The Quasi-steady State Performance of a Solar-Biomass Hybrid Cooling System

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Abstract

The world is currently confronted with challenges of energy crisis and global warming. To address these serious problems, renewable energy is one of the major options. Solar energy along with biomass utilization is a win-win solution. This paper reports on the experimental study of a solar-biomass hybrid air conditioning system. The study aims at developing a fully renewable energy based air conditioning system and assessing the feasibility of this new hybrid system. The experimental data demonstrates that when the chiller was operated at about 75% of chiller nominal capacity its coefficient of performance was about 0.6. To compare the performance of solar cooling system with different driving energy sources, the experimental results of three modes of operation, with the same operating parameters and almost the same weather conditions, were compared. The comparative study results show that the proposed system can be operated with higher reliability and performance compared to the conventional systems which operate with and without auxiliary heater. Therefore, application of a solar-biomass hybrid air conditioning system is promising in tropical locations.

***Keywords**:* Solar; Absorption; Biomass; Cooling; Hybrid.

1. Introduction

The global warming problem is strongly affecting all lives on earth. The main greenhouse gas, CO_2 is generated from combustion processes. Air conditioners consume about 70% of the building's electricity consumption [1]. To address the environmental problems caused by the use of fossil fuel and chlorofluorocarbons, the development of an environmental-friendly renewable based cooling system become important.

The use of solar energy for cooling purpose is attractive because the cooling load is roughly in phase with solar energy availability and it uses the environmental friendly refrigerant. Currently, solar energy based air-conditioning systems are available [2,3]. However, solar energy is intermittent, and so an auxiliary heat source becomes inevitable. Furthermore, the weakness of a solar (solely) absorption cooling systems is that it can be used only during day time. There are few experimental studies on such systems [3] and [5]. Syed et.al [3] reported the experimental results from field testing of a solar energized cooling system without auxiliary heater. The experimental results show that their system was operated during hours of bright sunshine. Cooling was provided for 8.67 hrs with a maximum instantaneous, daily average and period average coefficient of performance were 0.6, 0.42 and 0.34, respectively. Hidalgo et.al [5] also presented experimental results on solar absorption cooling system. Their facility is based on an on-Campus field of 50 m^2 flat plate solar collectors driving a single-effect commercial 35 kW absorption machine. Their results show that it produced a daily average cooling power of 3 kW for 6.5 hrs with a low efficiency. Though the current research related to solar powered absorption cooling, most of this kind system use auxiliary based on fossil fuel, e.g.: electricity, gas, and oil [6-10]. So, these systems still are fossil energy based systems.

To develop the fully renewable energy cooling system, renewable energy source must be considered to function as an auxiliary heater. Regarding the use of biomass, which is a CO_2 neutral energy source, gasification of biomass offers advantages over other sources. Using solar and biomass can significantly contribute to the reduction of CO_2 emission. A theoretical study on the performance of a solar-biomass hybrid air conditioning (SBAC) system has been done [11]. Their results show that the proposed SBAC system for tropical locations is feasible, and can replace conventional vapor compression systems, thus reducing the need for fossil fuel based energy systems for cooling purposes.

This study aims at evaluate the performance of SBAC system as an alternative system and compare with conventional solar cooling systems. On this basis, the performances of a SBAC system, quantity of biomass use, coefficient of performance of the chiller and the overall system were investigated. Section 2 describes the experimental system. Section 3 presents the instrumentation and data acquisition system used. Section 4 presents the experimental procedure. Section 5 reports the observations and discusses the experimental results. Section 6 presents the comparison study. The conclusion of study is presented in section 7.

2. Description of Experimental System

The experimental system of solar-biomass hybrid absorption cooling system was set up as shown in Fig. 1. It consists of three main parts: solar water heating (SWH) system with a storage tank, biomass gasifier-boiler (BGB) system, and single-effect LiBr-H_2O absorption chiller. The solar energy is absorbed for heating the water as a working fluid at the collector field and pumped to the tank by the forced pump. This pump will be activated by controller. Usually, it remains off until the difference between collector outlet and tank temperatures is above the upper dead band value [12]. The controller will switch the pump off when this difference reaches the lower dead band.

