Simulation of a Residential Solar Assisted Air Conditioning System in Malaysia

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Abstract- Simulation of a solar powered air conditioning system using flat-plate collectors for a 10.5kW (3 tons) nominal cooling capacity has been conducted. A design method called ϕ-f-chart was adopted to simulate the fraction of the solar energy required for the system given the collector area and climatic conditions. Six cities representing different region in Malaysia were selected namely Kuala Lumpur, Petaling Jaya, Kota Bharu, Bayan Lepas, Kuching and Kota Kinabalu. Kota Kinabalu have the best performance for the same nominal capacity followed by Bayan Lepas and then Kota Bharu. Kuala Lumpur and Petaling Jaya have similar performance based on the yearly solar fraction.

Keywords-absorption air conditioning system, solar fraction, design methods, utilizibility

I. INTRODUCTION

ABSORPTION air conditioning is the only air conditioning system compatible with the upper collection temperature limits imposed by currently available flat-plate collectors. A schematic of the operation of a solar assisted air conditioner is shown in Figure 1. Home size absorption air conditioning units are more expensive than vapor compression air conditioning units, but to date only absorption air conditioning has been operated successfully in a full scale installation.

Absorption air conditioning system differs from vapor compression air conditioning only in the positive pressure gradient stage. In absorption air conditioning system, pressurization is accomplished by first dissolving the refrigerant in a liquid (the absorbent) in the absorber section, then pumping the solution to a high pressure with an ordinary liquid pump. The low-boiling refrigerant is the driven from the solution by the addition of heat in the generator. By this means, the refrigerant vapor is compressed without the large input of high-grade shaft work that the vapor compression air conditioning demands. The remainder of the system consists of a condenser, expansion valve and evaporator, identical in function to those used in a vapor compression system.

At present, two types of absorption air conditioning systems are marketed: the lithium bromide-water (LiBr-H2O) system and the ammonia-water (NH3-H2O) system. Of the two systems, lithium bromide-water is simpler since a rectifying column is not needed. In the ammonia-water system, a rectifying column ensures that no water vapor mixed with ammonia enters the evaporator where it could freeze. In the lithium bromide-water system, water vapor is the refrigerant. In addition, the ammonia-water system requires higher generator temperature (120°C to 150°C) than a flat-plate solar collector can provide without special techniques. The lithium bromide-water system operates satisfactorily at a generator temperature of 75°C to 100°C, achievable by a flat-plate collector. The lithium bromide-water system also has a higher COP than the ammonia-water system. The disadvantage of the lithium bromide-water systems is that the evaporators cannot operate at temperature below 0°C since the refrigerant is water vapor.

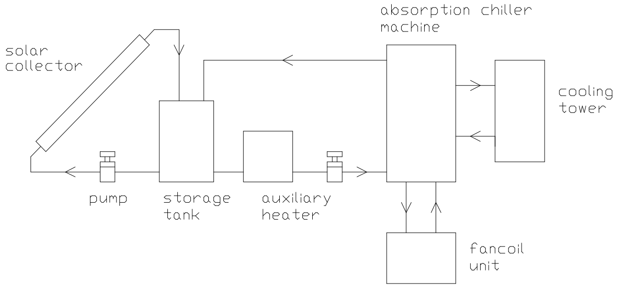

Fig. 1 Solar assisted absorption air conditioning system

Solar energy collectors are special kinds of heat exchangers that transform solar radiant energy to internal energy of the transport medium. There are two type of solar collectors: flat-plate and concentrating. A flat-plate collector usually has the same area for intercepting and absorbing solar radiation. Flat-plate collectors are usually permanently fixed in position and require no tracking of the sun. Flat-plate collectors are useful in supplying thermal energy at moderate temperatures, up to a nominal boiling point of water (100°C). They can be employed to supply hot water in absorption refrigeration system or space cooling.

II .ϕ-F-CHART DESIGN METHOD

The utilizability concept combined with the *f*-chart to produce the $\bar{\phi}$-f-chart design method for close-loop solar energy system shown in Figure 2. In this system, the storage tank is assumed to be pressurized or filled with a liquid having a high boiling point so that energy dumping through the pressure relief valve does not occur. The auxiliary energy system is in parallel with the solar system. Computer simulations for this system are done on the conditions that energy supplied to the load must be above a minimum useful temperature, T_{min} and the temperature of this energy supply has no effect on the performance of the load system as long as it is greater than T_{min}. It is useful to absorption chillers[1].

