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Performance Evaluation of Dual Purposes Solar Heating System Using Heat Pipe Evacuated Tube Solar Collector

H. H. El-Ghetany and S. A. Hassan

Solar Energy Department, National Research Centre, Dokki, 12622, Giza, Egypt

Abstract

The aim of this work is to develop dual purposes solar heating system using heat pipe evacuated tube solar collector. The heat transfer fluid between the thermal loads and the solar collector loop was heating oil. The study provided two thermal loads; solar water heating system and solar baking/cooking system that had experimentally investigated under various weather conditions. The experimental pilot unit was installed in Solar Energy Department, National Research Centre, Giza, Egypt. Several test runs were performed to measure all assigned parameters that affect the system performance. The system is designed to provide high thermal energy through hot oil surrounding the inner vessel of the baker while the raw food can be baked/cooked and the outlet thermal energy can be used for heating water via immersed coil in the hot water storage tank; then the relatively cooled oil is returned to the solar collector via hot oil circulating pump. The water tank heat exchanger is designed with the following design parameters; specific heat of oil and water were 1.67 kJ/kg °C and 4.186 kJ/kg °C respectively; density of oil and water were 850 kg/m^3 and 1000 kg/m^3 respectively; mass flow rate of oil and water were 12 liters/min and 6 liters/min respectively. It is clear that the system in addition to provide thermal energy for baking/cooking unit, it can provide thermal energy for water heating purposes. The tested system can be positively contributed in baking and cooking purposes and providing hot water as well. It is found that, for the same flow rates of hot oil and water, as the hot oil temperature difference increased, the outlet hot water increased. The system is capable to produce hot water temperature up to 85 °C if the hot oil temperature difference was 100 °C while it can produce hot water temperature about 60 °C if the hot oil temperature difference was 60 °C during the day which is suitable for residential purposes and industrial process as well. Based on the resultant data, it is found that the system solar fraction was estimated as 54%. The auxiliary heating system can be electric source in case of using in urban areas and can be renewable energy source like biogas or hydrogen fuels in rural and isolated areas.

Keywords— Solar energy, Water heating system, Evacuated tube heat pipe solar collector**,** Baking/Cooking, Water heating, Performance evaluation

1. Introduction

Utilization of solar energy as a clean source of energy is considered a great potential for using renewable energy sources. It is abundant, available with significant values of solar radiation dose with an average daily value of 5.6 kWh/m^2/day in Egypt. Utilizing solar thermal energy for cooking/baking and water heating to cover part of the thermal energy consumption demands in several communities is considered one of the best alternative energy sources. The higher solar thermal energy can be achieved either by using concentrating solar collectors or by using heat pipe evacuated tube collectors associated with auxiliary heating source. Solar cookers can be considered energy conversion equipment that convert solar energy into thermal energy to be utilized for cooking purposes. Based on the heat transfer procedure, solar cooking systems can be classified to direct solar cookers, DSC (hot box and point focusing parabolic concentrator) where the cooking process was done by the thermal enclosure inside the hot box solar cooker. The second type called indirect solar cookers that associated either with a flat-plate solar collector and a heat pipe evacuated tube solar collector) where the cooking process was done by the thermal energy in the heat transfer fluid between the outdoor solar unit and indoor cooking unit. The Indoor solar cookers/bakers (ISC) had the advantages that it can be used inside the building and the thermal energy transferred from the outdoor solar collector via heat transfer fluid can be utilized. Hot box solar cookers

