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Design and performance analysis of a new evacuated tube solar air heaters equipped with fins and coils

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ABSTRACT
Evacuated tube solar air heaters (ETSH) are efficient, easy to maintain, and have low energy losses due to the vacuum between the absorber and the outer tubes. In this study, a new ETSH with various configurations was built and experimentally tested to determine the best configuration with the highest thermal performance. The ETSH equipped with two different high thermal conductivity metal fins and coils to enhance the heat transfer between the fluid and the copper tube heat exchanger. The efficiency and temperature difference were experimentally investigated at different flow rates. It was observed that the system with aluminum fins has the highest air temperature difference at the lowest flow rate and the highest efficiency at the highest flow rate. At the highest solar irradiation of 1000 W/m^2, the maximum obtained temperature difference was 88°C at a flow rate of 0.6m^3/min, while the highest obtained efficiency was 37% at a flow rate of 1.25 m^3/min. For the three systems, the temperature difference decreased and the efficiency increased with the increase in the flow rate.

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Solar energy; evacuated tubes; air heaters; coil; fins; efficiency; thermal performance

1. Introduction

Air conditioning for heating and cooling is one of the major energy consumer sectors in the world (Zeng et al. 2011; Enteria, Yoshino, and Sataki 2016; Enteria et al. 2015; Chen, Yang, and Luo 2018; Tian et al. 2019; Bellos et al. 2016; Wan et al. 2011; Caliskana, Hongb, and Jangb 2019). In the European Union, the building sector is responsible for almost 40% of total energy consumption (European Commission, Buildings – European Commission 2018), space and water heating use 80% of the energy consumed in buildings (European Commission, Heating and cooling – European Commission 2016) and only 16% of this energy is generated using renewable energy sources (Fernández et al. 2016). In Israel, households account for about 32% of the economy’s total electricity consumption. The number of households that own an air conditioner is expected to reach close to 100% by the beginning of the next decade (Long-Term Trends in the Supply and Demand of Electricity in Israel, Bank of Israel 2016). In the United States, 42% of the energy used in homes is used for space heating, while in California, 27% of the energy is used for space heating (EIA, Residential Energy Consumption Survey 2009).

The use of renewable energy sources brings social and economic benefits and increases energy security (Abu Hamed and Bressler 2019). Israel and Jordan have one of the highest solar radiation in the world, in the Arava Valley, solar radiation can reach 1100 W/m^2 in the summer (Abu Hamed, Alshare, and El Khalil 2019). Israel, Cyprus, Palestine and Jordan efficiently utilise solar radiation for water heating. However, the development of solar air heating methods is slow compared to water heating methods, mainly due to lower thermal efficiency.

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The solar air heaters utilise the sun's energy for air heating, space heating, crop drying, and for various industrial applications (Gill, Bhushan, and Mahajan 2016). Solar heaters are cost-effective and simple in design compared to other renewable energy systems (Sabiha et al. 2015; Liu et al. 2013; Yadav and Bhagoria 2013). The most common fluids used in solar heaters are water, oil and air (Sabiha et al. 2015; Saxena, Varun, and El-Sebaii 2015; Abdullahi 2015). The use of air among various working fluids has the benefit of being free, non-corrosive, and does not require freezing or boiling protection. Moreover, air has a high pressure-bearing capacity which makes it suitable for high-temperature systems (Liang et al. 2011). Compared with other solar heating systems, solar air heaters are compact and less complicated, easier to manufacture with cheaper materials and easier to use.

The most commonly used types of stationary solar air heaters are divided into flat plates and evacuated tube solar air heaters (ETSH) (Wang et al. 2014; Ferdous, Sarker, and Beg 2018; Ayompe et al. 2011). Flat plate air heaters are commonly used for low-temperature applications up to 100°C (Abdullahi 2015), while ETSHs are designed for moderate temperature applications ranging between 50°C and 200°C (Sabiha et al. 2015; Abdullahi 2015; Wang et al. 2014).

Compared to flat plate heaters, the ETSHs are more efficient, easier to maintain, transport, install and the energy losses are minimised due to the vacuum between the absorber surface and the outer tube (Sabiha et al. 2015; Liu et al. 2013; Tang et al. 2006; Yuan, Li, and Dai 2010; Wang, Li, and Liu 2015; Abdullah and Bassiouny 2014; Zhu et al. 2015). Moreover, ETSHs offers excellent thermal performance in various climates. Even in extremely cold conditions such as −18°, ETSHs efficiency is satisfactory (Wang et al. 2014; Ferdous, Sarker, and Beg 2018). Also, ETSHs are faster in heat generation and highly capable of collecting both direct and diffused radiations.

Over the past few years, several studies have investigated the optimal operating conditions, manifold designs, optical designs (Sabiha et al. 2015; Liang et al. 2011; Budihardjo and Morrison 2009), solar collector tubes array, performance evaluations of ETSHs (Liang et al. 2011; Ma et al. 2010; Qi 2007), and improving heat transport in solar collector tubes. However, the main difficulty is in the heat extraction from the single-ended absorber (Liang et al. 2011). Recently, several methods for enhancing heat extraction have been developed by introducing metal rods (Sabiha et al. 2015; Nkwetta et al. 2012; Hayek, Assaf, and Lteif 2011), U-tube heat exchangers (Sabiha et al. 2015; Ma et al. 2010; Morrison, Budihardjo, and Behnia 2005; Tang, Yang, and Gao 2011), and intermediate conduction mediums (Ma et al. 2010; Yadav and Bajpai 2012) filled in the tube.

In order to achieve better ETSH collection performances, it is crucial to enhance the heat transport between the working fluid and the metal heat exchanger (Wang et al. 2014). The main goal of this work is to use fins and coil as passive elements to increase the heat transfer area and thus enhance the heat transfer rates. Studying the impact of different conductive materials on the thermal performance of ETSH will assist us to determine the best ETSH configuration with the highest efficiency. The novelty of this work lies in the following two aspects: first, high air flow rates are used and second, fins and coil are used to enhance the heat transfer rates.

