Improvement of a Flat-Plate Solar-Absorption Heat Transformer Combining with a R-236fa Vapor Compression Heat Pump Comparison with Evacuated-Tube Solar Water Heating System

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Abstract

This paper presents a concept for upgrading a high temperature heat by 2 techniques of an evacuated-tube heat pipe solar water heating system (ETWHS) and a flat-plate solar collector combining with an absorption heat transformer (AHT) and a vapor compression heat pump (VCHP), the whole unit is called Solar-Compression/Absorption Heat Transformer (Solar-CAHT). The solar radiations and the weather conditions of Chiang Mai, Thailand are taken as the input data. In the case of the ETWHS, the suitable number of collector is 40 units for generating hot water temperature over 90 °C. For the Solar-CAHT, the suitable number of flat-plate solar collector is 25 units combining with R-236fa VCHP for producing heat to the AHT unit. The modified Solar-CAHT uses the number of solar collector lower than the normal Solar-AHT about 2 times and higher COP around 80%. For the economic results, it could be seen that the investment cost of the Solar-CAHT is less than the ETWHS about 100,000 Baht at the heating capacity 10 kW.

Keywords**:** Absorption heat transformer, Solar collector, Vapor compression heat pump, Solar water heating system

1. Introduction

Absorption heat transformer (AHT) is one type of absorption heat pump for upgrading low temperature heat to a higher temperature level. In a normal AHT, low temperature heat is supplied at the generator and evaporator and a high temperature heat is delivered at the absorber, while the condenser rejects heat to the surrounding. Theoretical and experimental studies of the AHT have been evaluated by various literatures. Florides et al. [1] presented an absorption solar cooling system for CYPRUS which used 3 types of solar collectors for comparison by TRNSTS simulation program, flat plate solar collectors, compound parabolic collectors (CPC) and evacuated tube heat pipe solar collectors. It could be seen that CPC had appropriate for supplied hot water to solar absorption cooling and house load during the whole year. Chaichana et al. [2] also studied the simulated results of solar water heating systems in a small slaughterhouse of Chiang Mai, Thailand, using a flat-plate solar collector water heating and a solar-boosted heat pump system. It could be seen found that two techniques have similarly results to generate hot water, but the solar-boosted heat pump has shorter a payback period at the same storage tank. Rivera et al. [3] presented a single-stage AHT and the advanced AHT operating with the water-LiBr and water-CarrolTM mixtures to increase the useful heat of solar ponds. The results showed that the single-stage AHT and the double AHT increased solar pond's temperature until 50 °C at COP about 0.48 and 100 °C at COP about 0.33, respectively. Xuehu et al. [4], reported the experimental results of the industrial-scale water-LiBr AHT in China which was used to recover waste heat from organic vapor at 98 °C in a synthetic rubber plant. The recovered heat was used to heat hot water from 95-110 °C. The AHT system operated with a heat rate of 5,000 kW with a mean COP of 0.47. The payback was approximately 2 y. Sotsil Silva Sotelo et al. [5] presented a water-CarrolTM AHT cycle which was a higher solubility than water-LiBr solution. It could be found that the COP was higher and less crystallization risk which compared with the water-LiBr solution.

In this study a techniques to improve the thermal performance of a single-stage H_2O-LiBr AHT by combining the VCHP and flat-plate solar collectors for supplying heat to the AHT system has been considered. For the VCHP, the heat rejected at the AHT condenser is recovered and supplied back to the AHT evaporator at higher temperature and an appropriate working fluid has been chosen. The whole unit is compared with the normal solar water heating system by using evacuated tube heat pipe solar collector which is the objective of this study.

2. Research Methodology

Figure 1 shows a schematic diagram of a normal solar water heating system. Solar energy is absorbed at evacuated-tube heat pipe solar collectors to upgrade heat around 80-120 °C, which is kept in the water storage tank.

The second solar water heating system is flat-plate solar collector water heater combined with an absorption heat transformer (AHT) and the whole unit is called Solar-Absorption Heat Transformer (Solar-AHT) as shown in Figure 2. When the VCHP is used to recover the low temperature heat at the AHT condenser which is upgraded and supplied heat to the AHT evaporator at a higher temperature level as shown in Figure 3. The modified is called Solar-Compression/Absorption Heat Transformer (Solar-AHT) and the coefficient of performance (COP) of the modified units could be increased and the number of collector units could be decreased around 2 times compared with the normal Solar-AHT.

