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A Study on the Efficiency of Solar Radiation Collectors Applying for Agricultural Products and Food Drying

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Abstract — **Reducing the use of conventional energy in agricultural production and food processing via using renewable energy is one of the key points to protect our environment. Solar radiation might be an excellent source for replacing traditional heat sources in drying technology. This study aims to analyze and investigate the efficiency of different solar radiation collectors to apply for agricultural products and food drying. Seven solar radiation collectors have been developed and manufactured for experimental investigation. The first is a flat plate solar collector. The second is a pipe collector covered by transparent polyethylene. The third is a copper pipe collector placed on the focus of a parabolic trough. The fourth is a glass pipe collector placed on the focus of the parabolic trough (Experimental testing with fluid is air). The fifth is a glass pipe collector placed on the focus of the parabolic trough (Experiment testing with fluid is water). The sixth is the pipe collector placed on the focus of the parabolic cylinder with no extent to the collector (the parabola is insulated). The last is the pipe collector placed on the focus of the parabolic cylinder with an extended collector (the parabola is insulated). The experimental investigation results indicate that the collector efficiency depends on the solar radiation intensity, the mass flow rate of heating receiver substances, and the structure of the solar collectors. The high solar radiation intensity generates high efficiency. The Pipe collector is placed on the focus of the parabolic cylinder with an extension of the collector (the parabola is insulated); the highest solar collector efficiency with 50.58% at the air flow rate is 0.218 kg/s while the Glass pipe collector placed on the focus of parabolic trough (Experiment testing with fluid is air) has the lowest efficiency as 4.55%.**

Keywords— **Solar heating; collector efficiency; agricultural products drying; drying technology.**

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I. INTRODUCTION

Energy shortage has been becoming a major challenge that humanity must face in the coming years [1]-[6]. Renewable energy, in general, and solar energy in particularly are increasingly being widely applied in many fields such as lighting, power generation, hot water heating, cooling, and especially heat collection for agricultural products and food drying [7]-[18]. This is also alternative energy sources independent of fossil energy and playing as the key point to zero CO2 emission in the year 2050 globally [19]-[21]. Agricultural products normally contain a high moisture value of around 70% to 80%, much higher than the required one for long preservation [22]-[23]. As a result, the bacterial and fungal growth in products is quick, which might destroy the ingredient and reduce the nutrient content in food and products [23]. Therefore, decreasing the moisture content of products is the approach to long product storage. For example, the desired moisture content for paddy storage must be maintained at less than 14%, less than 12% for seed storage, and less than 9% for long-term seed preservation [24]. Removing water content from an agricultural or industrial product can be solved by many methods, which hot air drying is one of the simple processes. This is one of the oldest methods of food reserving. Traditionally, fossil energy like coal, diesel oil, and fuel is used to create hot air as an agent for dryers [25], [26]. This might lead to the increasing carbon emission into our air, which is the main reason for the earth's temperature rise in recent years [27]. Theoretically, the hot air collected from solar energy might be an agent used for different types of dryers called solar dryers that have many advantages such as pollution free, reducing emission of carbon particles in atmosphere, and high efficiency [28]-[30]. For example, the air-absorbed heat from solar energy might have got temperatures up to 1200^{0}C at a concentrated collector with efficiency up to 75% [31].

Solar drying is a device that absorbs solar radiation and then converts that into a heat source to heat the air. Then the hot air passes through the drying product, indirectly drying the product without using solar radiation directly. There are many advantages to using solar drying technologies over fossil fuels for product drying [28], [29]. The drying equipment is simple in structure, easy to manufacture, easy to use, and low cost. The dryer might also be used to dry various fruits or grains, such as mango, grapes, pepper, rice, etc. [22]. However, it is necessary to clean the drying equipment to avoid mold regularly, and the dryer operation depends on weather conditions, like whether it is clear or cloudy. A solar dryer includes the following components, as shown in Fig.1.

1) *Heat collector*: Consists of two main devices. The first one is a transparent coating that permits the short wavelength radiation $\lambda < 4$ µm transmission to the absorption plate and prevents long wavelength $\lambda > 4$ µm. Glass and transparent polymer films in which Glass is normally used to make the coating transparent and it has many good mechanical and optical properties. Polymer films might not be used because they are poor mechanical strength, are discolored, easily aging, easily scratched, and deformed under the influence of solar radiation. The second is the absorption plate which is usually manufactured by using black tole, copper, and aluminum. Due to needing absorbed radiation, it is coated with an absorbent such as black paint or black paint in combination with some other substance.