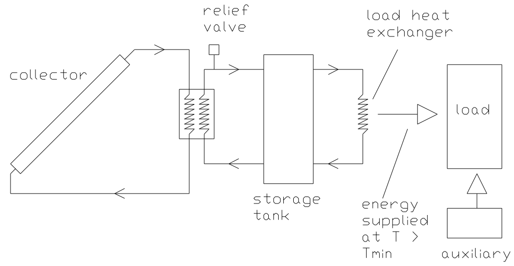

Fig. 2 Closed-loop solar energy system.

In the $\bar{\phi}$-f-chart design method, the maximum solar energy collection is attained when the collector fluid inlet temperature is at T_{min}. Thus the critical level is given by

$$H_{t,c,\min} = \frac{F'_R\left(T_{\min} - T'_a\right)}{F'_R\left(\overline{\tau\alpha}\right)} \tag{1}$$

The maximum monthly energy collection is

$$Q_{\max} = A_c F'_R \left(\overline{\tau\alpha}\right) \overline{H}_t N \overline{\phi}_{\max} \tag{2}$$

N =The number of days in the month
$\overline{\phi}_{max}$ = The maximum monthly average daily utilizability

The maximum critical ratio

$$\begin{aligned} X_{c,\min} &= \frac{H_{t,c,\min}}{r_n R_n \overline{\overline{H}}} \\ X_{c,\min} &= \frac{1}{r_n R_n \overline{\overline{H}}}\left[\frac{F'_R\left(T'_{\min} - \overline{T}'_a\right)}{F'_R\left(\overline{\tau\alpha}\right)}\right] \end{aligned} \tag{3}$$

The effective minimum useful temperature T'_{min} is introduced to deal with the load heat exchanger inefficiency in closed-loop system. To meet a solar fraction, f of a monthly energy load, D, the effective minimum useful temperature T'_{min} is defined by

$$f_1 = \frac{C_L\left(T'_{\min} - T_{\min}\right)}{D} \tag{4}$$

For a closed loop system

$$C_L = \varepsilon C_{\min} = \varepsilon\left(\dot{m} C_p\right) \tag{5}$$

C_L is the product of the load heat exchanger effectiveness and minimum of total monthly capacitance flowing through the heat exchanger.

Based on simulation results in the $\bar{\phi}$,f-chart design method, the actual monthly energy collection, Q_u and the maximum energy collection, Q_{max} can be correlated as follows

$$\begin{aligned} Q_u &= Q_{\max} - a\left[e^{bf} - 1\right]\left[1 - e^{cX}\right]\left[e^{dZ}\right] \\ a &= 0.015\left(\frac{M_s C_p}{350}\right)^{-0.76} \end{aligned} \tag{6}$$

M_s = Mass of liquid storage, kg per square meter of effective collector area ($A_c F'_R$)

$$\begin{aligned} b &= 3.85 \\ c &= -0.15 \\ d &= -1.959 \end{aligned}$$

$$X = A_c F'_R U_c \left(100^o C\right)\left(\frac{\Delta t}{D}\right) \tag{7}$$

$$Z = \frac{D}{C_L\left(100^o C\right)} \tag{8}$$

X and Z are dimensionless
Δt = number of seconds in the month

Storage tank energy loss is dealt with in the $\bar{\phi}$,f-chart design method by defining a monthly average storage temperature T_s that satisfies the energy balance equation.

$$fD = Q_u - (UA)_s\left(T_s - T_{env}\right)\Delta t \tag{9}$$

and

$$f_2 = \frac{Q_u - (UA)_s\left(T_s - T_{env}\right)\Delta t}{D} \tag{10}$$

$(UA)_s$ = Storage tank loss coefficient and area product
T_{env} = Temperature of the storage tank environment
Δt = Number of seconds in the month

The monthly average storage temperature T_s for energy loss calculations as defined in equation above, is correlated with the effective minimum useful temperature T'_{min} in the following expression:

$$T_s = T'_{\min} + g\left[e^{kf} - 1\right]e^{hZ} \tag{11}$$

$g = (0.2136\,℃)(M_s C_p)^{-0.704}$
$h = -0.4002$
$k = 4.702$

The use of the $\bar{\phi}, f$-chart method in the design of solar water heating systems requires an iterative solution for the effective minimum useful temperature T'_{min} and therefore the solar fraction, f.

A. The Utilizability Concept

The concept of utilizability pioneered by Hottel and Whillier [2] and later generalized by Liu and Jordan [3]. Then it has been simplified and extended by Klein and Beckman [4] to form a general design method for solar systems involving flat-plate collectors.

