ARID ZONE JOURNAL OF ENGINEERING, TECHNOLOGY & ENVIRONMENT
AZOJETE December 2019. Vol. 15(4):837-846
Published by the Faculty of Engineering, University of Maiduguri, Maiduguri, Nigeria.
Print ISSN: 1596-2490, Electronic ISSN: 2545-5818
www.azojete.com.ng

ORIGINAL RESEARCH ARTICLE

EVALUATION OF ENERGY CONSUMPTION AND CARBON DIOXIDE EMISSION FROM A SOLAR / GAS POWERED ABSORPTION AIR CONDITIONING SYSTEM IN ZARIA

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ARTICLE INFORMATION

Submitted 14 September, 2018
Revised 21 January, 2019
Accepted 28 January, 2019

Keywords:
Absorption cooling
Energy
Carbon dioxide
Refrigerant
energy efficiency ratio

ABSTRACT

Electrically powered vapour compression chillers consume high power and make use of synthetic refrigerants which when released have negative effect on the environment. In this study, the energy consumption and carbon dioxide (CO_2) emission from an absorption air conditioning system were evaluated. The experimental scale absorption air conditioning system has its thermal energy requirement supplied by the solar collector system and liquefied petroleum gas. The air conditioning system was operated for ten experimental days, in both solar and gas heating modes. Daily power consumption by the system was measured. The daily CO_2 emitted by the system was evaluated using the daily gas consumption. These were compared to electric power consumption and CO_2 emission from conventional chillers of varying energy efficiency ratio (EER). Results showed that the absorption cooling system has reduced power consumption in the range of 31.5% to 64.2% as compared to conventional vapour compression chiller of varying EER. Also, CO_2 emission was seen to have been reduced. This reduction was within the range of 13.3% to 43.2% when compared to that from conventional vapour compression chiller of low to average EER.

1.0 Introduction

The energy demand for refrigeration and air conditioning has increased over the years especially in developing countries. This is attributed to increasing need to prevent food spoilage as well as increasing indoor comfort demands (Kalkan et al., 2012). Usually, electrically powered vapour compression systems are used in refrigeration and air conditioning units. However, these vapour compression systems consume high electric power, which leads to high electricity bills (Henning, 2007). Also, these units operate with synthetic refrigerants such as hydro – chlorofluorocarbons (HCFCs) which when released into the atmosphere constitute high ozone depleting potential (ODP) (Sarbu and Sebarchievici, 2015). HCFCs are also known to exhibit high global warming potential (GWP) of up to 2000 times that of carbon dioxide (CO_2), which has a GWP of 1 (Nair-Bedouelle et al., 2014). As agreed in the Montreal protocol, the schedule for the phase out of production and consumption of HCFCs in developing nations is: 2015: reduction of HCFC consumption by 10%, 2020: reduction of HCFC consumption by 35%, 2025: reduction of

