Energy and Exergy Analysis of Evacuated Tubes Solar Air Collector With Micro-Heat Pipes Arrays (MHPA)

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The IAFOR International Conference on Sustainability, Energy & the Environment – Hawaii 2017
Official Conference Proceedings

Abstract

Solar air collector (SAC) occupies an important place among solar air heating systems because of simpler structure and lower manufacturing costs compared with a solar water collector. In order to improve the performance of SAC, micro-heat pipe arrays (MHPA) technique has been introduced in the presented study. MHPA looks like a flat aluminum plate with several independent micro-heat pipes in it, which owned extremely high heat transfer efficiency based on the phrase change heat transfer.

In this study, a type of evacuated tubes solar air collector (ETSAC) with MHPA is investigated based on exergy analysis. ETSAC with MHPA mainly comprises with several heat-collecting units, an air duct and a fan. Each heat-collecting unit is made up of a glass evacuated tube, an MHPA and a set of fins attached on the condenser section of MHPA. Solar energy is absorbed and transferred by the collecting unit, and the air can be heated do not need flow into the evacuated tube directly, but just rely on the convective heat transfer occurred in the air duct between the air and condenser fins.

A detailed parametric study is conducted to examine the effects of various operation parameters on energy and exergy efficiencies. Results indicated that the energy efficiency of the collector is approximately 64% and corresponding exergy efficiency is about 53%. Exergy efficiency can be used as the main criterion to evaluate the performance of MHPA-ETSAC. As an energy saving and emission reduction product, MHPA-ETSAC provide a new approach.

Keywords: micro-heat pipe arrays, solar air collector, exergy efficiency, energy saving, emission reduction

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1. Introduction

Facing energy security and ecological environmental challenges, using the renewable energy is one of the solutions for that. Solar energy is security, clean and inexhaustible without pollution for the environment. Solar heat energy utilization technology as a vital aspect was investigated by many scholars and experts in recent years. In North and Northwest areas of China, solar energy resource is very abundant, with huge using potential shown as Fig.1 [1]. However, the heating means of remote rural areas of these areas is burning biomass and fossil fuels mainly. There are problems exist, which is environmental pollution and low efficiency of the device. If solar energy of these areas can be used efficiently, indoor thermal environment of these areas can be improved.

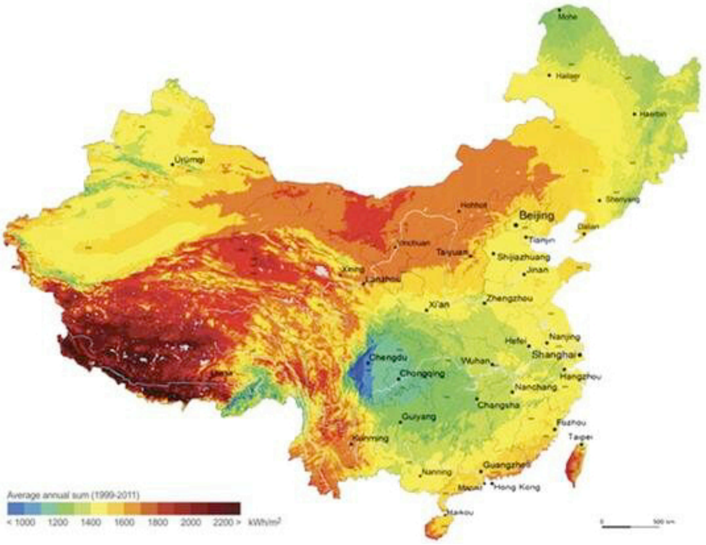

Figure 1: Solar energy distribution of China.

Solar air collectors being inherently simple are cheap and most widely used collection devices [2]. Solar air collector has been employed to deliver heated air at low to moderate temperatures for space heating, crop drying, and several industrial applications [3].The common types of solar air collectors are flat plate type, evacuated tubes type and focus type [4]. Flat plate solar air collector owns characteristics of simple structure, easy processing and low cost but with high heat loss. Evacuated tubes type has excellent heat insulation performance and can improve heat collection temperature and efficiency, but with high pressure drop. The focus type can obtain high outlet temperature, but with lower efficiency, complex system and commonly requires high investment. Thus, many ideas and attempts have been done to improve the performance of solar air collectors.