2) *Air conduction system and fan*: The fan is used to move air from the outside into the heat collector through the air duct system, then it blows hot air from the heat collector into the drying chamber to dry the product.

3) *Drying chamber*: this is a component to locate trays and products drying. It is made of metal, and its outside is glued with insulation to reduce heat loss to the outside environment.

A solar dryer works by using the heat that absorbs the sun's radiation via the black absorbing sheet to heat the air inside after solar radiation through the transparent coating (Glass, polymer sheet, etc). The hot air absorbed will expand and fly upward to enter the drying chamber under the force of fans. The movement of the air shall create an airflow that leads new air to enter the absorption component and continues to be heated by the heat trap. The hot air enters the drying chamber, flows through the mesh tray containing the products to be dried, and carries the moisture out of the exhaust hole.

Recently, based on the hot air move into the dryer chamber, the solar drying technology might be classified into direct solar drying, indirect solar drying, and mixed-mode solar drying. For direct solar drying, the light will shine directly on the drying material so that the solar energy is absorbed according to the principle of the greenhouse effect. As a result, the temperature of the drying products increases, and the circulating air spreads the moisture. Indirect solar drying differs from direct solar drying, such as the radiation does not directly shine on the drying material, and the air heated by the radiation collectors, called drying agents, will be used to dry. The circulation of hot air can be natural convection or forced convection. This dryer has some advantages, like a higher drying temperature, shorter drying time, and better product quality. Therefore, this is the common type of solar dryer used in products drying recently. The last one is mixed-mode solar drying which is combined with the two kinds of drying above.

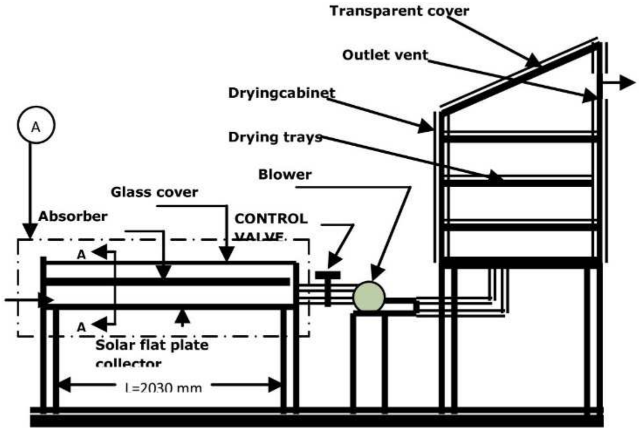

Fig. 1 Schematic of a solar dryer [32]

It is clear to mention that the quality of hot air absorbed from solar radiation as a drying agent is the key point to developing a good solar dryer. This depends strongly on the type of collectors. Different types of solar radiation collectors have different collectors' efficiency that affects the dryer design, manufacturing, and operation. Therefore, collectors' efficiency plays an important role in applying product drying and solar drying technologies. This paper presents the experimental investigation of the efficiency of seven types of radiation collectors that might be applied to the solar dryer.

II. Materials and Method

A. Devices for Experimental Investigation

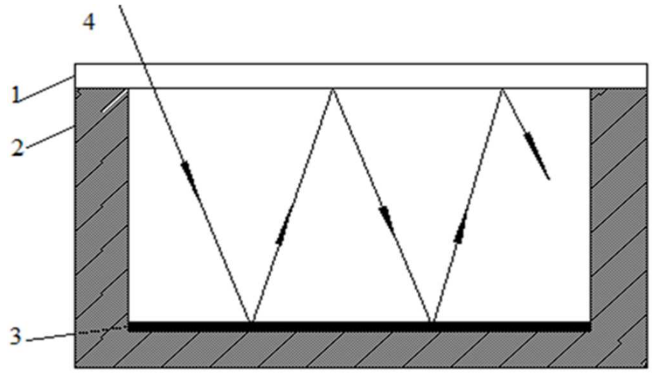

Fig. 2 Structure of a flat plate solar collector (1. Glass panels; 2. Insulation shell; 3. Absorber plate; 4. Solar radiation)

A flat plate solar collector was developed for experimental investigation, as shown in Fig.2 and Fig.3. Its length is L = 2.5 m, width B is 0.6 m, and height H is 0.08 m. The area of the heat collector plate is counted as A = L.B = 2,5*0.6 = 1.5 m2. The outlet cross-section of the collector is A' = B.H = 0.64.0.08 = 0.048 m2. The radiation that comes to the dryer has two parts: one part of the light passes through transparent Glass to the inside of the collector, and the other part reflects the environment. The radiation passes through the transparent glass, meets the black-painted absorbing plate, and turns into heat energy that heats the air inside the collector chamber supporting for drying chamber, where the product is dried.