HCFC consumption by 67.5%, 2030: total phase out (Nair-Bedouelle et al., 2014). With the phase out of HCFCs under the Montreal protocol on substances that deplete the ozone layer, the introduction of alternatives with not only zero ODP but also low GWP and improved energy efficiency is becoming an issue of increasing importance, especially in developing countries (Nair-Bedouelle et al., 2014). Most vapour compression systems commonly use chlorofluorocarbons (CFCs) and hydro – chlorofluorocarbons (HCFCs) refrigerants, which cause depletion in the ozone layer. The replacements, which are hydrofluorocarbons (HFCs) have zero ODP, but high GWP (Benhadid – Dib, 2012). A number of other available refrigerants that could serve as replacements have properties that prevent them from being unconditionally adopted (Nair-Bedouelle et al., 2014). Thermally driven absorption air conditioning systems have the ability of working with low grade energy such as waste heat or solar energy. They consume low electric power and have the ability to work with refrigerants with no harmful effect on the environment, such as water (Henning, 2007). Water, when used as a refrigerant has zero ODP (Benhadid – Dib, 2012). It is expected that the absorption air conditioning system can serve the purpose of providing cooling with less harmful emissions to the environment and achieve high energy efficiency. In this regard, several researchers have carried out works on absorption air conditioning in recent years. Balghouthi et al., (2012) using a solar absorption air conditioning facility of 16 kW capacity located in Tunisia, achieved solar fraction between 0.54 to 0.77. Also, the facility was able to avoid CO_2 of about 3000 kg from being emitted into the atmosphere during the cooling season. Al – Alili et al. (2012), in Abu Dhabi, using a 10 kW NH_3/H_20 solar absorption air conditioning system consumed 47% less electrical energy, with 12 metric tonnes/ year of CO_2 emission reduction. Rosiek and Batlles (2012), in Spain, using a 70 kW absorption chiller reduced the electricity consumption by 31% and led to a CO_2 savings of 833kg. Sun et al. (2015) experimented on a solar and gas fired absorption system for cooling and heating in China. A 49.7% energy savings ratio was achieved. Zhai et al. (2015) experimented on a mini type solar absorption air conditioning system of 8 kW capacity in China. The system was found to consume 27% less power than a conventional chiller of same capacity. This study is aimed at reducing the power consumption and CO_2 emission associated with the use of conventional vapour compression chillers, as well as experiment the use of water as refrigerant. This was carried out by evaluating the power consumption as well as CO_2 emission from an experimental scale solar/ gas hybrid absorption air conditioning system of 3 kW cooling capacity, operating under Zaria weather conditions. The power consumption and CO_2 emission were compared to those of conventional chiller of varying energy efficiency ratio (EER) which uses conventional refrigerants.

2.0 Materials and Methods

Tests were conducted on an experimental scale solar/ gas hybrid powered absorption air conditioning system, developed at the Department of Mechanical Engineering, Ahmadu Bello University, Zaria, Nigeria.

2.1 Materials

The entire fabricated system consists of: An absorption chiller: This is of 3 kW cooling capacity, which works on the lithium bromide water pair, where water serves as the refrigerant. A solar collector: This uses solar radiation to generate the thermal energy required for the hot water. A

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gas burner: This is powered by liquefied petroleum gas and provides thermal energy required in cases of low solar radiation. A storage tank: This is used to store the hot water. A wet cooling tower: waste heat is rejected from the absorption chiller to the cooling tower. An indoor fan coil unit: This is used to distribute cooled air to the test room.

The following instruments were used in taking measurements during the experiment:

i. Digital solar power meter: model no.: DBTU 1300, measuring range: 0 – 2000 W/m^2, accuracy: $\pm$ 5% of reading

ii. Digital thermocouple thermometer: model no.: T407291, measuring range: -50 – 1300°C, accuracy: 0.1%+1°C

iv. Watt meter: model no.: H3680W, measuring range: 0 – 3680W, accuracy class: 1.0

v. Digital weighing scale: model no.: SF – 400, measuring range: 0 – 7000g, accuracy: $\pm$ 1g

2.2 Method

2.2.1 Experimental Procedure

Tests were conducted on selected days in the months of April and June 2017. Each day spanned from 9:00 am to 5:30 pm. The experimental procedure employed is similar to that of Balghouthi et al. (2012). Two heating modes were employed to provide the thermal energy required to generate the hot water at the hot water tank: the solar power heating mode, provided via the solar collector and the gas burner heating mode, provided by liquefied petroleum gas burner. The hot water is required to desorb the refrigerant (water) from the lithium bromide solution in the absorption chiller. At the start-up of each experimental day, thermal energy was supplied to the water in the tank using the gas burner. This was because solar radiation is usually very low at the early hours of the day to attain heating to required water temperature. When the required temperature in the tank was attained (90°C – 99°C), the hot water pump was then turned on to circulate the hot water between the tank and the absorption chiller. When the temperature of the collector fluid increased to 80°C and above, the gas burner was disengaged, and the system was switched to solar heating mode. When temperature of the collector fluid drops below 80°C, the system was switched back to gas burner heating mode. Chilled water was produced at the evaporator in the absorption chiller and pumped using the chilled water pump to the fan coil unit in the test room which covers a total floor area of 9.21m^2. Heat generated at the absorption chiller was rejected to the cooling tower. Temperature readings were taken every fifteen minutes from sensors attached to the system components and test room. Solar power was measured using a solar meter. Gas consumed was measured by placing the gas burner on a weighing scale and taking measurements as a result of weight loss at intervals. Power consumption by the absorption chiller was measured using a Watt meter. Figure 1 shows a schematic of the experimental set up.