The second part is automatic on/off biomass gasifier-boiler located between hot water storage tank and absorption chiller machine. This insulated boiler has two functions:

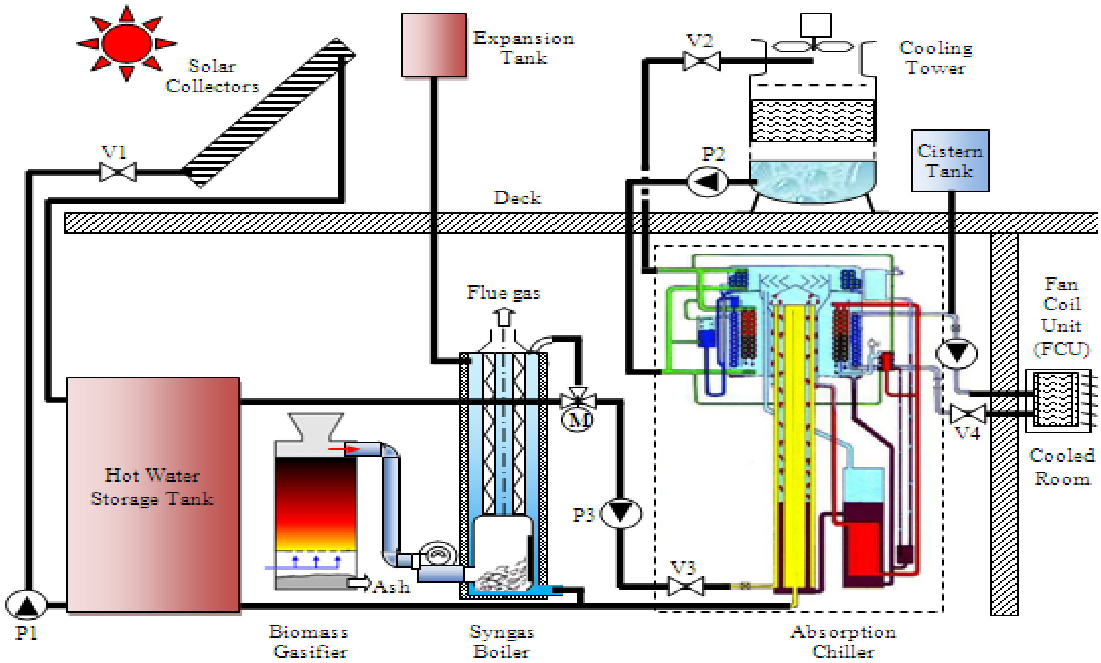

Fig. 1 Schematic diagram of the solar-biomass hybrid absorption cooling system

works as auxiliary boiler when solar energy is not enough and works as main heat source when the solar radiation is not available. Because of its intermittent working conditions, this kind of gasifier boiler is proposed to utilize the available biomass resources. The automatic gasifier boiler is controlled by controller and supplies hot water for chiller machine.

The cooling is provided by a single-effect LiBr-H_2O absorption chiller. Heat from solar collector or from biomass-boiler evaporates the water in the generator of the absorption chiller. This is led to the condenser, where it rejects heat to the ambient and condenses. This is taken to the evaporator (through the expansion valve), where it receives heat from the space to be cooled and evaporates. The evaporated refrigerant (water) is absorbed by the weak solution in the absorber (from the generator). The absorption process also releases heat to the ambient, and the solution, now rich in water (strong solution) is taken to the generator (by a pump) to complete the cycle. The heat required for its generator is drawn from hot water pumped from a storage tank fed by the solar collectors and/or sometimes boosted/fed by biomass boiler. The condenser and absorber of chiller are cooled by cooling water pumped through a cooling tower. The chilled water produced from evaporator is pumped for cooling proposes.

