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Energy and Exergy Analysis of a Air-Conditioning System with the solar collector

Takdanai Suparos[1*], Sirichai Thepa[1], Nat Kasayapanand[1]

[1] Department of Energy Technology, School of Energy, Environment and Materials,
King Mongkut's University of Technology Thonburi
*Email: takdanai.sup@mail.kmutt.ac.th
Corresponding author

Abstract

This paper presents a new system of air-conditioning to decrease the power consumption that uses the heat energy from the solar collector to support and enhance the heating of refrigerant, thus decreasing the workload of the compressor. It focuses on the new system of the air conditioner which is a solar collector, added after the compressor in the air conditioner cycle. The collector used for the experimentations is discussed, vacuum tube solar collector and flat plate solar collector is selected and the refrigerant used is R32. The results indicate that solar collector usage improves system COP by 30 %. Furthermore, overall exergy efficiency values of the system increase by using the solar collector and showing that the proposed design can reduce the power consumption by the air conditioner by about 24% lower than conventional air conditioner.

Keywords: *Energy Efficiency, Exergy Efficiency, Hybrid solar air conditioning, Solar Energy*

1. Introduction

The problem of global temperature rise affects the daily life of Thai people, resulting in the use of air conditioning systems more nowadays. In order to meet the need to reduce heat from external conditions, air- conditioning systems are used in households, office buildings, hospitals, schools and shopping malls. The massive use of air conditioning systems has resulted in more domestic electricity consumption. From the statistics of energy consumption in 2020, electricity is the second most used energy and tends to increase steadily. Most of the electricity generation comes from fossil energy. This fossil energy releases carbon dioxide and gasses that pollute the environment, humans and is the cause of global warming. Therefore, the Department of Alternative Energy Development and Efficiency has developed “The Alternative Energy Development Plan” (AEDP 2018) to reduce the use of fossil fuels and importing energy from overseas. It aims to support using many kinds of renewable energy sources such as solar energy, wind energy, geothermal energy, wave energy and hydropower.

Even though there are energy-saving measures or setting energy-saving standards in air conditioners, But the situation of electricity usage continues to increase. Thailand is located near the equator so it receives solar energy and results in hot weather throughout the year. In particular, the temperature in summer is up to 40 ºC. Such hot weather is another factor of increasing energy use of the country every year. It results from the increase of air-conditioning system installment for all sectors. A proportion of energy use for both building industry and dwellings, it was found that more than 60% of energy use of both types resulted from refrigeration and air conditioning systems. The researcher sees the problem in this part and is therefore interested in studying the use of solar energy in conjunction with air conditioning systems. Because it is a clean energy with high potential. solar collector that can be installed in buildings or households are vacuum tube solar collector and flat plate solar collector. The stored solar energy will be applied to reduce the use of electricity in air conditioning systems.

This research has the concept of studying and analyzing the energy and exergy efficiency of split type air-conditioning system in combination with vacuum tube solar collector and flat plate solar collector. With the goal of increasing efficiency and saving energy during the day as well as to study the cost-effectiveness of using air conditioning systems in combination with solar energy.

1.1 Objectives of the research

- Design and build a split type air-conditioning system working with solar energy.
- Study the energy efficiency and exergy efficiency of the split type air-conditioning system working with solar energy.
- Study the parameters affecting the energy efficiency and exergy efficiency of the split type air-conditioning system working with solar energy.
- Study energy saving and cost-effectiveness of split type air-conditioning system working with solar energy.

1.2 Literature Review

Chanida Pomsaen [1] conducted an experiment to increase the efficiency of air conditioners by using the waste heat from air conditioners of 18,000 Btu/h. with refrigerant R410A. Heat exchange using flat plate solar collectors. The cooling load was 1.6, 2.8 and 4.0 kW. The room temperature was set at 25˚C. The results showed that the average COP was 5.17 and the average EER was 17.64. The average electric power is 1.02 kW/h, saving up to 36.72 baht per 8 hours/day.

Ha and Vakiloroaya [2] design the PLC control system by heating the refrigerant from a solar hot water generator with a compressor in the air conditioning system. Use air conditioner 6 kW and 1.8 kg R410A refrigerant used for heat exchange by solar collector. Room size 38 m^2, height 3 m. Flow rate of air entering the evaporator unit 850 m^3. Flow rate of air entering the condensing unit 2500 m^3. Store heat energy with a 35 liter hot water tank. Experimental results COP increased by 6.7%.

Bouadila, et al. [3] conducted an experimental study to assess the thermal potential of solar collectors in combination with spherical capsule latent heat energy storage devices. Inside the capsule contains paraffin-type PCM. Thermal energy is obtained from the latent heat in the paraffin phase transition. Store energy during 9:00 a.m. - 4:00 p.m. and use it during the night. The experimental results showed that the daily energy efficiency varies between 32% and 45%, while the daily exergy efficiency varies between 13% and 25%. The heat generated by the solar collector stored in the thermal energy storage device is 200 W/m^2. The hot water tank provides 11 hours of constant heating at night and is not affected by fluctuations in solar radiation.

Xingjuan, et al. [4] studied and experimented with a new solar energy absorption air conditioning system by adding a heat pump to the system. The former is an absorption air conditioning system that uses a heat source from a flat plate solar collector. R134A and R600A refrigerants were used in the experiment. The results were analyzed for efficiency. The results of the experiments were used to analyze the efficiency. When the intensity of solar radiation is high. The cooling capacity of the new system is 1.7 times of the old system. When the intensity of solar radiation is low. The cooling capacity of the new system is reduced by 70% compared to conditions of high radiation intensity. Systems using R600A refrigerant have higher COP and lower energy consumption than R134A.

