Impact of Waste Heat Recovery of Chimney Using U-Shaped Pulsating Heat Pipe to Generate Hot Water- Experimental and Environmental Analysis

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Research Article

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Abstract

Many studies have been done on the Pulsating heat pipes (PHP) using energy applications system. In this study a heat exchanger PHP is analyzed. A heat pipe prototype is manufactured for waste heat recovery. The present study experimentally investigated the effect of pulsating heat pipe on the waste heat recovery of the chimney and produce hot water for household consumption. The evaporator is placed in a smoke exhaust duct and the condenser is located in a water chamber in which the smoke heat is transferred through. The results are presented for different heat pipe angles to the horizon from 0 to 90. The PHP is filled 60% by distilled water as operating fluid. The highest hot water temperature in outlet of reservoir was about to 58 ^{o}C. Also, The CO_2 mitigation and CPH of the waste heat recovery system was equal to 84.82 tons and 0.1\$/m^3. Moreover, the efficiency is changing from 19% for a horizontal PHP to 54% for a vertical one.

1. Introduction

Heat pipes are effective instruments in the heat transfer of different energy applications (Guo et al. 2022, Jung &Boo 2021). The heat pipe used in solar desalination (Fallahzadeh et al. 2020, Khalilmoghadam et al. 2021, Rastegar et al. 2020) to enhance the drinking water productivity, in thermoelectric generator (Date et al. 2014, Makki et al. 2016) to produce electrical, in photovoltaic thermal system (Jouhara et al. 2021, Zhang et al. 2021) to use from waste heat recovery of the system, and in HVAC system (Sukarno et al. 2021) to use energy recovery of the device. The heat transfer coefficient in the evaporator and condenser is significantly high and therefore the heat pipe is widely used in energy systems. As the thermal resistance of heat pipes is too low, it causes heat exchanger to have a smaller area and less mass compared to other traditional heat exchanger types. The use of pulsating heat pipes (PHP) is broadly extended to the vast variety of industrial sciences such as air preheater PHPs in thermal power plants, heat recovery from exhaust smoke and even electronic components cooling.

The pulsating heat pipe has a significant effect on solar energy applications. Xu et al. (Xu et al. 2020) numerically studied the thermal performance of compound parabolic concentrator solar collector using pulsating heat pipe. They found that the highest thermal efficiency of the system was about 74.5%. Kargarsharifabad et al. (Kargar Sharif Abad et al. 2013) improved the freshwater generation of solar desalination system with a pulsating heat pipe. The obtained outcomes revealed that the highest productivity of modified solar desalination was about 875 ml/m^{2}hr. Also, the optimum water height in the solar desalination was equal to 0.01 m. Aref et al. (Aref et al. 2021a) evaluated the effect of closed-loop pulsating heat pipe on water generation of humidification/dehumidification desalination. The outlet air from the dehumidifier was preheated and pre-humidified by closed-loop pulsating heat pipe before entering the humidifier of the desalination system. They found that the highest daily freshwater generation of humidification/dehumidification desalination was about 8.7 L/m^2. Xu et al. (Xu et al. 2017) evaluated the impact of compound parabolic concentrator (CPC) and PHP on performance of solar collector. The CPC has a significantly enhance the intensity of solar radiation to the PHP as an absorber and also decrease the heat loss due to reduce in area of the hot zone. They showed that the highest energy efficiency of solar collector using CPC and PHP was about 50%. Aref et al. (Aref et al. 2021b) investigated the effect of filling ration, inclination angle and solar intensity on performance of the novel closed-loop pulsating heat pipe. A flat plate collector was coupled with dual-diameter of pulsating heat pipe. The pulsating heat pipe was made of copper. The obtained results indicated that the highest efficiency of the solar collector with a filling ration of 60% was about 72.4%. Alizadeh et al. (Alizadeh et al. 2020) improved the performance of photovoltaic system with using closed-loop PHP. The PHP was used to cool the photovoltaic module and also increase the electrical efficiency of the PV panel. The outcomes indicated that the improvement performance of the system with PHP was increased about 35%. Alizadeh et al. (Alizadeh et al. 2018) increased the electrical performance of photovoltaic module using pulsating heat pipe. The results indicated that the power generation of photovoltaic module using pulsating heat pipe as a cooling system was enhanced about 18% compared with conventional photovoltaic module. The effect of very long PHP on performance of the solar water heater was studied by Arab et al. (Arab et al. 2012). The PHP was made of copper pipes with internal diameters of 2 mm. They reported that the thermal efficiency of the thermosyphon mode of solar water heater using very long PHP was about 36%. Chen et al. (Chen et al. 2020) studied the performance of the solar collector using flower type pulsating heat pipe. The acetone used as a working fluid in pulsating heat pipe. The results revealed that the thermal efficiency of system with filling ration of 50% was equal to 50%.

A pulsating heat pipe was used in waste heat recovery system. Deng et al. (Deng et al. 2017) experimentally investigated the thermal performance of the anti-gravity pulsating heat pipe and heat recovery of the system. Their results revealed that the optimum filling ratio of the pulsating heat pipe was about 70%. Also, the system was assisted to use the waste heat recovery to preheat the fuel oil. Li et al. (Li et al. 2020) studied the performance of pulsating heat pipe in low temperature heat recovery using graphene nanofluid. They reported that the thermal resistance amount reduces by raising the volume fraction of the graphene nanoparticles and also with raising the thermal load to the evaporator. An end closed one PHP which is used as an air preheater has been studied by Rittidech et al. (Rittidech et al. 2005). This PHP consists of an evaporator, an adiabatic part and a condenser. The 2 mm internal diameter heat pipe is made of copper. Water and R-123 are used as operating fluids. It is shown that any increase in temperature, causes the efficiency to increase. Also, the system operation will increase if R-123 is used instead of water. A preheater end closed PHP with one-way valve was fabricated by Meena et al. R-134a with a 50% filling ratio was used as an operating fluid. Any increase in the hot air velocity and temperature would reduce the efficiency. Also this system has the capability to reduce the humidity from 80-100% to 54-72% (Meena et al. 2007). In another research, studied by Nuntaphan et al. (Nuntaphan et al. 2010), a heat exchanger is made of some PHPs. Hot water and air are used in this heat exchanger. The PHP is filled by methanol, Acetone and R-123. The results show that if the PHPs are used as fins, the heat transfer rate will be increased by 10%. Mahajan et al (Mahajan et al. 2020) investigated the performance of the finned and bare tube oscillating heat pipe for waste heat recovery application. The results revealed that the average waste heat recovery of the finned oscillating heat pipe was about 80% higher than bare tube oscillating heat pipe at the same filling ration. Khodami et al. (Khodami et al. 2016) evaluated the effect of PHP used to waste heat recovery of the chimney. They showed that the exergy of the system using silver nanofluid is much better that ethanol as working fluid and also increased the exergy efficiency about 3%. Dhone and Pise (Dhone &Pise 2021) investigated the effect of waste heat recovery of the diesel generator using pulsating heat pipe. The different filling ratio of working fluid was used in pulsation heat pipe. The results showed that the optimum filling ratio of pulsating heat pipe on waste heat recovery was equal to 50%.