2. Experiment system and method

2.1. Experiment setup

The ETSH system consists of ten glass evacuated tubes. The cross-sections of the evacuated tubes are shown in Figure 1(a,b). Each tube is made up of two concentric borosilicate glass pipes, the vacuum between the two glass pipes minimises heat losses. The external tube is transparent, and the interior tube is coated with a (Al-N/Al) cover to increase the solar radiation absorption. The length, outer diameter of the external glass tube and diameter of the absorber tube is 1.8, 0.058, and 0.042 m respectively. The evacuated tube has a surface area of 3.28 m^2. The evacuated tubes are connected to a 1.6 m manifold channel. The manifold channel is a square box (0.15 × 0.15 m) made of aluminum and a circular inner iron tube with a closed end in the middle of the channel with a length of 1.5 m and a diameter of 0.06 m. The aluminum outer box covered by a Rockwool insulation to

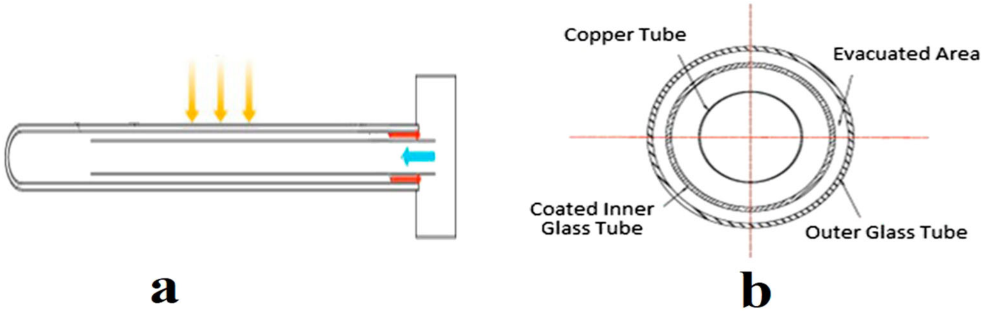

Figure 1. Cross section of the evacuated tube.

minimise heat losses to the atmosphere. The inner iron circular tube is vertically connected with ten copper tubes. The copper tube has a diameter and length of 0.02 and 1.5 m, respectively. All the copper tubes are inserted inside the glass evacuated solar tubes. A blower is used to feed the evacuated tubes with air via the copper tubes. The inlet air flow was controlled by using a valve connected between the air blower and glass evacuated solar tubes.

Three systems were set up; the first system is the control system and had a copper tube without fins neither coils attached to it as shown in Figure 2(a). The second system with copper coil spiraled on the copper tube as shown in Figure 2(b), while, the third system had a copper tube with aluminum fins attached to it as shown in Figure 2(c). The mass of the copper wire and the aluminum fins were similar and equal to 300 ± 5 g in all the evacuated tubes. The length of the copper wire is 6 m and the length of the aluminum fin is 1.5 m (with edges of 0.005 m).

2.2. Measured parameter

The air temperature was measured using TP-01 K type temperature probe made of copper with temperature range of −50–204 C∘ ± 0.75% rdg connected to BTM-4208SD 12 channels temperature recorder (Lutron company, Taiwan) with a resolution ranging between 0.1°C and 1°C. The air

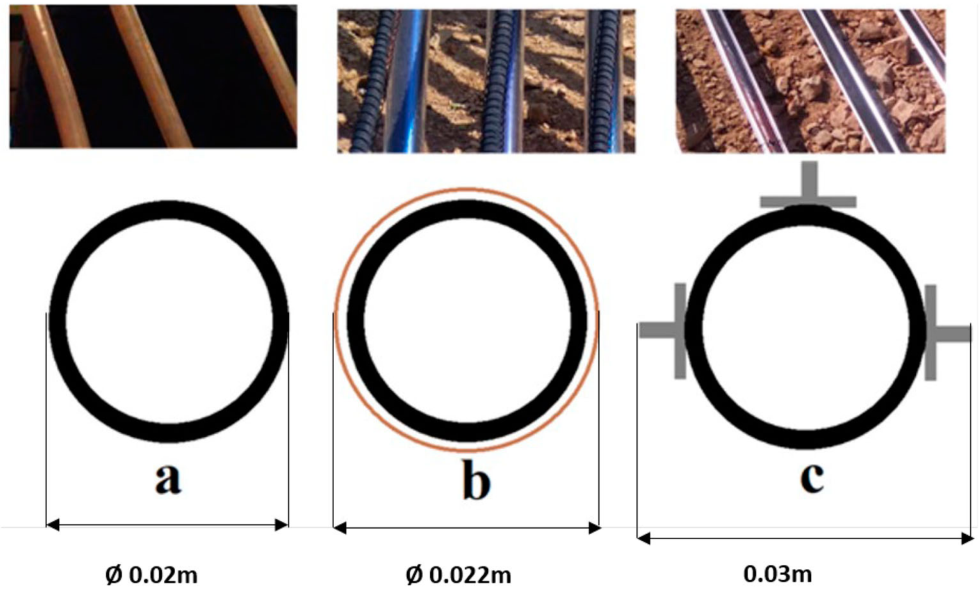

Figure 2. Cross-section of the copper tube used for (a) control system, (b) system with copper coil, (c) system with aluminum fins.

temperature was measured at both the inlet and the outlet of the system. A Kipp and Zonen CMP3 pyranometer was used to measure the global solar irradiation intensity. The temperature and radiation data were recorded every 10 min.

The outlet air flow rate was measured three times a day for each system. The air flow rate was measured by an anemometer model AM-4233SD with a resolution of 0.001 m^3/min. The anemometer provides quick and precise measurements at different speeds because the vanes have a low friction ball bearing.