Vakiloroaya, et al. [5] studied how to develop an air conditioning system in combination with solar energy to increase energy efficiency. Using a 6 kW split type air-conditioner with R410A refrigerant and a vacuum tube solar hot water generator. The system is equipped with an automatic PLC control system for controlling the refrigerant to exchange heat with hot water. The experiment was performed with the air conditioner on for 24 hours. The results showed that exchanging heat with hot water reduces electrical energy costs by 25-43%.

Buddhi, et al. [6] analyzed the efficiency of a compressor split type air-conditioning system combined with solar energy and waste heat. Using a 3.5 kW air conditioner with 1 kg. R410A refrigerant. Laboratory size 18 m^2 at room temperature 20-22˚C. The experiment was conducted from 10:00 a.m. - 1:30 p.m. The results showed that the electric power of the compressor was reduced from 0.85 kW to 0.47 kW. The vacuum tube solar collector can produce 2.6-2.9 liters of hot water per 30 minutes. The system average COP was 4.56 at 11.00-13.00 and maximum COP was 5.19.

Laknizi, et al. [7] evaluated solar air conditioning systems under various weather conditions. Use a 3.5 kW air conditioner with R410A refrigerant. Compressor power is 0.85 kW., The air conditioner's COP is 4.1 and the room size is 18 m^2. Use a vacuum tube solar collector. The room temperature is controlled at 20-22˚C and humidity is 40-60%. Four-way reversing valve is used to redirect the refrigerant into the solar collector. The results showed that the compressor power was reduced to 0.47 kW and the COP was increased to 7.4. Payback period is 2 years. The system can reduce electricity usage by 21% compared to running the air conditioner 24 hours a day.

Assadi, et al. [8] studied the design of a vapor compression air conditioning system working with solar energy. Using 5 different air conditioner sizes: 10000, 13000, 18000, 19500 and 24000 Btu/h. Air- conditioning system test uses R22 refrigerant to flow directly through a vacuum tube solar collector to heat the refrigerant to 160˚C. A new condenser has been designed to cool the refrigerant from 160˚C to 40˚C. The results showed that the COP was 5.46. The air conditioning system size 24000 Btu/h can save electricity by an average of 45% and save the most during the period from 10 a.m. to 5 p.m.

Aung, et al. [9] studied a theory on energy saving of vapor compression air conditioning systems using solar thermal energy. Use a 3.52kW air conditioner with R410A refrigerant. Compressor power is 0.82 kW, COP is 4.29 and room temperature is set to 24˚C. The pressure of the refrigerant before entering the solar collector is 1.02 MPa and leaving the solar collector is

3.21 MPa. The results of the experiment showed that the cooling capacity was increased by 41%, the electricity was saved by 40% and the COP was increased to 7.29.

Fajar, et al. [10] analyzed the energy and exergy efficiency of a micro-vapour compressed air conditioning system using R410A refrigerant compared with R290 to improve efficiency. Experiment with 340 g. of R410A refrigerant and 85 g. to 204 g. of R290 refrigerant. The experiment worked under atmospheric pressure and room temperature set at 25˚C. The results were analyzed for energy and exergy efficiency. The results showed that using 340g. of R410A refrigerant was the most cooling but with a COP of 4.5, while 170 g. and 187g. of R290 refrigerant was cooling less but with a COP of 4.9. Exergy destruction is most found in condenser and evaporator. R410A refrigerant has an average exergy destruction of 524.7 W and an average exergy efficiency of 0.24. R290 refrigerant has an average exergy destruction of 336.1 W and an average exergy efficiency of 0.20. R410A has 56% higher exergy destruction than R290.

Rosiek [11] studies the performance of an absorption air conditioning system in conjunction with a solar collector. Its purpose is to improve system efficiency and find an optimal operating range between cooling and thermal power generation. The system uses a flat plate solar collector, 70 kW LiBr-H2O absorption chiller, two hot and cold water tanks and an auxiliary heater. The experimental results were used to calculate Exergy and Exergy efficiency. The results showed that the absorption air conditioning system had a maximum efficiency of 0.8 when the hot water temperature was 65-75°C at the inlet of the heat generator and the temperature of water at the exit of evaporator is 6-15°C. Flat plate solar collector has a maximum exergy efficiency of 0.3 when the hot water inlet temperature is 55-70°C. The best operating point of the air conditioning system in combination with a flat plate solar collector is a temperature range of 70-80°C.

1.3 Principles of vapor compression air conditioning systems

The Vapor Compression Refrigeration Cycle that shows in Figure 1 involves four components: compressor, condenser, expansion valve/throttle valve and evaporator. It is a compression process to raise the refrigerant pressure in the compressor. The high-pressure refrigerant flows through a condenser to exchange heat with ambient air before attaining the initial low pressure and going back to the evaporator to evaporate and absorb latent heat of vaporization. This cycle is aimed at cooling the air-conditioned room.