The couple of PHP by energy applications can have high impact on the performance of these systems. The pulsating heat pipe used to reduce the heat loss of the system and also recovery of the waste heat. To our best knowledge, the PHP is not used for waste heat recovery of the chimney and use this thermal energy for increase water temperature. In this present study, the effect of pulsating heat pipe on the waste heat recovery of the chimney and produce hot water for household consumption is experimentally investigated. Also, the CO_2 mitigation, economic analysis and environmental parameters was studied to assess the performance of the waste heat recovery system with PHP.

2. Experimental Procedure

2.1. Experimental setup

The heat exchanger consists of three main parts includes the pulsating heat pipe, exhaust air channel from chimney and water reservoir for produce hot water. The PHP is fabricated by using copper pipes with suitable internal diameter of 0.002 m. The rolling around a 0.02 m shaft, the 0.002 m copper pipe turns to 21 U shape ones in only 1 m distance. The pipe firstly is evacuated to the 175 Pa and then filled with distilled water up to 60% filling ratio. Fig. 1 shows the fabricated pulsating heat pipe.

The exhaust air channel was made of galvanized sheet where the evaporation part of the PHP is placed with dimensions of 100×0.55×0.05 m with a sheet thickness of 0.0005 m. The heat exchangers are used to seal internal and external connections of the channel, as shown in Fig. 2. The evaporators of PHPs are installed through the channel.

The water reservoir was made of galvanized plate with dimensions of 100×0.55×0.05 m and a 0.003 plate thickness. The condensers of PHPs (U shaped pipes) are installed through the reservoir and the connections are sealed by welding and silicone adhesive. Fig. 3 indicates water reservoir and installed pulsating heat pipe in it. A thin sheet of aluminum is used for keeping the adhesives away from sunlight. To decrease the heat loss, the parts of the PHPs which are neither in channel nor in reservoir, are covered by asbestos yarn.

The test setup was installed in which the exhaust air goes through the channel for heat exchanging (PHPs) in a constant temperature 180°C, and then it leaves to the atmosphere in a temperature near 108°C. In this experiment exhaust air is the air produced by household devices. Fig. 4 shows the test setup of waste heat recovery system using pulsating heat pipe. The water reservoir has an inlet at the bottom and an outlet at the top. Household water is used to be heated. Actually in this setup a heat exchanger for indoor use is described. Temperatures are measured by 5 sensors, a thermometer and a key selector to switch between sensors. The sensors are installed at reservoirs inlet and outlet, channel inlet and outlet, and heat pipes. The water flow is measured by a 10-100 L/h rotameter. The water flow rate of water reservoir was considered equal to 30 L/h and air exhaust velocity from chimney was equal to 0.7 m/s. An anemometer is used for air velocity measurement. Fig. 5 illustrates the schematic of pulsating heat pipe.

2.2. Uncertainty of results

Uncertainty evaluating of test measuring data was investigated. The value of uncertainty is achieved by data sheet of the devices and some by the builder and is calculated by (Shoeibi et al. 2020):

$$u=\frac{a}{\sqrt{3}} \quad (1)$$

Where a and u represent the standard uncertainty and accuracy of equipment. Table 1 illustrates the uncertainty of the measuring device.

Table 1
Uncertainty of devices

Devices	Accuracy	Range	uncertainty
Thermometer (^{o}C)	0.1	-100 – 1300	0.06
Rotameter (L/h)	0.1	0-100	0.06
Anemometer (m/s)	0.5	0-30	0.3

3. Theoretical Background

3.1 Thermal efficiency

The energy efficiency of the system is defined as thermal energy produce for raising the water temperature to the heat energy inlet from exhaust air of chimney and is calculated as follow:

$$\eta =\frac{\dot{Q}_{w}}{\dot{Q}_{a}}$$

2

Where $\dot{Q}_{w}$ and $\dot{Q}_{a}$ are the thermal energy produce in water and thermal energy inlet to the system, respectively. The main heat transfer mechanisms in PHPs are sensible heat transfer and phase change. The sensible heat transfer is due to fluid and vapor movement through the pipe causing heat to be transferred from evaporator to condenser. It can be easily shown that the amount of heat transfer to the water from exhaust air of chimney and is obtained by:

$$\dot{Q}_{w}=\dot{m}_{w}C_{p,w}\left(T_{w,o}-T_{w,i}\right)$$

3

where $\dot{m}_{w}$, $T_{w,o}$ and $T_{w,i}$ show the mass flow rate of the water, water temperature inlet and oulet, respectively. Similarly, the amount of waste heat leaves exhaust air is shown by:

$$\dot{Q}_{a}=\dot{m}_{a}C_{p,a}\left(T_{a,i}-T_{a,o}\right)$$

4

where ${\dot{\text{m}}}_{\text{a}}$, ${\text{T}}_{\text{w},\text{o}}$ and ${\text{T}}_{\text{a},\text{i}}$ represent the mass flow rate of the water, temperature outlet and inlet air, respectively. Consequently, efficiency of the heat exchanger is shown as follows:

$${\eta }=\frac{{\dot{\text{m}}}_{\text{w}}{\text{C}}_{\text{p},\text{w}}\left({\text{T}}_{\text{w},\text{o}}-{\text{T}}_{\text{w},\text{i}}\right)}{{\dot{\text{m}}}_{\text{a}}{\text{C}}_{\text{p},\text{a}}\left({\text{T}}_{\text{a},\text{i}}-{\text{T}}_{\text{a},\text{o}}\right)}$$

5

If there was no heat loss in the system, the efficiency would be equal to one, but the heat loss affects directly on the efficiency reduction.