*Corresponding author e-mail: hamdy.elghetany@gmail.com (Hamdy El-Ghetany).
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had also some advantages; like low cost, effective and simple in terms of manufacturing, installation, operation and maintenance and can be used in rural and isolated areas successively [1–6]. They have limitation to cook outdoors during clear sky periods around solar noon. The point focusing concentrating solar dish cookers had several limitations like needing continuous tracking system which is costly and need professional manpower [7, 8]. On the other hand, ISC were observed more convenient than DSC. They provided high thermal energy without needing to change the cooker orientation, in addition, cooking can be performed indoors [9–12]. ISC was associated with plane reflectors to enhance the amount of solar radiation falling on the solar collector surface [13,14]. ISC suffered from some disadvantages like performance degradation due to the night reversed cycle and partially cloudy periods. therefore, it is recommended to improve the heat transfer mechanism in the solar loop. For the previously mentioned reasons, the ISC using evacuated tubes heat pipe solar collectors is recommended for cooking systems as the heat of evaporation and condensation were transferred between the evaporator section and condenser section. Khalifa et al. [15,16] experimentally investigated solar cooking system that had solar heat pipes impeded inside flat-plate solar collector as outdoor unit while the indoor cooking unit was installed inside the building. A thermal oil was used as heat transfer fluid between the indoor and outdoor units. It was recommended that using ISC had a good potential in renewable energy cooking technologies. Stumpf et al. [17] performed theoretical study with experimental investigations of different heating mechanisms of the ISC. They found that the heat pipe solar collector was more stable than flat plate solar collector as energy source of the solar cooker. Hussein H.M.S. et al. [18] performed theoretical study and experimental investigation of ISC associated with outdoor elliptical cross section, wickless heat pipes, flat-plate solar collector and integrated indoor PCM thermal storage and cooking unit under actual meteorological conditions of Giza, Egypt. The outdoor unit was augmented with two plane reflectors to enhance the solar radiation falling on the collector surface. The utilized PCM was magnesium nitrate hexa-hydrate (melting point = 89 ^{o}C, latent heat of fusion 134 kJ/kg). They concluded that the reflectors enhanced the solar radiation by 24% and the studied ISC can be used successfully for cooking different kinds of meals during night and daytime. In the current study, the evacuated tube heat pipes solar collector is used to provide the required thermal energy for baking process. The evacuated tube heat pipe was efficiently used to provide high thermal energy and low heat loss to the surrounding. El-Ghetany H. H. [19] experimental investigated the solar baking system using parabolic trough solar collector, they concluded that It is found that to reach the desired moisture content for baking process (35%-40%), the solar radiation dose should be not lower than 4.0 kWh/m^2. For the multi-purposes solar heating system, El-Ghetany H. H. [20] studied the performance evaluation and, experimental verification of a novel solar water desalination system and concluded that the solar water heating system can be used for water desalination production with a daily water yield of 5 m^3/day. The present work experimentally verifies the behavior of the possibility of using the evacuated tube heat pipe as a part of a bakery. The baking/cooking system is designed to investigate the thermal performance and experimentally verify the baking process under the actual meteorological conditions of ambient temperature, wind speed and solar radiation. Abdellah Shafieian et al. [21] conducted a research to evaluate the performance of a heat pipe solar water heating system to meet a real residential hot water consumption pattern theoretically and experimentally. Their results showed that hot water extraction had significant impact on the thermal performance of solar water heating system by increasing the amount of the absorbed energy and overall efficiency and decreasing exergy destruction. Two empirical equations relating the thermal and exergetic efficiencies of the heat pipe solar collector to the operational and environmental parameters were proposed. Comparison of the theoretical and experimental outlet temperature of the collector showed very good agreement with the maximum absolute and standard errors being 5.6% and 1.77%, respectively. Mahmoud B. Elsheniti et al., [22] studied the thermal performance of adsorption cooling system using heat-pipe evacuated-tube solar collector. Hot water is targeted at a relatively high inlet temperature of 70–90 °C to predict the collector performance that utilized in solar cooling system. Their model studied the effects of the inlet water and ambient temperatures, number of evacuated tubes, water mass flow rate, and solar irradiance on both the exit water temperature and the collector's efficiency. They concluded that at certain values of the water mass flow rate and solar irradiance, the exit temperature increases with the increase in the number of evacuated-tubes. They developed an expression for predicting the collector efficiency based on the mathematical model's results that can be used in calculating the exit water temperature at different operating conditions and number of evacuated tubes. Which can be effectively used for modeling such type of collector employed in a thermally driven cooling cycle. Gorakshnath Takalkar and Rahul R. Bhosale [23] studied the thermal performance for water desalination using evacuated tube heat pipe solar collector. The effects of the mass flow rate of water, inlet temperature, solar intensity, the ratio of the condenser to absorber area, heat transfer coefficients on energy and exergy efficiency, the absorber temperature, condenser temperature, and the outlet temperature are explored by using a heat transfer **resistance model.**