Fig. 3 The flat plate solar collector manufactured.

Pipe collector covered by transparent polyethylene: The collector is made of a transparent polyethylene thin film with the structure shown in Fig.4. The collector has a length of L = 3.9 m, a pipe diameter is D = 0.8 m, a diameter at the outlet of the tube is d = 0, 3 m. It consists of a tubular metal frame covered with a transparent polyethylene film, a plate as a heat receiver made of tole painted black, and an exhaust fan to draw hot air from the collector to the drying chamber. The width of the receiver plate is B = 0.6 m, so the area of the heat receiver is A = B.L = 0.6*3.9 = 2.34 m^2.

Fig. 4 Pipe collector covered by transparent polyethylene.

For this collector, the solar radiation passes through the transparent polyethylene sheet into the inside of the collector, and then the solar radiation is absorbed by the absorber with a painted black surface. Therefore, the air inside the collector will be heated and is directed to flow to the drying chamber via a fan. One end of the collector is connected to the fan, and the other is for ventilation for better air circulation into the collector.

The copper pipe collector placed on the focus of a parabola surface is the third one with the structure shown in Fig.5. The device consists of a parabolic trough, a copper pipe placed at the focal point of a concentrator, and a heat exchanger. Its length is 2m (L = 2 m), the outside diameter of the absorption copper tube is 0.016m (Do = 0.016 m), the extension of the collector is 1.08m (W = 1.08 m), and the area of the heat exchanger plate is 2.16 m^2 (A = W.L = 1,08*2 = 2.16 m^2). For this collector, water is pumped from the storage tank into a black-painted copper pipe at the parabolic trough's focal point. The parabolic trough receives solar radiation and reflects it to the pipe to heat the water inside. After that, the hot water will continue to pass through the heat exchanger. The fan of the heat exchanger draws the hot air to supply it to the drying chamber where the drying material is placed.

Fig. 5 The copper pipe collector placed on the focus of a parabolic surface.

The fourth collector used for experimental investigation is similar to the third one, as presented in Fig.6. The copper pipe is replaced and changed to a glass tube with a length is 2m (L = 2 m), and its outside diameter is 0.05m (Do = 0.05 m). The solar energy is absorbed by the glass tube via the sunlight and reflects into the focal point of the parabolic trough to heat the drying agent (air or water) supporting the drying chamber.

Fig. 6 The glass tube collector placed on the focus of a parabola surface.

The pipe collector placed on the focus of the cylinder parabola with no extent the collector (the parabola is insulated) consists of 3 main parts insulation frame, parabolic trough, and heat-collecting tube shown in Fig.7. The collecting tube is made of a metal sheet placed at the focal point of the centralized collector. This device has a length of 10 m (L = 10 m), a width of 1 m (B = 1.0 m), and a height of 0.8 m (H = 0.8 m). The area of the collector is about 10 m^2 (A = L.B = 10*1 = 10 m^2). The outlet cross-section of the collector is 0.13 m^2 ($A' = \pi * R^2 = 3.14*(0.2)^2 = 0.13$ m2). The fan draws fresh air from the outside environment into the collector by the collector's inlet, and the insulated enclosure traps the air in the collector. Here, the air is partially heated before passing through a collector tube at the cylindrical parabola's focal point. The air then enters the collector tube and is heated again.

Fig. 7 The pipe collector placed on the focus of the parabolic cylinder with no extent the collector (the parabola is insulated)

The pipe collector placed on the focus of the cylinder parabola with extend the collector (the parabola is insulated) is most similar to the device in Fig.7, except the collector can be extended shown in Fig. 8. The area of the heat collector is 3.68 m^2 (A = L.B = 2.1*1.75 = 3.68 m^2).

Fig. 8 Pipe collector placed on the focus of parabolic cylinder with extend the collector (the parabola is insulated).

