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MODELLING OF A RECENTLY INVENTED SOLAR POT

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ABSTRACT

The subject of the research is a so-called the solar pot which is a new invention protected at the Hungarian Intellectual Property Office (utility model, patent number 5489). The pot can be used for heating or cooking (foods, drinks or other fluids). It has a similar structure to a double pipe heat exchanger with an outer jacket and an inner cooking space. Although it has been manufactured, its capabilities have not been tested neither by modelling and simulation nor with experiments and measurements, so these investigations represent a completely new research field. The goal of this work is the mathematical modelling of the pot which allows the prediction of the pot temperature. The modelling and the first simulation results based on it are presented in this paper, based on which conclusions can be drawn regarding the efficiency and applicability of the pot. Future research plan is also presented which includes the construction of an experimental system of the pot and a solar collector, and further modelling of the system and system elements. On the system, measurements will be made under different conditions, allowing the assessment of the pot's functionality and the validation of the mathematical models.

Keywords: solar pot, solar collector, mathematical modelling, simulation results, planning of experiments

1. INTRODUCTION

The heat energy provided by the sun is used to treat food in different ways. Examples include drying [1], baking, cooking [2], heating or keeping food warm. Solar food preparation devices operated with solar energy are known, in which solar energy directly heats a surface or air along it in a closed box, and the heat is transferred from there to the closed vessel placed in the box [3]. With this solution, the preparation of food by cooking cannot be solved in many cases [4]. However, there are solar cookers able to produce the temperature required for cooking. Typical types are the reflective panel [5], the parabolic [6] and the evacuated tube solar cooker [7]. These are the so-called direct-type food handlers. Indirect types use a solar collector to produce the thermal energy needed for food processing.

In [8] a solar cooker with solar collector and heat storage is investigated in China that uses oil as heat transfer medium. The main elements of the system are the solar collector, the heat storage and the cooking plate, which can be converted into a traditional electric cooking plate when supplemented with a heating element, enabling cooking even when there is not enough solar energy available. The main goal of the research was to investigate the effect of the quartzite heat storage medium on the system. For this, a mathematical model describing the performance of the system was prepared. The design with heat storage was compared with a version with one and two heat storage tanks. Based on the results, the version with quartzite heat storage increases the performance of the system, and the investment cost also decreases. The specific cost of cooking was 0.3884 USD/kWh, the solar share was 71%. When using the equipment to replace an electric stove, the annual reduction in carbon dioxide emission is 1.75 tons, in the case of a gas stove, it is 0.52 tons. In [9] a research is conducted on an indirect type solar food processing device with nanofluid working medium. One of the main elements of the system is the parabolic solar collector, at the focal point of which the working medium is heated by flowing through it. The other important element is the cooking unit, which consists of a copper pot and the copper pipe that surrounds it (wrapped around it). The heated working medium flows in this pipe, thus transferring the heat to the cooking space. A separate tank was also installed between the cooking unit and the collector, through which the working medium also flows. Due to the parabolic collector,