Enhancing the heat transfer of the absorber plate for a flat plate is the common method. The use of an artificial rough surface can significantly improve fluid flow and heat transfer performance, and different types of roughness elements were observed in previous studies [5-12]. Apart from the flat-plate collector, other types of solar air collectors have also been investigated by experts. Türk Toğrul and Pehlivan [13] studied the efficiency of a solar air collector with a conical concentrator which can track the sun at different time. Abdullah and Bassiouny [14] proposed a flexible cylinder type solar air collector, which thermal efficiency decreases linearly with the parameter $\Delta T/I_c$. A novel evacuated tubular solar air collector combined with simplified CPC to provide air with high and moderate temperatures was proposed by Liu et al. [15]. The maximum air outlet temperature exceeds 170°C at the air volume rate of 7.6 m^3/h in winter. A tubular solar air collector with inner intubation was investigated by Yuan et al. [16], the collector with a good thermal performance but with more fan power input. In order to increase the efficiency and decrease the pressure drop, a new solar air collector based on micro-heat pipe arrays has been proposed by Zhu et al. [4].

An experimental investigation is required to be carried out on the thermal performance of the collector. Thus, an experimental investigation is conducted in the present study to determine the effects of air flow rate and different seasons on the thermal efficiency of the Evacuated Tubes Solar Air collector. The pressure drop of the collector is also studied experimentally. This paper carried out an investigation of the collector proposed by Zhu et al. [4] in view of energy and exergy analysis to evaluate the performance.

2. Experimental procedure

In order to study the performance of the proposed collector, an experimental system is carried out. The experimental system includes two parts: the collector and the testing system.

2.1 ETSAC with micro-heat pipes arrays

The evacuated tubes solar air collector (ETSAC) with micro-heat pipes arrays (MHPA) is proposed in the present paper. ETSAC with MHPA is mainly consist of MHPA, several evacuated tubes, air duct and a fan. MHPA is a kind of high efficient heat transfer component which works rely on phase change. The shape is aluminum alloy plate. Within each plate has dozens of independent operation micro-heat pipe, which can be widely used in a variety of thermal problems. The temperature difference between the evaporator section and the condenser section is less than 1℃ [17]. As shown in Fig.2, It looks like an aluminum sheet, and there has some liquid material in its several independent micro-channels.

It can be seen as two sections when it is working in solar air collector. The bottom section with heat in is evaporation section, and the top section is called condensation section. MHPA can works automatically when the heat in put in the evaporation section. The liquid material evaporated as vapor and goes up along with the wall of each heat pipe channels when it absorber heat. In the condensation section, the heat released, the vapor condensed into liquid and flows back to the evaporation section depend on the gravity and capillary force. The process is continuous and ongoing.

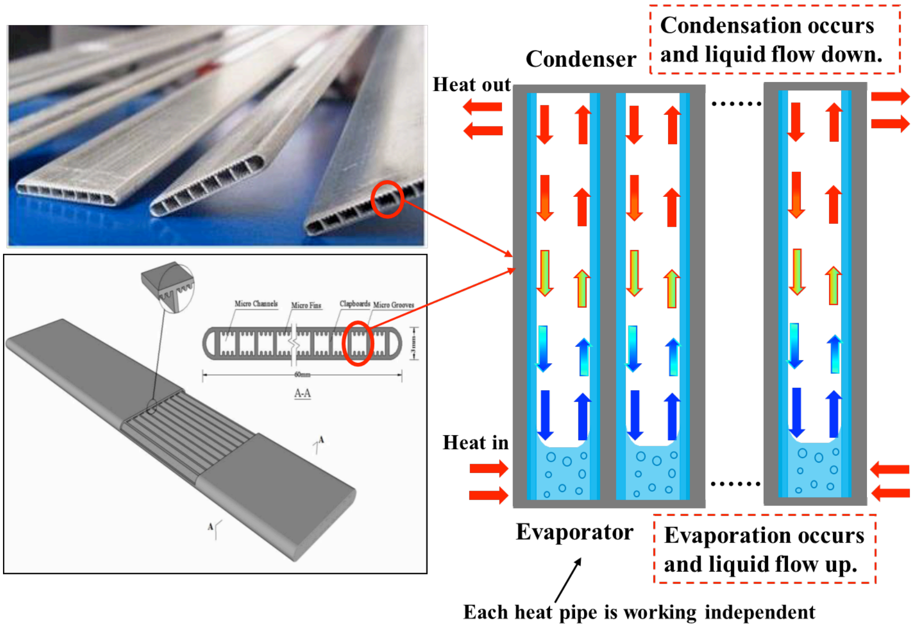

Figure 2: Micro-heat pipe arrays.

