the actual operational conditions.

		Value	Unit
Temperature of water after irrigation (dirty water)	T_1	20-30	[°C]
Volumetric flow rate of water after irrigation (dirty water)	$\dot{V}_1$	7-8	m^3/h
Temperature of water for irrigation	T_2	20-25	[°C]
Temperature of deep well water (fresh water)	T_3	7-10	[°C]

3.2 Model

The software used to create the heat recovery model was the FLOWNEX® 8.7 Simulation Environment. Flownex is the software in which steady-state and transient simulations can be carried out. It allows complex simulation, design and optimisation of thermal-flow systems. Furthermore, it allows simulation calculations to be performed both in real time and at the speed selected by the user [29]. This software is widely used in nuclear power [30–33], for modelling energy systems [34], biogas plants [35] or air conditioning system [36].

Simulations in the Flownex are based on the solution of the partial differential equations for mass, momentum and energy conservation (equations (1-3) respectively). The solutions of these equations allow the determination of mass flow, pressure and temperature distributions throughout the simulated system in 1D domain [37].

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho V)=0 \tag{1}$$

$$\frac{\partial(\rho V)}{\partial t}+\frac{\partial(\rho V^2)}{\partial x}=-\frac{\partial p}{\partial x}-\rho g\frac{\partial z}{\partial x}-\frac{f\rho|V|V}{2D} \tag{2}$$

$$\frac{\partial(\rho(h_o+gz)-p)}{\partial \mathrm{t}}+\frac{\partial(\rho V(h_o+gz))}{\partial \mathrm{x}}=\dot{Q}_H-\dot{W} \tag{3}$$

The software uses the Effectiveness-NTU method to calculate the heat transfer in a heat exchanger. This method makes it possible to calculate the energy transfer without knowing the outlet temperatures and does not require any details of the device geometry. The actual heat transfer rate is determined from equation (4) [38].

$$\dot{Q}_H = \varepsilon\left(\dot{m}c_p\right)_{min}(T_{i,min}-T_{i,max}) \tag{4}$$

where:
ε – effectiveness,
$\dot{m}$ – mass flow [kg/s],
c_p – specific heat [J/kgK],
T – temperature [K],
i – indicates the inlet,
min – indicates the minimum value,
max – indicates the maximum value

Figure 3 shows an installation model for waste heat recovery from the crop production process. Cold fresh water is exhausted through a deep well using pump DP with a nominal capacity of approximately 50 m^3/h. The DP operates at constant pressure and is controlled by a PID controller (CDP) to maintain a constant pressure in the pipeline after the filter section (FWF). The assumed pressure is equal to 320 kPa. Fresh water flows into a plate counter-current heat exchanger (TR-HE), where it is heated by warm dirty water. The dirty water is stored in the DWT tank. The mass flow of water from the DWT is carried out by a dirty water pump (DWP) with a nominal capacity of approx. 75 m^3/h and variable speed. The DWP is controlled by a PID controller (CDWP) to maintain a constant fresh water temperature downstream of the TR-HE. This temperature is fixed at 19.7°C.