3.2. Price of hot water generation

The price per liter of hot water generation was assessed to cost effective of the fabrication of the waste heat recovery application using pulsating heat pipe. The capital recovery coefficient is used for economic evaluation, which defines the achievement of the investment and is defined by the ratio of a fixed annuity to the value of obtaining that annuity for a specific duration of time and is calculated by (Shoeibi et al. 2021e):

$$\mathbf{C}\mathbf{R}\mathbf{F}=\frac{\mathbf{i}{(1+\mathbf{i})}^{\mathbf{n}}}{{\left(1+\mathbf{i}\right)}^{\mathbf{n}}-1} \quad (6)$$

where i and n depict the interest rate of a bank loan (20% in this paper) and the lifespan of waste heat recovery system, which is assumed to be twenty years. The first annual cost is shown as follow (Shoeibi et al. 2021c):

$$\mathbf{F}\mathbf{A}\mathbf{C}=\mathbf{P}\times \mathbf{C}\mathbf{R}\mathbf{F} \quad (7)$$

where P shows the capital price of waste heat recovery application. The annual salvage value is determined as the value of the goods of waste heat recovery system and is calculated by (Shoeibi et al. 2021d):

$$\mathbf{A}\mathbf{S}\mathbf{V}=\mathbf{S}\times \mathbf{S}\mathbf{S}\mathbf{F} \quad (8)$$

where S is the salvage amount of waste heat recovery system and is about 20% of the used all goods value of the system. The sinking fund factor is obtained by (Shoeibi et al. 2021b):

$$\mathbf{S}\mathbf{F}\mathbf{F}=\frac{\mathbf{i}}{{\left(1+\mathbf{i}\right)}^{\mathbf{n}}-1} \quad (9)$$

The annual maintenance costs such as the annual cost of maintenance of the system, which is assumed to value for ten percentage of the FAC and obtained by (Shoeibi et al. 2021a):

$$\mathbf{A}\mathbf{M}\mathbf{C}=0.10\times \mathbf{F}\mathbf{A}\mathbf{C} \quad (10)$$

The uniform annual price of the application is obtained as follow:

$$\mathbf{U}\mathbf{A}\mathbf{P}=\mathbf{F}\mathbf{A}\mathbf{C}+\mathbf{A}\mathbf{M}\mathbf{C}-\mathbf{A}\mathbf{S}\mathbf{V} \quad (11)$$

The cost per cubic meter of hot water generation is determined as the ratio of the UAP to the annual hot water generation (HW) of the system and is achieved by (Shoeibi et al. 2021d):

$$\mathbf{C}\mathbf{P}\mathbf{H}=\frac{\mathbf{U}\mathbf{A}\mathbf{C}}{\mathbf{H}\mathbf{W}} \quad (12)$$

3.3. CO_2 mitigation

The annual CO_2 mitigation in the waste heat recovery system is calculated as ${{(\text{E}}_{\text{e}\text{n}})}_{\text{o}\text{u}\text{t}}\times 2$ and the CO_2 removal in the period of lifespan is determined as

$\left(E_{en}\right)_{out}\times 2\times year$. The value of CO_2 removal in the period of lifespan is achieved as follow (Joshi &Tiwari 2018):

$$\phi_{\mathbf{c}\mathbf{o}_2}=\frac{2\left(\mathbf{E}_{\mathbf{e}\mathbf{n}}\right)_{\mathbf{o}\mathbf{u}\mathbf{t}}\times \mathbf{n}-\mathbf{E}_{\mathbf{i}\mathbf{n}}}{1000} \qquad (13)$$

3.4. Enviroeconomic parameter

The enviroeconomic parameter is specified as the price achieved by the CO_2 reduction in the period of lifespan of the waste heat recovery system and is achieved by:

$$\mathbf{Z}_{\mathbf{c}\mathbf{o}_2}=\mathbf{z}_{\mathbf{c}\mathbf{o}_2}\times \phi_{\mathbf{c}\mathbf{o}_2} \qquad (14)$$

The cost of CO_2 is about 14.5$ per ton (Parsa et al. 2020).

4. Results And Discussion

In this study, the inlet and outlet air exhaust temperatures from chimney, the inlet and outlet water temperature from water reservoir, and thermal efficiency of the waste heat recovery application. The experimental study was used to assess the performance of the waste heat recovery application using pulsating heat pipe to produce hot water. Furthermore, cost of one cubic meter of hot water generation (CPH), and environmental analysis of waste heat recovery system are presented and discussed. The different angles of the pulsating heat pipe was tested to optimized best angle of heat pipe. Each experiment is done four times to reduce the errors. With respect to the annual measuring of energy produce and hot water, the data of the one-day experiment (December 2, 2020) were applied to all days of the year. Fig. 6 shows the inlet and outlet temperature of the air exhaust from chimney. The outcomes revealed that the lowest temperature of outlet air temperature from channel was obtained at angle of 90 degrees, which was equal to 105.1 ^{o}C. Also, the amount of inlet air temperature in channel was the same at different and was equal to 180 ^{o}C. Moreover, the angle of the pulsating heat pipe has an inverse effect to air outlet temperature of channel due to increasing the heat transfer rate between air exhaust and water reservoir.

Figure 7 depicts the temperature of inlet and outlet water of the hot water reservoir. The results showed that the maximum hot water temperature in outlet of reservoir was achieved at angle of 90 degrees, which was about to 58 ^{o}C. Also, the amount of inlet water temperature in reservoir was about 33 ^{o}C. Moreover, the angle of the pulsating heat pipe has a direct impact to hot water outlet temperature of reservoir due to enhance in heat transfer rate between an air exhaust and water reservoir.

Figure 8 indicates the energy efficiency and pulsating heat pipe temperature of the waste heat recovery system. As observed, the highest energy efficiency and pulsating heat pipe temperature was achieved in angle of 90 degrees, which were equal to 54% and 80 ^{o}C, respectively. By increasing the evaporator surface temperature of PHP, the thermal efficiency of the application increased due to increasing the heat transfer between water and heat pipes. Also, the lowest energy efficiency was about 19% which was occurred in angle of 0 degrees.

Figure 9 illustrates the energies of hot water, air exhaust and waste heat energy from the system. The obtained outcomes showed that as the energy of hot water raised, the energy of air exhaust decreasing due to high heat transfer between heat pipes and water. The highest energy of hot water was equal to 872 W which was occurred in angle of 90 degrees. Also, the waste heat energy of the system was increased by increasing the angle of the PHP. The highest waste heat energy of the system was occurred in angle of 0 degree, which was about 1303 W.