The experimental SBAC system was installed at the Asian Institute of Technology (AIT), Bangkok. This system consists of an existing 26 flat plate collector field with total area of about 49 m^2, a hot water storage tank of 0.4 m^3 and a 7 kW single-effect LiBr-water absorption chiller.

3. Instrumentation and Data Acquisition

To carry out the study of the performance evaluation of the SBAC system, measurements of temperatures, flow rates, electricity and solar insolation were carried out. A data logger (Campbell Scientific Inc. model

CR-10X) equipped with multiplexer (solid-state type AM25T) were used to record temperature with type-K thermocouples installed at different locations and solar insolation data were measured at the meteorological station. These data were recorded every five-minute intervals. The others data were manually measured and recorded every half an hour.

4. Experimental Procedure

The experimental studies consisted of three modes of operation: A) solar cooling system with electrical auxiliary boiler, B) solar-biomass hybrid cooling system, and C) solar solely cooling system. Mode A) and C) of experiments were done aims at estimating performance of the system as base cases. The quasi-steady state condition for each experimental result was defined with the criteria that all variation between time steps of each measured parameters must be less than 10% for all measuring parameters over a period of 30 minutes or longer. The data during the quasi-steady state conditions will be chosen and used for the performance analysis.

The SWH and BGB systems were started at about 8:00. The water flow rate of collector, generator, cooling tower and chilled water pumps were set at 1,200, 1,500, 5,400 and 900 kg/hr, respectively. To prevent crystallization, the chiller was started later when the boiler temperature was higher than 70 °C. The BGB was switched OFF whenever the average tank temperature reached 84 °C and switched ON whenever this temperature is lower than 80 °C. When the BGB is switched on, the hot water temperature was controlled at the set point temperature of 84 °C. When the temperature difference between the collector outlet and average tank temperature was less than 2 °C, the collector pump was switched off.

5. Results and Discussion

The SBAC system was tested during 3 to 30 September 2010. The experimental data of system components and overall system performances during a partly cloudy day (16 Sep 2010) are demonstrated as an example. An overview of measured temperatures and quasi-steady state periods during this experimental day are shown in Fig. 2. The other experimental days were used for the daily average performance analysis.

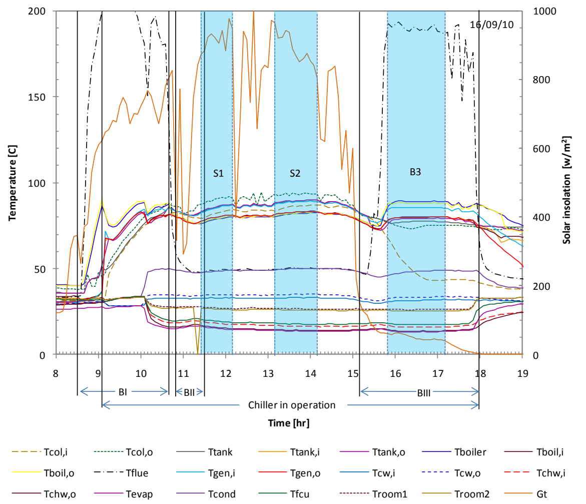

Fig. 2 Temperature profiles and quasi-steady state periods of an example day

As shown in Fig. 2, the BGB was operated in three periods: 8:00 to 10:40 (BI), 10:50 to 11:30 (BII) and 15:10 to 18:00 (BII) and for rest, the chiller was energized by solar energy. Considering the quasi-steady state condition criteria, there are three periods of quasi-steady state condition: running on solar from 11:25 to 12:10 (S1), running on solar from 13:10 to 14:10 (S2) and running on biomass from 15:50 to 17:10 (B3). The performances of the components and overall system are described using these quasi-steady state period's data.