The structure of ETSAC with MHPA studied in this paper is shown in Figure 3. It is made up of by 15 collecting core units, an air duct and a fan. Each core unit consists of aluminum fin, MHPA and an evacuated tube. Evacuated tube act as the role of absorb solar energy by the absorber film attached on it. Evaporation section of MHPA is inserted in the tube. Evaporation section of MHPA is the heat transfer component to transfer heat from evacuated tube to the condenser section. In the condenser section, the aluminum fin is attached on it to extend heat exchange area. The condenser section with fin makes heat exchange with air flow in the air duct. And working principle of the collecting core unit is showed in Figure 4.

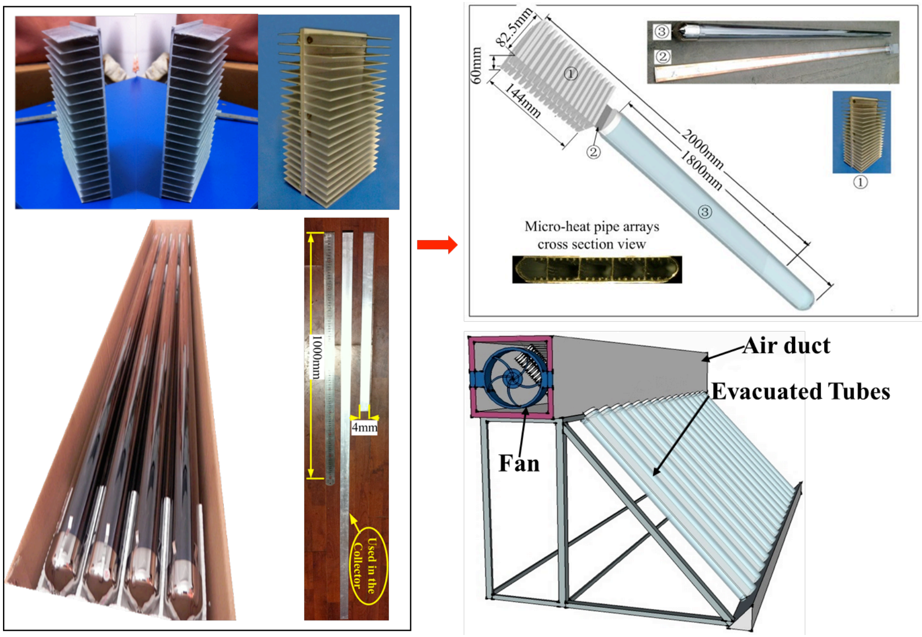

Figure 3: Structure of ETSAC with micro-heat pipes arrays (MHPA).

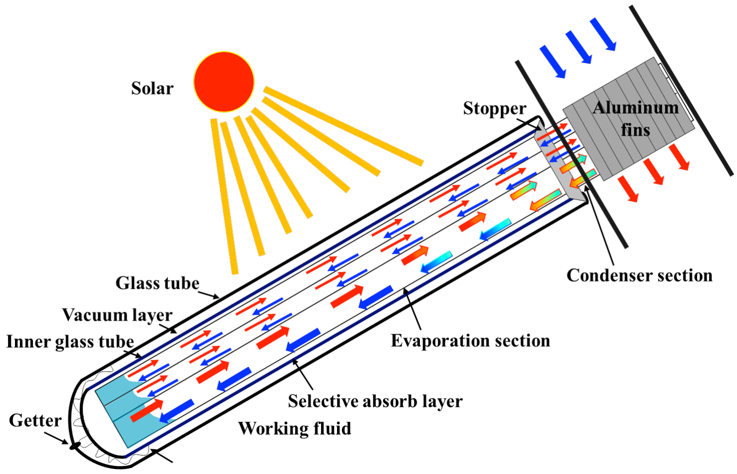

Figure 4: Working principle of the collecting unit.

2.2 Testing system

The experimental platform was constructed in Beijing University of Technology; the area surrounding the experimental platform is open and unsheltered. The experimental test system includes a new solar air collector, an axial flow fan, and other test instruments, including a weather station (total radiation meter, temperature and humidity sensor, and wind vane), thermal resistors, thermocouples, an Agilent data acquisition instrument, and a computer. Inlet and outlet air temperatures were measured with four well-insulated thermal resistors installed evenly on the cross section of the dust inlet and outlet at corresponding positions along the direction of air flow.