Table 2 provides the price of fabrication of the waste heat recovery system. The results revealed that the price of fabrication and salvage value of the waste heat recovery system are about 117$ and 23.4$, respectively. Table 3 depicts the price of one cubic meter of hot water production with using waste heat recovery system. The results indicated that the annual hot water generation and CPH of the system were equal to 262.8 m^3/year and 0.1 \$/m^3, respectively.

Table 2
Cost of fabricated of waste heat recovery application using pulsating heat pipe

Waste heat recovery system` components	Cost of system ($)	Salvage value ($)
Galvanized body of channel	35	7
Pipes of air exhaust	10	2
Galvanized support	12	2
Pulsating heat pipe	30	6
Water reservoir	20	4
Aluminum sheet	10	2
Total cost	117	23.4

Table 3
Economic analysis of waste heat recovery system

Type	n (year)	i (%)	CRF	FAC ($/year)	SFF	S ($)	ASV ($/year)	AMC ($/year)	UAP ($/year)	M (m^3/year)	CPH ($/$m^3$)
Waste heat recovery	20	0.2	0.205	24.03	0.005	23.4	0.125	2.4	26.3	262.8	0.10

Table 4 presents the embodied energy to generate various goods and material used in the application using PHP for generate hot water. The embodied energy of the waste heat recovery system was about 439.7 kWh.

Table 4
Embodied energy of different material of waste heat recovery application

Type	Name of material	Energy density		Weight of component (kg)	\text{E}\text{m}\text{b}\text{o}\text{d}\text{i}\text{e}\text{d} \text{e}\text{n}\text{e}\text{r}\text{g}\text{y} (kWh)
		MJ/kg	kWh/kg		
Waste heat recovery system					
	Aluminum sheet	199	55.2	1.3	71.8
	Galvanized body of channel	50	13.9	3.5	48.6
	Galvanized body of reservoir	50	13.9	8	111.2
	Copper pulsating heat pipe	100	27.7	4	110.8
	Support (Galvanized)	50	13.9	7	97.3
	Total Embodied energy (kWh)	-	-	-	439.7

Table 5 shows the environmental, enviroeconomic parameters in the waste heat recovery system for a lifespan of 20 years. The results indicated that the CO_2 reduction and enviroeconomic parameter of waste heat recovery application were equal to 84.82 tons and 1217.2 $, respectively, during life time. Also, the CO_2 emission of the waste heat recovery system during life time based on embodied energy was equal to 879.4 kg.

Table 5
Environmental and enviroeconomic parameter for waste heat recovery system

Parameter	Waste heat recovery system
Life time (years)	20
Embodied Energy (kWh)	439.7
Annual energy produce by waste heat recovery (kWh/year)	2120.6
CO_2 emission during life time (kg)	879.4
CO_2 mitigation during life time (ton)	84.82
Environmental parameter (ton {\text{C}\text{o}}_{2})	83.94
Enviroeconomic parameter ($)	1217.2

5. Conclusion

In this research a novel application of PHPs in heat exchangers are reviewed and experimentally tested. The results show that this prototype of heat exchanger that is working by PHPs can reach an efficiency up to 54% which is noticeable. This type of heat exchanger is applicable in any place that hot air and cold water do exist. In many industries, hot exhaust air produced by industrial instruments is easily left to atmosphere which can simply affects unwanted global warming. If such a heat exchanger were used on the exhaust air channel before leaving to the atmosphere, not only the heat could be easily be recovered, but also it would prevent the unwanted global warming. This type of heat exchanger can even be used as an appliance for such houses which use fossil fuel (such as oil or gas fuel) as the main resource for household heating. Exhaust air of heating devices can easily be used to get the household water hot. The main conclusion presented as follow:

- The CO_2 mitigation and enviroeconomic parameter of waste heat recovery system were equal to 84.82 tons and 1217.2 $, respectively.
- The annual hot water generation and CPH of the system were equal to 262.8 m^3/year and 0.1 $/$m^3$, respectively.
- The price of fabrication of the waste heat recovery system was about 117$.
- The highest energy of hot water was equal to 872 W which was occurred in angle of 90 degree.
- The highest energy efficiency and pulsating heat pipe temperature was achieved in angle of 90 degree, which were equal to 54% and 80 ^oC.
- The angle of the pulsating heat pipe has a direct impact to hot water outlet temperature of reservoir.
- The highest hot water temperature in outlet of reservoir was about to 58 ^oC.

Abbreviations

AMC	Annual maintenance price ($)
CPH	Cost per cubic meter of hot water ($)
ASV	Annual salvage amount ($)
CRF	Capital recovery coefficient
FAC	First annual cost ($)
UAP	Uniform annual cost ($)
Z_{CO2}	Enviroeconomic parameter ($)
z_{CO2}	Carbon price ($)
E_{in}	Embodied energy (kWh)
HW	Annual hot water generation, (m^3/year)
${\dot{\text{Q}}}_{\text{w}}$	Thermal energy of hot water, W
${\dot{\text{Q}}}_{\text{a}}$	Waste heat energy of the chimney, W
T_i	Inlet temperature, ^oC
T_o	Outlet temperature, ^oC
${\varphi _{CO2}}$	Environmental parameter (ton $\mathbf{c}{\mathbf{o}}_{2}$)
	Subscripts
w	Water
a	Air
en	Energy

Declarations

Author contribution Shahin Shoeibi: Conceptualization, investigation, data curation, writing original draft, and editing.

Hadi Kargarsharifabad: Conceptualization, resources, performing experiments, formal analysis, writing-review and editing.

Mohammad Mehdi Rashidi: Conceptualization, writing-review and editing.

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Figures

Figure 1

The fabricated pulsating heat pipe.