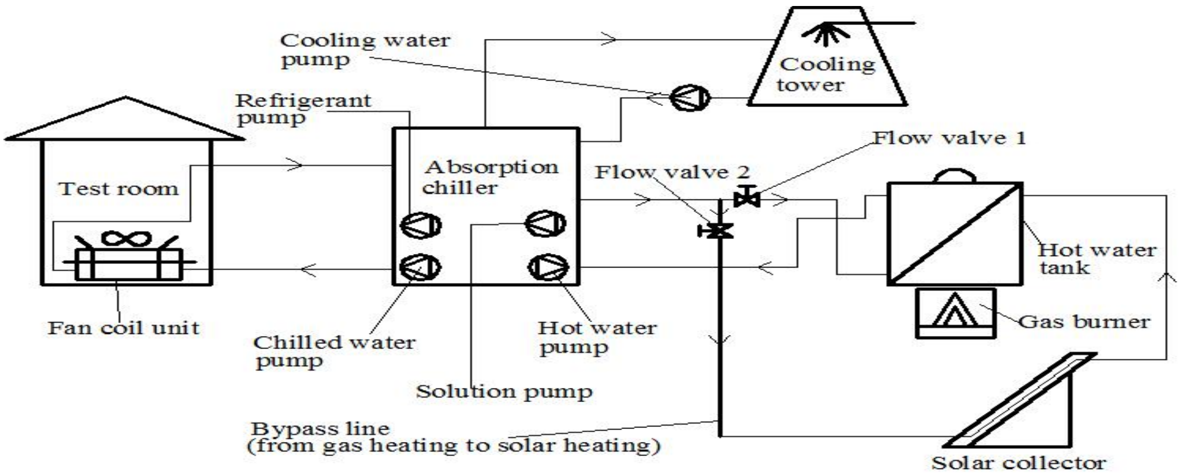

Figure 1: Schematic of the experimental set up

The experimental days in which the experiments were conducted were chosen so as to reflect varying weather conditions. This was done so as to test the performance of the system under varying weather conditions. Accordingly, the experimental days were classified as follows:

Hot clear sky day: days with very clear sky, high solar radiation, no rain.

Fairly clear sky day: days with intermittently clear sky and partly cloudy sky, average solar radiation, no rain.

Cloudy sky day: days with very cloudy sky, low solar radiation, no rain.

Rainy day: days in which rain occurred within any interval of the experimental day.

Figures 2 and 3 show components of the experimental absorption air conditioning system and section of the absorption chiller respectively.

Figure 2: Outdoor components: Solar collector, Hot water tank, gas burner, cooling tower

Figure 3: Section of the absorption chiller

2.2.2 Evaluating solar fraction

The solar fraction was calculated as a ratio of the number of hours of the day in which the system was powered in the solar heating mode to the total hours of operation of the day.

2.2.3 Measuring gas consumption

The weight of gas consumed at an interval of time was determined by weight difference over the time interval using a digital weighing scale. The gas consumption in kW(P_{gas}) was computed using equation 1 as:

$$P_{gas} = \frac{mCal_g}{t} \quad (1)$$

where:

m is the weight of the gas consumed in the time interval (kg)

Cal_g is the calorific value of liquefied petroleum gas taken as 46.1MJ/kg (Demirel, 2012)

t is the time interval (seconds) for which the gas was used.

The gas consumption in kWh was obtained by multiplying the gas consumed in kW by the period in which the system was operated in gas burner heating mode (hours).

2.2.4 Evaluating CO_2 emission

According to Balghouthi et al., (2012), 680g of CO_2 are emitted into the atmosphere for every kWh of electricity produced by fossil fuel fired power plant. That is 0.68 kg CO_2 emitted/kWh electricity produced. Also 0.2 kg of CO_2 is emitted into the atmosphere for every kWh of LPG gas consumed. That is 0.2 kg CO_2 emitted/kWh LPG gas consumed.