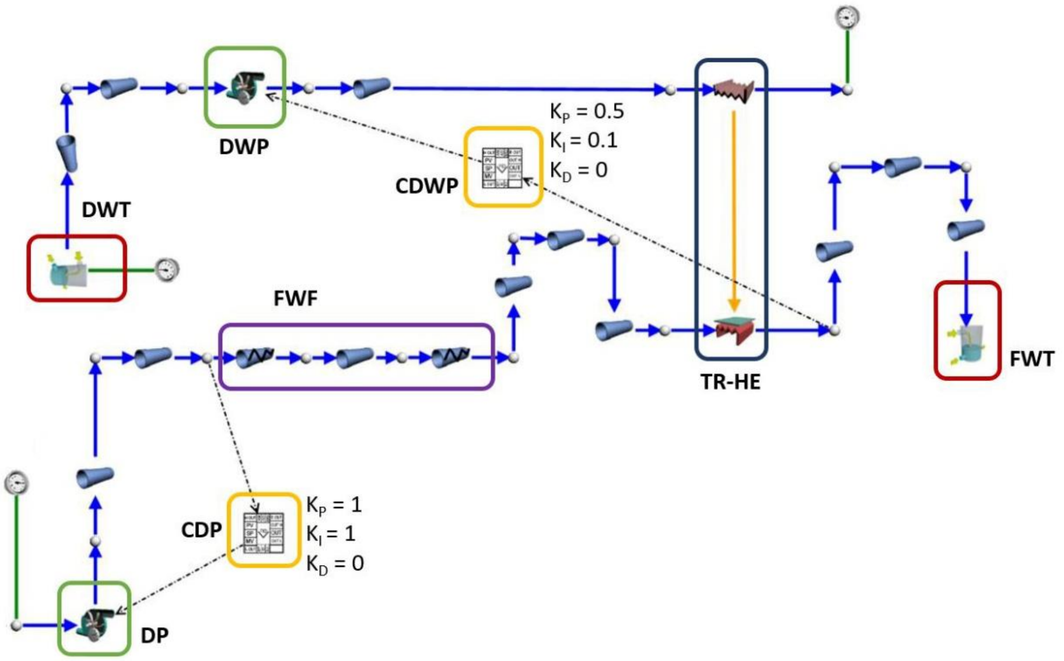

Figure 3. Installation model for waste heat recovery from the crop production process (DWT – dirty water tank, DWP – dirty water pump, DP – deep well pump, FWT – fresh water tank, CDWP – PID controller for dirty water pump, CDP – PID controller for the deep well pump, FWF – fresh water filter section, TR-HE – plate heat exchanger).

In the DWT, constant temperature is assumed. Under the actual conditions, the waste water temperature from the irrigation process is variable and depends on the production stage. This temperature varies from 20 to 30°C. However, the dirty water tank is large and has a high heat capacity. In addition, the water from different production chambers, where production occurs at different stages, mixes in the tank. As a result, the temperature in the dirty water tank remains constant at 25°C.

After the TR-HE, fresh water flows into the tank (FWT), and dirty water is removed into the sewage. Two PID controllers are used, the settings of each shown in Figure 3. Since there are lack of data concerning the type and properties of the controller used in the actual installation, the general PID controller model is used. The settings of proportional, integral and derivative term of the model are made in the iteration procedure to properly match the actual controller response. First the PI model is tested and finally resulting a good accuracy. Adding a derivative term to the model do not lead to a better results; therefore, the PID model without derivative term, which in fact is a PI controller model, is used.

The most significant parameters of the heat exchanger model are shown in Table 2.

Table 2. The most significant parameters of the heat exchanger model.

Element	Parameter	Value	Unit
Heat exchanger - Primary (TR-HE, hot stream)	Heat exchanger type	Counter flow	-
	Product of area and overall heat transfer coefficient (AU)	147.38	kW/K
	Pressure loss coefficient (Ck)	6342.86	-
	Pressure loss coefficient (Beta)	2	-
	Pressure loss coefficient (Alpha)	2	-
Heat exchanger - Secondary (TR-HE, cold stream)	Pressure loss coefficient (Ck)	54.52	-
	Pressure loss coefficient (Beta)	2	-
	Pressure loss coefficient (Alpha)	2	-

4. Results and discussion

Steady-state and transient simulation calculations are carried out using the developed heat exchanger model. In the first step, the heat exchanger's power is determined and equal to 1 MW. Next, the possibility of maintaining a constant fresh water temperature behind the TR-HE is checked with varying water temperatures from the deep well. This water after TR-HE should have a temperature of 19.7°C. To maintain a continuous temperature behind the TR-HE under these conditions, the CDWP controller changes the water flow rate from the DWT.