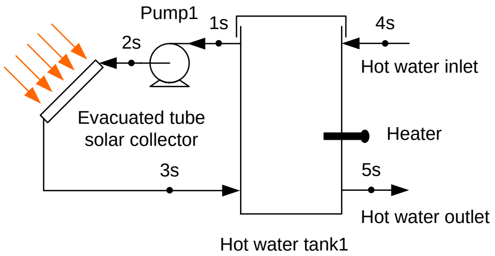

Figure 1 Schematic diagram of a solar water heating system by evacuated tube heat pipe solar collector.

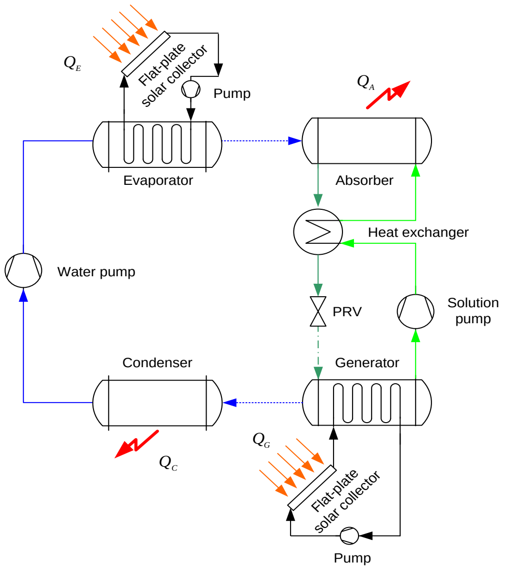

Fig. 2 Schematic diagram of a solar absorption heat transformer.

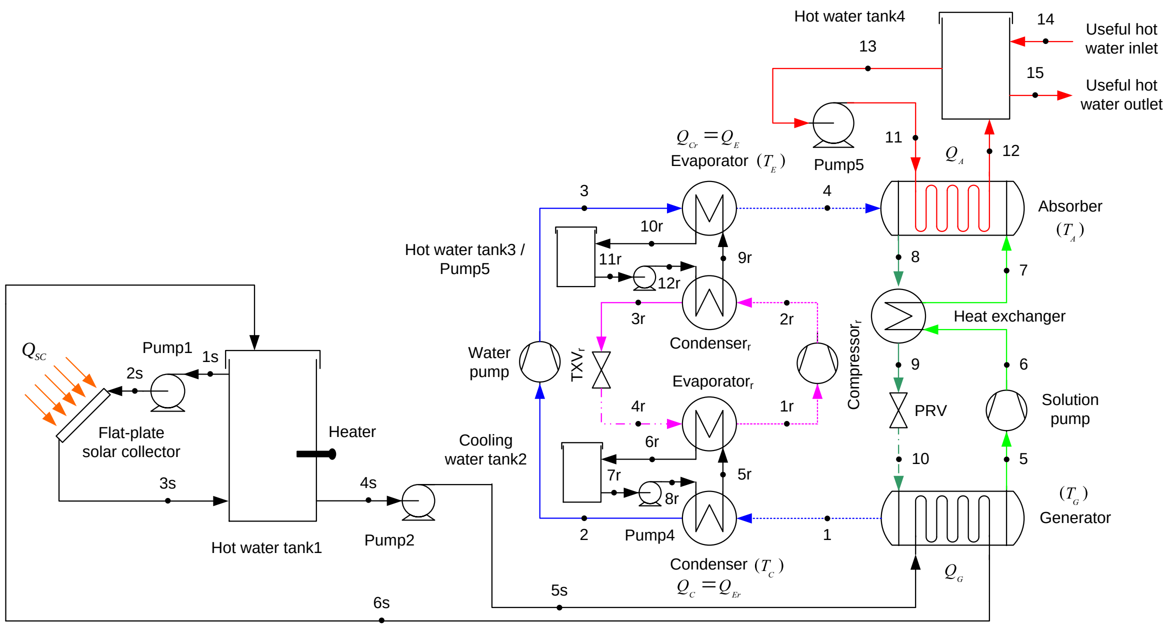

Figure 3 Schematic diagram of a CAHT coupling with flat-plate solar collector.

