Jurnal Intelek (2015) Vol 9(2): 14-20 © PJIM&A, UiTM Perlis

Effect of Solar Fraction on the Economic Performance of a Solar Air-Conditioning by an Adsorption Chiller

*F. Basrawi[1], K Habib[2], H. Ibrahim[1], GC Lee[1]

[1]*Universiti Malaysia Pahang, Faculty of Mechanical Engineering, 26600 Pekan Pahang*
[2]*University Technology Petronas, Department of Mechanical Engineering, Bandar Seri Iskandar,*
31750 Tronoh, Perak

mfirdausb@ump.edu.my

Abstracr

Solar cooling is a promising way for a sustainable air-conditioning system. However, since solar has intermittent output, it is usually backed-up by a conventional heater. Thus, it still needs electricity or fossil fuel to operate stabily. This study presents the effect of ratio of heat delivered by solar to the total heat delivered to an adsorption chiller (solar fraction) on the economic performance of a solar cooling system. This cooling system need covers cooling demand for an office building in a tropical region (Kuala Lumpur). Cooling demand was simulated using well-known energy analysis software for building, Equest. Flat-plate collectors and an adsorption chiller were the main component of the cooling system. Flat-plate collecters were simulated using another software, Watsun, and the adsorption chiller was based on our simulation model that is comparable with other studies. Economic performance was analyzed by life cycle cost analysis. Solar fraction of 0.33, 0.74 and 0.98 were studied. It was found that none of the solar fraction studied can generate Net Profit under subsidized electricity. It was also found that a natural gas boiler is a better solution than an electric heater as an auxiliary heater in term of economic. For a natural gas boiler, Net Profit increased when solar fraction decreased; the highest one was solar fraction of 0.33 with US$15,600. However, since more energy is used for the auxiliary heater in lower solar fraction, more emissions is expected to be released. Thus, emissions for all solar fraction need to be considered and studied further.

Keywords: Solar Cooling, Adsorption Chiller, Solar Fraction, Economic

Introduction

Solar cooling system is an attractive way for air conditioning because it can reduce operational cost, and it is also environmental friendly. There are two main pathways for solar air-conditioning, either using absorption chiller or adsorption chiller. The former is more common because it has higher COP and slightly of lower price, but it requires higher regeneration temperature. The later is comparatively less used because it has lower COP and slightly of higher price, but it can operate at lower temperature. This study focuses on the adsorption chiller because it has lower regeneration temperature that lower price flat-plate collecter can provide.

Normal temperature range that adsorption chiller can operate between 60 to 99 °C. Hot water at that temperature range needs to be supplied by the flat-plate collector. Although the tropical region receives solar radiation over a long period throughout the year, the insolation received on the earth surface fluctuates due to day/night and sunny/cloudy cycle. Thus, an auxiliary heater that consumes fossil fuel or electricity needs to be operated to increase the water temperature. The use of a larger collector can reduce the use of an auxiliary heater, but this will increase the capital cost. However, if the collector is too small, more fossil fuel/electricity needs to be consumed and this will increase the operational cost and in contrast will create more emissions than conventional air-conditioning.

Many studies have been done on the design of adsorption chiller (Qian et al., 2013; Ahmed et al., 2012; Yuriy et al., 2012), analysis on the performance of adsorption chiller (Hamid et al., 2012; Lu et al., 2013; Spencer et al., 2013), but only a few studies have been carried out on the economic performance of an adsorption chiller. Bruno et. al clarified that when flat-plate collector is used, adsorption chiller is more suitable than absorption chiller (Bruno et al., 2006). T. Tsoutsos clarified that solar adsorption chiller is marginally competetive with a conventional vapour compression chiller in Greece (Tsoutsos et al., 2003).