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the spiral heat exchanger and the additional tank, the structure of the system is more complex and thus its implementation is obviously more expensive than the system of the solar pot of this paper, which uses a more conventional evacuated tube collector and the solar pot similar to a simple, jacketed heat exchanger. The authors investigated the effect of mixing nano-sized particles with the oil serving as the working medium, how the mass fraction of the particles and the volumetric flow rate of the medium affect the development of the system's energy efficiency. The mass fraction was varied between 0 and 0.5% by mass, and the flow rate between 0.25 and 0.55 litres/minute. Based on their tests, it was found that while the efficiency of the collector increases continuously with the increase in volumetric flow rate, the highest efficiency is achieved in the case of the cooking unit at 0.25 litres/minute. Increasing the mass ratio increases the energy efficiency of both main units. The energy efficiency of the entire system increases by 20.08% in the case of a particle concentration of 0.5% by mass and a flow rate of 0.25 litres/minute, and 2 litres of water at 30°C could be heated to boiling point in 31.51% less time as in the case of the version using oil only. In [10] an indirect-type solar cooker is prepared in Egypt with flat plate collectors equipped with reflectors. They used phase change material, magnesium nitrate hexahydrate, mixed with steel shavings as heat storage material. The equipment is capable of cooking general meals in the midday and afternoon hours. In the evening it can be used to prepare special dishes that can be cooked at low temperatures for a long time (e.g. beans). In the night and morning hours it can be used to keep or reheat food. In [11] it was investigated how the performance of the system changes when the collector is supplemented with reflectors in an indirect solar food processing system equipped with a flat collector with water as working medium and supplemented with a heat storage tank containing a phase change material. They found that without a reflector, the highest average temperature of the absorber is 92°C, the highest temperature of the exiting working medium is 71°C, and the highest energy efficiency is 63%. It can be stated that the system is not suitable for cooking as the minimum safe temperature for cooking is 73.9°C according to [12]. On the other hand, thanks to the addition of reflectors, these values were respectively 130°C, 103.65°C and 79%. The device was used to cook 1 kg of rice and 1 kg of pasta in 1.5 litres of water. In both cases they were successful. It should be mentioned that the additions made in order to increase the performance of the equipment significantly increased the complexity of the system. The system examined in this paper has a simpler design and does not contain phase change material. In [13] a solar pressure cooker is investigated, which is connected to an evacuated tube solar collector to provide the necessary energy for operation. The water heated in the collector flows directly into the cooking chamber (under pressure) without the intervention of a heat exchanger. Thus, during operation, the condition of the heat-treated raw material/food must be difficult to check. The system we are examining is more practical, the cooking space is accessible during operation too, as it is hydraulically separated from the collector circuit under pressure. In [13] they used experiments to investigate the thermal behaviour of the equipment, under different weather conditions (radiation intensity, ambient temperature), regarding the boiling of different masses of water. Based on their results, a larger mass of water boils proportionally in less time, so the efficiency of the system improves when larger quantities are boiled. In [14] a large-scale cooking system was created capable of supplying energy to several cooking units at the same time. The flat plate collector system also includes a heat storage tank made of oil and stone, in addition to the cooking units. The flow of the working medium is not forced, no pump is needed. The system has been successfully used for food preparation in several developing countries (e.g. Mali, India). The system, that is the subject of this paper's research, works with a pump, so its placement/implementation can be done in a less constrained manner, it is also simpler and does not contain heat storage.

The main elements of the system examined are the solar collector and the solar pot. In the literature, there are mathematical models for collectors and solar collector systems [15], [16], however, as it is a new invention, no model has yet been created for the solar pot. In terms of design, the solar pot can be compared to a tube-in-tube heat exchanger or a solar storage tank. Models for those are already available in the literature. There are two main types of models. One is the black box type and the other is the physically based model. The physically based model is based on the physical background of the modelled system or process, which is therefore often difficult to set up in the case of a complex system [17]. Black box modelling does not take into account the physical background, it means a more result-oriented approach, the creation of the model is typically simpler [18], [19].

The Hottel-Whillier-Bliss physically based, mathematical model created for flat collectors [20] can be used to describe the temperature distribution of the working medium along the length of the collector as a function of place and time. In [21] a physically based mathematical model was developed that can be used to describe the temporal behaviour of a flat plate collector. Estimation of the temperature of the exiting working medium is made possible by a differential equation written on the basis of the energy balance of the collector. Ref. [22] presents several physically based mathematical models describing the dynamic behaviour of unglazed flat plate collectors. In [23] the possibility of a device that can be used for heating and domestic hot water production was developed, in which the collector is paired with a mirror. In connection with this, a physically based model was created for evacuated tube solar collectors, which can be used to estimate the total solar radiation reaching the collector. In [24] a black box type neural network model was created, which can be used to model the thermal behaviour of a flat collector. Knowing the intensity of solar radiation, the ambient temperature and the temperature of the working medium entering the collector, with a constant mass flow, the temperature of the exiting heat transfer medium can be predicted with the model. In [25] a black box model based on multivariate linear regression was developed for solar collectors. As a result, the appropriate temperature of the exiting working medium can be calculated. The identified and validated model was compared to the physically based model in [21]. The results showed that the model in [25] was able to predict the temperature of the exiting working medium more accurately. The importance of the model, in addition to the appropriate accuracy (average accuracy better than 5%), is due to its simplicity. It requires little calculation and can be used for any type of collector (e.g. evacuated tube collector).