In the initial phase of the simulation, the water temperature from the deep well is 7°C. Transient calculations begin once the system has reached a steady state under these conditions. After seeking a set temperature after the heat exchanger (i.e. 19.7°C), the water temperature in the DWT is raised consecutively to 8°C, 9°C and 10°C. Each time, the system reacts to the change in conditions and reaches the set temperature after the TR-HE.

Figure 4 shows the power of the heat exchanger during the whole simulation. Each decrease in power corresponds to an increase in fresh water temperature. The water from the DWT has a constant temperature, so reducing the temperature difference on the TR-HE causes a lower amount of heat transfer. When the temperature of the water in the deep well changes, there is a sudden drop in the output of the heat exchanger, and following it is levelling off. This nature of the course results directly from the operation of the CDWP controller. The controller is characterised by time constants that do not allow for a step change of the pump rotational speed and require some time for stabilisation —obtaining an exchanger output of approx. 560 kW for the largest temperature difference between the dirty and well water.

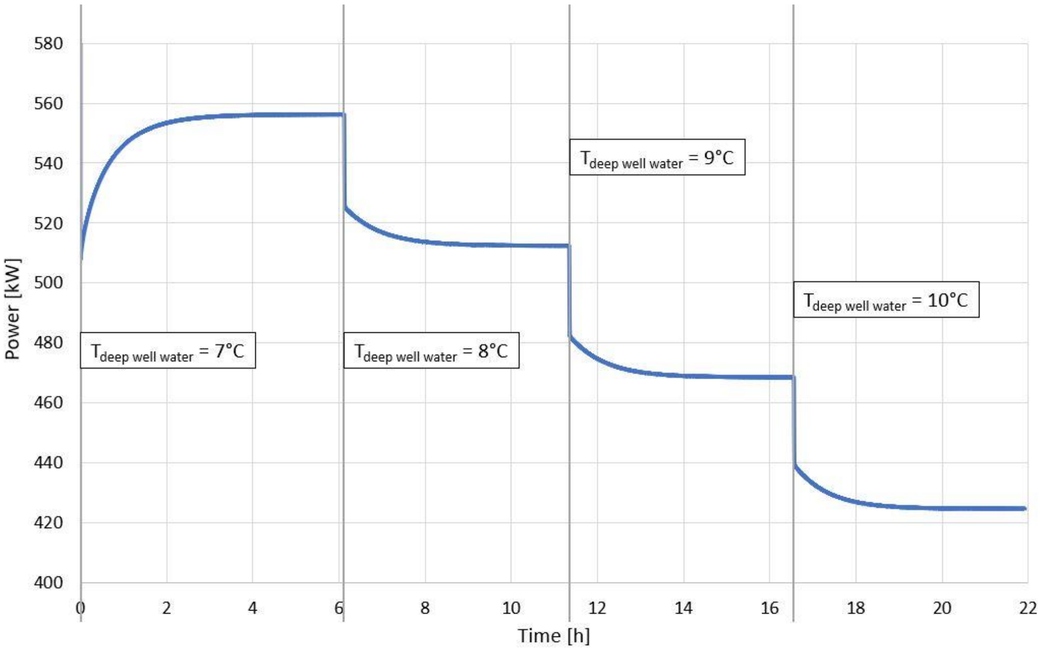

Figure 4. Heat exchanger power during the entire simulation.

Figure 5 shows the mass flow of fresh and dirty water through the TR-HE. Once the system has stabilised, the fresh water flow rate is constant at 10.5 kg/s. This value is due to the need to maintain constant pressure in the filter section. The dirty water flow rate ranges from 8.5 kg/s to 7.4 kg/s, related to the changes in fresh water temperature. With each change in this temperature, the system adapts to the new operating conditions. The dirty water mass flow rate decreases as the fresh water temperature increases before the heat exchanger. This change is directly related to the response of the PWB to the changing temperature of the deep well water.