3. Simulation Model

The basic equations for the behavior of each component in the AHT cycle are as follows:

- Generator

$$Q_G = \dot{m}_1 h_1 + \dot{m}_5 h_5 - \dot{m}_{10} h_{10}\,, \tag{1}$$

$$\dot{m}_{10} = \dot{m}_1 + \dot{m}_5\,, \tag{2}$$

$$\dot{m}_{10} X_{10} = \dot{m}_5 X_5\,, (X_1 = 0)\,. \tag{3}$$

From equation (14) and (15),

$$\dot{m}_5 = \frac{\dot{m}_1 X_{10}}{X_5 - X_{10}}\,, \tag{4}$$

and

$$\dot{m}_{10} = \frac{\dot{m}_1 X_5}{X_5 - X_{10}}\,. \tag{5}$$

- Condenser

$$Q_C = \dot{m}_{ref} (h_1 - h_2)\,, \tag{6}$$

$$\dot{m}_{ref} = \dot{m}_1 = \dot{m}_2 = \dot{m}_3 = \dot{m}_4\,. \tag{7}$$

- Pump and solution pump

$$W_P = (P_E - P_C) \frac{v_2 \dot{m}_2}{\eta_P}\,, \tag{8}$$

$$W_{SP} = (P_E - P_C) \frac{v_5 \dot{m}_5}{\eta_{SP}}\,, \tag{9}$$

$$h_2 \approx h_3, \quad (10)$$

$$h_5 \approx h_6. \quad (11)$$

- Evaporator

$$Q_E = \dot{m}_{ref}(h_4 - h_3). \quad (12)$$

- Absorber

$$Q_A = \dot{m}_4 h_4 + \dot{m}_7 h_7 - \dot{m}_8 h_8, \quad (13)$$

$$\dot{m}_8 = \dot{m}_4 + \dot{m}_7, \quad (14)$$

$$\dot{m}_8 X_8 = \dot{m}_7 X_7. \quad (15)$$

- Heat exchanger

$$Q_{HX} = \dot{m}_8 Cp_8 (T_8 - T_9) = \dot{m}_6 Cp_6 (T_7 - T_6), \quad (16.1)$$

$$Q_{HX} = \varepsilon_{HX}(mCp)_{min}(T_8 - T_6), \quad (16.2)$$

$$\dot{m}_8 = \dot{m}_9, \quad (17)$$

$$\dot{m}_6 = \dot{m}_7. \quad (18)$$

- Expansion valve

$$h_9 = h_{10} \text{ (Throttling process).} \quad (19)$$

- Coefficient of performance (COP)

$$COP_{AHT} = \frac{Q_A}{Q_E + Q_G + W_P + W_{SP}}. \quad (20)$$

For the VCHP, the basic equations for the behavior of each component in the VCHP cycle as presented in Figure 3 are as follows:

- Evaporator$_r$

$$Q_{Er} = \dot{m}_r(h_{1r} - h_{4r}), \quad (21)$$

$$\dot{m}_r = \dot{m}_{1r} = \dot{m}_{2r} = \dot{m}_{3r} = \dot{m}_{4r}. \quad (22)$$

- Compressor$_r$

$$W_{Comp} = \dot{m}_r(h_{2r} - h_{1r}), \quad (23)$$

$$s_{1r} = s_{2r} \text{ (Isentropic process),} \quad (24)$$

$$\eta_{Comp} = \frac{h'_{2r} - h_{1r}}{h_{2r} - h_{1r}}. \quad (25)$$

- Condenser$_r$

$$Q_{Cr} = \dot{m}_r(h_{2r} - h_{3r}). \quad (26)$$

- Expansion valve$_r$

$$h_{3r} = h_{4r} \text{ (Throttling process).} \quad (27)$$

Then the overall coefficient of performance (COP) of the CAHT will be:

$$COP_{CAHT} = \frac{Q_A}{Q_G + W_P + W_{SP} + W_{Comp}}. \quad (28)$$

It could be seen that W_{Comp} in Eq (20) is less than Q_E in Eq (28) then the COP_{CAHT} will be higher than that of COP_{AHT}.

R-236fa is selected as the working fluid of the VCHP due to its low compression work at a high temperature range and the cycle pressure ratio is not high.

Figure 4 shows the simulation program for evaluating the normal solar water heating system.