There are several mixed storage models in the literature. In [15] a physically based mathematical model was developed. An ordinary differential equation based on the energy balance of the tank allows the temperature of the tank to be calculated. The model does not take into account the heat capacity of the solar storage material. In [26] a physically based mathematical model for a mixed storage was created, based on the heat balance characteristic of the storage, which can be used to calculate the temperature of the storage. A similar model can be found in [27]. In [28] a black-box model based on multivariate linear regression was developed for mixed solar storages, which can be used to determine the geometric average temperature of the storage.

When modelling tube-in-tube heat exchangers, energy balance is often assumed between the working media of the two sides, neglecting the environmental heat exchange [29], [30]. In [31] various mathematical models for tube-in-tube heat exchangers similar to the solar pot examined in this paper were developed. The physically based model takes into account the heat exchange with the environment, too. They also developed a black box type mathematical model based on multivariate linear regression, which also takes environmental heat exchange into account. The models were validated using measurements on a heat exchanger. Based on the results, the physically based model can more accurately estimate the temperature of the exiting working medium than the version assuming energy balance, if the heat exchange with the environment is not negligible. The black box model proved to be more accurate than both models, in the case of considerable environmental heat exchange. In [32] there are physically based models for tube-in-tube heat exchangers. The first is a model with distributed parameters, which can be used to calculate the temperature of the working medium on the cold and hot sides of the heat exchanger. The second is a second-order concentrated parameter model, which can be used to determine the outlet temperature of the cold and hot side working fluids. According to the authors' conclusion, second-order concentrated parameter models based on the logarithmic mean temperature difference approach can reliably describe the dynamics of heat exchangers.

2. MATERIALS AND METHODS

The subject of the research, the solar pot (shown in Fig. 1) is a new invention that received utility model protection at the Hungarian Intellectual Property Office in 2021 (patent number 5489) [33]. The pot can be used for environmentally conscious and energy-efficient heating or cooking of food, heating drinks (or other liquids). In terms of design, it is similar to a tube-in-tube heat exchanger, with an outer jacket and an inner cooking space. Heating or cooking takes place in the following way. The jacket heats the cooking space by circulating the working fluid (water or collector fluid) along the outer surface of the cooking space, forming a closed hydraulic unit with a solar collector equipped with a safety valve. The liquid in the jacket and the load in the cooking space are hydraulically separated from each other, so cooking or heating food can be done hygienically, in accordance with the relevant food regulations. The solar cooker can be used not only for preparing food, but also for reheating already prepared food and for heating liquids for other purposes. With the equipment, cooking or heating can be done in a 100% renewable, environmentally friendly way, using solar energy. An important advantage of the solar pot is that it can be integrated into existing solar collector systems (for domestic hot water production or heating purposes) and can even be used interchangeably with a solar storage tank. The solar pot is an indirect food processing device that can be used with any type of solar collector with liquid working medium, and in case of insufficient solar radiation, it can be heated with a cooking plate or stove as an additional option.

Figure 1. The solar pot

Although the solar pot had already been physically manufactured, its capabilities have not been tested neither by modelling and simulation nor with measurements and experiments, so these investigations represent a completely new research field. The goal of this work is the mathematical modelling of the solar pot, which allows the prediction of the temperature of the pot. The modelling and the first simulation results based on it are presented, based on which conclusions can be drawn regarding the efficiency and applicability of the solar pot.