2.3 Data reduction

The instantaneous thermal efficiency of collector were calculated from the experimental data for each flow rate from daytime measurements using the equations below,

$$S = I\tau\alpha \cdot A \tag{1}$$

$$Q_u = c_p m(t_o - t_i) \tag{2}$$

$$\eta = \frac{Q_u}{S} \tag{3}$$

The exergy can be calculated as,

$$\Delta \mathrm{E} = \mathrm{m}\left[\left(h_o - h_i\right) - T_\mathrm{a}\left(s_o - s_i\right)\right] \tag{4}$$

$$\Delta \mathrm{E} = \mathrm{mC_p}\left[\left(T_o - T_i\right) - T_\mathrm{a}\mathrm{In}\frac{T_o}{T_i}\right] \tag{5}$$

Exergy efficiency of the collector can be express as:

$$\eta_\mathrm{ex} = \frac{\Delta E}{A_c I} = \frac{\Delta E}{C_\mathrm{p}\mathrm{m}\left(T_o - T_i\right)} \cdot \frac{C_\mathrm{p}\mathrm{m}\left(T_o - T_i\right)}{A_c I} \tag{6}$$

Where, m-mass flow rate of air, kg/s; A_c-total net collector area, m^2 ; T_o-outlet temperature, °C; T_i -inlet temperature, °C; c_p-specific heat of air, kJ/(kg· K); I- solar radiation, W/m^2; Q- volume flow rate, m^3/h; Ta- ambient temperature, °C; ΔT- temperature difference, °C; ΔP- pressure drop, Pa; ΔI- solar radiation difference, W/m^2; Q_u - useful energy gain, W/m^2; ΔE- Exergy difference;h- enthalpy, kJ/kg; S- entropy, kJ/kg·K; η_{th}- thermal efficiency; η_{ex}- exergy efficiency.

2.4 Uncertainty

The relative uncertainty of thermal efficiency was determined by the related independent variables, and the error for thermal efficiency was obtained through the error propagation method [4]. The data recording type and uncertainty analysis based on the precision of the equipment used during the experiment are illustrated in Table 2. The error estimation of thermal efficiency depends mostly on the thermal resistance errors at eight points and on the accuracy of the other parameters. Considering the relative errors of the individual factors, the relative error of efficiency was calculated using the following equations [4]:

$$\Delta\eta = \left[\left(\frac{\partial\eta}{\partial\dot{Q}}\Delta\dot{Q}\right)^2 + \left(\frac{\partial\eta}{\partial T_o}\Delta T_o\right)^2 + \left(\frac{\partial\eta}{\partial T_i}\Delta T_i\right)^2 + \left(\frac{\partial\eta}{\partial I}\Delta I\right)^2\right]^{1/2} \tag{5}$$

where $\Delta\eta$, $\Delta\dot{Q}$, ΔT_o, ΔT_i, and ΔI are the uncertainties of η, $\dot{Q}$, T_o, T_i, and I, respectively. The precision of the measurements and calculated variables are shown in Table 1. The experiments were conducted under different weather conditions. Therefore, the uncertainty value of η was 7.73%.

Table 1 Precisions of the measurements of different testing equipment

Instrument	Model Specifications	Precision
Data acquisition instrument	Agilent 34970A	-
Total radiation meter	TRT-2	<2%
Thermocouple	WRNK-191	I
Thermal resistance	Pt100	A, 0.15 °C
Hot bulb anemometer	ZRQF-F30J	±4%U
Differential manometer	Testo512	5%U

3. Results and discussions

Tests were conducted in 2013, Beijing University of Technology ((latitude: N39.9°, longitude: E116. 3°)), under sunny conditions. The instantaneous thermal efficiency of solar air collector was calculated from the experimental data for each flow rate of daytime. The variables measured by the thermal resistors and thermocouples were recorded at time intervals of 10 s. These variables include inlet and outlet temperatures of the working fluid flowing through the solar air collector, ambient temperature. Fig.5 showed the weather parameters on Mar.13 with the air velocity of 1.4 m/s. It can be found that the ambient temperature range from 4.1~10.8 ℃,and the average value is 7.4℃. Solar radiation range from 441~951W/m^2, and the average value reached 771 W/m^2. Outlet temperature range from 11.1~17.8 ℃. The variation of thermal efficiency and exergy efficiency is showed in Fig.6 Energy efficiency is about 49~82%, the average value is 62%, and exergy efficiency is ranged between 37.9~64%，the average value is 46.3%.