2.3. System performance

The ETSH's thermal performance was evaluated by efficiency measurements. The ETSH efficiency is defined as the ratio between gained and used energy. The gained or output energy is the heat gained by the flowing air in the ETSH system and the used or input energy is the solar radiation energy received by the evacuated tubes. The efficiency was measured using the following equation;

$$\eta = m.C_p(T_{out} - T_{in})/I.A_p$$

where η is efficiency, m is the air mass flow rate (kg/s), C_p is the air specific heat (J/(Kg·°C)), T_{out} is outlet air temperature (°C), T_{in} is inlet air temperature (°C), I is the solar irradiation (W/m^2), A_p (A_p = n.π.D.L) is the aperture area (m^2) of the ETSH and calculated as: number of tubes × πDL, where D is the outer diameter (m) of the external glass tube and L is the length of the evacuated tube (m).

2.4. System operation

The three solar air collector systems using one-ended evacuated tubes were experimentally investigated at different flow rates (0.6, 0.9, and 1.25 m^3/min). Figure 3 shows the ETSH schematic diagram. In this process, the air flowed through the inner iron circular tube of the manifold channel with one closed end. This air flows through circular copper tubes inbuilt with an iron circular tube into the bottom of the evacuated tubes. Then, the air flows back over the circular copper tubes to the outer square box of the manifold channel. Therefore, the air gains heat while it is flowing inside the collector due to the solar radiation.

3. Results and discussion

3.1. Effect of flow rate on the temperature difference

Figure 4 shows the variation in temperature and solar irradiation with time at various flow rates. As seen in Figure 4(a–c), the temperature of the air increases as soon as the solar radiation hits the

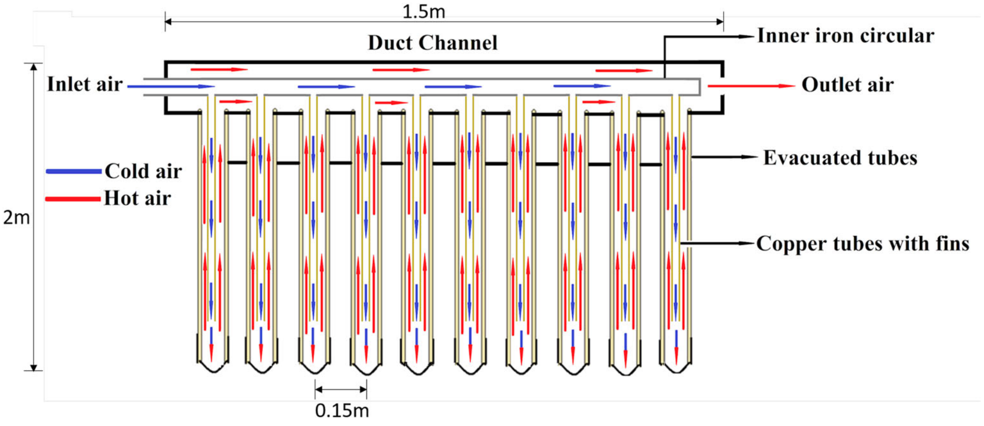

Figure 3. Schematic diagram of the ETSH.