2.1. Materials

The temperature of the solar pot can be calculated with the created physically based mathematical model. During the preparation of the model based on the energy balance, as a simplification the jacketed structure was neglected. The model was simulated using the Matlab and Simulink software package. With the help of the simplified model, simulation tasks were performed, the running time of which was 1 hour. The solar pot was tested with and without insulation with different pump volumetric flow rates and different working fluid inlet temperatures entering from the solar collector. Volumetric flow rate values were 100, 150, and 200 litres/hour. Inlet medium temperatures were 90, 95, 100 and 105°C. The solar collector connected to the pot can operate at a pressure higher than atmospheric pressure, so the temperature of the water entering the cooking vessel can exceed 100°C. The material of the pot is stainless steel with a wall thickness of 2 mm. The insulation is made of 50 mm thick polyethylene insulating material. There is no overpressure in the cooking space, the lid can be removed at any time. The lid was not on the solar pot during the tests, so the surface of the cooking pot bordering the environment was divided into two parts. The surface of the lid is 0.018 m^2, where the heat transfer coefficient is 132.5 W/m^2K, while the remaining surface of the cooking pot is 0.2129 m^2, where the heat transfer coefficient is 20.3 W/m^{2}K without insulation and 0.733 W/m^{2}K with insulation. The heat transfer factors are average values based on [34]. Additional inputs to the model are the volume of the cooking vessel, which is 8.109 litres, the specific heat and density of the water serving as the working medium, which are respectively 4200 J/kg°C and 1000 kg/m^3 (we neglect their temperature dependence) and the ambient temperature. The latter, which is also the temperature of the solar pot at the initial moment, is 25°C, since the pot is located in an air-conditioned room. The results of the tests include the heat loss that the solar collector must compensate in order to maintain the temperature of the solar pot, the time required to approach the steady state, the temperature of the pot when the steady state is approached, the difference between the inlet and solar pot temperatures when steady state is approached and the time required to reach 73.9°C under different conditions. According to [12], 73.9°C is the minimum cooking temperature required to sterilize food. Steady state is never actually reached but approached. In this work, the steady state is approached when the change in the temperature of the solar pot is less than 0.01°C/minute. The calculation of heat loss was made using overall heat transfer coefficients, heat transfer surfaces and temperature differences. Based on the results, conclusions can be drawn regarding the cooking capabilities of the pot. Future research plan includes the construction of an experimental system of the solar pot and an evacuated tube solar collector as the two main components, the creation of more complex models not neglecting the jacketed structure of the pot and the validation of the models with the help of data from measurements carried out on the experimental system.

2.2. Model

The mathematical model is as follows:

$$\frac{dT_p}{dt} = \frac{v_c}{V} \cdot \left(T_{in} - T_p\right) + \frac{A_1 \cdot k_1 + A_2 \cdot k_2}{\rho \cdot c \cdot V} \cdot \left(T_a - T_p\right), \tag{1}$$

where v_c is the volumetric flow rate of the pump, V is the volume of the solar pot, T_{in} is the temperature of the working medium entering the jacket from the solar collector, A_1 is the outer surface of the cooking pot without the lid, k_1 is the overall heat loss coefficient of the solar pot, A_2 is the surface of the lid, k_2 is the overall heat loss coefficient of the lid, ρ is the density of water, c is the specific heat capacity of water, T_a is the ambient temperature, T_p is the temperature of the solar pot. The model is a differential equation that can be used to calculate the temperature of the solar pot. The jacketed structure has been neglected, so the equation is written for the simplified case where the heated working fluid from the solar collector is circulated directly through the solar pot, without hydraulic separation. Fig. 2 presents the realization of the model in the Matlab and Simulink software package.

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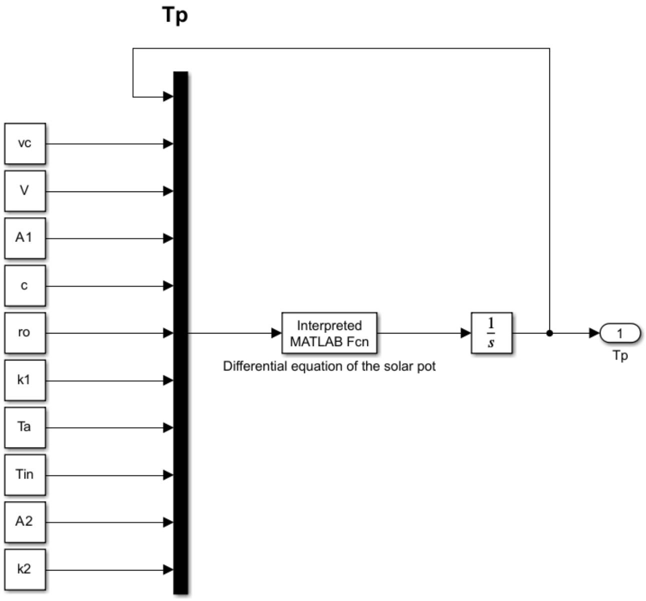