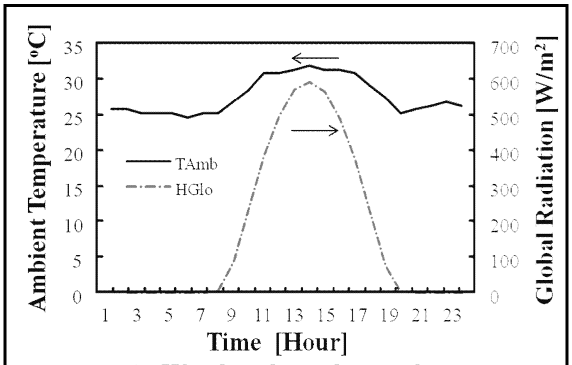
M. A. Lambert concluded that an adsorption chiller is appropriate with a location that has less subsidized electricity rate (Lambert et al., 2007). However, from the literature reviewed there is no study focusing on the effect of solar fraction on the performance of solar cooling by adsorption route. Thus, the objective of this study is to investigate the effect of solar fraction on the economic performance of solar cooling system by adsorption route. Cooling load of an office building in Kuala Lumpur was simulated using Equest. The amount of heat and its temperature were then calculated using the load required and performance of the adsorption chiller. Then, the load was covered with a flat-plate solar thermal collecter with various area (solar fraction). Performance of each solar fraction was calculated and compared using Life Cycle Cost Analysis.

Materials and Methods

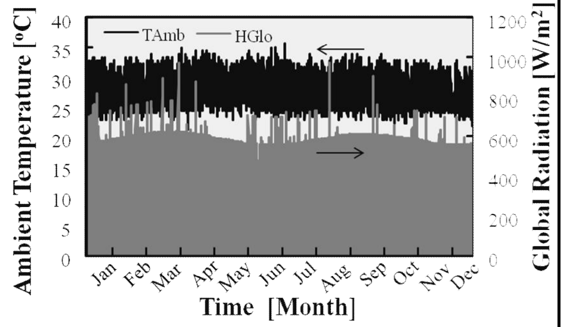
Location and Climatic Data

The location of study is the capital city of Malaysia, Kuala Lumpur, at 3.1357 ° N, 101.6880 ° E. The weather data used was hourly weather data from ASHRAE International Weather for Energy Calculation (IWEC).

Figure 1 shows the ambient temperature and global radiation data for a day and a year. It was found that hourly average ambient temperature is around 24-35 ^{o}C and hourly average solar radiation is 450-1000 W/m^2. It was also found that radiation varies slightly, lower in May, then increased towards peak in August, decreasing again towards November, and increasing again towards February.



(a) Weather throughout a day



(b) Weather throughout a year

Figure 1: Ambient temperature and global radiation data

Table 1 Parameters of the simulated office building

Building shape		Rectangle
Building rientation		North
Running Hours	hour	9 (8:00-17:00)
Wall layer		Plaster-Clay Brick-Plaster
Width	m	9.14
Gross Area	m^2	167
Building Area	m^2	183.5
Wall height	m	2.7
Ground floor ceiling to first floor height	m	0.91

Building Cooling Load

A two-storey office building was simulated using Equest to obtain the cooling load. Parameters of the simulated building are shown in Table 1. There was no insulation material used for the wall and ceiling because this is the actual practice.

Adsorption Chiller

The adsorption chiller used was a double bed silica gel-water with maximum cooling capacity of 16 kW. Parameters used are shown in Table 2. Since an adsorption chiller is commonly used when the ambient temperature is hot (cooling), the heat sink is usually almost constant. Thus, its performance can be simply estimated by only using the regeneration temperature (Basrawi et al., 2010; Basrawi et al., 2013). Figure 2 shows the relation between regeneration temperature with cooling capacity and COP of the adsorption chiller model.