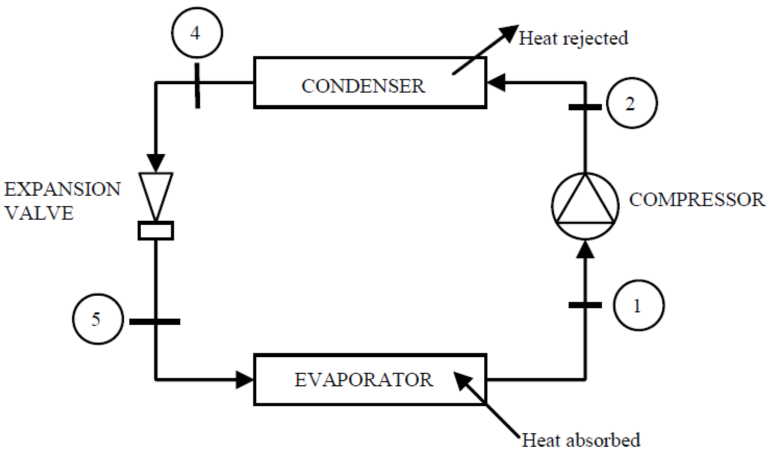


Figure 1: Schematic Diagrams of Vapor Compression System

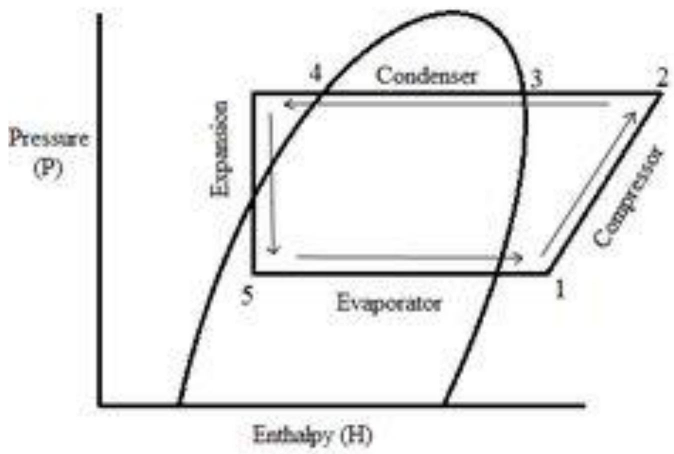


Figure 2: P-h Diagrams of vapor compression air conditioning system

From Figure 2, we could Analysis of the vapor compression air conditioning system to the following equation

1.4 Analysis of vapor compression air conditioning system

1.4.1 Equation of the vapor compressor.

$$W_{com} = \dot{m}(h_2 - h_1) \quad (1)$$

When W_{com} = work of vapor compressor (kW), h_1 = enthalpy of refrigerant entering the vapor compressor (kJ/kg), h_2 = enthalpy of refrigerant leaving the vapor compressor (kJ/kg) and $\dot{m}$ = mass flow rate of refrigerant (m^3/s).

$$\dot{X}_{comp} = \dot{m}[(h_2 - h_1) - T_0(S_2 - S_1)] \quad (2)$$

When $\dot{X}_{comp}$ = exergy of vapor compressor (kW), S_1 = entropy of refrigerant entering the vapor compressor (kJ/kg), S_2 = entropy of refrigerant leaving the vapor compressor (kJ/kg) and T_0 = ambient temperature (˚C).

1.4.2 Equation of heat transfer rate of the condenser.

$$Q_{con} = \dot{m}(h_2 - h_3) \quad (3)$$

When Q_{con} = heat transfer rate of the condenser (kW), h_2 = enthalpy of refrigerant leaving the vapor compressor (kJ/kg), h_3 = enthalpy of refrigerant leaving the condenser (kJ/kg) and $\dot{m}$ = mass flow rate of refrigerant (m^3/s).

1.4.3 Equation of the expansion valve

In this process refrigerant flows through the device. It is a pressure reducing process without work or heat transfer, so $h_3 = h_4$.

1.4.4 Equation of thermal exchange in the evaporator

$$Q_{Evap} = \dot{m}(h_1 - h_4) \quad (4)$$

When Q_{Evap} = heat transfer rate of the evaporator (kW), h_4 = enthalpy of refrigerant entering the evaporator (kJ/kg) and h_1 = enthalpy of refrigerant leaving the evaporator (kJ/kg).

$$\dot{X}_{evap} = \dot{m}[(h_1 - h_4) - T_0(S_1 - S_4)] \quad (5)$$

When $\dot{X}_{evap}$ = exergy of evaporator (kW), S_4 = entropy of refrigerant entering the evaporator (kJ/kg),

S_1 = entropy of refrigerant leaving the evaporator (kJ/kg) and T_0 = ambient temperature (˚C).

1.4.5 Equation of Coefficient of performance of the system (COP)

$$C.O.P. = \frac{Q_{Evap}}{W_{com}} \quad (6)$$

When Q_{Evap} = heat transfer rate of the evaporator (kW). and W_{com} = work of vapor compressor (kW).

1.4.6 Equation of Exergy efficiency

$$\eta_x = \frac{\dot{X}_{evap}}{\dot{X}_{comp}} \quad (7)$$

When η_x = exergy efficiency of air conditioning system, $\dot{X}_{evap}$ = exergy of evaporator (kW) and
$\dot{X}_{comp}$ = exergy of vapor compressor (kW).

1.4.7 Equation of solar collector efficiency

$$\eta_c = \frac{\dot{m}(h_{out} - h_{in})}{I_T \times A_c} \quad (8)$$

When η_c = efficiency of solar collector, h_{out} = enthalpy of refrigerant leaving the solar collector (kJ/kg),
h_{in} = enthalpy of refrigerant entering the solar collector (kJ/kg), I_T = solar intensity (W/m^2) and A_c = area of solar collector (m^2).