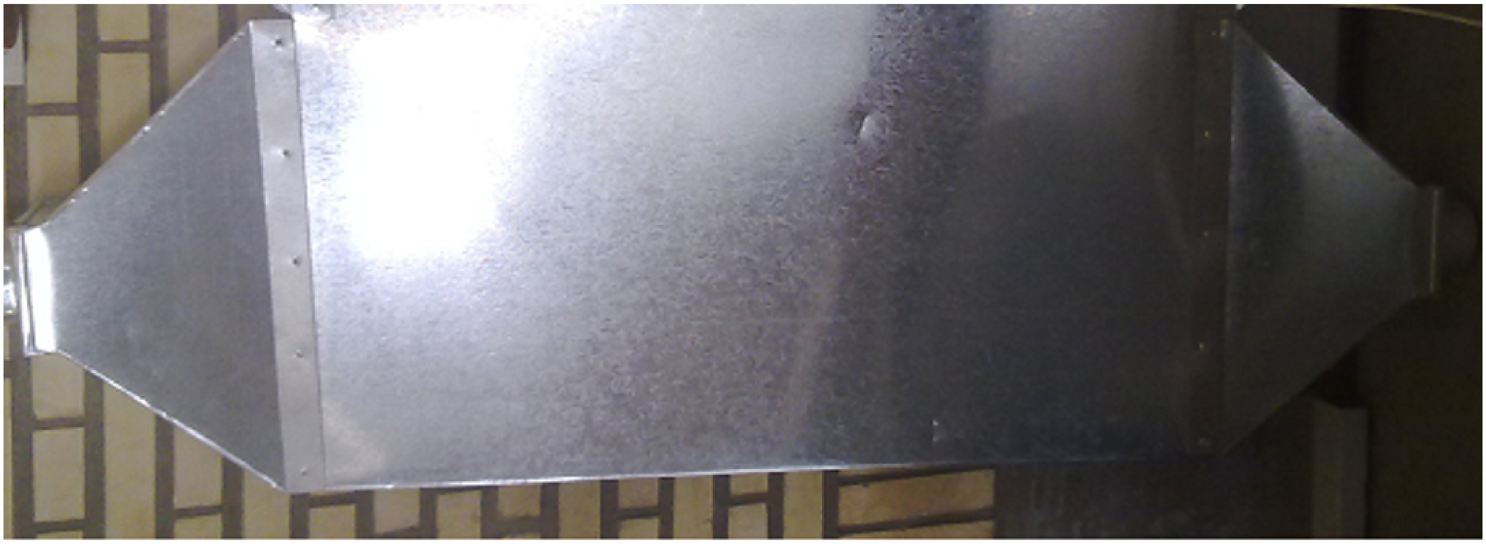

Figure 2

Exhaust air channel which the evaporators are placed inside.

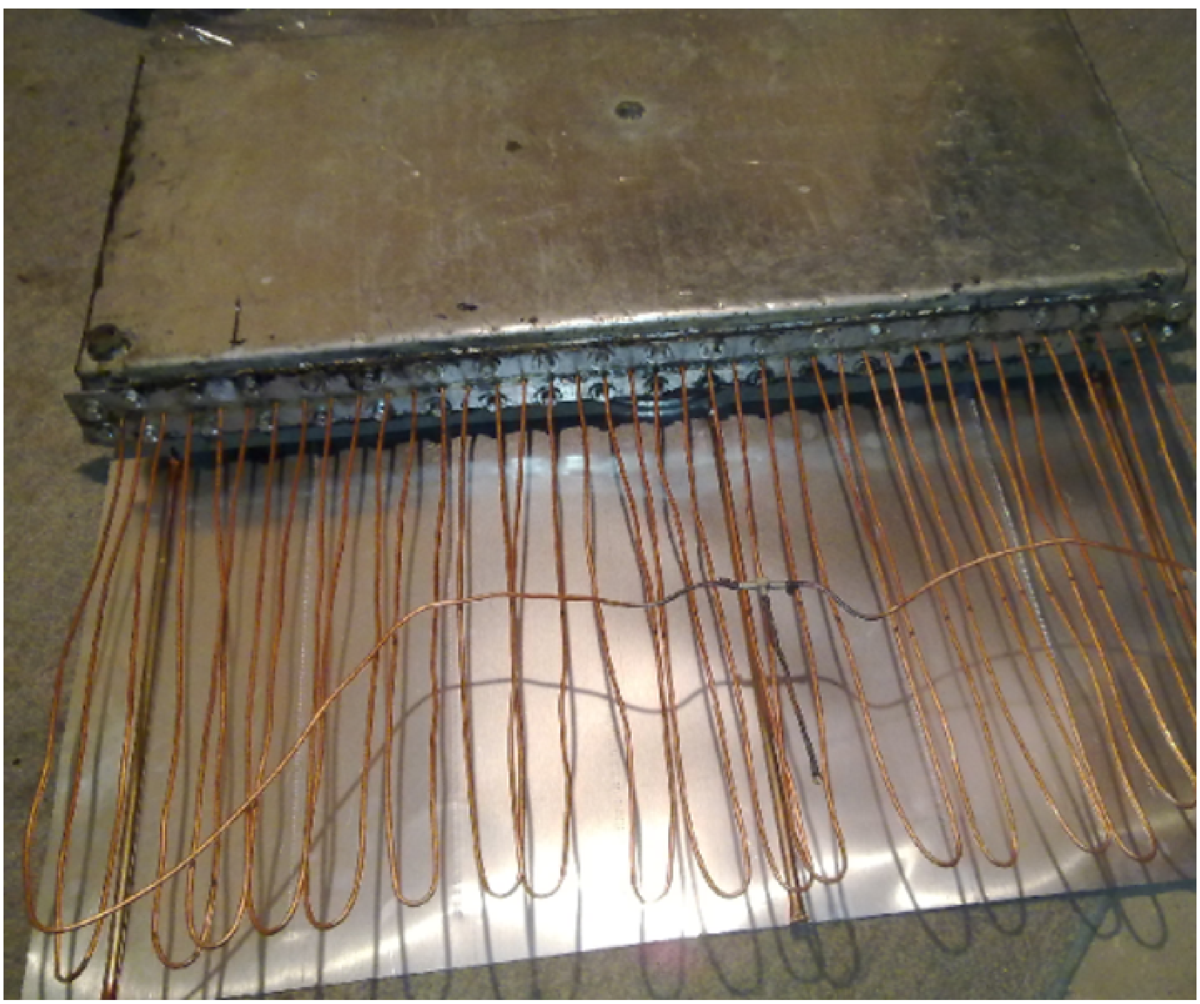

Figure 3

The water reservoir coupled with PHP.