B. Calculating the efficiency of the collector

1) Calculation of efficiency of the collector: The airflow through the collector is calculated as G = v.A'.ρ where v is the air speed through the collector section, ρ = 1.12 kg/m^3 is the density of air, and A' is the absorption area. The output energy of the heat collector is calculated according to the formula:

$$Q_{out} = G.c.\,(T_{out\text{-}av} - T_{in\text{-}av}) \qquad (1)$$

where: c = 1005 J/kg.K is the specific heat capacity of the air; $T_{in\text{-}av}$ and $T_{out\text{-}av}$ are the inlet and outlet average temperatures of the collector, respectively. The efficiency of the collector supporting hot air for the drying chamber is calculated as follows:

$$\eta = q_{out\_av} / q_{in\_av} *100 = Q_{out} / (A.\, q_{in\_av}) *100 \qquad (2)$$

where: q_{in_av} is the average solar radiation reaching the collector surface counted by the total solar radiation measured divided by the number of measurements per day. When the water is used to receive heat from solar radiation, G is the mass flow rate of the water passing through the collector, and c is the specific heat of water (c = 4184 J/kg.K).

2) The concentrated collectors: the output energy is calculated as follows:

$$Q_{out} = F_R (W - D_o) L \left[S - \frac{U}{C_R} (T_{in} - T_a) \right] \qquad (3)$$

Different from the flat plate collectors, the description of the above formula is as follows:

- F_R is the heat out efficiency.
- S is optical efficiency.
- C_R is the concentration ratio that is counted as the Collector aperture area/Receiver surface area (CR).
- T_{in} and T_a are input temperature and ambient temperature, respectively.
- U is the lost energy coefficient between the blacked plate and the ambient.

III. Results and Discussion

The flat plate solar collector was tested at four different air flow rates: 0.027 kg/s, 0.054 kg/s, 0.08 kg/s, and 0.10 kg/s. Before conducting the test, the collector was placed outdoors for 30 minutes for stabilization to an investigation. The experimental investigation results at four different air flow rates indicated that the outlet temperature of the air varies with the change in solar radiation intensity. When the solar radiation intensity peaks between 11:30 am and 1:30 pm, the outlet temperature of the air passing through the collector also reaches the maximum value from 43^0C - 51^0C depending on the velocity of the air. Figure 9 presents the input and output temperature and the temperature difference following the solar radiation intensity at each time of a checked day for the case of 0.08 kg/s of a flat plate collector.

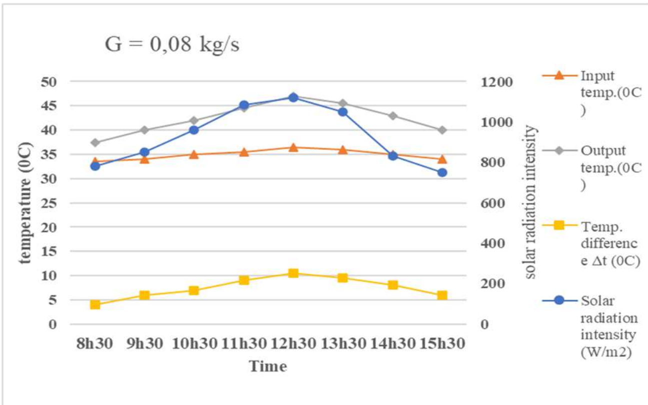

Fig. 9 The input and output temperature and the temperature difference following the solar radiation intensity for the case of 0.08 kg/s.

It is also noted that in the afternoon, the ambient temperature is always higher than one in the morning, reducing the heat lost from the collector to the outside and increasing the outside temperature of the collector. In terms of the collector's efficiency, the results indicate that as the airflow increases, the efficiency increases. The efficiency of the collector is reached to highest value as η = 40.64% in case the air flow rate is 0.08 kg/s, and when the flow exceeds 0.08 kg/s, the efficiency of the collector decreases, as shown in

Fig.10. The lowest value efficiency of collector is η = 24.6% when the air flow rate is G = 0.027 kg/s

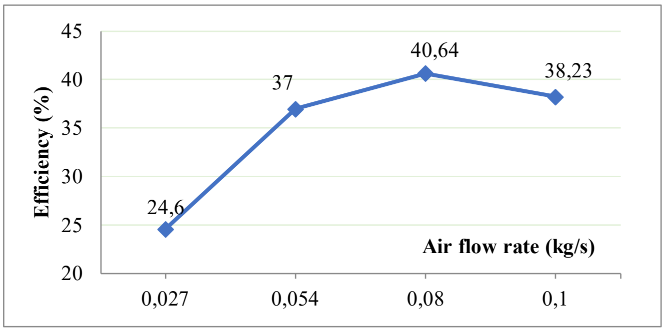

Fig. 10 The efficiency of flat plate solar collector with air flow rate difference

The transparent thin polyethylene film solar tube collectors were tested at four different air flow rates 0.039 kg/s, 0.078 kg/s, 0.117 kg/s, and 0.156 kg/s. Figure 11 presents the results of input and output temperatures at different times of the day with different solar radiation intensities of air flow rates as 0.117 kg/s. Similarly, in the case of a flat plate collector, the temperature and the air temperatures (Δt) change with the change in solar radiation intensity.