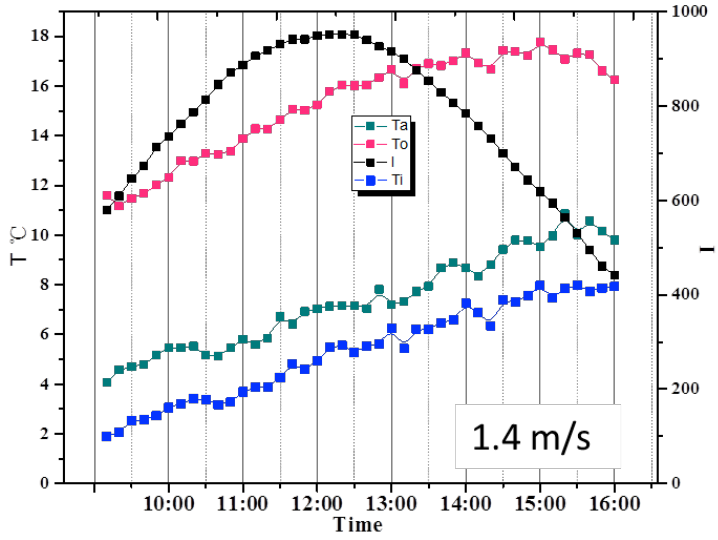

Fig. 5: Variations of /I/ηth / ηex versus time. (2013/Mar/13)

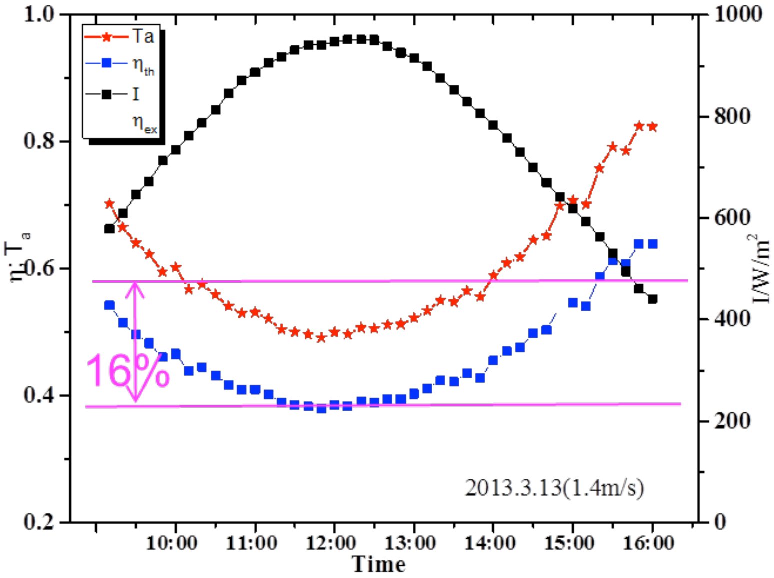

Fig. 6: Variations of Ta/I/ηth / ηex versus time. (2013/Mar/13)

Fig.7 showed the weather parameters on Apr. 16 with the air velocity of 1.2 m/s. It can be found that the ambient temperature range from 14~21 ℃,and the average value is 7.4℃. Solar radiation range from 375~870 W/m^2, and the average value reached 695 W/m^2. Outlet temperature range from 24.8~32.5℃. The variation of thermal efficiency and exergy efficiency is showed in Fig.8. Energy thermal efficiency is about 64%, and exergy efficiency is 53%.

The external parameter influence the thermal performance of the collector involves solar radiation, inlet temperature, air velocity, and the ambient temperature. The internal parameter influence the performance of the collector involves the structure, the material, as well as the insulation condition of the collector. The air temperature difference decreases with the increase in mass flow rate and flow velocity because of the increase in the heat capacity of air at the same solar input. The EVTSAC with high thermal efficiency and low pressure drop can be utilized in room heating and agricultural products drying. The temperature level of the collector can be controlled by adjusting the flow rate. Increasing the number of collecting core units can also increase the outlet temperature, if necessary.