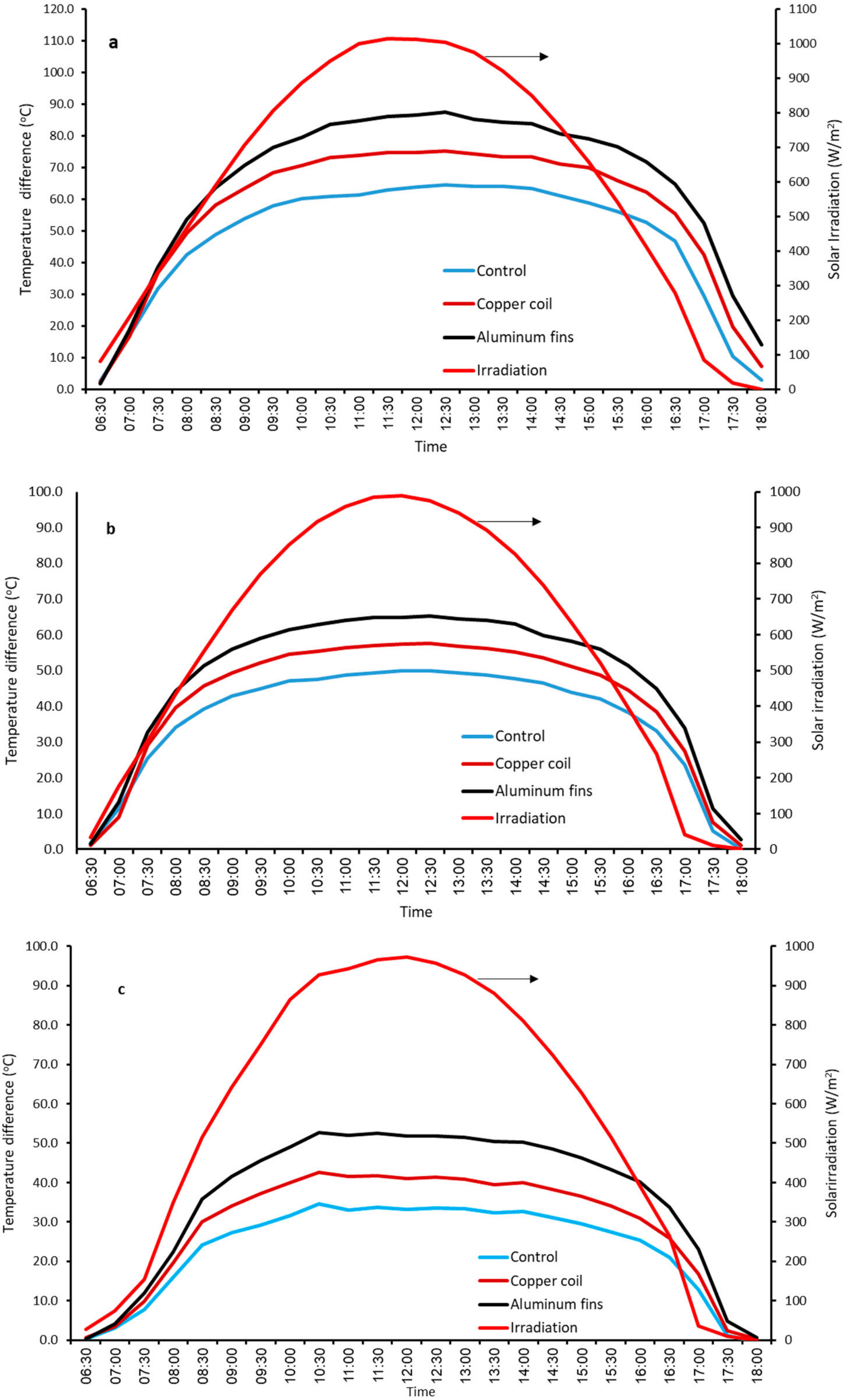

Figure 4. Temperature and solar irradiation with time for the three systems at various flow rates. (a) air flow rate of 0.6 m^3/min, (b) air flow rate of 0.9 m^3/min, (c) air flow rate of 1.25 m^3/min.

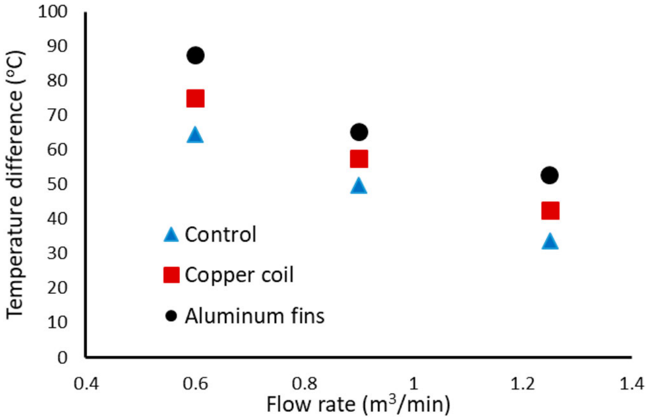

Figure 5. The maximum temperature differences at various air flow rates for the three systems.

systems. At the beginning of the day the temperature deference rises gradually for all the systems and then at noon time it becomes relatively stable. Then, the temperature decreases at 15:30 pm due to the low solar radiation intensity at that period of the day. Even though the solar intensity sharply decreases in the afternoon hours, all systems kept heating the air due to the thermal mass of the metal inner design which takes time to cool down. For all flow rates, the system with aluminum fins showed the highest thermal performance (Figure 5). The maximum obtained temperature difference was 65, 75 and 88°C, at air flow rate of 0.6 m^3/min for the control, copper coil and aluminum fins systems respectively (Figure 5).

The system with aluminum fins (Figures 4 and 5) has the highest temperature difference compared to the control and the system with a copper coil. Even though the copper has higher conductivity than aluminum, the difference in the shapes and surface area between aluminum fins and copper coil lead to this result.

Figure 5 shows also that the temperature difference decreases with the increase in flow rate for all systems. Similar trends were obtained by the experimental results of Li et al. (2014) and the simulation conducted by Paradis et al. (2015), where they found that the air flow rate is the most influential parameter on the ETSH's thermal performance. The temperature difference at a low air flow rate is higher than the temperature difference at a high air flow rate, as at any given time, the same amount of solar radiation was absorbed by a smaller quantity of air. This can be explained by the increase in the air heat capacity at the same solar intensity. Thus, the desired air temperature can be controlled by regulating the air flow rate. The maximum obtained temperature difference in the system with aluminum fins at 1000 W/m^2 was 88, 65 and 53°C for air flow rates of 0.6, 0.9 and 1.25 m^3/min respectively.

3.2. Effect of flow rate on the system efficiency

Figure 6 shows the efficiency and the solar irradiation change with time for the three systems at various flow rates. As seen in Figure 6(a–c), the efficiency hits its lowest values at the maximum solar intensity values. In the first two hours, the efficiency increased for all the systems due to the sharp increase in temperature and slightly low solar irradiation. Then, the efficiency slightly decreases until 10:00 am due to the increase in the temperature difference. Further, the efficiency value decreases between 10:00 am and 12:00 h because of the small variation of outlet temperature. Then, the efficiency increases gradually for the three systems and reaches maximum values in the evening at 16:30 pm because the solar irradiation intensity decreases faster than the decrease in the temperature difference. A similar efficiency increase trend was observed by Tyagi et al. (2012) where they studied