Table 2 Parameters of the adsorption chiller

Mass of the adsorbent, m_a	kg	40
Heat transfer coefficient and Area of the bed, UA_{bed}	kW/K	3.50
Heat transfer coefficient and Area of the evaporator, UA_{eva}	kW/K	4.87
Heat transfer coefficient and Area of the condenser, UA_{con}	kW/K	15.33
Mass of the condenser, m_{con}	kg	24.28
Mass of the evaporator, m_{eva}	kg	12.45
Specific heat of the adsorber, $C_{p,a}$	kJ/kgK	0.96
Latent heat of working fluid, h_{fg}	kJ/kg	2800
Specific heat of the heat exchanger, $C_{p,hex}$	kJ/kgK	0.95

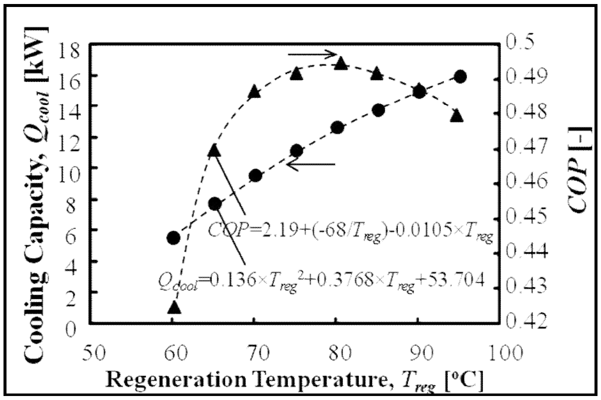


Figure 2: Relation between regeneration temperature with cooling capacity and COP

Solar Water Heater

The schematic diagram of the overall system is shown in Figure 3. Solar energy is collected by the flat-plate collector and stored in the hot water tank through a heat exchanger. Then, heat is supplied to the adsorption chiller through a heat exchanger. If heat from the solar water heater is insufficient to achieve the desired cooling, the auxiliary heater will operate. It should be noted that the efficiency of heat exchangers and auxiliary heater were assumed to be 0.8 constant.

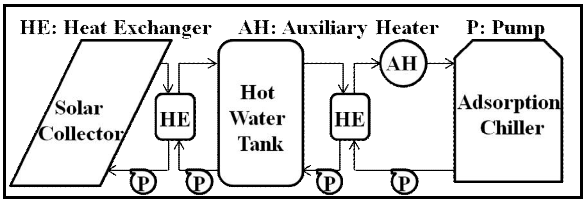


Figure 3: Schematic diagram of the solar water heater

Three different solar fractions of 0.33 to 0.98 were studied as shown in Table 3. Other parameters including panel area, pump flow rate, pipe length and hot water tank volume vary depending on the solar fraction.

Table 3: Parameters for different solar fraction

Solar Fraction	Panel Area (No of panel)	Pump flow rate	Pipe length	Tank Volume
-	m^2(Unit)	kg/s	m	m^3
0.33	19.9 (10)	0.44	52	1.0
0.74	39.8 (20)	0.88	80	2.0
0.98	59.7 (30)	1.32	108	3.0

Flat-Plate Collector

The significant part of the solar water heater is the solar heat collector. Diagram of the single glazed flat-plate collector is shown in Figure 4. Test data of a commercial flat-plate was used as the model of the collector. Table 4 shows the basic parameters of the flat-plate collector. It was a glazed collector with an area of 1.99 m^2 each with mass flow rate of 0.044 kg/s.

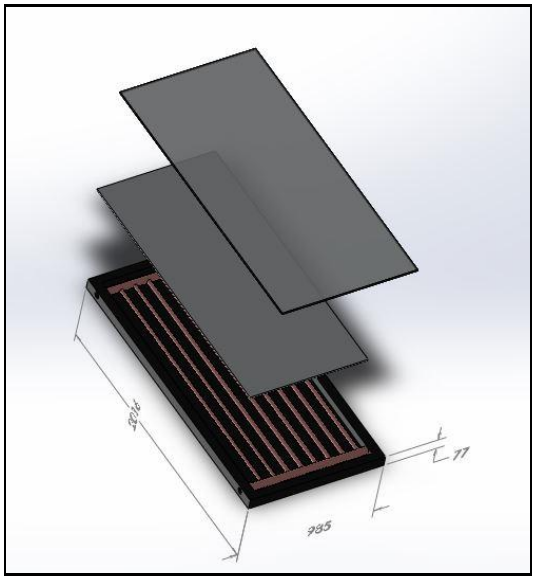


Figure 4: Flat-plate collector diagram

Table 4 :Basic parameters of the flat-plate collector

Type		Glazed flat-plate
Dimension	m	2.016×0.985×0.077
Groos Area	m^2	1.99
Dry Weight	kg	34
Nominal flow rate	kg/s	0.044
Tilt angle	°	10