Utilizability is defined as the fraction of the incident solar radiation that can be utilized by an ideal collector having no optical losses ($\tau = 1, \alpha = 1$) and a perfect heat removal circuit ($F_R = 1$).

The definition of utilizability follows directly from the *Hottel-Whiller-Blise* equation, expressed in terms of the hourly incident radiation, H_t on the collector surface, and the effective transmissivity-absorptivity product, $\tau\alpha$ of the collector.

$$Q_u = A_c F_R \left[H_t(\tau\alpha) - U_c(T_i - T_a) \right] \tag{12}$$

T_i is the inlet collector fluid temperature.

According to this equation, there is a minimum radiation level required to maintain the collector plate at the temperature of the inlet collector fluid. This minimum radiation level, called the critical level and derived by $H_{t,c}$, can be found by setting Q_u equal to zero. Thus

$$H_{t,c} = \frac{F_R U_c (T_i - T_a)}{F_R(\tau\alpha)} \tag{13}$$

Solar radiation must be above the critical level so that a flat-plate collector can yield a useful energy

$$Q_u = A_c F_R(\tau\alpha)\left(H_t - H_{t,c}\right) \tag{14}$$

gain, Q_u.

The hourly useful energy collection at a given hour of the day averaged over a long term (usually a month) of N days can be written as

$$\overline{Q'}_u = \frac{A_c F_R(\tau\alpha)}{N} \sum^{N} \left(H_t - H_{t,c}\right)^+ \tag{15}$$

The + superscript is used to indicate that only positive values are to be considered. Let H'_t represent the monthly average hourly radiation for a given hour of the day. By definition, the hourly utilizability, ϕ is the fraction of H'_t that is above the critical level $H_{t,c}$. Thus

$$\phi = \frac{1}{N} \sum^{N} \frac{\left(H_t - H_{t,c}\right)^+}{\overline{H}_t} \tag{16}$$

Where the critical is redefined in terms of monthly average values of transmissivity-absorptivity ($\tau\alpha$) product and a daytime ambient temperature T'_a as follow

$$H_{t,c} = \frac{F_R U_c \left(T_i - \overline{T'}_a\right)}{F_R\left(\overline{\tau\alpha}\right)} \tag{17}$$

The monthly average daily useful energy collection is then given by

$$\overline{Q}_u = A_c F_R\left(\overline{\tau\alpha}\right)\overline{H}_t \overline{\phi} \tag{18}$$

It has been found by Klein [5] and Mitchell et al. [6] that the value of $\bar{\phi}$ can be completely specified in terms of the monthly clearness index $\overline{K}_T$, the geometry factor R/R_n and the monthly average critical radiation ratio, X_c, by the following relation:

$$\bar{\phi} = \left\{ \left[A + B\left(\frac{R_n}{\overline{R}}\right) \right] \left(\overline{X}_c + C\overline{X}_c^2 \right) \right\} \tag{19}$$

$$A = 7.10 - 20.00\overline{K}_T + 12.08\overline{K}_T^2$$
$$B = -8.02 + 18.16\overline{K}_T - 10.68\overline{K}_T^2$$
$$C = -1.02 + 4.10\overline{K}_T - 1.96\overline{K}_T^2$$

R is the monthly ratio of radiation on a tilted surface to radiation on a horizontal surface. It is known as the monthly mean total radiation tilted factor and is given by

$$\overline{R} = \frac{\overline{H}_t}{\overline{H}} = \left(1 - \frac{\overline{H}_d}{\overline{H}}\right)\overline{R}_B + \frac{\overline{H}_d}{\overline{H}}\left(\frac{1+\cos s}{2}\right) + \rho_g\left(\frac{1-\cos s}{2}\right) \tag{20}$$

ρ_g is the ground reflectivity.
$\overline{R}_B$ is the monthly average beam radiation tilt factor

and given by

$$\overline{R}_B = \frac{\cos(L-s)\cos\delta\sin h'_s + \left(\frac{\pi}{180}\right) h'_s \sin(L-s)\sin\delta}{\cos L\cos\delta\sin h_s + \left(\frac{\pi}{180}\right) h_s \sin L \sin\delta} \tag{21}$$

Where s is the tilt angle of the solar collector and h_s is the sunset hour angle on a horizontal surface and defined by
The sunset hour angle on the tilted surface is the minimum value given by

$$h_s = \arccos(-\tan L \tan\delta) \tag{22}$$

The sunset hour angle on the tilted surface is the minimum value given by

$$h'_s = \min\left\{h_s, \arccos\left[-\tan(L-s)\tan\delta\right]\right\} \tag{23}$$

L is the latitude in degrees and δ is the solar declination given by

$$\delta = 23.45\left[\frac{360}{365}(248+n)\right] \tag{24}$$

Where n is the day of the year.