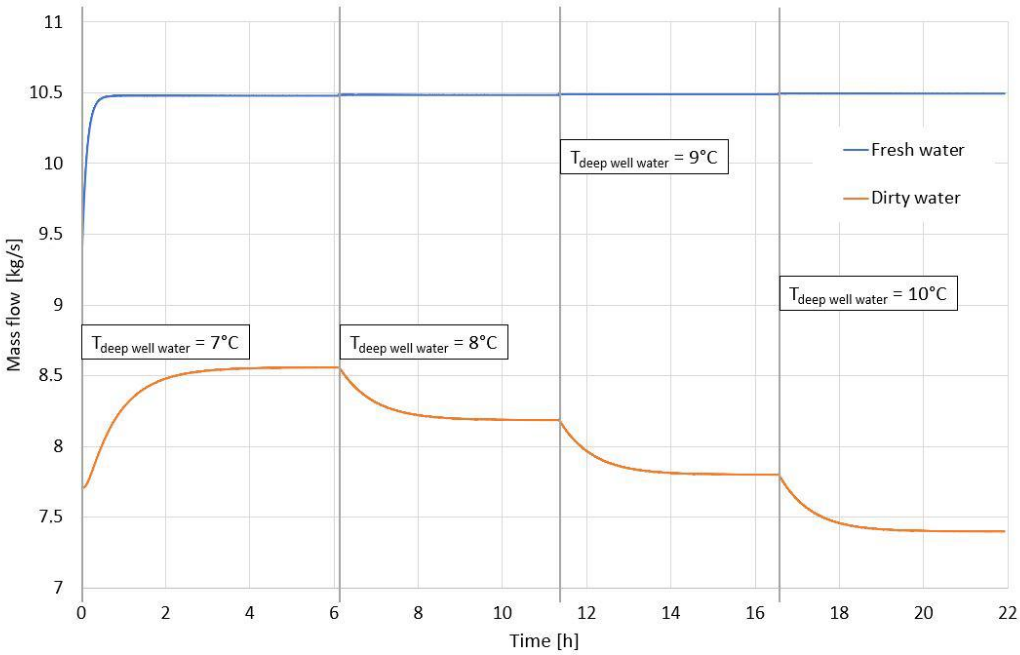

Figure 5. Mass flow of dirty water and fresh water throughout the heat exchanger.

Figure 6 shows the fresh water temperature after the TR-HE and selected results obtained during measurements in the actual WHR installation (points I-VII). The fresh water temperature peaks and decreases to a constant value of 19.7°C. The time constants of the SPWB cause such changes. These constants cause delays in adjusting the dirty water mass flow to the set temperature after the TR-HE. In addition, the pump has certain inertia that prevents abrupt changes in the flow rate. As a result, the system needs time to adjust to changing conditions.