Solar Fraction and Life Cycle Cost Analysis

Heat from solar and auxiliary heater is supplied to the adsorption chiller for air-conditioning purpose. Solar fraction is defined as the ratio of solar energy to the total energy delivered. Solar fraction *SF* can be calculated by the following equations:

$$SF=\frac{Q_{SWH}}{Q_{del.}}=\frac{Q_{del.}-Q_{AH}}{Q_{del.}} \quad (1)$$

where Q_{SWH} is heat from solar water heater [kW], $Q_{del.}$ is heat load delivered [kW] and Q_{AH} is heat from auxiliary heater [kW].

Life cyle cost analysis which consider time value of money was used to evaluate the economic performance of the solar cooling system. All cashflow throughout the life cycle were calculated based on present worth. Net Profit *NP* gained for 25 years of life cycle of the investment on the energy system can be expressed as the following equation:

$$NP = Rev_{elec.sav.} - \left(C_{eq} + C_{ins} + C_{AH-ener.}\right) \qquad (2)$$

where $Rev_{elec.\ sav.}$ is revenue from electricity saving [US$], C_{eq} is the equipment cost [US$], C_{ins} is the installation cost [US$], and $C_{AH\text{-}ener.}$ is cost of energy for the auxiliary heater [US$]. The cost of installation was assumed to be 10 % of the total cost, and energy for the auxiliary heater can be electricity or natural gas.

Revenue from electricity saving and cost of energy for auxiliary heater are series of cashflow in the future. To get their presesent values, Present Worth Factor (*PWF*), therefore must be calculated. *PWF* can be calculated by the following equation:

$$PWF_x = \frac{\left(1+i\right)^n - 1}{i\left(1+i\right)^n} \qquad (3)$$

where *i* is the interest/discount rate [-] and *n* is the lifetime [year]. Interest rate, lifetime and other parameters used for the life cycle cost calculation are shown in Table 5. Moreover, capacity and unit for every solar fraction for all equipment are shown in Table 6.

Table 5: Parameters used for the life cycle cost analysis

Exchange rate		1 US$=RM3
Electricity Tariff	US$/kWh	First 200kWh, 0.145 After 200kWh, 0.170
Gas Tariff	US$/m3	0.197
Lifetime	year	25
Interest rate	-	0.035
	Initial cost	
Adsorption chiller	US$/kW	800
Flat-plate collector	US$/m^2	300
Heat Storage	US$/m^3	5500
Electric Heater	US$/kW	125
Gas boiler	US$/kW	90
Water pump	US$/(m^3/h)	100
Pipeline	US$/m	50

(Bruno et al., 2006; Basrawi et al., 2014)

Table 6 :Capacity and unit for every solar fraction

		0.33	0.74	0.98
Adsorption chiller cooling capacity	kW	16	16	16
Solar collector area	m^2	19.9	39.8	59.7
Heat storage volume	m^3	1	2.0	3.0
Auxiliary heater heating capacity	kW	19.2	13.1	13.1
Water pump flow rate	m^3/h	1.5	3.2	4.8
Pipeline length	m	52	80	108

Results and Discussion

Heat Balance of the System

Figure 5 shows the heat balance between heat demand/delivered, heat from solar and auxiliary energy for 1st February. Result for solar fraction from 0.33 to 0.98 are shown from Figure 5 (a) to Figure 5(c). As shown in the figure, as the solar fraction increased, the portion of heat from solar increased, whereas the auxiliary energy decreased. However, heat balance is not totally matched especially for solar fraction of 0.98, where heat from solar is higher that heat demand. This is because of the existence of preheat tank where heat is stored, and also the targeted temperature in which the quality of the heat is also considered.