To analyze the transient energy balance of each component and overall system during the experimental day, the energy transfer (in MJ) of each 5-minute interval was determined. The daily average or quasi-steady state energy balance results can be used for pointing out the amount of energy at each direction. The overall system performance/efficiency can be directly improved using this result, especially reducing the major losses of the culprit components.

5.1 Weather Condition during the Experiment

Fig. 3 shows the solar insolation and ambient temperature of the experimental day. The maximum insolation of this partly cloudy day is about 1,000 W/m^2 and the daily radiation incident on the tilted collector is about 19 $MJ/m^2 day$. The ambient temperature varied in the range of 25 to 35 °C.

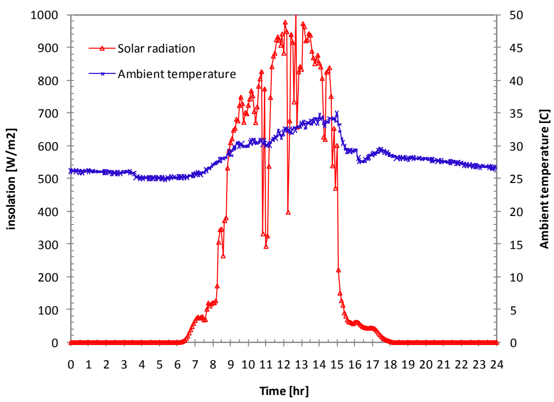

Fig. 3 Solar insolation and ambient temperature of the experimental day (16 Sep 10)

5.2 System Performance

The energy balance of the SBAC system can be described as shown in Fig. 4 and determined using Eq. (1).

$$G_T + Q_{BM} + Q_{ev} = Q_{re} + \Delta U_{sys} + Q_l \quad (1)$$

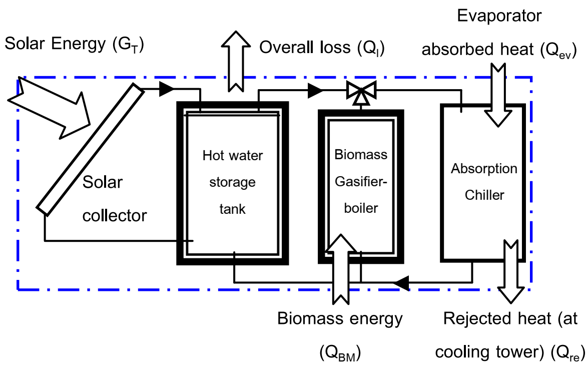

Fig. 4 Energy balance of SBAC system

Fig. 5 shows the energy transfer of each 5-minute interval of the overall system. The average values during each quasi-steady state condition are summarized as shown in Table 1. When the system was operated on solar energy (S2, 13:10 to 14:10), the average solar energy input was about 13 MJ. Due to its very large surface loss and fluid loss during long water circulation loop, the total energy loss is high, and the average value is 10.24 MJ or about 78.5% of solar input energy. The system energy loss, when it was energized by BGB, was 4.56 MJ or about 72% of biomass input energy.

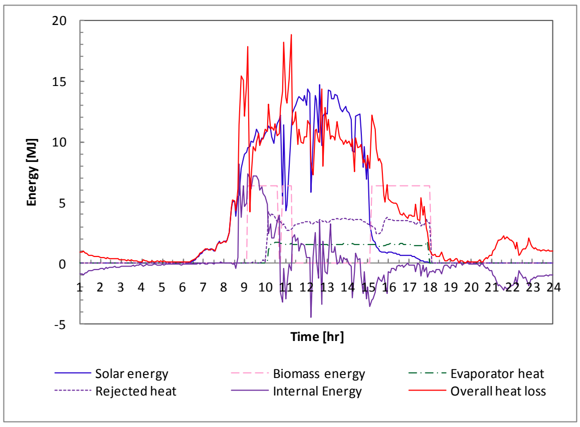

Fig. 5 Energy balance of SBAC system

Table. 1 Average values of energy transfer (in MJ) during each quasi-steady state condition