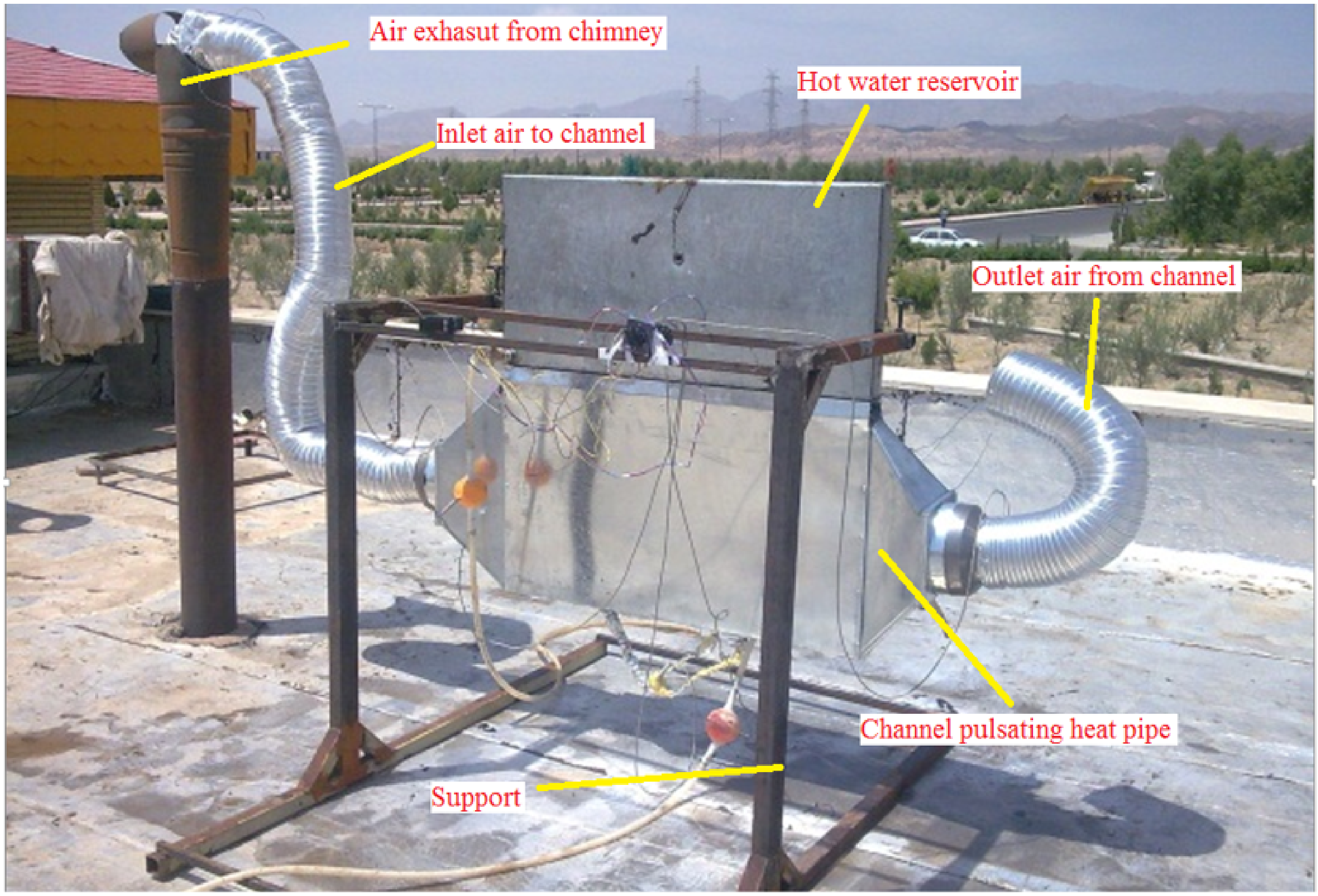

Figure 4

The experimental setup of heat recovery using PHP.

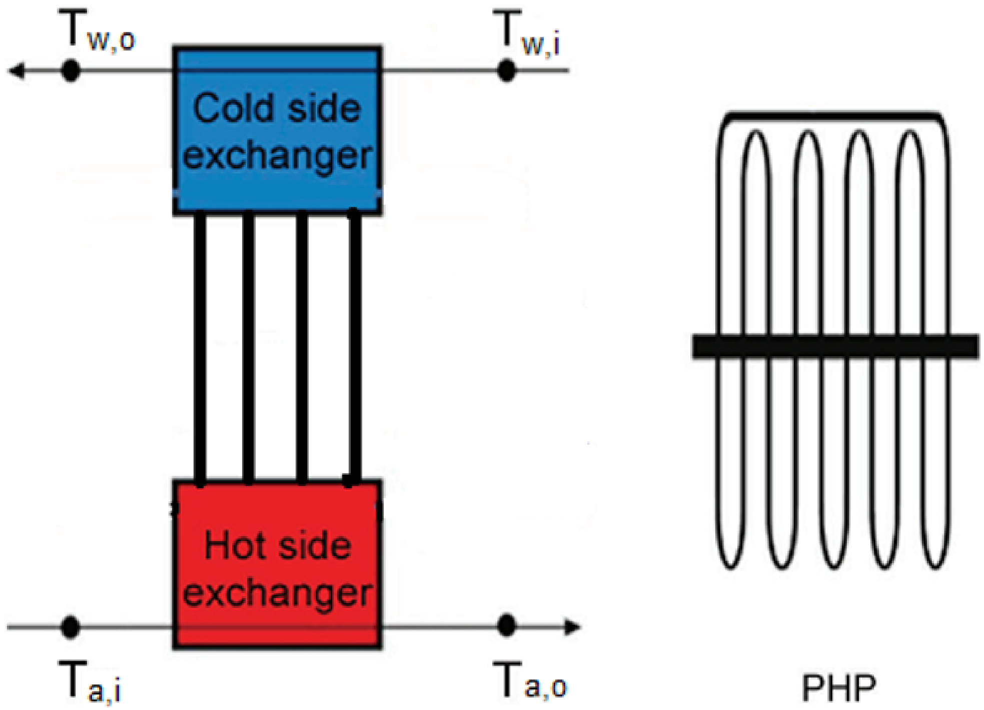

Figure 5

The schematic of pulsating heat pipe.