R_n is the ratio of radiation at noon on the tilted surface to that on a horizontal surface based on a monthly average.

Where $r_{d,n}$ is the ratio of the diffuse radiation at noon to the daily diffuse radiation, and r_n is the ratio of the total radiation at noon to the daily total radiation.

$$R_n = \left(1 - \frac{r_{d,n}}{r_n}\frac{\overline{H}_d}{\overline{H}}\right) R_{B,n} + \left(\frac{r_{d,n}}{r_n}\frac{\overline{H}_d}{\overline{H}}\right)\left(\frac{1+\cos s}{2}\right) + \rho_g\left(\frac{1-\cos s}{2}\right) \tag{25}$$

$$r_{d,n} = \frac{\pi}{24}\left[\frac{1-\cos h_s}{\sin h_s - \left(\pi/_{24}\right) h_s \cos h_s}\right] \tag{26}$$

$$r_n = r_{d,n}\left[1.07 + 0.025\sin\left(h_s - 60\right)\right] \tag{27}$$

The ratio of beam radiation on the tilted surface to that on a horizontal surface at noon, $R_{B,n}$ is given by

$$R_{B,n} = \frac{\cos(L-s)\cos\delta + \sin(L-s)\sin\delta}{\cos L\cos\delta + \sin L\sin\delta} \tag{28}$$

The H_d/H is the monthly average daily diffuse fraction. It can be expressed in terms of the monthly average daily clearness index K_T as follows:[8]

$$\frac{\overline{H}_d}{\overline{H}} = 1.317 - 3.023\overline{K}_T + 3.372\overline{K}_T^2 - 1.769\overline{K}_T^3 \tag{29}$$
$$for\ 0.3 \le \overline{K}_T \le 0.8$$

A more recent correlation proposed by Erbs *et al.* [7] and applicable for the range of $0.3 \le K_T \le 0.8$ are

for $h_s \le 81.4°$

$$\frac{\overline{H}_d}{\overline{H}} = 1.391 - 3.560\overline{K}_T + 4.189\overline{K}_T^2 - 2.137\overline{K}_T^3 \tag{30}$$

for $h_s > 81.4°$

$$\frac{\overline{H}_d}{\overline{H}} = 1.311 - 3.022\overline{K}_T + 3.427\overline{K}_T^2 - 1.821\overline{K}_T^3 \tag{31}$$

The monthly average critical radiation ratio X_c is the ratio of the critical level to the radiation at noon for an average day during the month in which the total radiation for the day is the same as the average for the month.

$$\overline{X}_c = \frac{H_{t,c}}{r_n R_n \overline{H}}$$
$$or$$
$$\overline{X}_c = \frac{1}{r_n R_n \overline{K}_T \overline{H}_o}\left[\frac{F_R U_c\left(T_i - \overline{T'}_a\right)}{F_R\left(\overline{\tau\alpha}\right)}\right] \tag{32}$$

H_o is the monthly average daily extraterrestrial radiation on a horizontal surface.

III. RESULTS AND OBSERVATIONS

Figures 3 through 5 show the climatological data for the selected cities. Figure 3 shows the monthly average daily insolation on a horizontal surface, $\overline{H}$; Figure 4 shows the average daytime ambient temperature, T'_a; and Figure 5 shows the monthly clearness index, K_T. The collector has $F_R'(\tau\alpha)_n$ = 0.70, $(\tau\alpha)/(\tau\alpha)_n$ = 0.90, $F_R'U_c$ = 3.20 W/m^2.K, and are slope towards the south at β = 10° at the latitude of 5°18'N, 6°10'N, 5°56'N, 3°7'N, 1°29'N and 3°6'N for Bayan Lepas, Kota Bharu, Kota Kinabalu, Kuala Lumpur, Kuching and Petaling Jaya respectively. The collector area A_c = 20m^2, 40m^2, 60m^2, 80m^2 and 100m^2. The storage tank has M_s = 83.5 kg/m^2, the overall heat lost, $(UA)_s$ = 5.8 W/K, T_a = 24°C and C_p = 4.19 kJ/kg.K for water. The effectiveness of the load heat exchanger ε_L = 0.70 and $(mC_p)_{min}$ = 3100 W/K. The nominal capacity of the absorption air conditioning system is 3 tons (10.5 kW) and the load energy required by the absorption system is about 13.33 kW, 12 hours per day and at the minimum temperature of 75°C. By using equations (1) through (33), the monthly and annual fraction of solar energy delivered to the air conditioning system are calculated. By making an assumption value of $T'_{min,}$ we could get the value of f_1, $X_{c,min}$, ϕ_{max}, Q_{max}, Q_u, T_s and f_2. If the value of f_1 is not equal to f_2, our assumption value of T'_{min} is wrong. Iteration is to be continued until the value of f_1 is almost equal to f_2 with different not more than 1%.