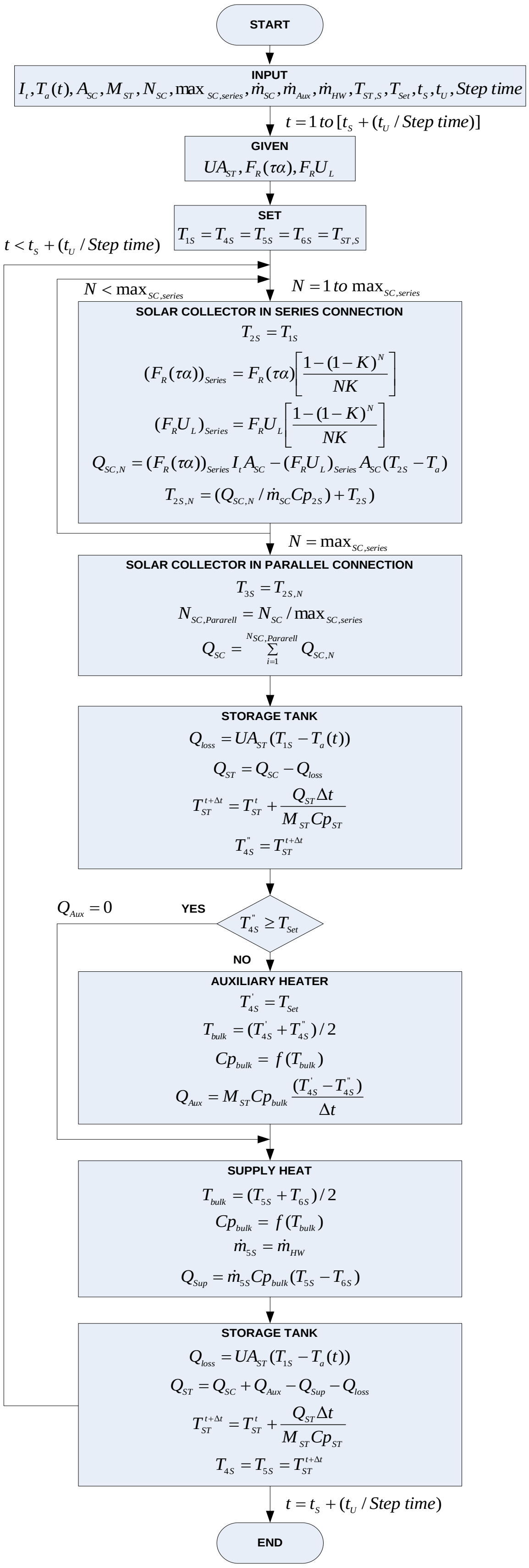

Fig. 4 Flow chart of the simulation program for evaluating the solar water heating system.

4. Results

In this section, the performance of evacuated tube heat pipe solar collector tests by the Florida Solar Energy Center [8], $F_R(\tau\alpha)$ and $F_R U_L$ are 0.53 and 1.7 W/m^2.K, respectively.

Figure 5 shows the variations of water temperature at various the number of evacuated-tube solar collectors between 20-40 units in parallels connection. For 11:00 a.m., 40 units of the collectors could generate heat continuously at 8 h while the other units have the maximum operating time around 5 h. Therefore, the appropriate number of evacuated tube heat pipe collectors is 40 units which calls that a set of collectors and water tank is Evacuated Tube-Water Heating System (ETWHS). Its simulation result is used to compare with the Solar-CAHT.

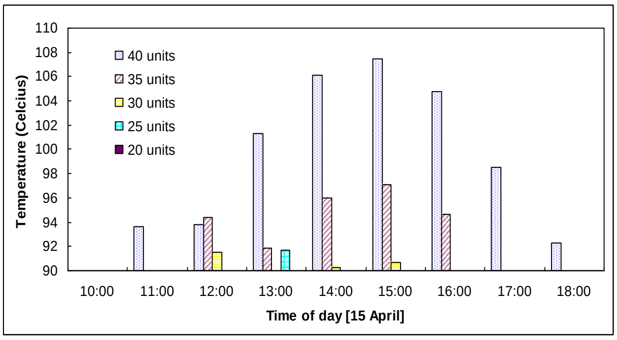

Figure 5 Effect of the number of collector units on hot water temperature in storage tank at 1,500 l and flow rate of useful water 0.5 l/s for used auxiliary heater 15 kW.

Figure 6 shows the variations of water temperature in tank at 1,500 l with various the solar radiations in term of time of day of the Solar-CAHT and the ETWHS. After 11:00 a.m., it could be seen that hot water temperature leaving the Solar-CAHT is constant around 96 °C while the ETWHS varies with the solar radiations. For the Solar-CAHT, water temperature leaving the system is upon the AHT evaporator temperature (T_E) which is nearly constants due to supplied hot water level from the VCHP is kept at constants temperature.

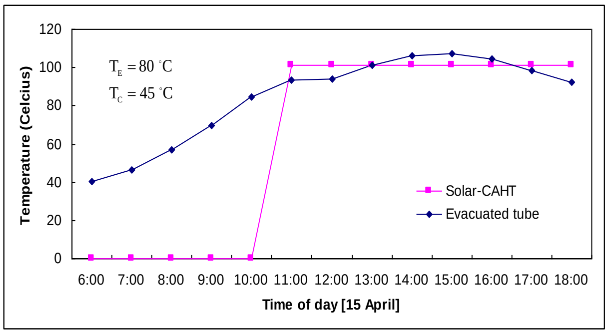

Figure 6 Comparison hot water temperature of the Solar-CAHT and the ETWHS.