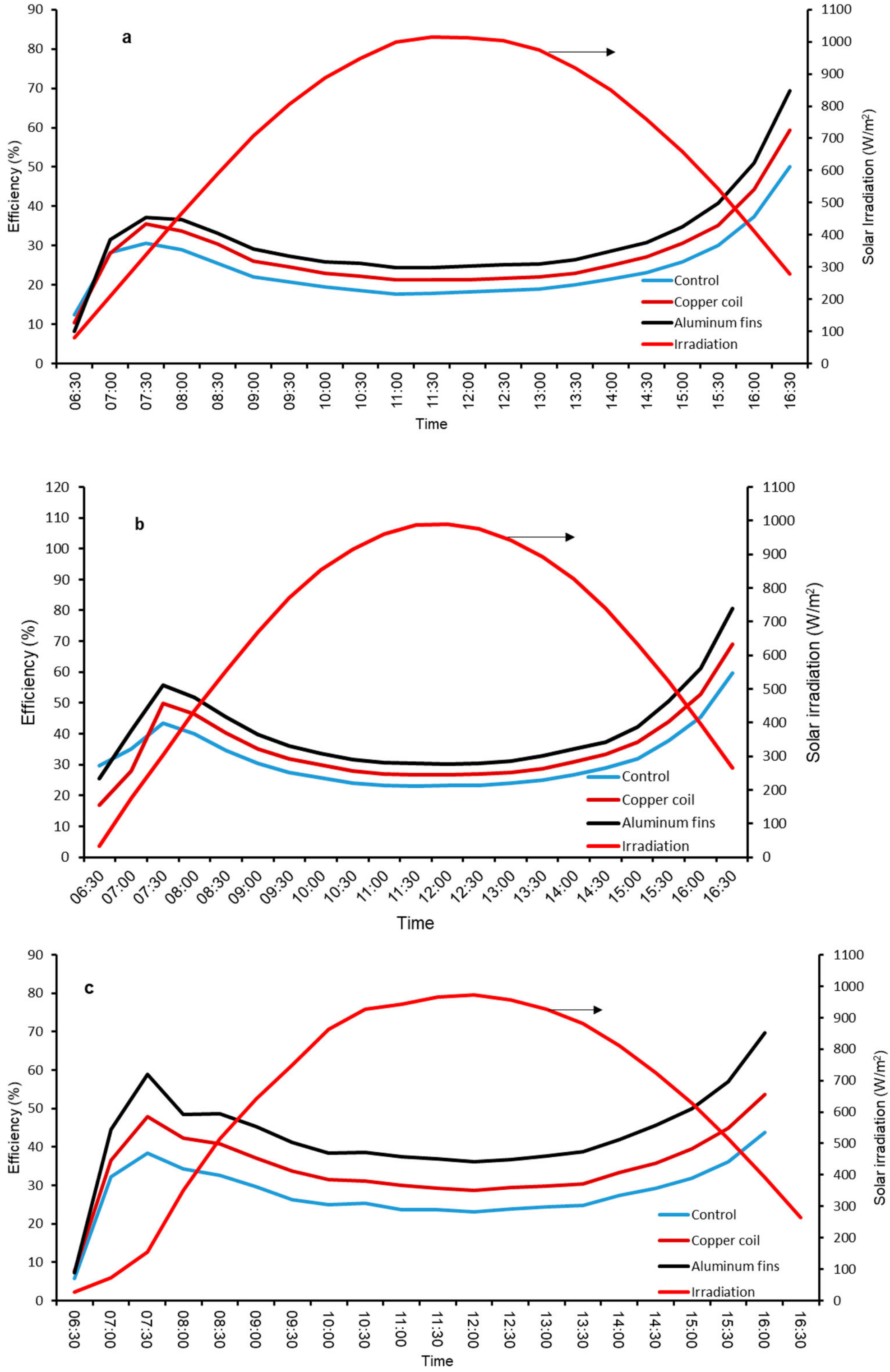

Figure 6. Efficiency and solar irradiation intensity with time for the three systems at various air flow rates. (a) air flow rate of 0.6 m^3/min, (b) air flow rate of 0.9 m^3/min, (c) air flow rate of 1.25 m^3/min.

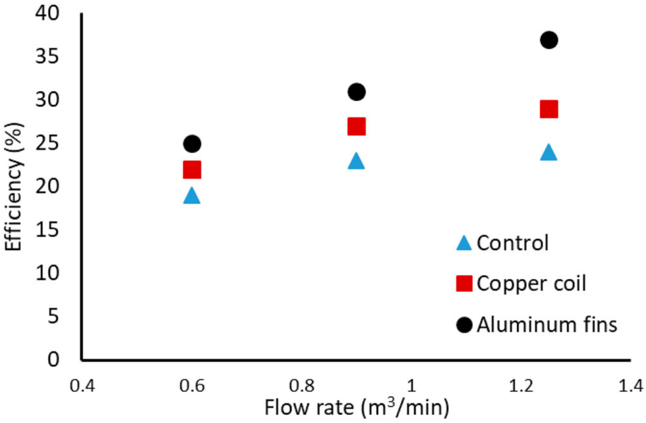

Figure 7. The efficiency of the three systems at the highest solar irradiation and at various air flow rates.

the impact of phase-changing material on the solar air heater efficiency. Kumar et al. (2013) and, Yadav and Bajpai (2012) found also that the efficiency is directly proportional to temperature difference and inversely proportional to solar intensity.

In Figure 6(c), the fluctuation in the efficiency between 6:30 and 9:00 is a result of the rabid increase and fluctuation in the irradiation intensity. Where at the first hour and half the inlet temperature was low (13–16°C) and the irradiation intensity was in the range of 16–200 W/m^2. However, at 8 am, the irradiation intensity doubled in less than 30 min and resulting in lowering the efficiency.

The system with aluminum fins (Figure 6(a) and Figure 7) has the highest thermal efficiency compared to other systems for all flow rates. The efficiency at the highest solar radiation (around 1000 W/m^2) and air flow rate of 1.25 m^3/min was 24, 29 and 37% for the control, copper coil and aluminum fins systems respectively.

Figure 7 also shows that the efficiency increases with the increase in flow rate for all systems. The maximum efficiency in the system with aluminum fins at the maximum solar intensity was 25, 31 and 37% for air flow rate of 0.6. 0.9 and 1.25 m^3/min respectively. The increase of efficiency with increasing the flow rates was also observed by Wang, Li, and Liu (2015), Li et al. (2014), the simulation conducted by Paradis et al. (2015), and the results of Delisle and Kummert (2012). These authors concluded that air flow rate is the primary factor influencing the thermal performance of the ETSH.