Figure 2. The Simulink model

3. RESULTS AND DISCUSSION

3.1. Figures, graphs and tables

Tab. 1 shows the results for the non-insulated version and Tab. 2 shows the results of the insulated design. These are the temperature of the solar pot when it approaches the steady state (T_{ss}), the time required to reach this temperature (t_{ss}), the temperature difference between the inlet water and solar pot when steady state is approached (ΔT), the time required to reach 73.9°C ($t_{73.9°C}$) and the heat loss of the solar pot (P_{loss}).

Table 1. Results of simulation with no insulation

T_{in}, v_c	T_{ss} (°C)	t_{ss} (min)	ΔT (°C)	$t_{73.9°C}$ (min)	P_{loss} (W)
90°C, 100l/h	86.29	26.75	3.71	7.5	411.06
90°C, 150l/h	87.48	19.5	2.52	4.75	419.05
90°C, 200l/h	88.1	15.5	1.9	3.75	423.2
95°C, 100l/h	91.01	27	3.99	6.25	442.72
95°C, 150l/h	92.3	19.75	2.7	4.25	451.37
95°C, 200l/h	92.95	15.5	2.05	3	455.73
100°C, 100l/h	95.75	27.5	4.25	5.5	474.51
100°C, 150l/h	97.1	19.75	2.9	3.75	483.57
100°C, 200l/h	97.81	15.75	2.19	3	488.34
105°C, 100l/h	100.47	27.75	4.53	5	506.17
105°C, 150l/h	101.92	20	3.08	3.25	515.89
105°C, 200l/h	102.68	16	2.32	2.5	520.99

Table 2. Results of simulation with insulation

T_{in}, v_c	T_{ss} (°C)	t_{ss} (min)	ΔT (°C)	$t_{73.9°C}$ (min)	P_{loss} (W)
90°C, 100l/h	88.43	27.75	1.57	7	161.18
90°C, 150l/h	88.94	19.75	1.06	4.75	162.48
90°C, 200l/h	89.21	15.75	0.79	3.5	163.16
95°C, 100l/h	93.32	28	1.68	6	173.6
95°C, 150l/h	93.87	20	1.13	4	175
95°C, 200l/h	94.15	15.75	0.85	3	175.71
100°C, 100l/h	98.22	28.5	1.78	5.25	186.06
100°C, 150l/h	98.8	20.25	1.2	3.5	187.53
100°C, 200l/h	99.1	16	0.9	2.75	188.29
105°C, 100l/h	103.11	28.75	1.89	4.75	198.48
105°C, 150l/h	103.73	20.5	1.27	3.25	200.06
105°C, 200l/h	104.05	16.25	0.95	2.5	200.87

On Fig. 3 one can see the change in the temperature of the solar pot and the temperature of the inlet water in the time domain of the simulation, in the case of 90°C inlet water temperature and a flow rate of 100 litres/hour, without insulation. Fig. 4 shows the case of the insulated pot, where the inlet water is 105°C hot and the pump flow rate is 200 l/h. The two figures therefore illustrate the two extreme cases examined.

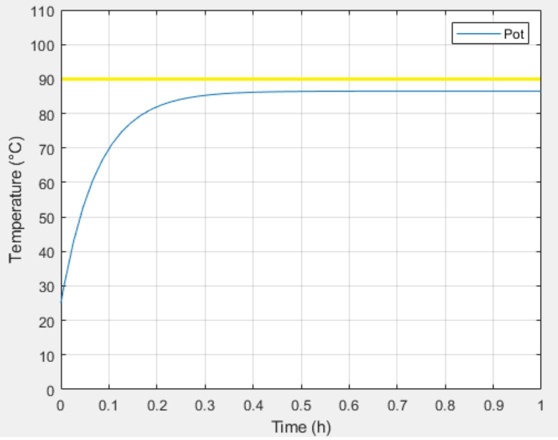

Figure 3. Solar pot temperature, inlet water 90°C, flow rate 100 litres/hour, without insulation