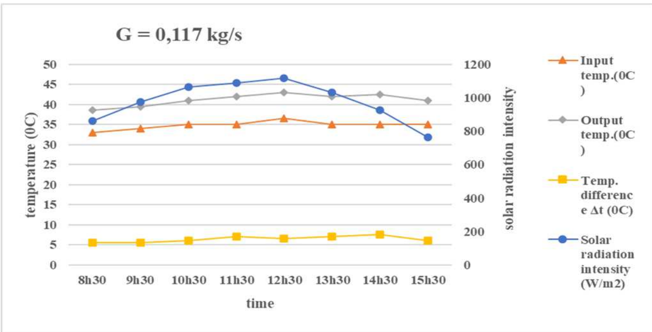

Fig. 11 The input and output temperature and the temperature difference following the solar radiation intensity for the case of 0.117 kg/s.

Figure 12 shows the results of calculating the collector's efficiency with a difference in air flow rate. When the air flow rate increases, the collector efficiency rises. The highest efficiency of this collector is 30.01%, with an airflow rate is 0.017 kg/s. However, the collector efficiency decreases when the flow exceeds G = 0.117 kg/s.

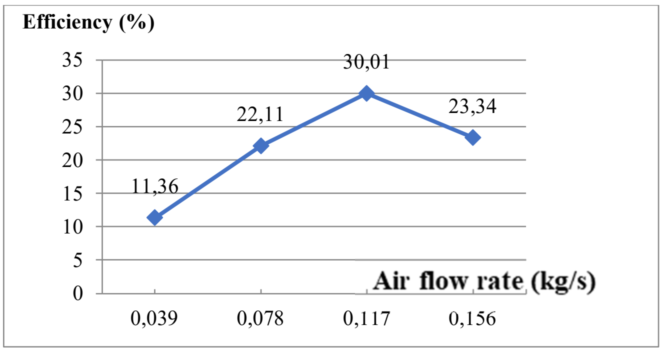

Fig. 12 The efficiency of solar tube collectors made of transparent polyethylene thin film with air flow rate difference.

Figure 13 presents the experimental results in the solar collector using copper tubes placed at the parabolic trough's focal point with a water flow rate of 0.012 kg/s. The results show that the water outlet temperature and the temperature difference between the water inlet and outlet (Δt) vary with the change in solar radiation intensity. When solar radiation intensity reaches its maximum, the outlet temperature and the value of Δt also reach maximum.

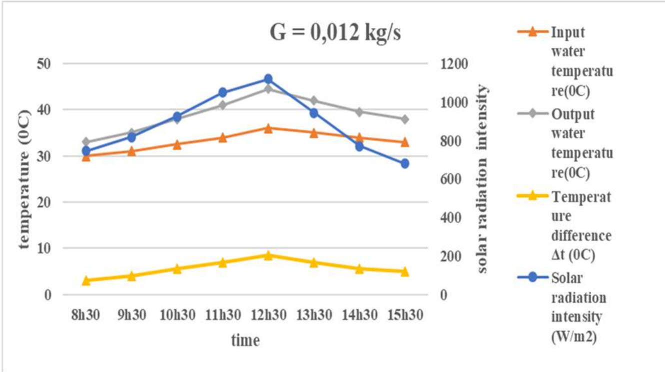

Fig. 13 The input and output water temperature and the temperature difference following the solar radiation intensity for the case of 0.012 kg/s.

Three different water flow rates are applied to investigate the collector's efficiency 0.006 kg/s, 0.012 kg/s, and 0.024 kg/s. Figure 14 presents the results of the collector's efficiency in which the highest efficiency is 15% with a water flow rate of 0.012 kg/s. Increasing double the water flow rate reduces the collector's efficiency. This reminds us that the efficiency and the water flow rate are not linear, and it is needed to test for optimal efficiency.