3.3. Comparison with literature

Table 1 summarises the results of different thermal performance studies of ETSHs. To increase the outlet temperature of the air, some of these studies used a parabolic trough or compound parabolic concentrator. The number of evacuated tubes used in the studies varied from one study to another. The efficiency of ETSH varies significantly and it depends on the flow rate and the number of used tubes. It is clear from the table that using a parabolic concentrator significantly increases the air outlet temperature. The temperature differences obtained by Bakry et al. (2018) were higher that the temperature differences obtained in this study, this is due the very low flow rates (0.0003–0.0006 Kg/s) used in that study. As seen from the table, and taking into consideration the high air flow rates, the highest temperature difference between inlet and outlet were obtained in this study.

4. Conclusion

In this study, the thermal performance of three different designs of ETSH were experimentally investigated. The ETSH systems are made of one ended evacuated tube fed with air by a copper tubes. In

Table 1. Summary of literature studies on performance analysis of one ended evacuated tube solar air heaters.

Number of tubes/type of heat exchanger	Solar irradiation (W/m^2)	Air flow rate	Temperature Difference between inlet and outlet (°C)	Efficiency	Concentrator	Reference
10 tubes equipped with copper tube (control)	1000	0.6 m^3/min	64.6	19	Without parabolic concentrator	This study
		0.9 m^3/min	49.8	23		
		1.25 m^3/min	33.7	24		
10 tubes equipped with copper tube and copper coil	1000	0.6 m^3/min	75.1	22	Without parabolic concentrator	This study
		0.9m3/min	57.5	27		
		1.25 m^3/min	42.6	29		
10 tubes equipped with copper tube and aluminum fins	1000	0.6 m^3/min	87.5	25	Without parabolic concentrator	This study
		0.9 m^3/min	65.2	31		
		1.25 m^3/min	52.7	37		
One tube	700	0.0003 kg/s	118	–	With parabolic concentrator	Bakry et al. (2018)
	700	0.0003 kg/s	60	28	Without parabolic concentrator	
	800	0.0006 kg/s	130	–	With parabolic concentrator	
	800	0.0006 kg/s	85	65	Without parabolic concentrator	
Performance analysis of a single-pass both ends open evacuated tube.	–	0.0077 m^3/s	59.6	48	With compound parabolic concentrator	Li et al. (2013)
One tube	–	0.0077 m^3/s	3.4	66	With compound parabolic concentrator	
One tube Nitrogen gas used as a working fluid.	916	0.0024 kg /s	358 °C (outlet temperature)	44	With compound parabolic concentrator	Li and Wang (2006)
	950	0.0012 kg/s	463°C (outlet temperature)	28	With compound parabolic concentrator	
19 tubes equipped with micro heat pipe arrays as a heat transfer element	654–804	320 m^3/h	5.4–11.2	49–70	Without concentrator	Zhu et al. (2017)
	580–837	180 m^3/h	8.4–13.3	44–51.5	Without concentrator	
	560–732	100 m^3/h	9.1–17.4	30–31	Without concentrator	
One-ended evacuated tube solar air heater equipped with a micro-heat pipe arrays. 10 tubes	900	160 m^3/h	10 (outlet temperature)	80	Without concentrator	Wang et al. (2019)
20 tube	800	140 m^3/h	45	38	Without concentrator	Li et al. (2014)
30 linked collecting tubes	835	25 m^3/h	45	52	With concentrator	Wang, Li, and Liu (2015)
40 evacuated tubes	900	0.0268 kg/s	17	13	Without reflector	Yadav and Bajpai (2012)
	810	0.0576 kg/s	21	30	Without reflector	
	750	0.0576 kg/s	32	55	With CPC and copper coil	
15 tubes	900	6.7 kg/h	27	6	Without CPC	Kumar et al. (2013)
	800	13.28 kg/h	44	11	Without CPC	
	850	6.7 kg/h	70	10	With CPC	
	800	13.28 kg/h	50	15	With CPC	

order to achieve higher thermal performance, the copper tube was equipped with aluminum fins and copper coil.

The three systems were tested under various air flow rates of 0.6, 0.9 and 1.25 m^3/min. All systems were able to significantly increase the air temperature during the daytime and even slightly during the early evening hours. The three systems showed similar thermal behaviour and efficiency trends under the studied flow rates.

The highest temperature difference was 88°C and it was obtained by the system with aluminum fins. Further, our research showed that the temperature difference decreased when flow rate increased. The highest efficiency was 37% and it was obtained by the system with the aluminum fin and the highest air flow rate. For all systems the efficiency decreased with decreasing in the air flow rate.

During the morning hours, the three systems were very sensitive to variations in solar radiation and showed high effectiveness and immediate response. During the afternoon and evening hours, the temperature difference was almost stable, this can be explained by the continuation of both radiative and convective heat transfer to the air by both solar radiation and the metals thermal.

The best thermal performance was obtained in the system with aluminum fins, next was the system with copper coil and finally the control system. The system with aluminum fins showed a superior thermal performance compared to the control, the copper coil systems and also compared to the corresponding literature results. For the three systems and under the studied parameters, the obtained efficiency and the temperature differences are significantly higher than those of the literature (Table 1).

The obtained results show that the air flow rate is the most influential parameter in controlling both the thermal efficiency and the obtained temperature difference of the ETSH. The presented design not only demonstrated excellent thermal performance but it is also simple, durable, reliable, and cost-effective. This design can be used for heating buildings and other applications such as a heat source for industrial dryers of vegetables and fruits. The findings of this study can serve as a tool to advance the performance of ETSH by adding fins to the heat transfer (heat exchanger) elements. To further increase the collector efficiency, the future work will investigate the impact of larger areas aluminum fins and a simplified parabolic concentrator to the system. The larger fin areas will enhance the heat transfer between the air and the copper tube. This enhancement in heat transfer may lead into new technological development such as reduction in the future evacuated collector areas.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Abdullah, A. S., and M. K. Bassiouny. 2014. “Performance of Cylindrical Plastic Solar Collectors for Air Heating.” *Energy Conversion and Management* 88: 88–95.