Steady state	Solar	Biomass	Absorbed	Rejected	Internal	Loss
S1	13.52	0.62	1.52	3.30	1.30	10.89
S2	13.05	0.00	1.56	3.62	0.61	10.24
B3	0.74	6.34	1.55	3.53	-0.54	4.56

Fig. 6 shows the chiller coefficient of performance (COP) and the overall system coefficient of performance (COP_{sys}) calculated using Eqs. (2) and (3), respectively, where $\dot{Q}_{ge}$ is generator heat rate, A_c is collector area, $\dot{m}_{BM}$ is biomass consumption rate and LHV_{BM} is biomass heating value. Since the chilled water was produced at around 10:10 (about 1.40 hr from the start), both COP and COP_{sys} values were higher than zero at this time. During quasi-steady state conditions, the COP_{sys} varied in the range 0.45 to 0.64 and 0.15 to 0.33, respectively. The average value of COP is 0.53.

$$COP = \dot{Q}_{ev}/\dot{Q}_{ge} \quad (2)$$

$$COP_{sys} = \dot{Q}_{ev}/(G_T A_c + \dot{m}_{BM} LHV_{BM}) \quad (3)$$

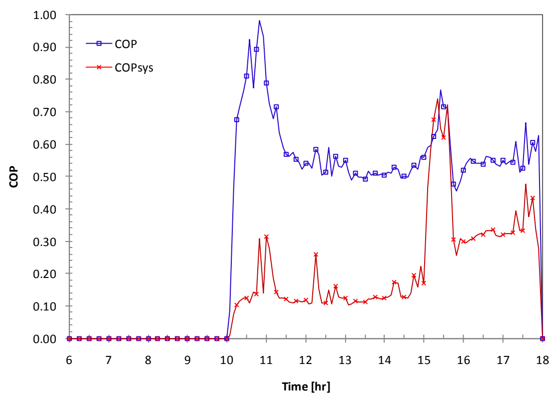

Fig. 6 Chiller and overall system coefficient of performance

6. Comparison Study

To know how the proposed system performance compares with the conventional system, a comparison between the proposed system performance and the conventional systems: with electrical AUH and without auxiliary heat source, will be discussed. In addition, the important performance indicators between the proposed and the literature will also be compared.

- *Comparison to the conventional systems*

The performance of the proposed system was compared to the conventional modes of operation. The daily average performances of two conventional systems, with electrical auxiliary heater and without auxiliary heat source (as mentioned in section 4), were compared with the proposed system performance. Mode B) represents the proposed system and the others stand for the conventional system. These results were chosen with the criteria that each mode must be tested under almost the same operation time period and solar insolation.

The solar insolation of mode A), B) and C) are 14.5 (3 Sep 10), 14.6 (4 Sep 10) and 14.32 MJ/m^2.day (26 Sep 10), respectively. In case of mode A), a 20 kW electrical boiler was used as an auxiliary heater. Because it has a high capacity and small volume, the supplied hot water can be rapidly heated to the set point temperature. With its sufficient power, the chiller can quickly generate chilled water and the hot water can be controlled within very small fluctuations. However, its electrical consumption is about 34.3 kWh (only for heater electricity consumption).

In case of mode B), a 29.3 kW gasifier was operated together with a 60 l boiler. The hot water cannot be rapidly reached the set point temperature; it requires about 1.5 hours for heating. In case of mode C), with this 0.4 m^3 storage tank, the chilled water was produced only at 12:50 and the minimum chilled water temperature was only about 18 °C. For such system, its performance directly depends on solar energy source, and then the control strategy with suitable tank size is important. However, this system cannot be used when there are not enough or fluctuating solar energy, especially in rainy season, and at night time.