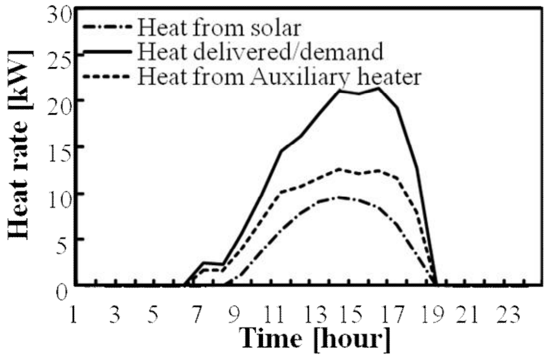
Thus, heat from solar is sometimes higher and sometimes lower than the heat demand/delivered.

The result of heat balance throughout the year is shown in Figure 6. It has similar trend with the result for a single day, auxiliary energy decreased when solar fraction increased. It also further shows there is slight fluctuation of auxiliary energy, due to variation of solar radiation throughout the year. Even the highest solar fraction (*SF*=0.98) still needs auxiliary energy from March to September in which the solar radiation is comparatively lower.

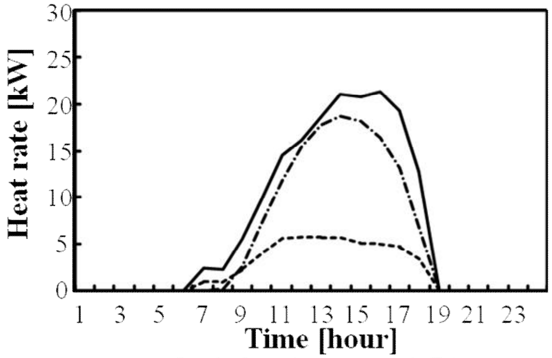
Life Cycle Cost of the system

The net profit throughout the life cycle cost analysis is shown in Figure 7. The left side of figure represents the case when an electric heater was used as the auxiliary heater, whereas the right side of the figure represents the case when a natural gas fired boiler was used. Since electricity is heavily subsidized in Malaysia, unsubsidized electricity priced which is 2 times higher was also considered for each solar fraction.

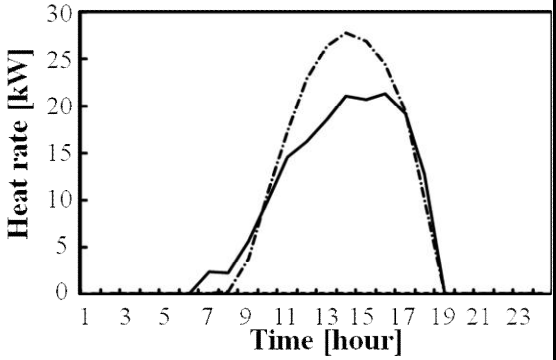
As shown on the top of Figure 6, none of the solar fraction can generate Net Profit under subsidized electricity price. High capital cost of adsorption chiller and solar collector is the main factor that makes installation of Solar Cooling System is still unattractive at the moment. The government needs to provide incentive or subsidy for installation of the Solar Cooling System.