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2. System Description

The presented solar heating system can be used to provide thermal energy for cooking/baking purposes and water heating system as well. Solar energy can be stored through heat transfer fluid. The HTF (Heating oil 32) is chosen in the current system to carry the thermal energy from the heat pipe evacuated tube collector to the thermal oil storage tank. The heat transfer oils were high quality paraffinic oils, they were manufactured from highly refined oils with specific additives to resist chemical oxidation and thermal cracking. It had high heat transfer efficiency, its specific gravity at 15 ºC, kinematic viscosity at 40 ºC and initial boiling point ºC are 0.88, 28.8/35.2, and 300 respectively. It had several advantages like high resistance to thermal cracking, excellent heat transfer properties, long life, minimal maintenance costs, and easy starting-up. The system is consisted of two loops; heat transfer loop and water loop. The heat transfer loop consisted of heat pipe evacuated tube solar collector, heat transfer fluid, hot oil circulating pump, auxiliary heater storage tank, solar cooker/baker and heat exchanger inside the water storage tank. While the second loop consisted of heating water storage tank impeded with heat exchanger and the water demand load as shown in Fig. 1.

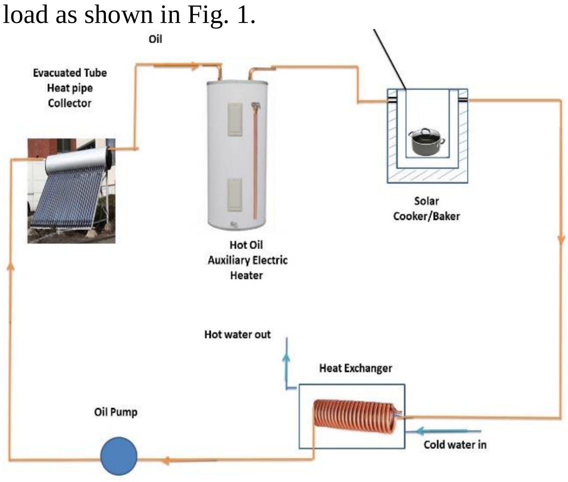

Fig.1. Layout of the solar heating system for baking/cooking and water purposes

Evacuated Tube Solar Collectors (ETSCs) are one of the most innovative forms of solar thermal technology. ETSCs are very efficient and can achieve very high temperatures. Heat pipe evacuated tube collectors contain a copper heat pipe, which is attached to an absorber plate, inside a vacuum sealed solar tube. The heat pipe is hollow and the space inside is also evacuated. Inside the heat pipe is a small quantity of liquid, such as alcohol or purified water plus special additives. The vacuum enables the liquid to boil at lower temperatures than it would at normal atmospheric pressure. When sunlight falls on the surface of the absorber, the liquid in the heat tube quickly turns to hot vapor and rises to the top of the pipe [24]. Water or glycol, flows through a manifold and picks up the heat. The fluid in the heat pipe condenses and flows back down the tube. This process continues, as long as the sun shines. Since there is a "dry" connection between the absorber and the header, installation is much easier than with direct flow collectors. Individual tubes can also be exchanged without emptying the entire system of it's fluid and should one tube break, there is little impact on the complete system [25]. The solar collector consists of 30 tubes to heat up 300 litres volume storage tank that consisted of two tanks, the inner tank is made from stainless steel 304-2B with 1.5 mm thickness while the outer tank is painted with anti-corrosion layer and the inner space between the two tanks was filled with 5 cm polyurethane rigid foam. It is cons Heat pipe collectors must be mounted with a minimum tilt angle of around 25° in order for the internal fluid of the heat pipe to return to the hot absorber as shown in Fig. 2.

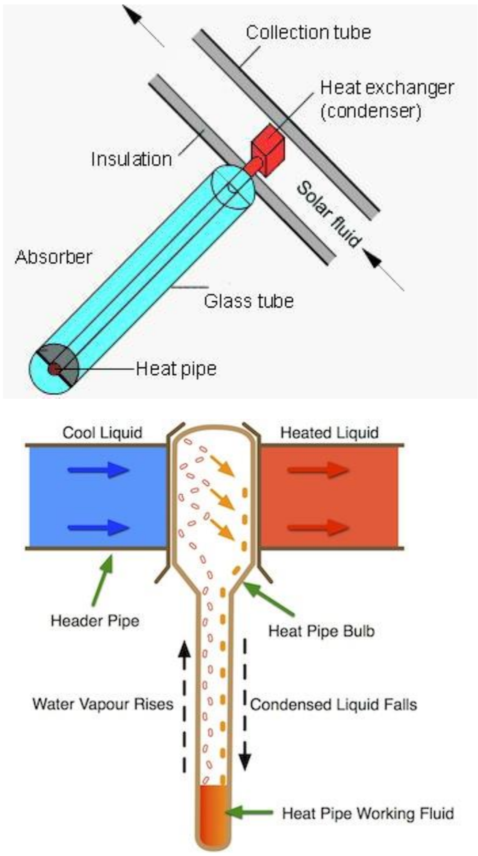

Fig. 2. Heat pipe evacuated tube collectors [26]