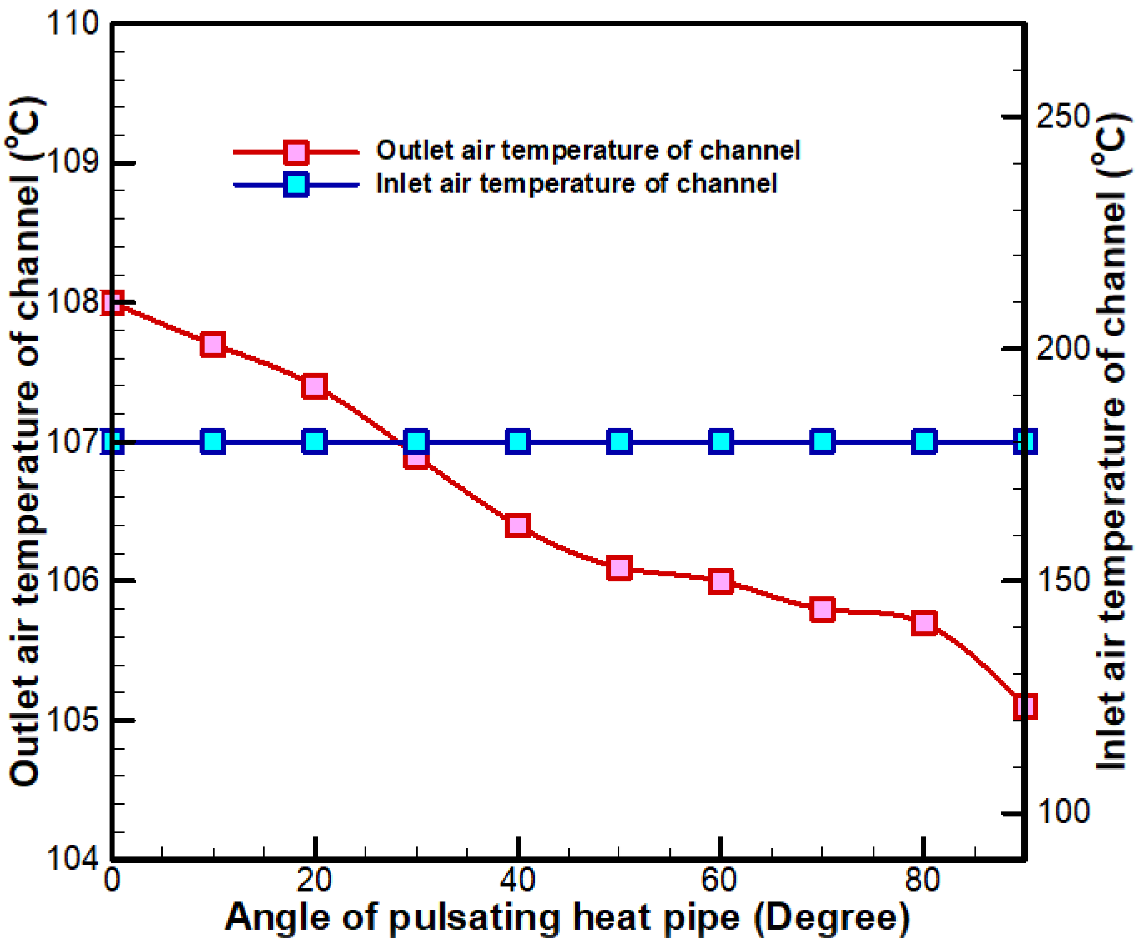

Figure 6

The inlet and outlet air from heat exchanger channel.

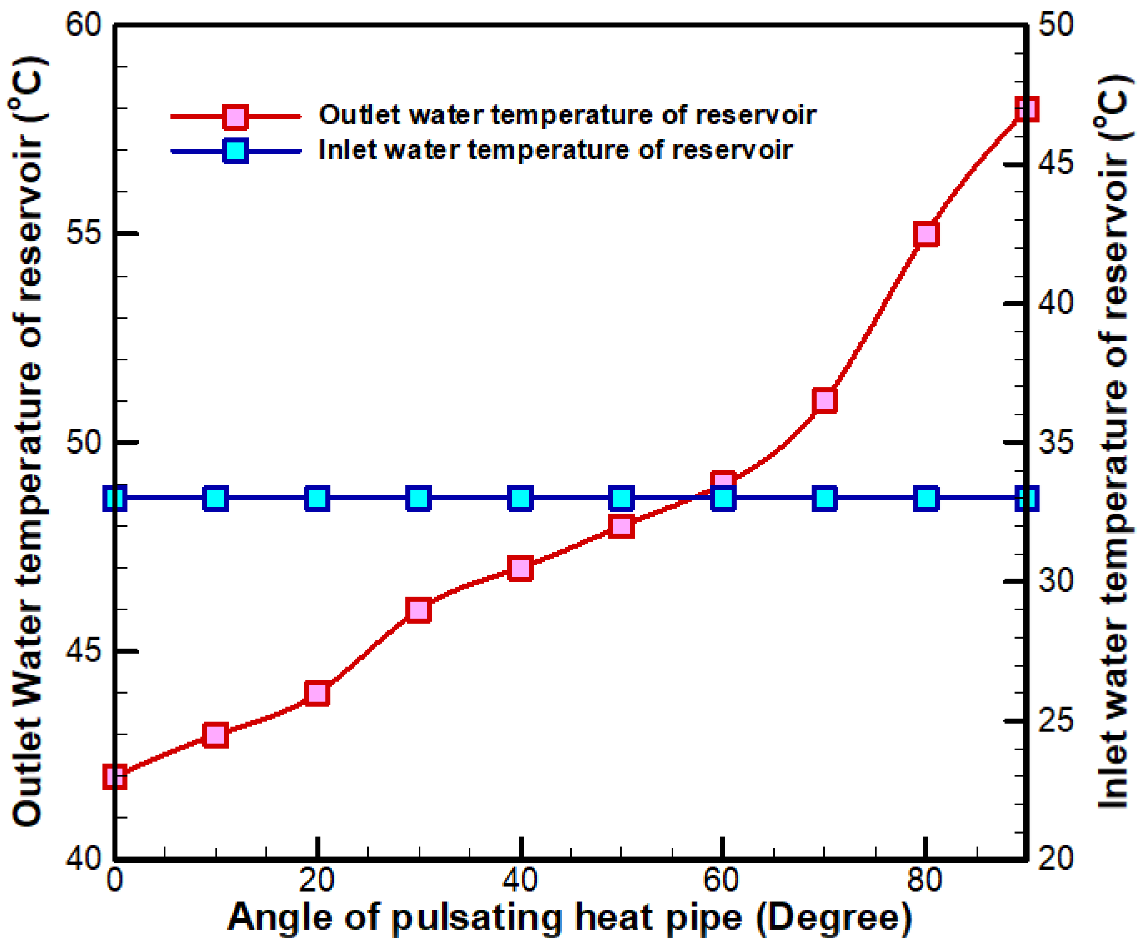

Figure 7

The inlet and outlet water temperature reservoir of the system.