The mass of CO_2 emitted to the atmosphere on using conventional chiller was computed according to Balghouthi et al., (2012) using equation 2 as:

$$CO_{2(c)} = \text{power consumed}_{(c)}(\text{kW}) \times \text{hours of operation (h)} \times \text{no. of days} \times f_e(\text{ kg/kWh }) \quad (2)$$

The mass of CO_2 emitted to the atmosphere on using the experimental absorption cooling plant was computed using equation 3 as:

$$CO_{2(a)} = \left(\text{power consumed}_{(a)}(\text{kW}) \times \text{hours of operation (h)} \times \text{no. of days} \times f_e(\text{kg/kWh})\right) + (f_g(\text{kg/kWh}) \times \text{gas consumed(kWh)}) \quad (3)$$

where:

f_e is a conversion factor for CO_2 emitted using fossil fuel (0.68 kg CO_2/kWh)

f_g is a conversion factor for CO_2 emitted burning LPG gas (0.2 kg CO_2/kWh)

$\text{power consumed}_{(a)}(\text{kW})$ is the measured power consumption of the absorption cooling plant which was 0.5 kW. This comprises the power consumption of the pumps and fan.

$\text{power consumed}_{(c)}(\text{kW})$ is the power consumption by conventional vapour compression chiller of varying energy efficiency ratio (EER), calculated using Equation 4:

$$\text{power consumed}_c(\text{kW}) = \frac{\text{Cooling output}}{\text{EER}} \quad (4)$$

The energy efficiency ratio (EER) is the ratio of cooling output from the chiller to the power consumed by the chiller. Average allowable EER specifications for conventional vapour compression chillers manufactured in different countries according to Phadke et al. (2014), was used. Consequently, the power consumption for conventional vapour compression chillers resulting from the different EERs was computed for a 3 kW cooling capacity chiller using Equation 4.

For the whole experimental days, the absorption cooling plant was able to achieve an average cooling power of 1.5 kW, while an average space cooling temperature of 24°C was attained.

2.2.5 Electric power consumed by the absorption cooling system (kWh)

This was obtained by multiplying the power consumed by the absorption cooling system (kW) by the hours of operation (h). The system was operated for eight hours in each of the experimental days.

3. Results and Discussion

In this section, results from the evaluation of energy consumption and CO_2 emission by the absorption cooling system are presented. Comparison is made between the absorption system and conventional vapour compression system in terms of energy consumption and CO_2 emission.

Following the classification of the experimental days done in section 2.2.1, accordingly, the days were classified as follows:

Hot clear sky: April 22, June 6, 2017

Faily clear sky: June 3, June 8, 2017

Cloudy sky: June 12, June 18, June 19, 2017

Rainy day: June 7, June 13, June 17, 2017

Table 1 shows the average solar radiation, solar fraction and hours of electricity consumption for the experimental days.

Table 1: Average solar radiation, solar fraction and hours of electicity consumption for Experimental Days

	Apr-22	Jun-03	Jun-06	Jun-07	Jun-08	Jun-12	Jun-13	Jun-17	Jun-18	Jun-19
Av. Solar radiation (W/m^2)	967	751	918	95	785	574	206	158	568	513
Solar fraction	0.6	0.34	0.51	0	0.27	0	0	0	0	0
Hours of electricity consumption	8	8	8	3	8	8	5	4	8	8

The solar fraction is the fraction of thermal energy requirement for the day that was supplied by the solar collector. From Table 1, it can be observed that the days of April 22 and June 6 which were classified as hot clear sky days recorded average solar fractions above 900 W/m^2. This resulted in the relatively higher solar fractions of 0.6 and 0.51 recorded respectively on these days. Solar fractions of 0.34 and 0.27 were also recorded on June 3 and 8 respectively, which were classified as fairly clear sky days. The other days recorded no solar fraction as a result of the very cloudy or rainy nature of the days. From the Table, it can be seen that the hours of

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electricity consumption for five of the experimental days is eight hours. However, the days of June 7, 13 and 17 which were classified as rainy days all have lower hours of electricity consumption. This is because, during the hours in which the rain lasted, there was no cooling demand from the test room as the room was naturally cooled. The chiller was therefore shut down during these hours, thus there was no electricity consumption.