2. Methodology

2.1 Equipment and Methodology

This research is the study of energy efficiency, exergy efficiency and energy saving of a solar air-conditioning system. The system consists of Wall mounted inverter split type air conditioner cooling capacity 12,000 Btu/h (3.517 kW) using R32 refrigerant. The solar collector used is vacuum tube solar collector size 0.42 m^2 and flat plate solar collector size 0.475 m^2. Inside the solar collector has a 3/8 inch copper pipe for transport refrigerant. The experiment was conducted in March 2022 from 9:00 a.m. to 5:00 p.m. in a 16 m^2 insulated room.

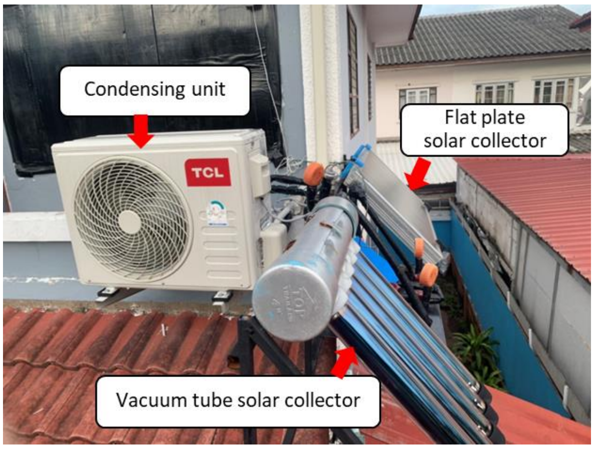


Figure 3: Split type Air conditioner with solar energy system

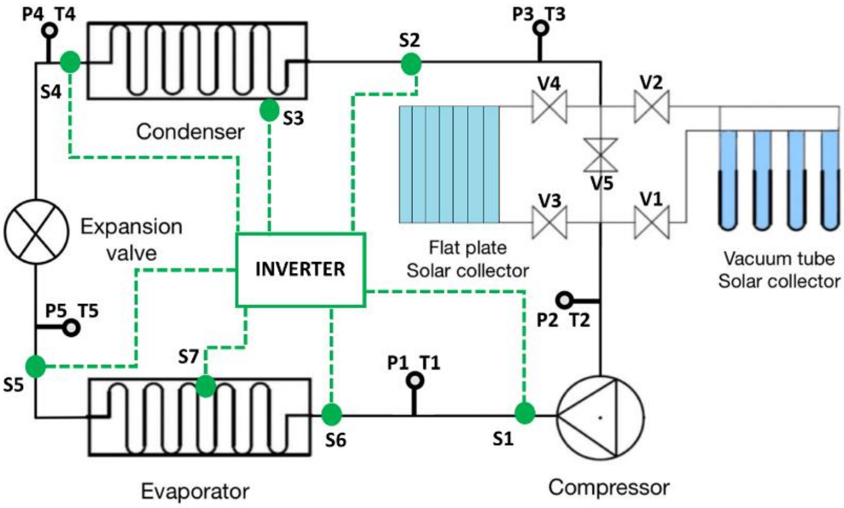


Figure 4: schematic diagram of solar air-conditioning system

Figure 4 shows a solar air-conditioning system with measurement equipment. In the experiment, temperature was measured with Thermocouple type K, pressure was measured with Pressure Gage and Pressure Transducer, solar radiation intensity was measured with a Pyranometer and the power of the air conditioning system was measured with a Power meter. All data were recorded with an automatic data recorder. Location of all measuring instruments used in the experiment. Shown as the following table.

Table 1: Location of measuring instruments in a solar air-conditioning system

Location	Data
P_1 and T_1	pressure and temperature of refrigerant before entering the compressor.
P_2 and T_2	pressure and temperature of refrigerant before entering the solar collector.
P_3 and T_3	pressure and temperature of refrigerant before entering the condenser.
P_4 and T_4	pressure and temperature of refrigerant before entering the expansion valve.
P_5 and T_5	pressure and temperature of refrigerant before entering the evaporator.
S_1	sensor for measure temperature of refrigerant entering the compressor.
S_2 and S_4	sensor for measure temperature of refrigerant entering and leaving the condenser.
S_3	sensor for measure temperature of air ambient entering the condenser.
S_5 and S_6	sensor for measure temperature of refrigerant entering and leaving the evaporator.
S_7	sensor for measure freezing temperature of refrigerant inside the evaporator.

2.2 Experimental procedure

The air conditioner was turned on at 8.30 am. (30 minutes before the start of the experiment), the air conditioning temperature was set at 25 ˚C. Turn on the heat load simulation with the incandescent light bulb.
There are 3 cases of the experiments which are split type air-conditioning system without solar collector, split type air-conditioning system uses a vacuum tube solar collector and split type air-conditioning system uses a flat plate solar collector. All experiments provided a thermal load of 1.0, 1.5, 2.0, 2.5, 3.0 and 3.5 kw. All data were recorded from 9:00 a.m. to 5:00 p.m. with an average solar radiation intensity of 500-600 W/m^2. The recorded data will be used to calculate the energy efficiency, exergy efficiency, economic savings and payback period.