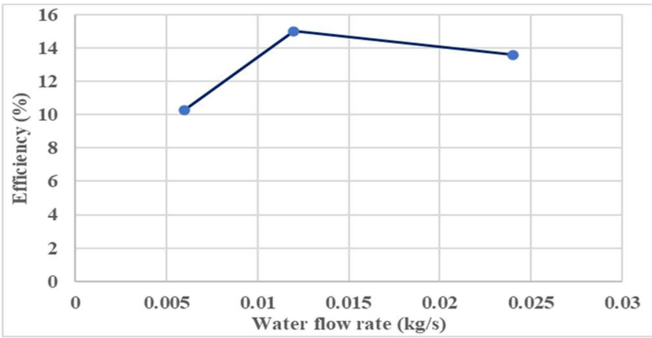

Fig. 14 The efficiency of the solar collector using copper tubes placed at the focal point of the parabolic trough with different water flow rate.

The solar collector with glass tubes placed at the focal point of the parabolic trough was tested with air at three different air flow rates: 0.00112 kg/s, 0.00224 kg/ s and 0.00336 kg/s. The results of testing, like some cases above, are illustrated in Fig. 15. The results show that the outlet temperature of the air and the temperature difference between the inlet and outlet of the air (Δt) vary with the change of solar radiation intensity. The results are similar to some cases above. Fig. 16 presents the efficiency calculation results and indicates that the collector efficiency reaches the maximum value of 4.55% at the air flow rate G = 0.00224 kg/s. This case has very low efficiency. This collector is also tested with water with three different water flow rates 0.012 kg/s, 0.0475 kg/s, and 0.064 kg/s. The result of the case of 0.0475 kg/s are shown in Fig.17 and are similar to the cases above.

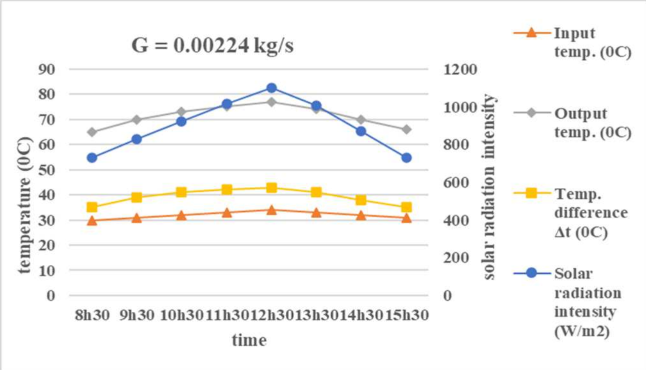

Fig. 15 The input and output temperature, and the temperature difference following the solar radiation intensity for the case of 0.00224 kg/s

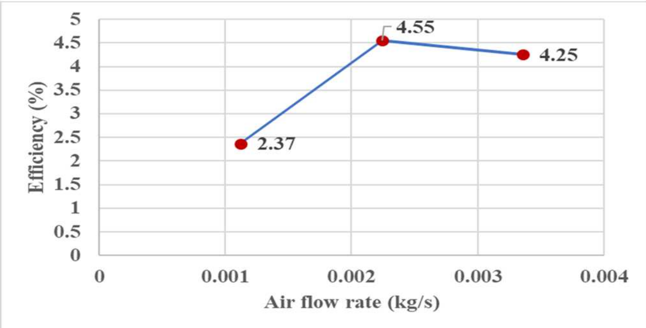

Fig. 16 The efficiency of the solar collector with glass tubes placed at the focal point of the parabolic trough tested with air at three different air flow rates: 0.00112 kg/s, 0.00224 kg/ s, and 0.00336 kg/s.

The water outlet temperature and the temperature difference between the water inlet and outlet (Δt) vary with the change in solar radiation intensity. When solar radiation intensity reaches its maximum, the outlet temperature of the water passing through and the value of Δt also reaches the maximum value. As solar radiation decreases, the value of Δt also decreases.