The experimental results of three operation modes are summarized in Table 2. The results show that the solar cooling with auxiliary heat source (mode A) and B)) can be used with higher reliability, means that it can be operated for longer cooling period, lower chilled water and room temperatures. It requires auxiliary heat energy, of about 34 kWh for electrical heater or about 20 kg of charcoal for biomass boiler. Starting period (system is started until it can generates the chilled water) depends on the heating power of auxiliary heater. The bigger auxiliary heater size, the shorter starting period can be obtained, and it will be operated with higher energy consumption and losses. With biomass auxiliary heat source, the cooling quality can be obtained as well as the electricity heat source, the same average chilled water and room temperatures. For solar solely mode, its cooling period is twice lower than the others modes with very low cooling quality.

Table. 2 Experimental results of three operation modes (unit: MJ/day)

Date	Daily G_T	Daily BM	Daily Q_u	Daily $Q_{l,c}$	Daily Q_{tl}	Daily $Q_{l,t}$	Daily Q_{bl}	Daily $Q_{l,BGB}$	Daily Q_{ge}	Daily Q_{ev}	Daily $Q_{co}+Q_{ab}$	Daily $Q_{l,ABC}$	Daily ave. COP	Daily ave. COP_{sys}
3/09	710.45	122.40	67.66	642.79	75.57	50.00	0.00	0.00	237.15	153.91	344.03	47.02	0.65	0.18
4/09	715.23	508.86	103.62	611.61	29.81	73.81	293.74	215.12	157.51	120.75	241.73	36.53	0.77	0.10
26/09	701.58	0.00	208.87	492.71	98.56	110.30	0.00	0.00	96.68	61.57	114.41	43.84	0.64	0.09

Note: These days, the system was operated with almost the same G_T and operating time, 8.92, 8.75 and 8.66 hr, respectively.

The experimental results also show that the daily average chiller coefficient of performance of mode A), B) and C) are 0.65, 0.77 and 0.64, respectively. As the generator supplied heat at the starting period of mode B) is lower than mode A), their absorbed heat at evaporator are almost the same then the COP of mode B) is higher than mode A). The daily average overall system coefficients of performances of each mode are 0.18, 0.10 and 0.09, respectively. With almost the same solar radiation, As the efficiency of the BGB is lower than electrical boiler, the COP_{sys} of mode A) is higher than mode B).

- *Comparison to previous works*

The comparison between the experimental performance obtained from this study and those obtained from the literature (as shown in Table 3) are discussed in this section.

Table 3 shows the data of 9 experimental studies from the literature concerning solar air conditioning systems. To compare the performance, the systems which have comparable (almost same) chiller and