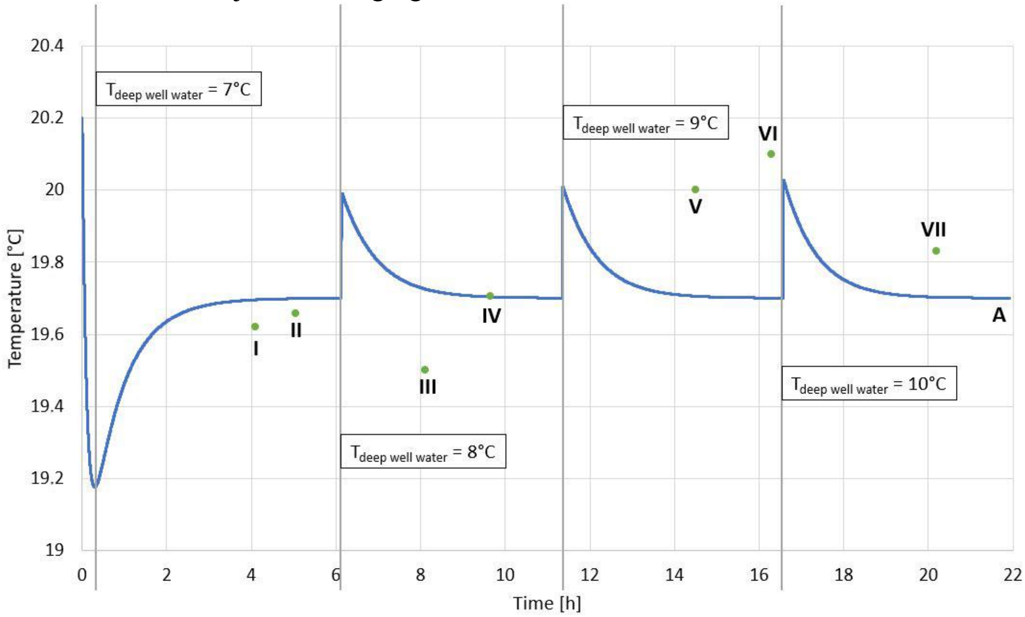

Figure 6. Temperature of fresh water after the heat exchanger (A – model, points I – VII – actual WHR installation)

Table 3. Summary of the relative error for all selected actual measurements.

	Temperature of fresh water after the heat exchanger		
Number	Value from model [°C]	Value from real installation [°C]	Relative error [%]
I	19.70	19.62	0.41
II	19.70	19.66	0.20
III	19.73	19.50	1.18
IV	19.71	19.71	0.00
V	19.71	20.00	1.45
VI	19.71	20.10	1.94
VII	19.70	19.83	0.66

To verify the developed model, a comparison is made between the results obtained from simulation calculations and those obtained during the operation of the actual WHR. Unfortunately, under the actual conditions, the only measured values are the temperatures of the heat exchanging media before and after the TR-HE. For this reason, only the fresh water temperature values at selected points of the system are chosen to verify the model. The results obtained during the operation of the actual installation are marked in Figure 6, (points I-VII).

For the parameters being verified, the relative error value given by equation (5) is calculated.

$$\delta = 100\% \cdot \frac{|V_e - V_m|}{V_e} \tag{5}$$

where:

V_e – value from actual measurements,

V_m – value from model calculations.

The relative error for all selected actual measurements is shown in Table 3.

By comparing the selected operating points of the actual installation and the results obtained from the model, it can be concluded that the model is a reliable representation of the existing WHR installation.

5. Conclusions

Performing low-temperature waste heat recovery is difficult due to its low exergy. Therefore, choosing suitable installation parameters is crucial for the effective recovery of this energy. Through simulation calculations, it is possible to verify whether waste heat recovery is possible at a specific location and adequately design such a WHR system.

It is possible to recover low-temperature heat from crop production using a highly efficient plate counterflow heat exchanger. With a waste water temperature between 20 to 30°C, the 1 MW heat exchanger can efficiently heat up the cold water from the deep well (7-10°C) to an assumed temperature of 19.7°C. The heated water can then be reused in the production process.

The results from the simulation calculations correspond to the results obtained under real conditions in the range of up to 2%. The Flownex software thus provides a reliable computational environment for the simulation of phenomena occurring in WHR installations in steady and transient states. It allows following the operation of the installation under changing conditions. It also enables the selection of appropriate power of the heat exchanger and system control rules that will achieve the assumed thermal-flow conditions behind the heat exchanger.

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References

[1] European Commission 2019 *The European Green Deal* Online: https://eur-lex.europa.eu/resource.html?uri=cellar:b828d165-1c22-11ea-8c1f 01aa75ed71a1.0002.02/DOC_1&format=PDF [cited 2022 May 11]
[2] Owusu P A and Asumadu-Sarkodie S 2016 *Cogent Eng.* **3** 1167990
[3] Forman C, Muritala I K, Pardemann R and Meyer B 2016 *Renew. Sustain. Energy Rev.* **57** 1568–79
[4] Eurostat 2022 *Energy statistics - an overview* Online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview#Final_energy_consumption [cited 2022 Feb 20]
[5] Haddad C, Périlhon C, Danlos A, François M-X and Descombes G 2014 *Energy Procedia* **50** 1056–69
[6] Xu Z Y, Wang R Z and Yang C 2019 *Energy* **176** 1037–43
[7] Fitó J, Hodencq S, Ramousse J, Wurtz F, Stutz B, Debray F and et al. 2020 *Energy Convers Manag.* **211** 112753
[8] Nematollahi O, Hajabdollahi Z, Hoghooghi H and Kim K C 2019 *J. Cleaner Prod.* **214** 705–16
[9] Uusitalo A, Honkatukia J, Turunen-Saaresti T 2017 *Appl. Energy* **192** 146–58
[10] Wu C, Wang S, Bai K and Li J 2016 *Appl. Therm. Eng.* **106** 661–73
[11] Varga Z and Csaba T 2018 *Energy Convers Manag.* **174** 793–801