3. Results

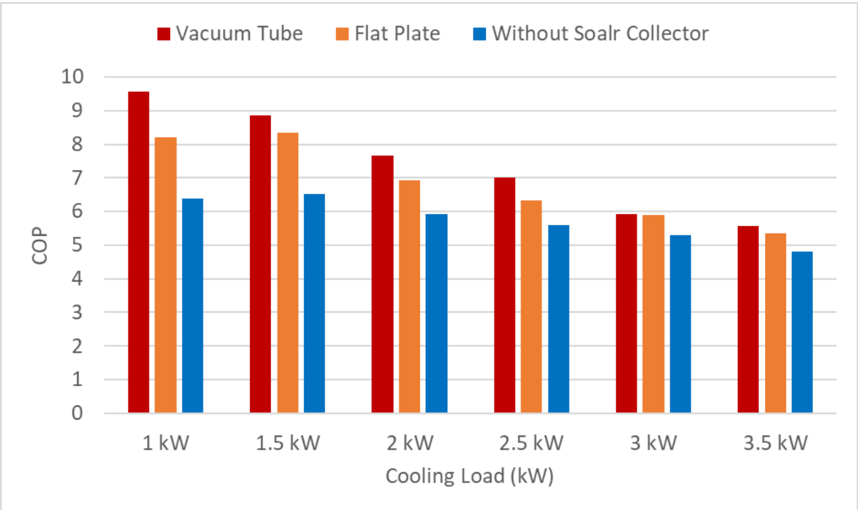


Figure 5: The coefficient of performance at 25 ºC with the room load by 1.0 kW – 3.5 kW.

From Figure 5, the coefficient of performance (COP) for the split type air conditioner with the solar energy system at 25 ºC of room temperature. The analysis showed that split type air-conditioning system working with solar collector had a higher COP. Because COP varies with the cooling load and power. In experiments with low cooling load and with a solar collector heating the refrigerant. The compressor had a lower cycle time and less power was used, causing COP to be higher. The split type air-conditioning system using vacuum tube solar collector had a 13-32% increase in COP and the split type air-conditioning system using flat plate solar collector had a 10-22% increase in COP compared to the split type air-conditioning system without solar collector.

Vacuum tube solar collector increase COP in air-conditioning systems by approximately 7% higher than flat plate solar collector.

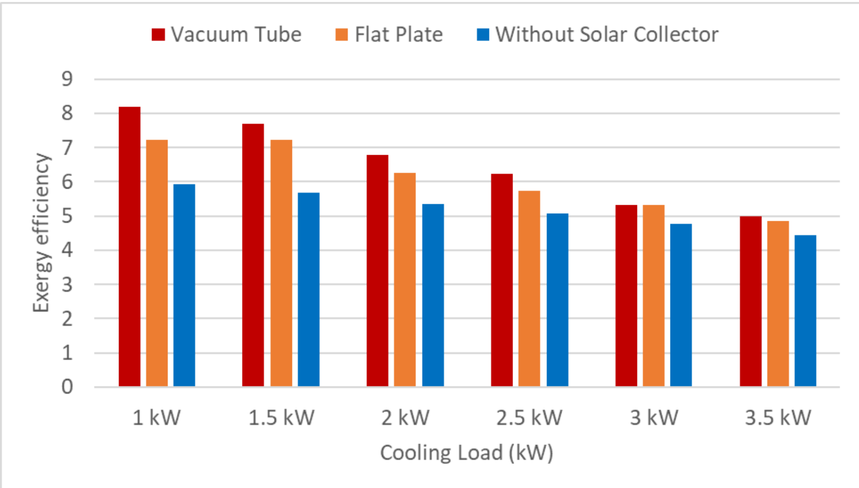


Figure 6 Exergy efficiency at 25 ºC with the room load by 1.0 kW – 3.5 kW.

From Figure 6, the exergy efficiency of the split type air conditioner with the solar energy system at 25 ºC of room temperature. The analysis showed that the split type air-conditioning system working with solar collector had a higher exergy efficiency. The split type air-conditioning system using vacuum tube solar collector had a 10-27% increase in exergy efficiency and the split type air-conditioning system using flat plate solar collector had a 8-21% increase in exergy efficiency compared to the split type air-conditioning system without solar collector. Vacuum tube solar collector increase exergy efficiency in air-conditioning systems by approximately 6% higher than flat plate solar collector.

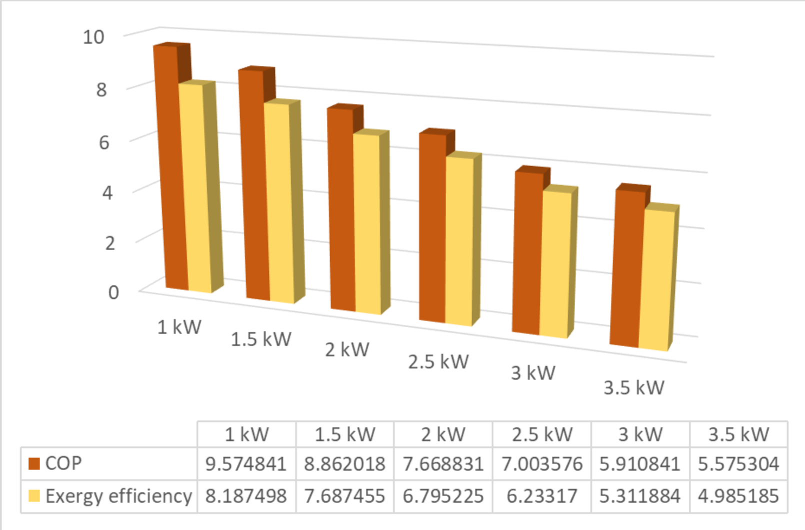


Figure 7: Compare COP with exergy efficiency of the split type air-conditioning system using vacuum tube solar collector.