The thermal oil solar bakery shown in Fig. 3 consists of three concentric rectangular boxes made from galvanized steel sheets with a thickness of 2 mm. The inner space between the inside two boxes was filled with hot oil coming from the solar heat pipe evacuated tube collector and auxiliary heating source. While the annular space between the outer two boxes was filled glass wool insulation to minimize the amount thermal energy losses to surroundings. A plane reflector the hot oil solar bakery unit was mounted on an elevated metallic frame with a height of 1m. A photographic view of the experimental system is presented in Fig. 4.

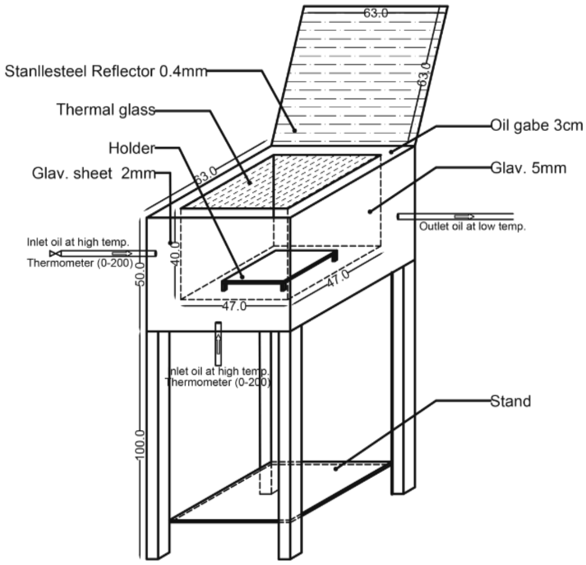

Fig 3: Layout of the hot oil solar bakery

3. Experimental procedure

Several experiments had been run to investigate the thermal performance of the studied solar heating system for both baking/cooking and water heating system. The temperatures inside, outside, top and bottom the solar oil baker are recorded and the solar radiation falling on the surface of evacuated tube is measured throughout the experiments. The thermal oil is heated in the solar heat pipe collector tank and the outlet hot oil was increased inside a backup auxiliary heater prior entering the baking/cooking unit. The thermal energy outlet from the baker is recovered in the water heating tank to save the oil pump from excessive heat and producing hot water. Then the oil is returned back to the solar collector tank via the oil circulating pump. As an example of the baking samples, a cake sample was prepared and placed inside the solar baker and during the experiment the cake was totally baked as shown in Fig. 5. The inlet and outlet temperatures of the hot oil solar collector tank, baking/cooking unit, and water heating tank were measures as well as the ambient temperature and solar radiation throughout the experiment. The thermocouples inside/outside, the baking unit is shown in Fig. 6. Type K thermocouples usually work in most applications as they are nickel based and exhibit good corrosion resistance. It is the most common sensor calibration type providing the widest operating temperature range with Standard: ± 2.2C% or ±.75%.

Fig 4 A photographic view of the solar heating system

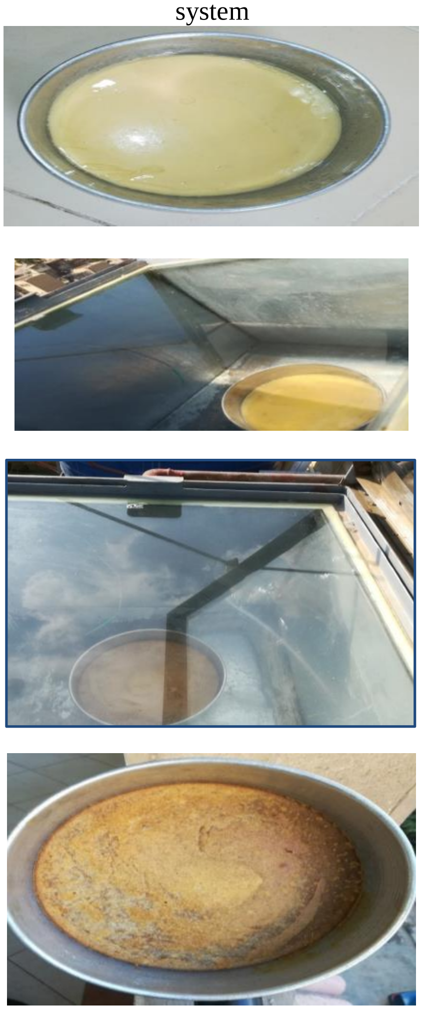

Fig.5. A photographic view of the baked cake inside the baking unit of solar oil bakery collector

Fig 6: A photographic view of the Thermocouples inside/outside the baking unit.