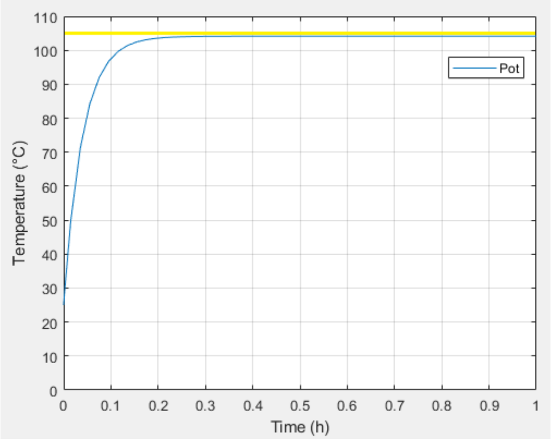

Figure 4. Solar pot temperature, inlet water 105°C, flow rate 200 litres/hour, with insulation

4. CONCLUSIONS

Based on the results, it can be observed that the time (t_{ss}) required to heat up the medium in the solar pot to T_{ss} decreases as the volumetric flow rate increases. The temperature of the inlet water does not significantly affect the value of t_{ss}. It took about the same time to approach steady state for different inlet temperatures and the same flow rates. The pot reached 73.9°C sooner if the inlet temperature was higher. An increase in the inlet temperature results in a higher solar pot temperature, but the temperature difference between them also increases. Increasing the volumetric flow rate reduces this difference. Heat loss increases continuously as the temperature of the pot increases. This can be significantly reduced by using insulation, and with insulation, the temperature difference between the inlet medium and the solar pot is also reduced.

Increasing the volumetric flow rate has a favourable effect on the operation of the system. For example, in the case of 90°C inlet water, the temperature of the pot without insulation increases from 86.29°C to 88.1°C by increasing the volumetric flow rate from 100 litres/hour to 200 litres/hour.

Based on the examinations, the use of insulation can be justified. For example, in the case of an inlet temperature of 95°C and a flow rate of 100 litres/hour, the solar pot heats up to 91.01°C without insulation, but to 93.32°C with insulation. The heat loss in this case is 442.72 W without insulation, and only 173.6 W with insulation. The favourable price of polyethylene insulation material also supports the use of insulation. The cooking pot is able to perform cooking tasks based on the simulation. It can maintain the temperature required for cooking for a longer period of time, so different dishes can be prepared with it within a foreseeable time. Even in the most unfavourable case, the cooking pot heated up to the cooking temperature in less than half an hour. If the solar collector is able to operate at higher pressure and the intensity of the solar radiation is adequate, values of around 100°C can be reached in the cooking space (e.g. even at a pressure of 1.5 bar, the boiling point of water is already 111°C). The continuation of the research in the future is justified by the results. The plans include the creation of more accurate physically based and black box type models not neglecting the jacketed design of the solar pot. These models can be used to calculate the temperature of the cooking space. Assembling the experimental system consisting of an evacuated tube solar collector and the solar pot, performing measurements on the system, and using the measurement data to identify and validate the models are among the future goals of the research as well. Measurements and cooking experiments with the assembled experimental system allow the results of this work to be clarified and further verified.