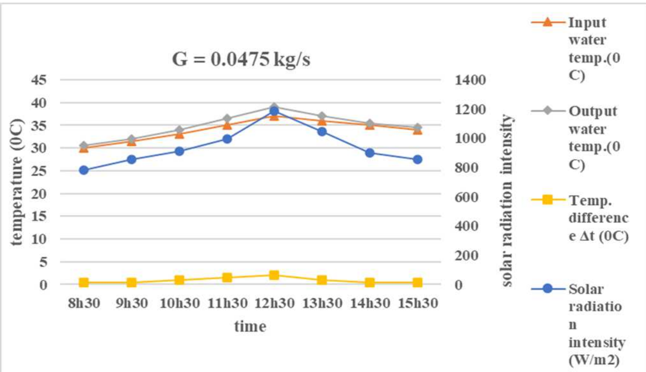

Fig. 17 The input and output temperature and the temperature difference following the solar radiation intensity for the case of water 0.00475 kg/s

Figure 18 presents the results of calculating the efficiency of the solar collector with glass tubes placed at the focal point of the parabolic trough with water as the medium. The results show that the collector efficiency will increase when the water flow rate increases. However, the collector efficiency decreases when the water flow exceeds G = 0.0475 kg/s.

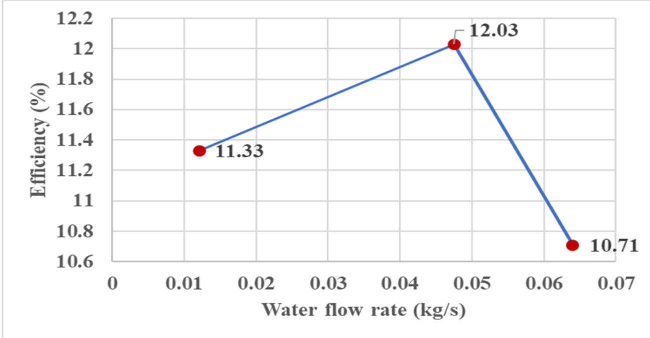

Fig. 18 The efficiency of the solar collector with glass tubes placed at the focal point of the parabolic trough with water flow rate difference.

The testing for the solar collector using the heat collector tube placed at the focal point of the parabolic cylinder (without expanding the receiver surface area, with a parabolic trough insulation frame) is conducted at four different air flow rates as 0.072 kg/s, 0.145 kg/s, 0.218 kg/s, and 0.291 kg/s. Figure 19 illustrates the testing results in the case of air flow rate is 0.218 kg/s.

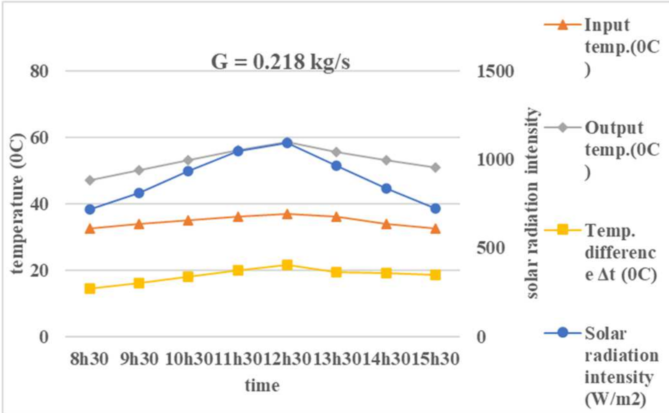

Fig. 19 The input and output temperature and the temperature difference following the solar radiation intensity for the case of 0.218 kg/s

The results show that the outlet temperature of the air varies with the change of solar radiant intensity, similar to all cases. At the time solar radiation intensity peaks, the outlet temperature of the air passing through the collector also reaches the maximum value of 770C, and the value of Δt also reached its maximum value, which is very high as 41^{0}C (case of 0.072 kg/s at noon).

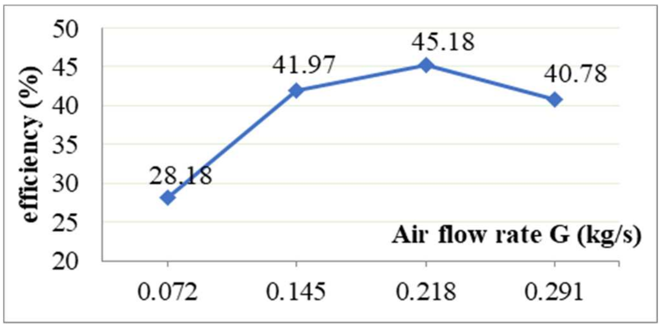

Fig. 20 The efficiency of the solar collector using the heat collector tube placed at the focal point of the parabolic cylinder (without expanding the receiver surface area).