4. Results and Discussions

Several runs are made to investigate the thermal performance of the system. Hot oil temperatures, solar radiation, and air temperature inside the baker enclosure and ambient temperature were measured. Due to the plenty of available solar radiation in Egypt throughout the year, it can be said that solar energy provides good potentials for utilization in thermal applications throughout the year. A sample of the experimental results showed that the total solar radiation falling on the solar system was 20.47 kWh and the total electric energy consumed was 18 kWh resulting solar fraction value of 54%. The temperature variations of the inlet and outlet hot oil in the baking unit are shown in Fig. 7.

It is clear that the hot oil temperature increased during the daytime as it gained thermal energy from solar energy in the evacuated tube heat pipe solar collector tank and from the auxiliary thermal energy. Also both the hot oil tank and baking/cooking unit were well insulated to minimize the thermal losses to surroundings. The temperature variations of the ambient temperature and air temperature inside the baker enclosure and the solar radiation variation throughout the experiment is shown in Fig. 8

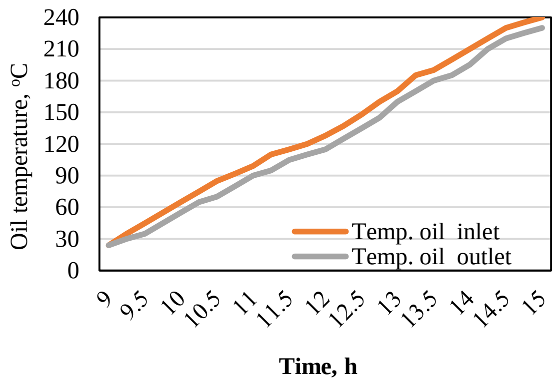

Fig.7: Temperature variations of the inlet and outlet hot oil in the baking unit

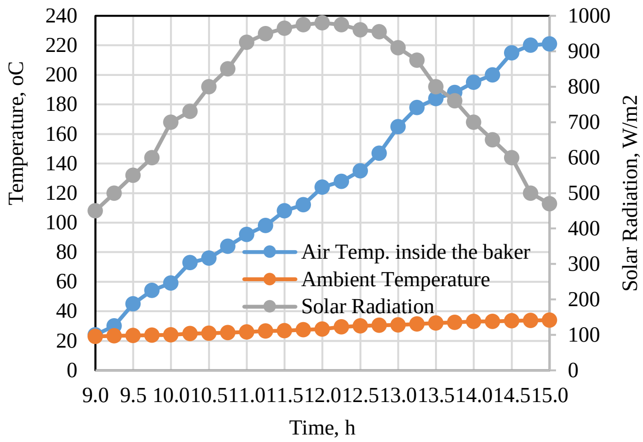

Fig 8: The temperature variations of the ambient temperature and air temperature inside the bake enclosure and the solar radiation variation throughout the experiment

As the baking tray was placed inside the cooking/baking unit, it was exposed to conductive heat transfer from the bottom of the baking unit and convective heat transfer from the enclosure that received the convective thermal energy from baking unit sides and the incoming solar radiation from the top side as well. The hot oil outlet from the baking/cooking unit is passed through a spiral coil heat exchanger immersed inside a water tank to produce hot water and cooling down the oil temperature prior returning the solar collector oil tank through hot oil circulating pump. The temperature distribution of the inlet and outlet water temperature and water tank inlet oil temperature is shown in Fig. 9. The amount of solar radiation falling on the collector surface is calculated as follows