Figure 4 shows the energy consumption for the experimental days. It can be observed that the electricity consumption was regular at 4.0 kWh for the experimental days, except for the rainy days of June 7, 13 and 17 which had lower electricity consumption. This was because the chiller was run for fewer hours on the rainy days as seen earlier from table 1. Also, the gas consumption can be seen to be lowest at 4.09 kWh on April 22. This was due to the high solar radiation which resulted in high solar fraction, as seen earlier from Table 1. The cloudy days of June 12, 18 and 19 can be observed to have the highest gas consumption of 12.3 kWh. This was because the solar radiation was too low and the system thermal energy had to be provided by the gas burner throughout these days.

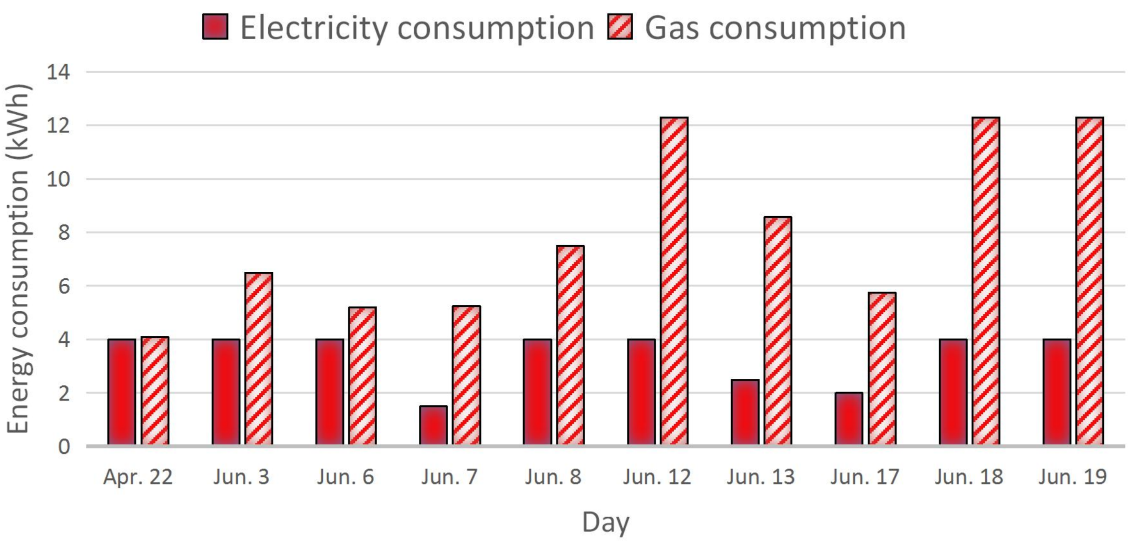

Figure 4: Energy consumption of the absorption chiller for the experimental days

Figure 5 shows the CO_2 emitted from the absorption cooling system for the experimental days. From the figure, it can be observed that the rainy days of June 7, 13 and 17 had the lowest CO_2 emissions of 2.07, 3.4 and 2.5 kg respectively. This was because the system was run for fewer hours on gas burner mode in these days. Also, the electricity consumption on these days was very low, thereby reducing the electricity component of CO_2 emission. The hot clear sky days of April 22 and June 6 also recorded relatively low CO_2 emissions of 3.5 and 3.7 kg respectively. This was due to high solar radiation availability which resulted in lower gas consumption. The cloudy sky days of June 12, 18 and 19 recorded the highest CO_2 emissions of 5.1 kg each. This was because gas was consumed throughout these days to provide the required thermal energy.