From Figure 7, the exergy efficiency is lower than COP because COP calculations do not take into account the temperature and entropy of the environment. But calculating the exergy efficiency that brings temperature and entropy of the environment is calculated to determine the actual efficiency of the system after some energy has been lost to the environment. This makes exergy efficiency less than COP of about 10-14%.

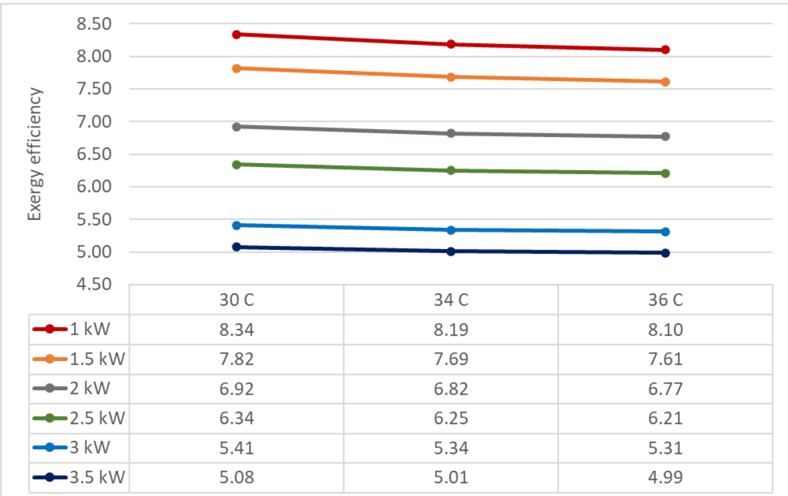
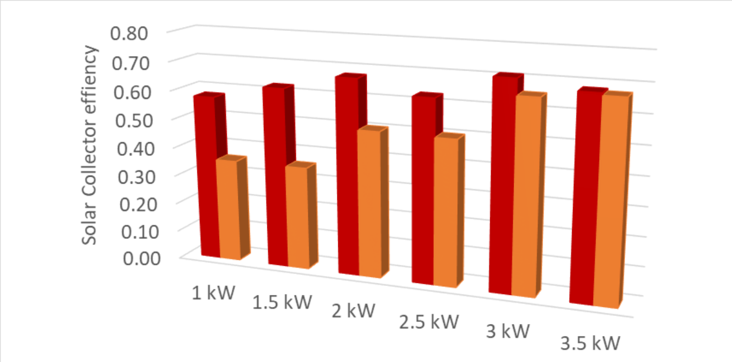


Figure 8: Exergy efficiency of the split type air-conditioning system using vacuum tube solar collector with the ambient temperature at 30 ºC, 34 ºC and 36 ºC.

From Figure 8, it showed that the exergy efficiency varies with the environmental temperature. As the ambient temperature increases, the exergy efficiency decreases because the air conditioning system was cooled to the air at the condenser. If the air temperature is high, there will be less cooling. As a result, the exergy efficiency was lower. At a low cooling load of 1.0 kW, the exergy efficiency difference was approximately 2.8%. At a high cooling load of 3.5 kW, the exergy efficiency difference was approximately 1.8%.

Figure 9 showed that the efficiency of the solar collector varies with the cooling load and the intensity of solar radiation. When the air conditioning system has a higher cooling load, the solar radiation receiver contributes to a greater increase in the temperature and pressure of the refrigerant. As a result, the efficiency of the solar collector was increased. From analysis, the efficiency of the vacuum tube solar collector was 22% higher than the flat plate solar collector.



	1 kW	1.5 kW	2 kW	2.5 kW	3 kW	3.5 kW
Vacuum Tube	0.58	0.62	0.67	0.63	0.71	0.68
Flat Plate	0.36	0.36	0.50	0.50	0.65	0.67

Figure 9: The efficiency of vacuum tube solar collector and flat plate solar collector