[12] Ameel B, T'Joen C, De Kerpel K, De Jaeger P, Huisseune H, Van Belleghem M and De Paepe M 2013 *Appl Therm Eng.* **52** 130–40
[13] Li Y, Jin Y, Chen H, Tan C and Ding Y 2011 *Int J Energy Res.* **35** 1158–67
[14] Morgan R, Nelmes S, Gibson E and Brett G 2015 *Appl Energy.* **137** 845–53
[15] Jouhara H, Khordehgah N, Almahmoud S, Delpech B, Chauhan A and Tassou S A 2018 *Sci Eng Prog.* **6** 268–89
[16] Wang C, He B, Yan L, Pei X and Chen S 2014 *Energy* **65** 80–90
[17] Wang C, He B, Sun S, Wu Y, Yan N, Yan L and Pei X 2012 *Energy* **48** 196–202
[18] Niamsuwan S, Kittisupakorn P and Mujtaba I M 2013 *Appl Therm Eng*. **60** 188–99
[19] Çengel Y A. 2003 *Heat transfer: a practical approach* (Boston: McGraw-Hill)
[20] Adamski M 2008 *Energy Build.* **40** 1883–8
[21] Adamski M 2010 *Energy Build.* **42** 674–7
[22] Savchenko O, Zhelykh V and Voll H 2017 *Sel Sci Pap - J Civ Eng*. **12** 23–30
[23] Misevičiūtė V, Motuzienė V and Valančius K. 2018 *Appl Therm Eng*. **129** 772–81
[24] Fiaschi D, Manfrida G, Russo L and Talluri L. 2017 *Energy Convers Manag.* **150** 924–40
[25] Karanfil Celep G, Ener Rusen S, Topcu M A, Celtek S A and Rusen A 2019 *Anadolu Univ J Sci Technol- Appl Sci Eng* **20** 112-120
[26] Amiri A and Vaseghi M R 2015 *IEEE Trans Ind Appl.* **51** 13–9
[27] Shah R K and Sekulić D P 2003 *Fundamentals of heat exchanger design* (New Jersey: John Wiley & Sons)
[28] Aghayari R, Maddah H, Ashori F, Hakiminejad A and Aghili M 2015 *Heat Mass Transf.* **51** 301–6
[29] Flownex Simulation Environment Online: https://flownex.com/
[30] Rousseau P G, du Toit C G, Jun J S and Noh J M 2015 *Nucl Eng Des.* **291** 71–89
[31] van Ravenswaay J P, Greyvenstein G P, van Niekerk W M K and Labuschagne J T 2006 *Nucl Eng Des.* **236** 491–501
[32] Venter W C and Lamprecht E C 2012 *Ann Nucl Energy* **46** 1–10
[33] Walter A, Schulz A and Lohnert G 2006 *Nucl Eng Des.* **236** 603–14
[34] Fuls W F 2017 *Appl Therm Eng.* **116** 134–46
[35] Barnert T, Piesik E and Śliwiński M 2014 *Comput Electron Agric.* **108** 1–11
[36] Cui L, Sun H, Yang and Duan H 2020 *IFAC-Pap.* **53** 720–5
[37] Flownex Theory Manual. 2009.
[38] Flownex Library Manual. 2009.