For Solar-CAHT, could be increased T_E which means that the AHT absorber temperature (T_A) is increased, higher T_A will give higher hot water temperature leaving the AHT absorber while the ETWHS does not increase hot water temperature leaving the system. For the ETWHS, increasing the number of collector units will give the higher hot water temperature which means that the investment cost of this system increase following the number of collector units.

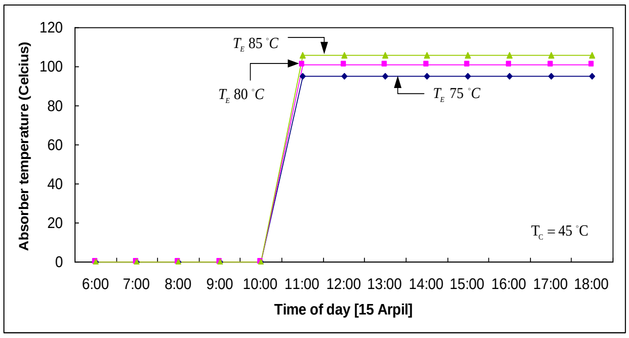

Figure 7 Effect of T_E on T_A of the Solar-CAHT at flat-plate solar collector 25 units and auxiliary heater 15 kW.

Figure 7 shows the variation of T_A with T_E. It could be seen that T_A increases significantly with T_E. Higher T_E will give higher pressure in the absorber which results in higher T_A value.

Figure 8 shows the overall COP various with the time of day in the normal AHT cycle and the CAHT cycle. It could be seen that the overall COP of the CAHT is higher than that of the normal AHT at similarly T_E, because the heat rejected in the AHT condenser is recovered which the energy supplied for the VCHP is not high. The overall COP improvement performed by the CAHT compared is around 80% higher than that of the normal AHT.

Figure 8 also show the overall COP of the CAHT cycle could be improved by decreasing T_E. Lower T_E requires less the VCHP compression work which results in higher COP of the CAHT cycle.

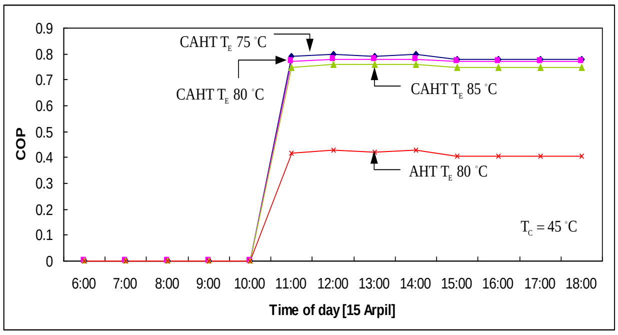

Figure 8 Effect of T_E on the overall COP of the normal Solar-AHT and the Solar-CAHT at flat-plate solar collector 25 units and auxiliary heater 15 kW.

From the previous results, it could be seen that the Solar-CAHT same generated hot water temperature as the ETWHS. Moreover, it could supply water temperature is nearly constants and has the overall COP higher than that of the normal Solar-AHT. For the economics, the investment cost of the Solar-CAHT is less than the ETWHS about 100,000 Baht at the output heating capacity 10 kW_{th}.

Table 1 Comparison investment costs of the Solar-CAHT and the ETWHS.

Details	**Solar-CAHT**	**ETWHS**
Type of collector	Flat-plate [9]	Evacuated-tube [8,10]
Cost of collector (Baht/m^2)	7,000	10,000
The number of collector units (each unit = 2 m^2, units)	25	40
Cost of the VCHP (Baht)	150,000	
Cost of the AHT (Baht)	200,000	
Investment cost (Baht)	700,000	800,000

Note: 32.44 (Baht) = 1 U.S. Dollar

5. Conclusions

From this study, the conclusions are as follows:

1. The suitable natural working fluid of the VCHP for recovering and upgrading heat of the AHT is R-236fa due to its low operating pressure and high COP of the VCHP cycle for supplying heat at around 80-90 °C.

2. The CAHT can produce upgraded heat at a nearly constant temperature at the absorber and the overall COP.

3. The overall COP of the Solar-CAHT cycle can increase around 80% over that of the normal AHT (the overall COP of the AHT around 0.5) and decrease the number of collector units about 2 times compared with the normal Solar-AHT.

4. The investment cost of the Solar-CAHT is about 700,000 Baht which is less than the ETWHS about 100,000 Baht at heating capacity around 10 kW. The comparison result used the number of flat-plate solar collectors and evacuated tube heat pipe solar collectors are 25 units and 40 units, respectively.

6. Acknowledgement

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