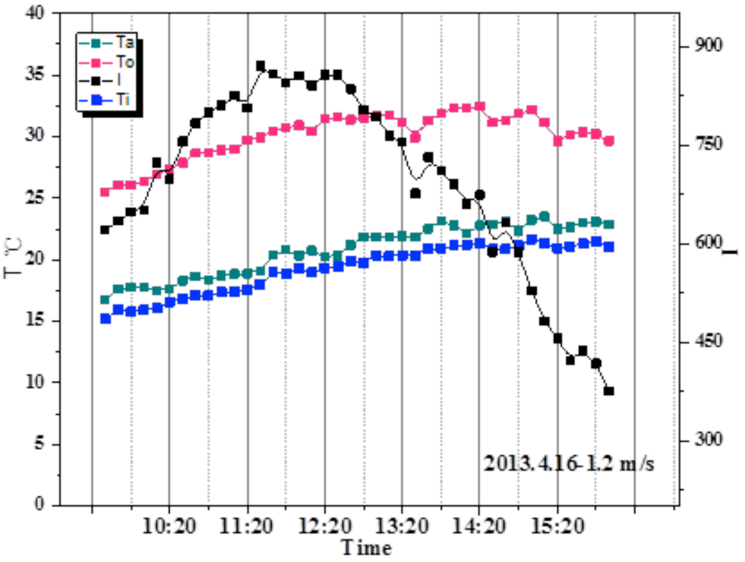

Fig. 7: Variations of /I/ηth / ηex versus time. (2013/Apr/16)

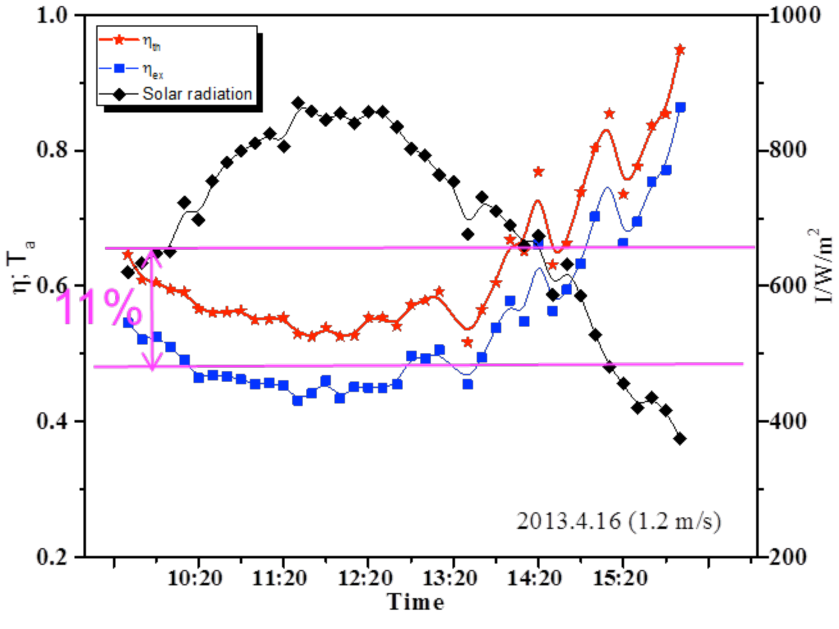

Fig. 8: Variations of Ta/I/ηth / ηex versus time. (2013/Apr/16)

Compared with Fig. 6 and Fig. 8, it can be found that the difference between η_{th} and η_{ex} is 16% and 11%, respectively. The difference between η_{th} and η_{ex} is decreased which is because of the decreasing in velocity provided by fan power. The phenomenon of that can be found in in Fig.9 and Fig.10 clearly. Generally, increasing the flow rate is an effective way to improve the thermal performance of a solar air collector, but it can result a high input of fan power. The variation of exergy efficiency η_{ex}, remind us it isn't an effective method always, it is based on the quality of the energy gained and the power input. The power input is the reflection of the flow resistance, the pressure drop of the air duct.

Fig. 9 is the variations of η_{th} and η_{ex}. Thermal efficiency and exergy efficiency significantly increases as the air flow rate increases. Further increase in velocity leads to a decrease in exergy efficiency due to the increase of fan power and heat loss. The result reveals that 1.2 m/s is the optimal flow velocity for the present MHPA-solar air collector.