(a) Solar fraction=0.33

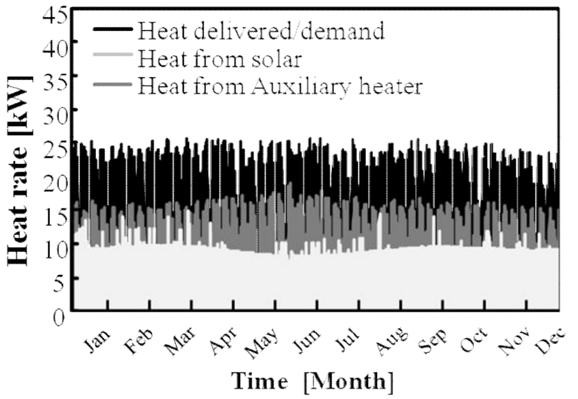


(b) Solar fraction=0.74

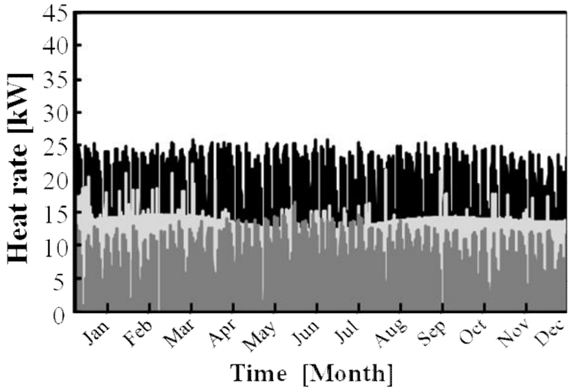


(c) Solar fraction=0.98

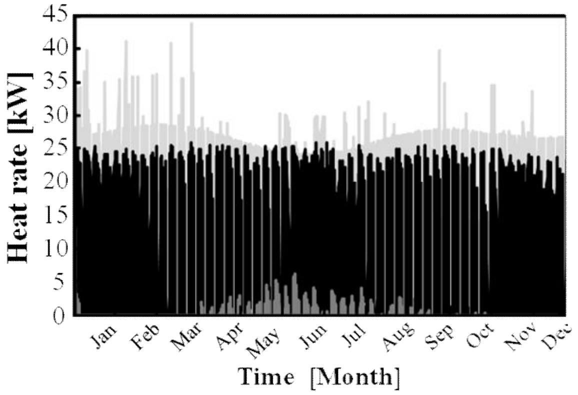
Figure 5: Heat balance throughout a day for different solar fraction



(a) Solar fraction=0.33

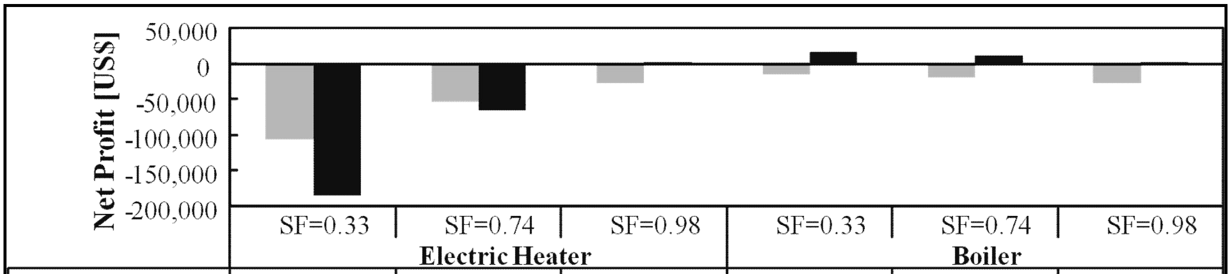


(b) Solar fraction=0.74



(c) Solar fraction=0.98

Figure 6: Heat balance throughout a year for different solar fraction



	Electric Heater SF=0.33	Electric Heater SF=0.74	Electric Heater SF=0.98	Boiler SF=0.33	Boiler SF=0.74	Boiler SF=0.98
▨ Subsidized	-107,580	-53,881	-27,915	-14,410	-19,047	-27,287
■ Unsubsidized	-184,919	-65,110	2,675	15,593	10,956	2,717

Figure 7: Result of Life Cycle Cost Analysis

When unsubsidized electricity price was considered, all solar fraction for a natural gas boiler, and an electric heater with solar fraction of 0.98 can generate Net Profit. This shows that a boiler is a better auxiliary heater than electric heater because the gas price is cheaper than electricity.

When an electric heater was used, Net Profit increased when solar fraction increased. This is because less operational cost (electricity for back-up heater) needed for the solar cooling system. Solar Cooling System can only generate Net Profit with an electricity heater under unsubsidized electricity price at solar fraction of 0.98.

When a boiler was used, Net Profit increased when solar fraction decreased. This is because the difference of fuel cost reduced and initial cost required between solar fraction of 0.30-0.98. When solar fraction increased, since initial cost increased was higher than fuel cost saved, Net Profit decreased. The highest Net Profit was US$ 15,593 at the solar fraction of 0.33.