$$Q_{Sol\ Rad} = \int_{ti}^{tf} I d\tau$$

Where

I is the solar radiation intensity, W/m^2

τ is the time interval, h and

t_f and t_i are the final and initial time interval

The water tank heat exchanger is designed with the following design parameters; specific heat of oil and water were 1.67 kJ/kg °C and 4.186 kJ/kg °C respectively; density of oil and water were 850 kg/m^3 and 1000 kg/m^3 respectively; mass flow rate of oil and water were 12 liters/min and 6 liters/min respectively. It is clear that the system in addition to provide thermal energy for baking/cooking unit, it can provide thermal energy for water heating purposes. The tested system can be positively contributed in baking and cooking purposes and providing hot water as well. It is found that, for the same flow rates of hot oil and water, as the hot oil temperature difference increased, the outlet hot water increased. The system is capable to produce hot water temperature up to 85 °C if the hot oil temperature difference was 100 °C while it can produce hot water temperature about 60 °C if the hot oil temperature difference was 60 °C during the day which is suitable for residential purposes and industrial process as well. Based on the resultant data, it is found that the system solar fraction was estimated as 54%. A sample of the experiments is shown in Fig. 10.

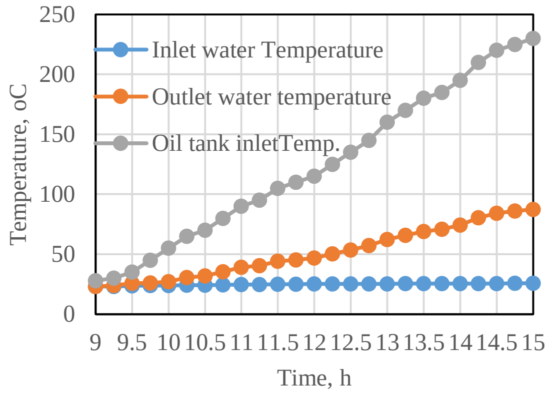

Fig 9: The temperature variations of the oil inlet, the oil outlet and the air enclosure loading bakery

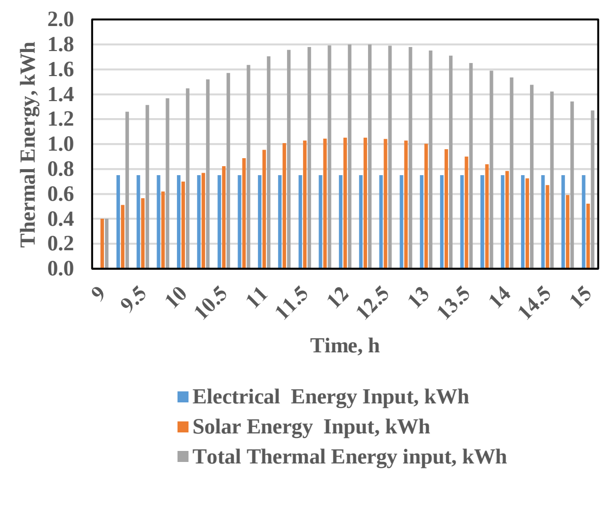

Fig 10: The variation of solar thermal energy used in the studied system

It is found that the daily amount of solar radiation input to the system was 20.47 kWh while the daily usage of the auxiliary electric energy was 18 kWh. Based on the resultant data, it can be said that the system solar fraction can be calculated approximately as 54%.

5. CONCLUSIONS

In the current study, the innovative indoor solar baking system using evacuated tube heat pipe solar collector was designed, constructed and tested experimentally. the solar baking system was tested under the weather conditions of Giza city and showed good significant values for performing baking/cooking process. It is found that the system baking/cooking time is affected by the amount of incident solar radiation dose, the ambient temperature throughout the experiment and the amount of food to be baked/cooked. In addition to provide thermal energy for baking/cooking unit, it can provide thermal energy for water heating purposes. The water tank heat exchanger is designed with the following design parameters; specific heat of oil and water were 1.67 kJ/kg °C and 4.186 kJ/kg °C respectively; density of oil and water were 850 kg/m^3 and 1000 kg/m^3 respectively; mass flow rate of oil and water were 12 liters/min and 6 liters/min respectively. It is clear that the system in addition to provide thermal energy for baking/cooking unit, it can provide thermal energy for water heating purposes. The tested system can be positively contributed in baking and cooking purposes and providing hot water as well. It is found that, for the same flow rates of hot oil and water, as the hot oil temperature difference increased, the outlet hot water increased. The system is capable to produce hot water temperature up to 85 °C if the hot oil temperature difference was 100 °C while it can produce hot water temperature about 60 °C if the hot oil temperature difference was 60 °C which is suitable for residential purposes and it can be sized for industrial process as well. In order to minimize the system auxiliary heat, a renewable energy source can be used like hydrogen generation kit, biomass energy, and solar liquid fuel. It can be concluded also that the system solar fraction can be calculated approximately as 54%.

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