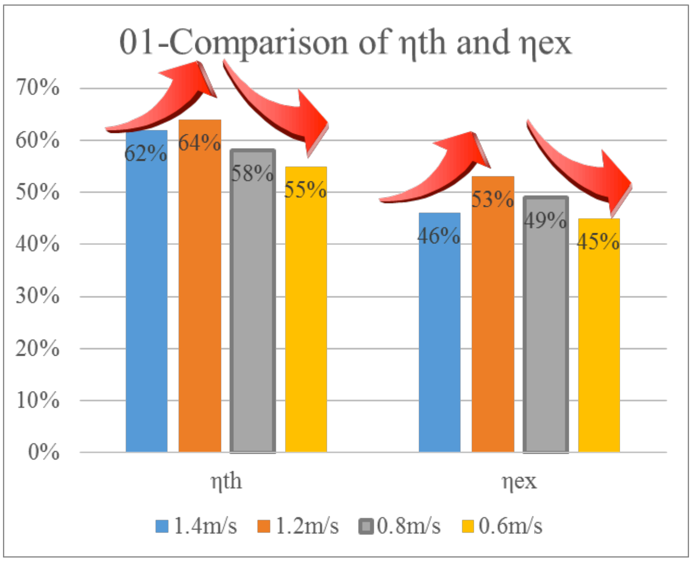

Fig. 9: Variations of ηth / ηex.

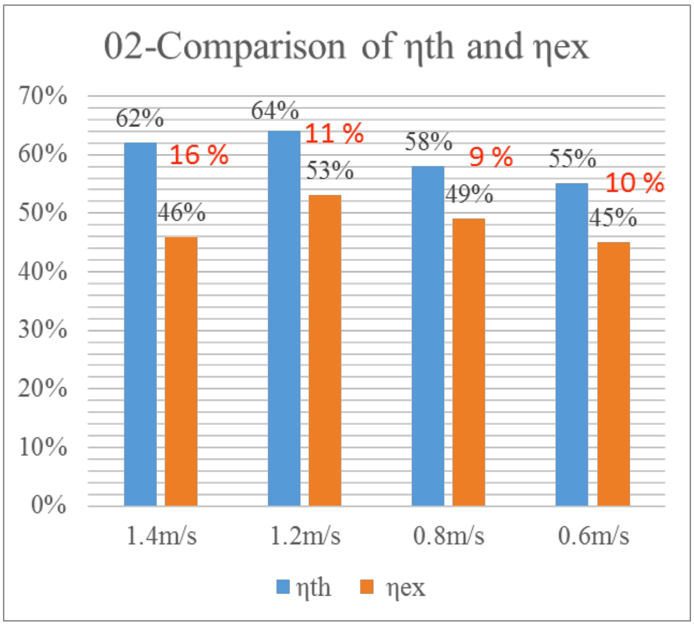

Fig. 10: Variations of ηth/ηex vs air velocity.

In the MHPA-evacuated tubes SAC, the air flow is not direct contact with heat absorbing tube and the heat transfer form is indirect heat exchange which relies on the phase change heat transfer of the liquid in MHPA. Reduce the flow resistance, with low fan power.

Pressure drop of MHPA-Evacuated Tubes SAC is less than 25 Pascal [4], shown as in Fig.11. In the new technology, air is not direct contact with heat absorbing tube, and the heat transfer form is indirect heat exchange which relies on the phase change heat transfer of the liquid in MHPA. Reduce the flow resistance, with low fan power.

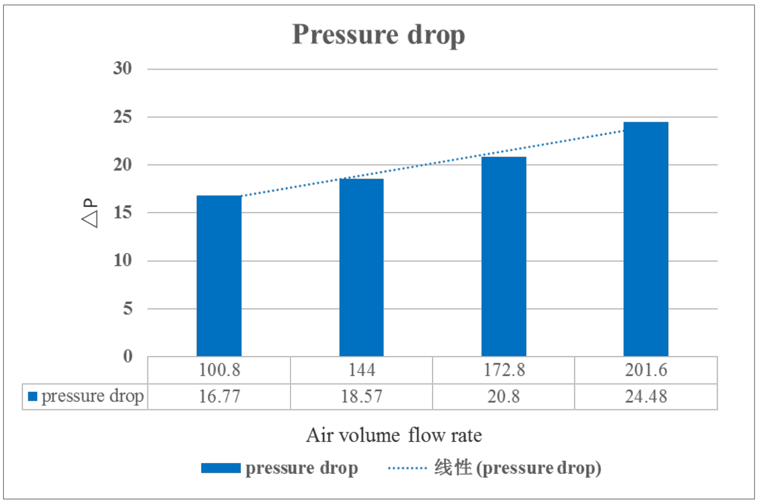

Fig. 11: Pressure drop of the EVSAC with MHPA.