Abdullahi, B. 2015. “Development and Optimization of Heat Pipe Based Compound Parabolic Collector.” PhD Thesis, University of Birmingham.

Abu Hamed, T., A. Alshare, and H. El Khalil. 2019. “Passive Cooling of Building-Integrated Photovoltaics in Desert Conditions: Experiment and Modeling.” *Energy* 170: 131–138.

Abu Hamed, T., and L. Bressler. 2019. “Energy Security in Israel and Jordan: The Role of Renewable Energy Sources.” *Renewable Energy* 135: 378–389.

Ayompe, L. M., A. Duffy, M. Mc Keever, M. Conlon, and S. J. McCormack. 2011. “Comparative Field Performance Study of Flat Plate and Heat Pipe Evacuated Tube Collectors (ETCs) for Domestic Water Heating Systems in a Temperate Climate.” *Energy* 36: 3370–3378.

Bakry, A. I., Y. A. F. El-Samadouny, S. A. El-Agouz, A. M. Alshrombably, K. S. Abdelfatah, and M. A. Said. 2018. “Performance of the one-Ended Evacuated Tubes as Medium Temperature Solar air Heaters at low Flow Rates.” *Sustainable Energy Technologies and Assessments* 30: 174–182.

Bellos, E., C. Tzivanidis, K. Moschos, and K. A. Antonopoulos. 2016. “Energetic and Financial Evaluation of Solar Assisted Heat Pump Space Heating Systems.” *Energy Conversion and Management* 120: 306–319.

Budihardjo, I., and G. L. Morrison. 2009. “Performance of Water-in-Glass Evacuated Tube Solar Water Heaters.” *Solar Energy* 105: 689–701.

Caliskana, H., H. Hongb, and J. K. Jangb. 2019. “Thermodynamic Assessments of the Novel Cascade air Cooling System Including Solar Heating and Desiccant Cooling Units.” *Energy Conversion and Management* 199: 112013.

Chen, Y., H. Yang, and Y. Luo. 2018. “Investigation on Solar Assisted Liquid Desiccant Dehumidifier and Evaporative Cooling System for Fresh air Treatment.” *Energy* 143: 114–127.

Delisle, V., and M. Kummert. 2012. “Experimental Study to Characterize the Performance of Combined Photovoltaic/Thermal Air Collectors.” *Journal of Solar Energy Engineering* 134: 031010.

EIA, Residential Energy Consumption Survey. 2009. Household Energy Use in California. Accessed September 15, 2019. https://www.eia.gov/consumption/residential/reports/2009/state_briefs/pdf/ca.pdf.

Enteria, N., H. Yoshino, A. Mochida, R. Takaki, A. Satake, S. Baba, and Y. Tanaka. 2015. “Performance Test of Desiccant Heating, Ventilating and Air-Conditioning System by Using Multiple Tracer Gas Dilution Method.” *International Journal of Air-Conditioning and Refrigeration* 23: 1550027.

Enteria, N., H. Yoshino, and A. Sataki. 2016. “Exergoenvironmental Evaluation of the Desiccant Air-Conditioning System Subjected to Different Regeneration Temperatures.” *International Journal of Air-Conditioning and Refrigeration* 24: 1650023.

European Commission, Buildings – European Commission. 2018. Accessed April 23, 2019. https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings.

European Commission, Heating and cooling – European Commission. 2016. Accessed May 25, 2019. https://ec.europa.eu/energy/en/topics/energy-efficiency/heating-and-cooling.

Ferdous, J., M. R. I. Sarker, and R. A. Beg. 2018. “Experimental Study of a Hybrid Evacuated Tube Solar Collector Using Methanol as Working Fluid.” *International Journal of Engineering Research and Management (IJERM)* 5 (7): 1–6.

Fernández MG, Roger-Lacan C, Gährs U, Aumaitre V. 2016. Efficient District Heating and Cooling Systems in the EU. Accessed October 9, 2019. https://publications.europa.eu/en/publication-detail/-/publication/f428333d-dede-11e6-ad7c-01aa75ed71a1.

Gill, B. S., B. Bhushan, and T. Mahajan. 2016. *Performance Investigation of Double Pass Solar air Heater Duct Having zig-zag Square Shape Protruded Absorber Plate*. Munich: GRIN Verlag. Accessed July 4, 2019. https://www.grin.com/document/338381.

Hayek, M., J. Assaf, and W. Lteif. 2011. “Experimental Investigation of the Performance of Evacuated-Tube Solar Collectors Under Eastern Mediterranean Climatic Conditions.” *Energy Procedia* 6: 618–626.

Kumar, A., S. Kumar, U. Nagar, and A. Yadav. 2013. “Experimental Study of Thermal Performance of One-Ended Evacuated Tubes for Producing Hot Air.” *Journal of Solar Energy* 2013: 524715.

Li, X., Y. J. Dai, Y. Li, and R. Z. Wang. 2013. “Performance Investigation on a Novel Single-Pass Evacuated Tube with a Symmetrical Compound Parabolic Concentrator.” *Solar Energy* 98 (4): 275–289.

Li, M., and L. L. Wang. 2006. “Investigation of Evacuated Tube Heated by Solar Trough Concentrating System.” *Energy Conversion and Management* 47: 3591–3601.

Li, X., G. Yuan, Z. Wang, H. Li, and Z. Xu. 2014. “Experimental Study on a Humidification and Dehumidification Desalination System of Solar Air Heater with Evacuated Tubes.” *Desalination* 351: 1–8.

Liang, R., L. Ma, J. Zhang, and D. Zhao. 2011. “Theoretical and Experimental Investigation of the Filled-Type Evacuated Tube Solar Collector with U Tube.” *Solar Energy* 85 (9): 1735–1744.