Figure 20 presents the results of calculating the efficiency of the solar collector using the heat collector tube placed at the focal point of the parabolic cylinder (without expanding the receiver surface area). The results show that the thermal efficiency reached the highest value with η = 45.18 % at G = 0.218 kg/s, and the lowest value is η = 28.18% at G = 0.072 kg/s. When the air flow rate exceeds 0.218 kg/s, the efficiency of the collector decreases.

The last collector is the solar collector using the heat collector tube placed at the focal point of the parabolic cylinder (expanding the receiver surface area and a parabolic trough insulation frame). This collector is tested with four different air flow rates 0.072 kg/s, 0.145 kg/s, 0.218 kg/s, and 0.291 kg/s which is the same as the case without expanding the receiver surface area. Figure 21 presents the results of the experimental investigation for this collector with an airflow rate is 0.218 kg/s.

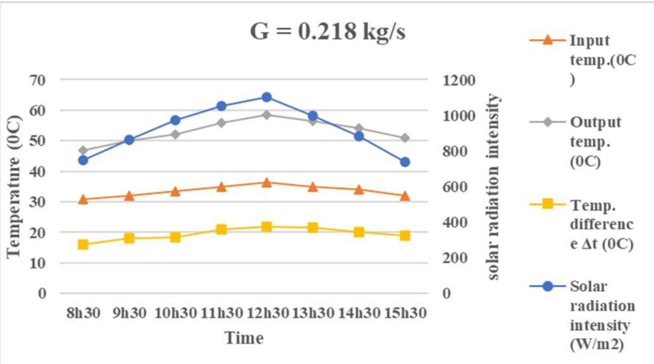

Fig. 21 The input and output temperature and the temperature difference following the solar radiation intensity for the case of 0.218 kg/s

Figure 22 presents the performance calculation results of the receiver. The results show that the collector's efficiency reached the highest value with η = 50.58% at G = 0.218 kg/s and the lowest value is η = 32.85% at G = 0.072 kg/s.

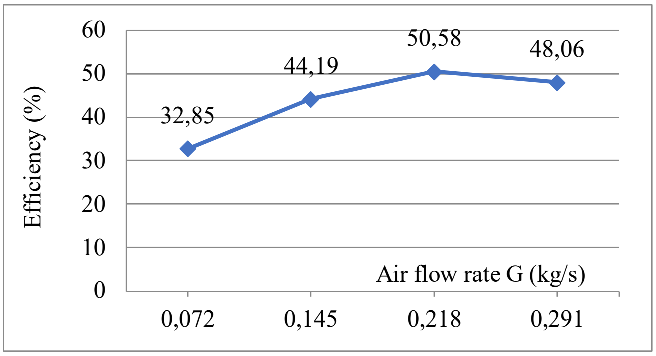

Fig. 22 The efficiency of solar collector using the heat collector tube placed at the focal point of the parabolic cylinder (with expanding the receiver surface area).

IV. Conclusion

Seven types of solar radiation collectors have been developed and manufactured to investigate the efficiency applied to solar dryers. The obtained energy efficiency depends entirely on the intensity of the solar radiation, the type and surface area of collectors, the heat-receiving medium (air, water, or other substances), and the flow rate. The solar radiation intensity increases, the efficiency increases, and it passes to the maximum value when the intensity of solar radiation is at the highest value. The concentrated collectors, such as the parabolic surface receivers, create a higher efficiency than one flat plate surface. It is clear that the solar collector using the heat collector tube placed at the focal point of the parabolic cylinder with expanding the receiver surface area and an insulated parabolic trough obtained the best efficiency of 50.58%. The similar solar collector, except for the expanding receiver surface, is different. The efficiency is only 45.18 % at the same air flow rate G = 0.218 kg/s and the average radiation intensity of 868 W/m2. Parabolic cylinder collectors with parabolic trough insulation frames are highly efficient, so these might be utilized in agricultural products and food drying. However, the amount of solar radiation that reaches the collector's surface depends on the tilt angle, which changes if the collector is fixed in a day. This is the disadvantage of the parabolic trough surface collector, and it needs automatic control to force the collector surface might move following the direction of sun rays in a day.

Nomenclature

Q	Energy	W
A	surface area	m^2
L	Length	m
B	Width	m
H	Height	m
W	Extension length	m
G	Flow rate	kg/s
c	specific heat	kJ/kg.^{0}C
Greek letters		
α	heat transfer coefficient	$Wm^{-2}K^{-1}$
λ	Wavelength	μm
η	Efficiency	%
Subscripts		
in		inlet
out		outlet
av		Average

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