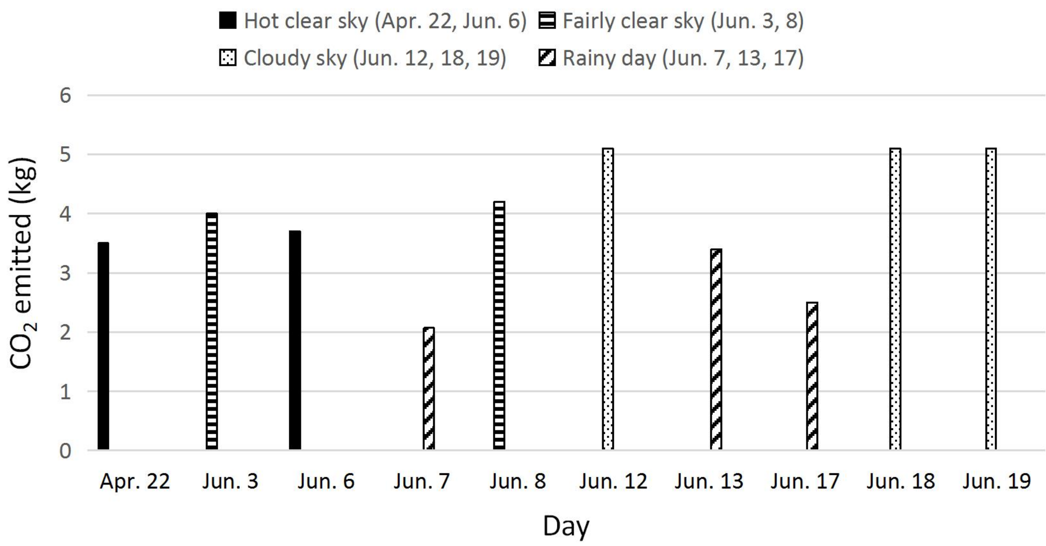

Figure 5: CO_2 emitted by the absorption cooling system for the experimental days.

Figure 6 compares the power consumption by the absorption cooling system with the power consumption by conventional vapour compression chillers of varying EER. From the Figure it is observed that the absorption system consumes power of 0.5 kW. This is much lower than the power consumed by the conventional chillers shown in the figure. While the chiller with EER of 2.14 consumes 1.4 kW, the chiller with EER of 3.16 consumes 0.9 kW and the chiller with EER of 4.1 consumes 0.73 kW. This implies the absorption cooling system has reduced power consumption in the range of 31.5% to 64.2% as compared to conventional vapour compression chiller of varying EER. Similar reduction in power consumption by absorption cooling system have been reported in the works of Alili et al. (2012) and Zhai et al. (2015).

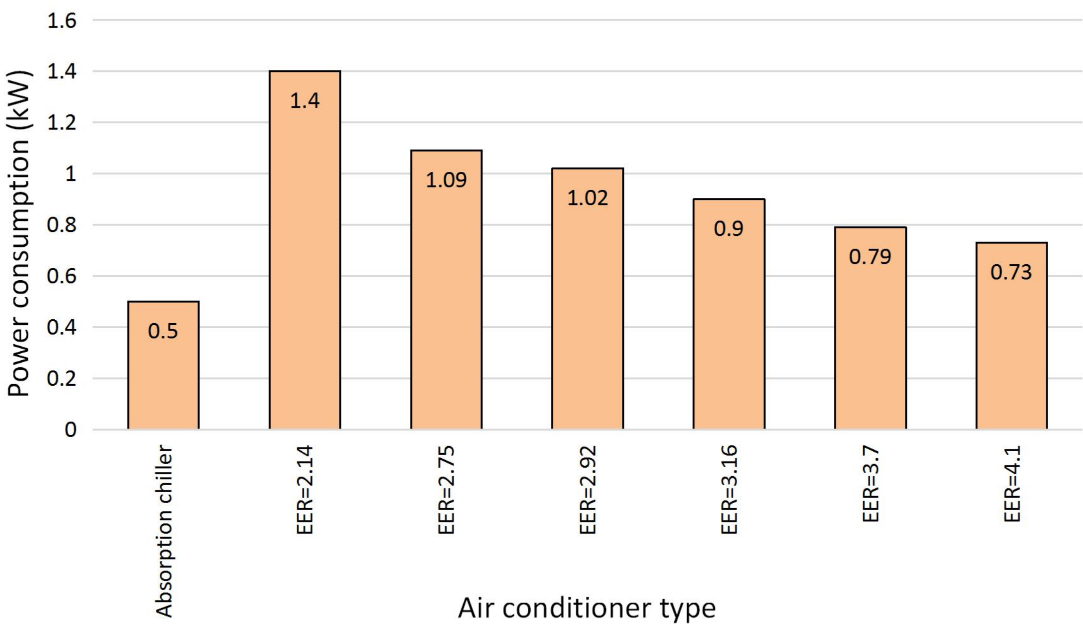

Figure 6: Comparison of power consumption by the absorption cooling system with that consumed by conventional vapour compression chiller of varying EER