4. Conclusion

In this paper, the energy and exergy performance of EVSAC with MHPA is presented. The heat collecting component is the micro-heat pipe arrays (MHPA). To study the thermal performance of the solar air collector, a series of tests were conducted in 2013 in Beijing, China. The test data were analyzed from the aspects of energy thermal performance and exergy performance. The MHPA-EVSAC presents a good performance with the weather in Beijing. The average thermal efficiency is 64% and exergy efficiency is 53% for the EVSAC. Test results can also serve as an important basis for understanding the performance of the EVSAC with MHPA. Exergy efficiency can be used as one of the main criterion to evaluate the performance of MHPA-ETSAC.

Acknowledgements

The project was financially supported by the Scientific Research Project of Beijing Educational Committee (Grant No. 004000546315527) and Scientific Research Project of Beijing Advanced Innovation Center for Future Internet Technology. The authors are grateful for the support of these sponsors.

References

Li, J.F., Wang, S.C., et.al. (2007). *China Solar PV Report*. Beijing: China Environmental Science Press.

Lanjewar, A., Bhagoria, J.L., Sarviya, R.M. (2011). Experimental study of augmented heat transfer and friction in solar air heater with different orientations of W-Rib roughness. *Experimental Thermal and Fluid Science, 35,* 986–995.

Kumar, A., Saini, R.P., Saini, J.S. (2012). Experimental investigation on heat transfer and fluid flow characteristics of air flow in a rectangular duct with Multi v-shaped rib with gap roughness on the heated plate. *Solar Energy, 86,* 1733–1749.

Zhu, T.T., Diao, Y.H., Zhao, Y.H., Deng, Y.C. (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.

Gama R. M. S. et al. (1986)Analysis of a V-groove solar collector with a selective glass cover. *Solar Energy, 36(6)*, 509–518.

Pehlvan D. (2003). The performance of a solar air heater with conical concentrator under forced convection. *Thermal Sciences, 42(6),* 571–581.

Ebrahim A. M. (2002).Heat transfer and friction in solar air heater duct with V-shaped rib roughness on absorber plate. *Heat and Mass Transfer, 45(16),* 3383–3396.

Tanda G. (2011). Performance of solar air heater ducts with different types of ribs on the absorber plate. *Energy, 36,* 6651–6660.

El-Sebaii A. A., Aboul-Enein S., Ramadan M. R. I., et al. (2011). Investigation of thermal performance of-double pass-flat and v-corrugated plate solar air heaters. *Energy 36,* 1076–1086.

Akpinar, E. K., Koçyiğit, F. (2010). Experimental investigation of thermal performance of solar air heater having different obstacles on absorber plates, *International Communications in Heat and Mass Transfer 37,* 416–421.

Yeh, H.-M., Ho, C.-D., Hou. J.-Z. (2002). Collector efficiency of double-flow solar air heaters with fins attached, *Energy, 27,*715–727.

Romdhane, B.S. (2007).The air solar collectors: Comparative study, introduction of baffles to favor the heat transfer, *Solar Energy 81,*139–149.

Türk Toğrul Ì, Pehlivan D. (2003). The performance of a solar air heater with conical concentrator under forced convection. *Int J Therm Sci, 42*, 571–81.

Abdullah A.S., Bassiouny M.K.(2014). Performance of cylindrical plastic solar collectors for air heating. *Energy Conversion and Management, 88,* 88–95.

Liu Z.H., Hua R.L., Lu L., Zhao F., Xiao H.S. (2013).Thermal performance of an open thermosyphon using nanofluid for evacuated tubular high temperature air solar collector. *Energy Conversion and Management,73,* 135–43.

Yuan Y.L., Li Y., Dai Y.J. (2010). Study on thermal performance of evacuated tubular solar air collector with inserted tubes. *Acta Energ Sol Sin, 31,* 1429–33.

Zhao Y.H., Zhang K.R., Diao Y.H. Heat pipe with micro-pore tubes array and making method thereof and heat exchanging system, P. US, NO. 20110203777.

ANSI ASHRAE 93-1986. (1986). Method of testing to determine the thermal performance of solar collectors [S]. ASHRAE Inc, New York.

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