Although the LCC analysis result shows that using a boiler at lower solar fraction is the best option in terms of economic performance, lower solar fraction means that more fossil fuel needs to be burned and the solar cooling system is expected to release more emissions as compared to the conventional system. Thus, further study on the effect of solar fraction on the environmental performance of the solar cooling system needs to be carried out.

Conclusions

I. Solar Cooling by adsorption chiller can cover the cooling demand of the office building throughout the year.

II. None of the solar fraction can generate Net Profit under subsidized electricity price. Thus, solar cooling system is not attractive because of the high capital cost of the adsorption chiller and solar heat collector.

III. A boiler is a better auxiliary heater than electric heater because the gas price is cheaper.

IV. When unsubsidized electricity price was considered, all solar fraction for a natural gas boiler, and an electric heater with solar fraction of 0.98 can generate Net Profit.

V. When a boiler was used, Net Profit increased when solar fraction decreased. The highest Net Profit was US$15,600 at the solar fraction of 0.33.

VI. However, more fossil fuel need to be burned and therefore more emissions is released. Thus, further investigation on the effect of solar fraction on the environmental performance need to be carried out.

Acknowledgment

The authors would like to thank Universiti Malaysia Pahang for the financial support under RDU1203101.

References

Ahmed, R., M., R., Raya, K., A. (2012). Physical and operating conditions effects on silica gel/water adsorption chiller performance. *Applied Energy*, 89, 921-929.

Basrawi, F., Yamada, T., Obara, S. (2014). Economic and environmental based operation strategies of a hybrid photovoltaic–microgas turbine trigeneration system. *Applied Energy*, 121, 174-183.

Basrawi, F., Yamada, T., Nakanishi, K., Naing, S. (2010). Effect of ambient temperature on the performance of micro gas turbine with cogeneration system in cold region. *Applied Thermal Engineering*, 31, 1058-167.

Basrawi, F., Yamada, T., Obara, S. (2013). Theoretical analysis of performance of a micro gas turbineco/trigeneration system for residential buildings in a tropical region. *Energy and Buildings*, 67, 108-117.

Bruno, J., C., Lopez, J., Ortiga, J., Coronas, A. (2006). Techno-economic design study of a large-scale solar cooling plant integrated in a district heating and cooling network. *61st ATI National Congress- International Session "Solar Heating and Cooling"*, 227-232.

Hamid, N., Talebian, H., Mahdavikhah, M. (2012). Bed geometrical specifications effects on the performance of silica/water adsorption chillers. *International Journal of Refrigeration*, 35, 2261-2274.

Lambert, M. A., Beyene, A. (2007). Thermo-economic analysis of solar adsorption heat pump. *Applied Thermal Engineering*, 27, 1593-1611.

Lu, Z., S., Wang, R., Z., Xia, Z., Z., Lu, X., R., Yang, C., B., Ma, Y., C., Ma, G., B. (2013). Study of a novel solar adsorption cooling system and a solar absorption cooling system with new CPC collectors. *Renewable Energy*, 50, 299-306.

Qian, S., Gluesenkamp, K., Hwang, Y., Radermacher, R., Chun, H. (2013). Cyclic steady state performance of adsorption chiller with low regeneration temperature zeolite. *Energy*, 60, 517-526.

Spencer, J., D., Moton, J., M., Gibbons, W., T., Gluesenkamp, K., Ahmed, I., I., Taverner, A., M., McGahagan, D., Tesfaye, M., Gupta, C., Bourne, R., P., Monje, V., Jackson, G., S. (2013). Design of a combined heat, hydrogen, and power plant from university campus waste streams. *International Journal of Hydrogen Energy*, 38, 4889-4900.

Tsoutsos, T., Anagnostou, J., Pritchard, C., Karagiorgas, M., Agoris, D. (2003). Solar cooling technologies in Greece. An economic viability analysis. *Applied Thermal Engineering*, 23, 1427-1439.

Yuriy, I., A., Ivan, S., G., Ilya S., G., Lambert, M. A., Beyene, A. (2012). Optimization of adsorption dynamics in adsorptive chillers: Loose grains configuration. *Energy*, 46, 484-492.