Liu, Z. H., R. L. Hua, L. Lu, F. Zhao, and H. S. Xiao. 2013. “Thermal Performance of an Open Thermosyphon Using Nanofluid for Evacuated Tubular High Temperature air Solar Collector.” *Energy Conversion and Management* 73: 135–143.

Long-Term Trends in the Supply and Demand of Electricity in Israel, Bank of Israel. 2016. Accessed August 3, 2019. https://www.boi.org.il/en/NewsAndPublications/PressReleases/Pages/21-03-2016-demandelectricity.aspx.

Ma, L., Z. Lu, J. Zhang, and R. Liang. 2010. “Thermal Performance Analysis of the Glass Evacuated Tube Solar Collector with U-Tube.” *Building and Environment* 45 (9): 1959–1967.

Morrison, G. L., I. Budihardjo, and M. Behnia. 2005. “Measurement and Simulation of Flow Rate in a Water-in-Glass Evacuated Tube Solar Water Heater.” *Solar Energy* 78: 257–267.

Nkwetta, D. N., M. Smyth, A. Zacharopoulos, and T. Hyde. 2012. “In-door Experimental Analysis of Concentrated and non-Concentrated Evacuated Tube Heat Pipe Collectors for Medium Temperature Applications.” *Energy and Buildings* 47: 674–681.

Paradis, P. L., D. R. Rousse, S. Halle, L. Lamarche, and G. Quesada. 2015. “Thermal Modeling of Evacuated Tube Solar air Collectors.” *Solar Energy* 115: 708–721.

Qi, T. 2007. “Thermal Performance of the U-Type Evacuated Glass Tubular Solar Collector.” *Building Energy and Environment* 26 (3): 51–54.

Sabiha, M. A., R. Saidur, S. Mekhilef, and O. Mahian. 2015. “Progress and Latest Developments of Evacuated Tube Solar Collectors.” *Renewable and Sustainable Energy Reviews* 51: 1038–1054.

Saxena, A., K.A Varun, and A.A El-Sebaii. 2015. “A Thermodynamic Review of Solar air Heaters.” *Renewable and Sustainable Energy Reviews* 43: 863–890.

Tang, R., Z. Li, H. Zhong, and Q. Lan. 2006. “Assessment of Uncertainty in Mean Heat Loss Coefficient of all Glass Evacuated Solar Collector Tube Testing.” *Energy Conversion and Management* 47 (1): 60–67.

Tang, R., Y. Yang, and W. Gao. 2011. “Comparative Studies on Thermal Performance of Water-in-Glass Evacuated Tube Solar Water Heaters with Different Collector Tilt-Angles.” *Solar Energy* 85: 1381–1389.

Tian, Z., S. Zhang, J. Deng, J. Fan, J. Huang, W. Kong, B. Perers, and S. Furbo. 2019. “Large-scale Solar District Heating Plants in Danish Smart Thermal Grid: Developments and Recent Trends.” *Energy Conversion and Management* 189: 67–80.

Tyagi, V., A. Pandey, S. Kaushik, and S. Tyagi. 2012. “Thermal Performance Evaluation of a Solar air Heater with and Without Thermal Energy Storage an Experimental Study.” *Journal of Thermal Analysis and Calorimetry* 107: 1345–1352.

Wan, K. K. W., D. H. W. Li, D. Liu, and J. C. Lam. 2011. “Future Trends of Building Heating and Cooling Loads and Energy Consumption in Different Climates.” *Building and Environment* 46 (1): 223–234.

Wang, P. Y., H. Y. Guan, Z. H. Liu, G. S. Wang, F. Zhao, and H. S. Xiao. 2014. “High Temperature Collecting Performance of a New all-Glass Evacuated Tubular Solar air Heater with U-Shaped Tube Heat Exchanger.” *Energy Conversion and Management* 77: 315–323.

Wang, P. Y., S. F. Li, and Z. H. Liu. 2015. “Collecting Performance of an Evacuated Tubular Solar High-Temperature Air Heater with Concentric Tube Heat Exchanger.” *Energy Conversion and Management* 106: 1166–1173.

Wang, T. Y., Y. H. Zhao, Y. H. Diao, R. Y. Ren, and Z. Y. Wang. 2019. “Performance of a New Type of Solar Air Collector with Transparent-Vacuum Glass Tube Based on Micro-Heat Pipe Arrays.” *Energy* 177: 16–28.

Yadav, A., and V. K. Bajpai. 2012. “Thermal Performance of One-Ended Evacuated Tube Solar Air Collector at Different Flow Rates: Experimental Investigation.” *International Journal of Ambient Energy* 33: 35–50.

Yadav, A. S., and J. L. Bhagoria. 2013. “Heat Transfer and Fluid Flow Analysis of Solar air Heater: A Review of CFD Approach.” *Renewable and Sustainable Energy Reviews* 23: 60–79.

Yuan, Y. L., Y. Li, and Y. J. Dai. 2010. “Study on Thermal Performance of Evacuated Tubular Solar Air Collector with Inserted Tubes.” *Acta Energiae Solaris Sinica* 31: 1429–1433.

Zeng, R., X. Wang, H. Di, F. Jiang, and Y. Zhang. 2011. “New Concepts and Approach for Developing Energy Efficient Buildings: Ideal Specific Heat for Building Internal Thermal Mass.” *Energy and Buildings* 43 (5): 1081–1090.

Zhu, T., Y. Diao, Y. Zhao, and Y. Deng. 2015. “Experimental Study on the Thermal Performance and Pressure Drop of a Solar Air Collector Based on Flat Micro-Heat Pipe Arrays.” *Energy Conversion and Management* 94: 447–457.

Zhu, T. T., Y. H. Zhao, Y. H. Diao, F. F. Li, and Z. H. Quan. 2017. “Experimental Investigation and Performance Evaluation of a Vacuum Tube Solar air Collector Based on Micro Heat Pipe Arrays.” *Journal of Cleaner Production* 142: 3517–3526.