Figure 7 compares the CO_2 emissions from the absorption cooling system with the CO_2 emissions from conventional vapour compression chiller of varying EER for the ten experimental days. It is seen that the absorption cooling system had a total CO_2 emission of 38.6 kg for the ten experimental days. This is observed to be lower than the CO_2 emissions from corresponding number of days from the chillers with low to average EER of 2.14, 2.75 2.92 and 3.16, which had CO_2 emissions of 68 kg, 53 kg, 50 kg and 44.5 kg respectively. It is observed to have about the same CO_2 emission with the chiller of high EER of 3.7 which had CO_2 emission of 39 kg. The CO_2 emission from the absorption chiller was however higher than that from the chiller with very high EER of 4.1, which had CO_2 emission of 36 kg. This could be attributed to the high gas consumption especially on cloudy days. This implies the absorption cooling system has CO_2 emission reduction within the range of 13.3% to 43.2% when compared to CO_2 emission from conventional vapour compression chiller of low to average EER. This is in agreement with CO_2 emission reduction by absorption cooling system as reported in the works of Balghouthi et al. (2012) and Rosiek and Batlles (2012). However, it has about the same CO_2 emission when compared to conventional vapour compression chiller with high EER. While the CO_2 emission from the absorption cooling system is higher than that from conventional vapour compression chiller of very high EER by 7.2%.

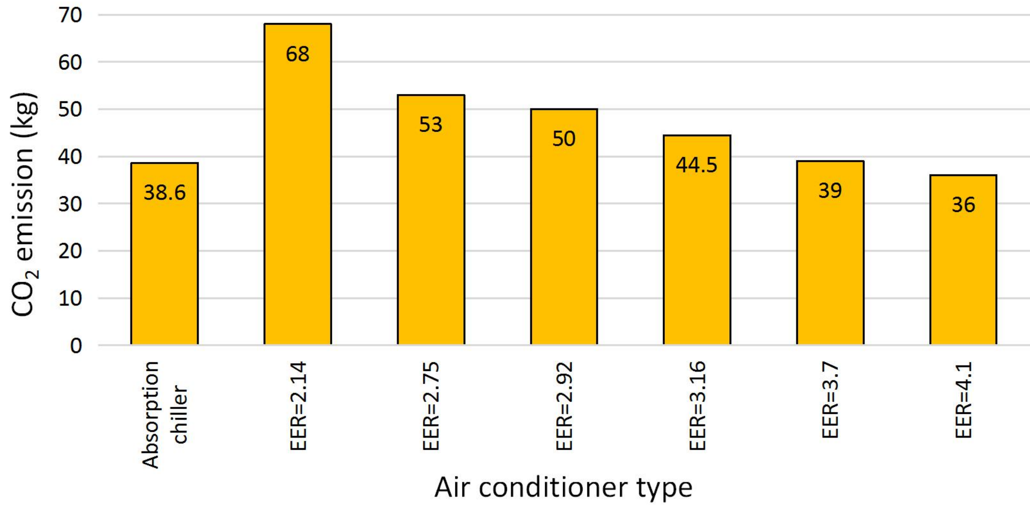

Figure 7: Comparison of CO_2 emission by absorption cooling system to CO_2 emission by conventional chiller of varying EERs

4. Conclusion

Electric power consumption, gas consumption and CO_2 emission from a solar/ gas powered absorption air conditioning system has been evaluated. Results from the ten experimental days showed the least gas consumption occurred on days with high solar fraction while the highest gas consumption occurred on days with very low or zero solar fraction. The absorption cooling system had reduced power consumption in the range of 31.5% to 64.2% as compared to conventional vapour compression chiller of varying EER. Also, CO_2 emission reduction within the range of 13.3% to 43.2% when compared to CO_2 emission from conventional vapour compression chiller of low to average EER were seen. CO_2 emission from the system was not significantly lower when compared to conventional vapour compression chiller with high EER and becomes higher when compared to that from chiller with very high EER. This implies the absorption cooling system offers the possibility of reduced electricity consumption, however, improvements to bring about reduced gas consumption which translates to further reduction in CO_2 emission are required.

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