Table 3. Comparison of experimental results between this study and literatures

	This study	Li and Sumathy [13]	Syed et.al [3]	Hidalgo et.al [5]	Qu et.al [6]	Agyenim et.al [14]	Mammoli et.al [15]	Marc et.al [16]	Moreno et.al [17]	Monné et.al [18]
Required cooling load (kW)	4.5	NA	NA	6-8	NA	2.82	NA	NA	(for 42 m^2 lab. Room)	NA
Collector (parameters)										
- Type, area (m^2)	FPC, 50	FPC, 38	FPC, 49.9	FPC, 50	PTC, 52	ETC, 12 (model DF100)	[FPC, 124]+[ETC 108]	FPC, 90 (double glass cover)	NA	FPC, 37.5
- Water flow rate	0.33	0.39 l/s	NA	NA	NA	NA	2.5 (water-glycol)	NA	NA	NA (via 34 kW HX)
- Differential temp. control	lower=1C, upper=2 C	Yes	Yes (set at 2-3 C diff.)	NA	NA	Yes	NA	Tc,o >=70& dT=5)	NA	NA
- Characteristic parameter	a1=0.789, a2=5.829	a1=0.62, a2=5.15	a1=0.68, a2=3.33	NA	a1=0.634, a2=1.4	a1=0.779, a2=1.07	NA	NA	NA	a0=0.9, a1=4.1, a2=0.01
Chiller spec., (&measured)										
- Brand-model	Yazaki-WFC600S	Yazaki-WFC400S	Yazaki-WFC-10	Yazaki-WFC10	NA	Rotartica semi-commerce	Yazaki (SH20)	Tunzini (LB30)	ROTARTICA 045	ROTARTICA 045
- Nominal cooling cap.	7 kW (nominal)	4.7 kW (rated)	35 kW	NA (should be 35kW)	16 kW- double effect	4.5	70 kW-thermal	30 (at gen. inlet of 90 C)	4.5	4.5
Hot water storage tank										
- vol. (m3)	0.4	2.75	2	2	4	-	34	1.5	NA (with 2 tanks)	not used
- UA (W/m2K)	4	1.6	0.5-0.9 W/m2K	NA	NA	-	NA	NA	NA	NA
Aux. heat source			Without aux. heater	Without aux. heater						
- Type	Biomass (charcoal)	NA	-	-	NG burner (in chiller)	-	steam & chilled water backup	- (using of ceiling fan)	NA	NA
- Size	29 kW-gasifier	12 kW (heating)	-	-	NA	-	NA	-	NA	NA
- Connection	parallel	parallel	-	-	NA	-	NA	-	NA	NA
- Set point temperature (C)	84	88	-	90	NA	-	NA	-	NA	NA
Operating period										
- Analyze period	10 hr (8:00-18:00)	10 hr (8:00-18:00)	11.5 hr (8:30-20:00)	6:00-24:00	9:30-17:00	6:00-20:00	6:00-20:00	24 hr	25 hr	9 hr (10:00-19:00)
System steady state criteria	all parameters diff. <10%	NA	NA	un steady	NA	NA	NA	NA	NA	NA (just defined)
Exp. parametric study	Insolation & gen. inlet T.	solar insolation	Solar insolation	solar insolation	solar insolation	gen. inlet T.& insolation	solar insolation	solar insolation	solar insolation	solar insolation
- Thermal efficiency										
# chiller COP	0.54 (st. state), 0.67 (all av.)	~0.55	0.42 (daily av.)	~0.33 (season av.)	1-1.1 (one day basis)	0.66 (av.11:00-13:30)	0.63 (averaged)	NA	NA	0.5-0.6 (mean measured)
# overall system COP	0.31 (st. state), 0.11 (daily)	~0.07	0.11	~0.07 (season av.)	0.33-0.44 daily basis	0.47 (average) electricity included	NA	3.8 elec., COP th. ~0.8	NA	NA
- Solar fraction (%)	70.8 (daily average)	NA		56 (average)	38 (cooling mode)	(designed for 100%)	NA	NA	NA	NA

collector type and size and configuration, were taken into account.

According to the available data of collector type and area and use for a small size chiller (smaller than 10 kW), the study of [119] is the most similar to the current study (all hot water loop can be mixed at the tank) while the others: [31, 32, 133, 134], use the plate heat exchanger between collector and tank water. While [31] and [135] use 35 kW absorption chiller, the others use about 4.5 kW with smaller collector area. Among these comparable systems, the comparison results show that, with biomass gasifier-boiler as auxiliary heat source, the proposed system outperforms the others, in terms of both chiller and overall system coefficient of performance.

7. Conclusion

The performance of a solar biomass hybrid air conditioning system was evaluated by an experimental study. The experimental system was tested for three modes of operation: conventional solar cooling with electrical heater, proposed system and solar solely system. The experimental results show that the developed solar-biomass hybrid absorption cooling system is promising. The experimental data demonstrate that the system was operated at about 75% of nominal capacity a COP about 0.6 was achieved. The results show that the proposed system can be operated with higher reliability than the conventional solar solely cooling system. However it can not be used when there are not enough or fluctuating solar energy, especially in rainy season, and at night time. Finally, the results show that the average COP and COP_{sys} of the proposed system outperform the conventional systems.

8. Acknowledgement

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