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REFERENCES

[1] I. Farkas, Solar energy in agriculture, Mezőgazda Lap- és Könyvkiadó Kft., Budapest, 2003 (in Hungarian)
[2] A. Saxena, N. Agarwal, Performance characteristics of a new hybrid solar cooker with air duct, Solar Energy, 159 (2018), pp. 628-637. https://doi.org/10.1016/j.solener.2017.11.043
[3] A. Saxena, E. Cuce, G. N. Tiwari, A. Kumar, Design and thermal performance investigation of a box cooker with flexible solar collector tubes: An experimental research, Energy, 206 (2020), pp. 1-15. https://doi.org/10.1016/j.energy.2020.118144
[4] A. W. Bigelow, J. Tabatchnick, C. Hughes, Testing Solar Cookers for Cooking Efficiency, Solar Energy Advantages, (2024), pp. 1-7. https://doi.org/10.1016/j.seja.2024.100053
[5] P. K. Gupta, A. Misal, S. Agrawal, Development of low cost reflective panel solar cooker, Materialstoday: Proceedings, 45 (2) (2021), pp. 1-4. https://doi.org/10.1016/j.matpr.2020.12.004
[6] P. Saini, S. Pandey, S. Goswami, A. Dhar, M. E. Mohamed, S. Powar, Experimental and numerical investigation of a hybrid solar thermal-electric powered cooking oven, Energy, 280 (2023), pp. 1-12. https://doi.org/10.1016/j.energy.2023.128188
[7] M. Hosseinzadeh, A. Faezian, S. M. Mirzababaee, Parametric analysis and optimization of a portable evacuated tube solar cooker, Energy, 194 (2020), pp. 1-12. https://doi.org/10.1016/j.energy.2019.116816
[8] C. Zhou, Y. Wang, J. Li, X. Ma, Q. Li, M. Yang, X. Zhao, Y. Zhu, Simulation and economic analysis of an innovative indoor solar cooking system with energy storage, Solar Energy, 263 (2023), pp. 1-15. https://doi.org/10.1016/j.solener.2023.111816
[9] M. Hosseinzadeh, R. Sadeghirad, H. Zamani, A. Kianifar, S. M. Mirzababaee, The performance improvement of an indirect solar cooker using multi-walled carbon nanotube-oil nanofluid: An experimental study with thermodynamic analysis, Renewable Energy, 165 (1) (2021), pp. 14-24. https://doi.org/10.1016/j.renene.2020.10.078
[10] H. M. S. Hussein, H. H. El-Ghetany, S. A. Nada, Experimental investigation of novel indirect solar cooker with indoor PCM thermal storage and cooking unit, Energy Conversion and Management, 49 (8) (2008), pp. 2237-2246. https://doi.org/10.1016/j.enconman.2008.01.026
[11] M. Y. Getnet, D. G. Gunjo, D. K. Sinha, Experimental investigation of thermal storage integrated indirect solar cooker with and without reflectors, Results in Engineering, 18 (2023), pp. 1-14. https://doi.org/10.1016/j.rineng.2023.101022
[12] USDA (Food Safety and Inspection Service, U.S. Department of Agriculture), Safe Minimum Internal Temperature Chart, https://www.fsis.usda.gov/food-safety/safe-food-handling-and-preparation/food-safety-basics/safe-temperature-chart (28th May 2024)
[13] R. Kumar, R. S. Adhikari, H. P. Garg, A. Kumar, Thermal performance of a solar pressure cooker based on evacuated tube solar collector, Applied Thermal Engineering, 21 (16) (2001), pp. 1699-1706. https://doi.org/10.1016/S1359-4311(01)00018-7
[14] K. Schwarzer, T. Krings, Demonstrations- und Feldtest von Solarkochern mit temporärem Speicher in Indien und Mali, Abschlussbericht, 1996
[15] J. Buzás, I. Farkas, Solar domestic hot water system simulation using blockoriented software, The 3rd ISES-europe Solar World Congress, CD-ROM Proceedings, København, Denmark, 2000, pp. 1-9.