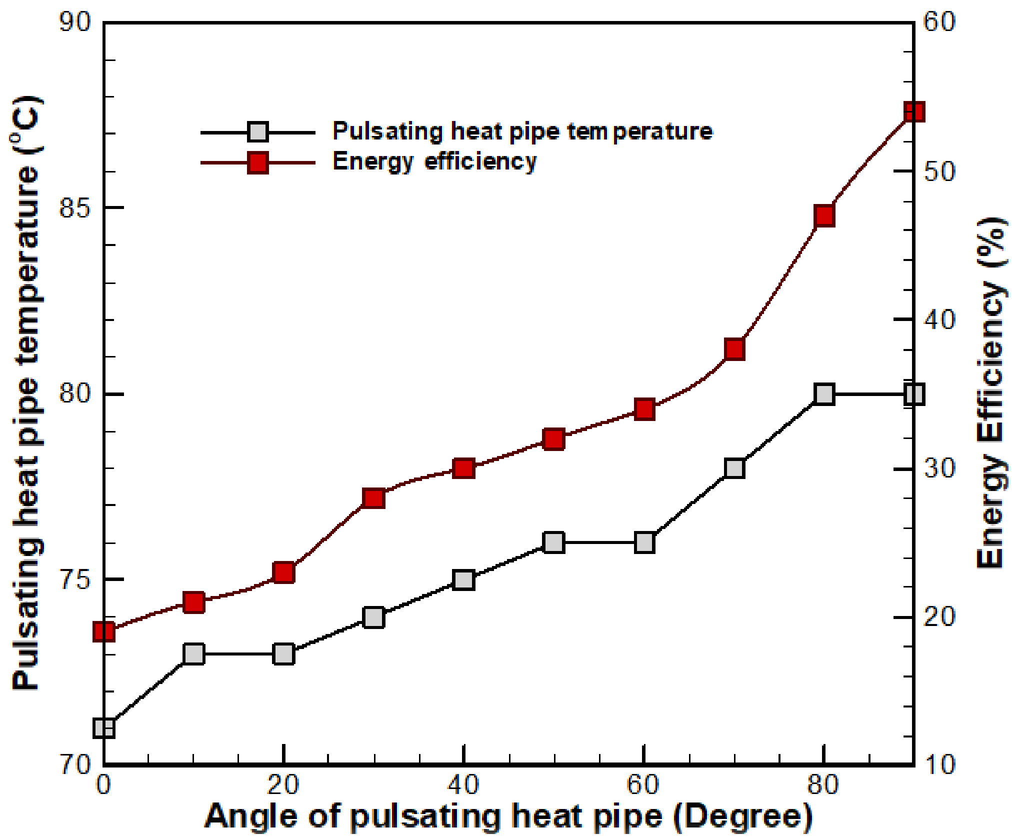

Figure 8

The energy efficiency and pulsating heat pipe temperature of the system.

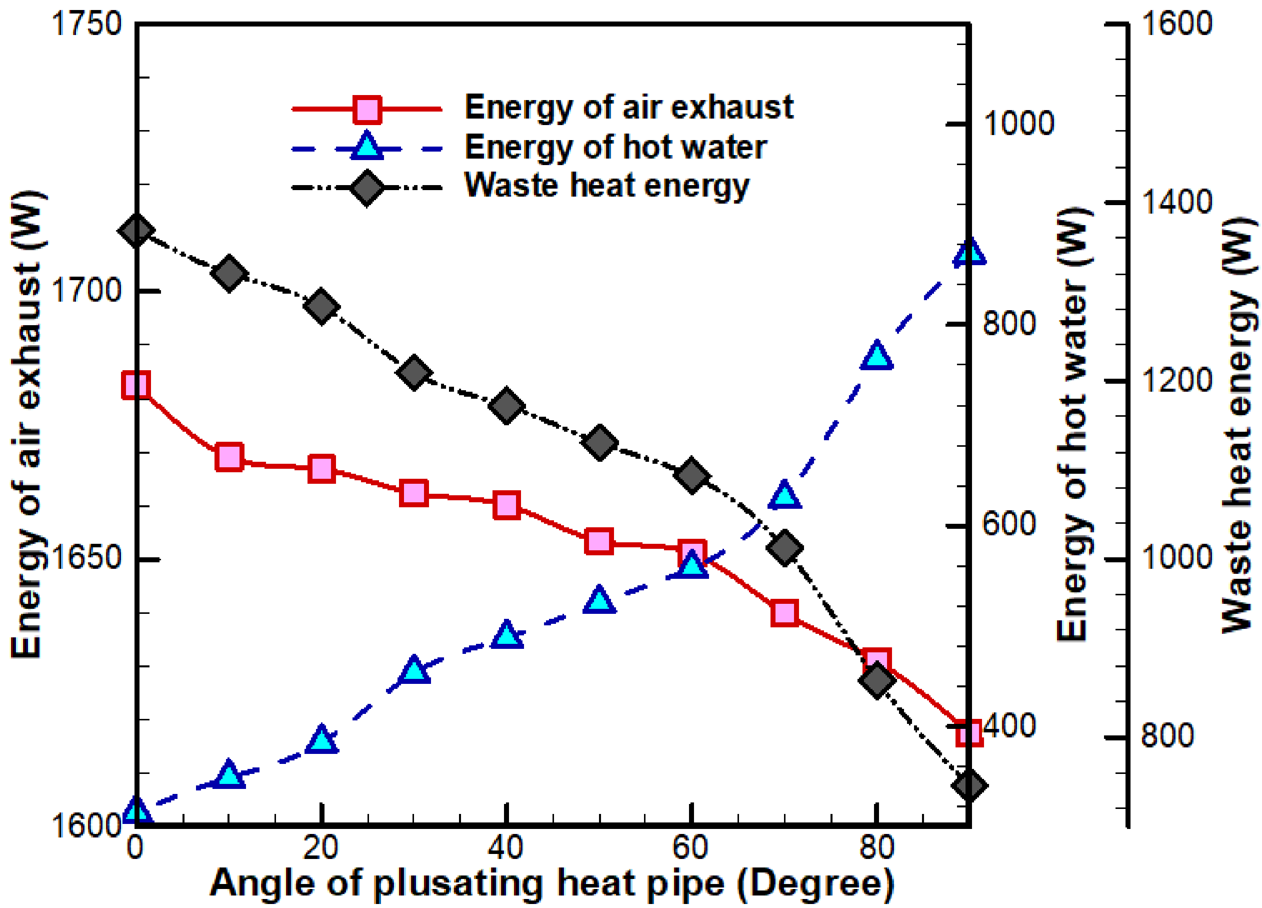

Figure 9

The energies of air exhaust, hot water and waste heat of the system.