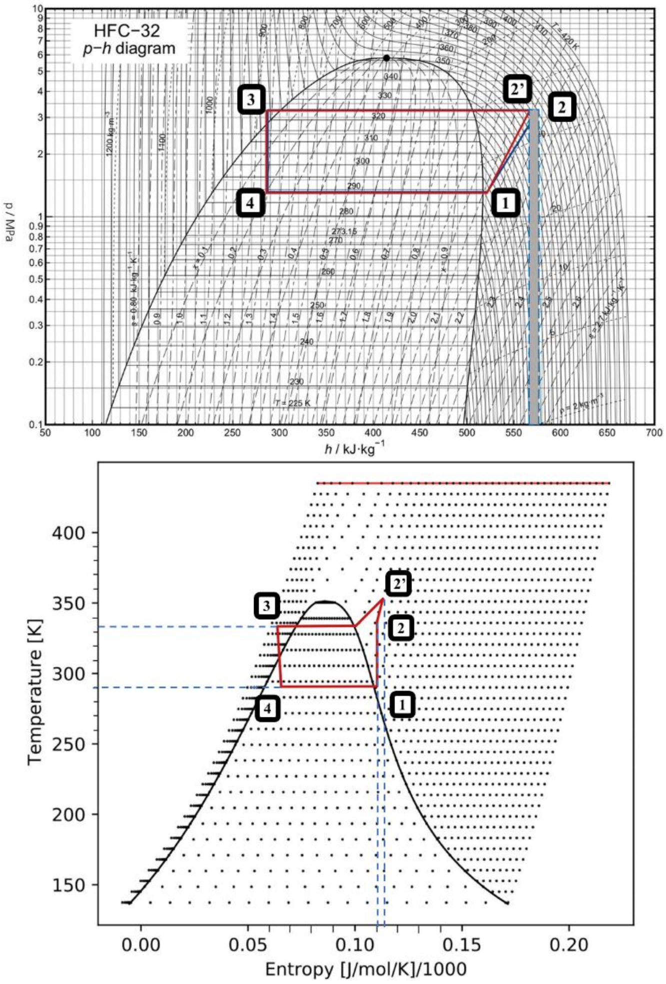


Figure 10: P-h Diagram and T-s Diagram the split type air-conditioning with the solar energy system comparing to general air conditioning system.

Figure 10 showed the comparison of refrigerant pressure leaving the vapor compressor. It was found that the split type air-conditioning with the solar energy system had lower refrigerant pressure than the split type air-conditioning without solar energy system because the refrigerant enters the solar collector to increase the temperature and pressure. The inverter control unit reduces the working of the compressor.

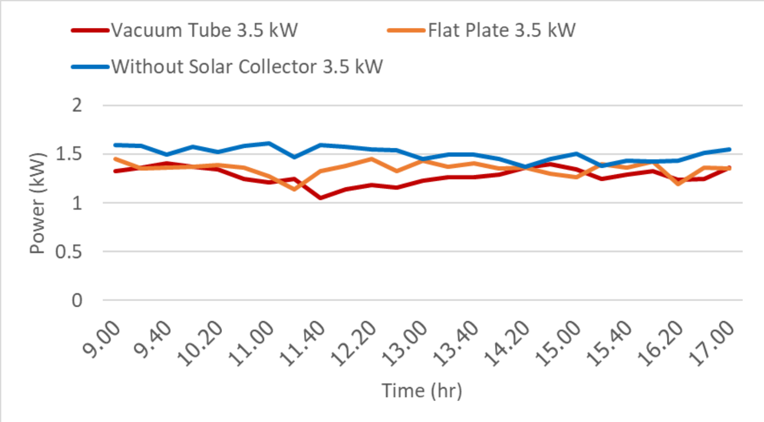


Figure 11: The electrical power at 25ºC with the room load by 3.5 kW.

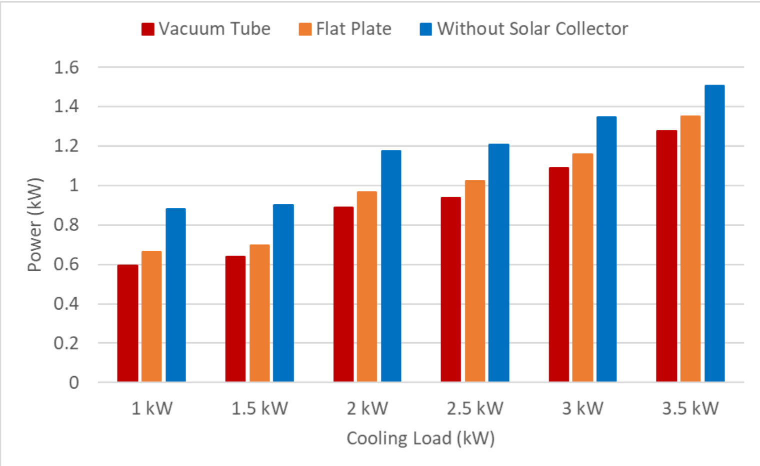


Figure 12: The electrical power at 25ºC with the room load by 1.0 kW – 3.5 kW.

Figure 11 showed the electrical power consumption while the room temperature was being adjusted to 25ºC with the cooling load by 3.5 kW. It was found that the split type air conditioner with the solar energy system had electrical power consumption lower than the split type air conditioner without solar collector. Because the refrigerant was heated by the solar collector until the temperature and pressure reached the system requirements. The inverter control unit will reduce the compressor duty cycle. As a result, the electrical power consumption in the air conditioner was reduced accordingly. Figure 12 showed that as the cooling load increases, the electrical power consumption in the air conditioner will also increase. The split type air-conditioning system using vacuum tube solar collector and flat plate solar collector had 25-30% and 10-24% power reduction respectively.