DOI: https://doi.org/10.14232/analecta.2024.2.38-48

[16] L. S. M. Castellanos, A. L. G. Noguera, E. I G. Velásquez, G. E. C. Caballero, E. E: S. Lora, V. R: M. Cobas, Mathematical modeling of a system composed of parabolic trough solar collectors integrated with a hydraulic energy storage system, Energy, 208 (2020), pp. 1-16. https://doi.org/10.1016/j.energy.2020.118255
[17] S. A. Kalogirou, S. Panteliou, A. Dentsoras, Modeling of Solar Domestic Water Heating Systems Using Artificial Neural Networks, Solar Energy, 65 (1999), pp. 335-342. https://doi.org/10.1016/S0038-092X(99)00013-4
[18] L. Brus, D. Zambrano, Black-box identification of solar collector dynamics with variant time delay, Control Engineering Practice, 18 (2010), pp. 1133-1146. https://doi.org/10.1016/j.conengprac.2010.06.006
[19] J. Zheng, R. Febrer, J. Castro, D. Kizildag, J. Rigola, A new high-performance flat plate solar collector. Numerical modelling and experimental validation, Applied Energy, 355 (2023), pp. 1-14. https://doi.org/10.1016/j.apenergy.2023.122221
[20] H. C. Hottel, A. Whillier, Evaluation of flat-plate collector performance, Trans. Conf. Use of Solar Energy, 3 (2) 1955
[21] J. Buzás, I. Farkas, A. Biró, R. Németh, Modelling and simulation aspects of a solar hot water system, Mathematics and Computers in Simulation, 48 (1998), pp. 33-46. https://doi.org/10.1016/S0378-4754(98)00153-0
[22] F. Hilmer, K. Vajen, A. Ratka, H. Ackermann, W. Fuhs, O. Melsheimer, Numerical solution and validation of a dynamic model of solar collectors working with varying fluid flow rate, Solar Energy, 65 (5) (1999), pp. 305-321. https://doi.org/10.1016/S0038-092X(98)00142-X
[23] C. Mao, M. Li, N. Li, M. Shan, X. Yang, Mathematical model development and optimal design of the horizontal all-glass evacuated tube solar collectors integrated with bottom mirror reflectors for solar energy harvesting, Applied Energy, 238 (2019), pp. 54-68. https://doi.org/10.1016/j.apenergy.2019.01.006
[24] P. Géczyné Víg, Modelling of solar collector systems with neural network, PhD thesis, Szent István University, Gödöllő, 2007 (in Hungarian)
[25] R. Kicsiny, Multiple linear regression based model for solar collectors, Solar Energy, 110 (2014), pp. 496-506. https://doi.org/10.1016/j.solener.2014.10.003
[26] D. P. Hiris, O. G. Pop, M. C. Balan, Analytical modeling and validation of the thermal behavior of seasonal storage tanks for solar district heating, Energy Reports, 8 (9) (2022), pp. 741-755. https://doi.org/10.1016/j.egyr.2022.07.113
[27] V. Badescu, Optimal control of flow in solar collector systems with fully mixed water storage tanks, Energy Conversion and Management, 49 (2) (2008), pp. 169-184. https://doi.org/10.1016/j.enconman.2007.06.022
[28] R. Kicsiny, Black-box model for solar storage tanks based on multiple linear regression, Renewable Energy, 125 (2018), pp. 857-865. https://doi.org/10.1016/j.renene.2018.02.037
[29] J. Bradley, Counterflow, crossflow and cocurrent flow heat transfer in heat exchangers: Analytical solution based on transfer units, Heat and Mass Transfer, 46 (2010), pp. 381-394. https://doi.org/10.1007/s00231-010-0579-5
[30] B. Zohuri, Compact Heat Exchangers, Selection, Application, Design and Evaluation, Springer International Publishing, Switzerland, 2017 https://doi.org/10.1007/978-3-319-29835-1
[31] G. Géczi, R. Kicsiny, P. Korzenszky, Modified effectiveness and linear regression based models for heat exchangers under heat gain/loss to the environment, Heat and Mass Transfer, 55 (2019), pp. 1167-1179. https://doi.org/10.1007/s00231-018-2495-z
[32] A. Zavala-Río, R. Santiesteban-Cos, Reliable compartmental models for double-pipe heat exchangers: An analytical study, Applied Mathematical Modelling, 31 (9) (2007), pp. 1739-1752. https://doi.org/10.1016/j.apm.2006.06.005

[33] G. Géczi, R. Kicsiny (inventors), Hungarian University of Agriculture and Life Sciences (owner), Apparatus for Preparing Food with Solar Energy and/or for Heating Liquid, Utility Model Protection, Hungarian Intellectual Property Office, patent number 5489, 2021 (in Hungarian)
[34] E. Cao, Heat Transfer in Process Engineering, 1st Edition, McGraw-Hill Education, ISBN: 9780071624084, 2010