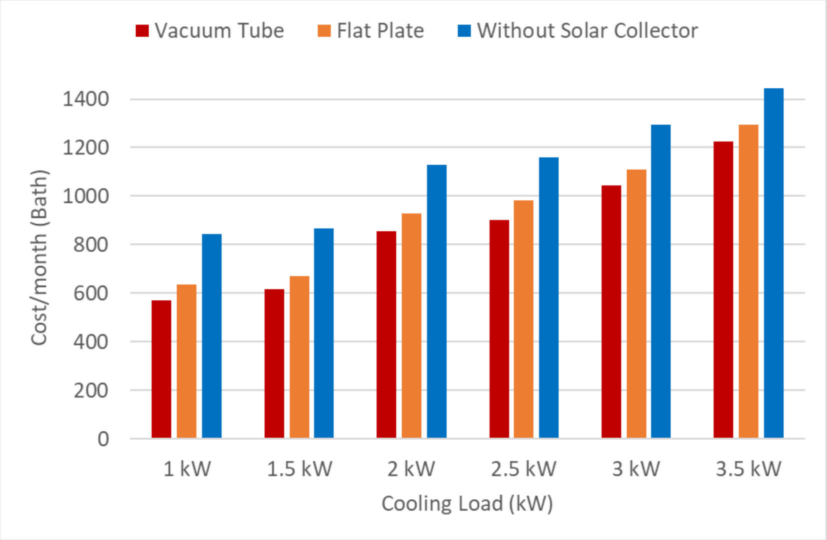
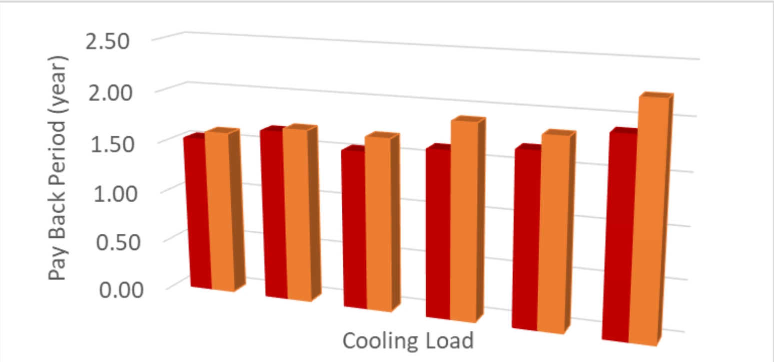


Figure 13: The electrical cost of air conditioner with the room load by 1.0 kW – 3.5 kW.

Figure 13 shows the electrical cost of the split air conditioning system. It was found that the split type air-conditioner with the solar energy system had electrical cost lower than the split type air conditioner without a solar collector. Because a solar collector increases the temperature and pressure on the refrigerant in the system, reducing the power used in the compressor. As a result, the cost of electricity was reduced. The split type air-conditioning system using vacuum tube solar collector can reduce electricity costs by 15.2-32.3% and the split type air-conditioning system using flat plate solar collector can reduce electricity costs by 10.3-24.6%.

From the analysis of economic results in Figure 14, the split type air-conditioning system using vacuum tube solar collector had the fastest payback period of 1.52 years while cooling load at 1.0 kW and the split type air-conditioning system using flat plate solar collector had the fastest payback period of 1.6 years while cooling load at 1.0 kW. Payback period of the vacuum tube solar collector was faster than the flat plate solar collector by 2-14%.



	1 kW	1.5 kW	2 kW	2.5 kW	3 kW	3.5 kW
Vacuum Tube	1.53	1.66	1.53	1.61	1.68	1.89
Flat plate	1.60	1.70	1.68	1.89	1.83	2.22

Figure 14: Payback Period of solar collector with the room load by 1.0 kW – 3.5 kW.

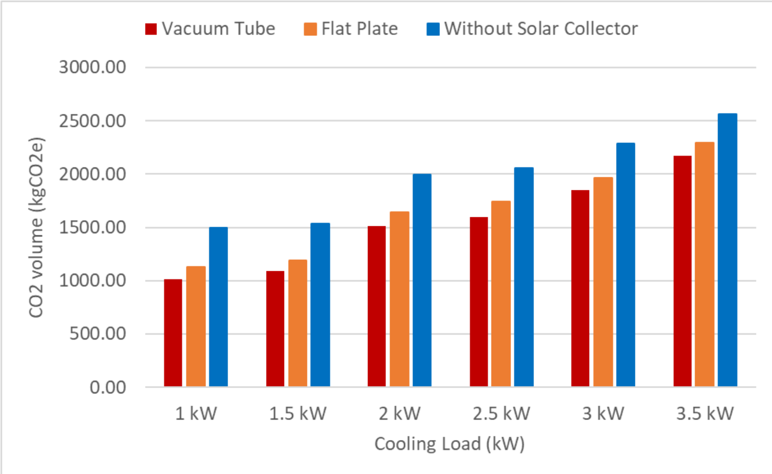


Figure 15: CO_2 emissions of air conditioner with the room load by 1.0 kW – 3.5 kW.

From the analysis of carbon dioxide emissions in Figure 15, It was found that the split type air-conditioner with the solar energy system had carbon dioxide emissions lower than the split type air conditioner without a solar collector. The split type air-conditioning system using vacuum tube solar collector can reduce average carbon dioxide emissions by 22.6% (449.6 $kgCO_2e$/year) and the split type air-conditioning system using flat plate solar collector can reduce average carbon dioxide emissions by 16.5% (328.2 $kgCO_2e$/year).

4. Conclusion and Discussion

The study was conducted by comparing energy efficiency, exergy efficiency and energy saving of the split air-conditioning system in combination with vacuum and flat plate solar collectors. It was found that the split air-conditioning system using vacuum glass tube solar collector had the highest coefficient of performance (COP) and exergy efficiency. The use of solar collectors results in lower electricity costs of air-conditioning systems. The average payback periods for vacuum tube and flat plate solar collectors were 1.6 years and 1.73 years, respectively. Vacuum tube solar collector was the best choice for air-conditioning systems. Because it increases COP and exergy efficiency more, consumes less electricity and has a faster payback period than flat-plate collectors.

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