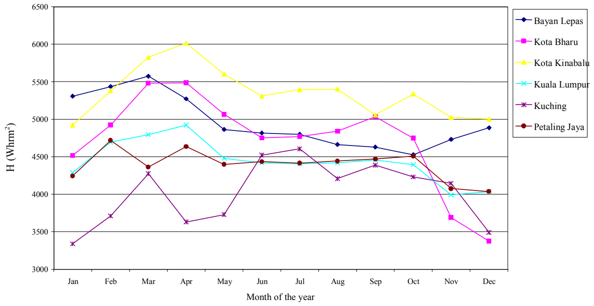

Fig. 3 The Monthly Average Daily Insolation on a Horizontal

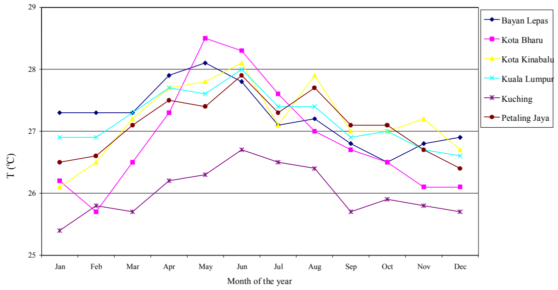

Fig. 4 The Monthly Average Daily Ambient Temperature

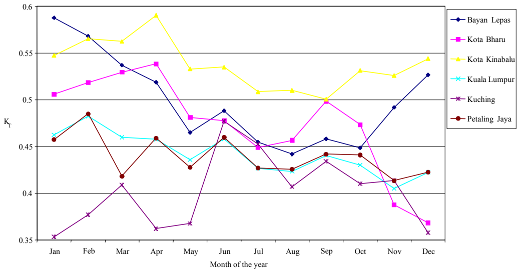

Fig. 5 The Monthly Clearness Index, K_T

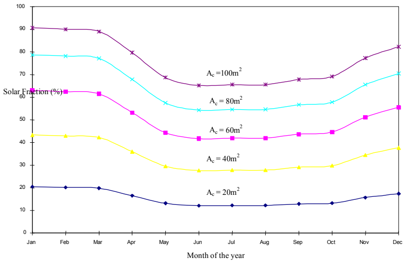

Fig. 6 The Monthly Solar Fraction for Bayan Lepas with 3 tons Cooling Capacity and s = 10^o

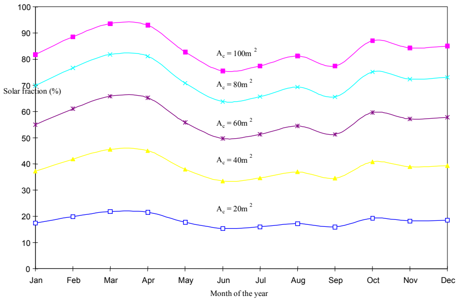

Fig. 7 The Monthly Solar Fraction for Kota Kinabalu with 3 tons Cooling Capacity and s = 10^o

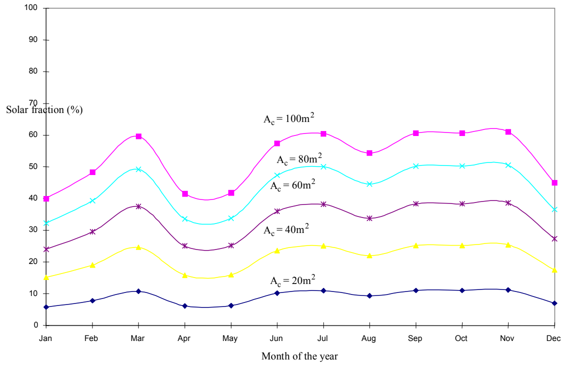

Fig. 8 The Monthly Solar Fraction for Kuching with 3 tons Cooling Capacity and s = 10^0

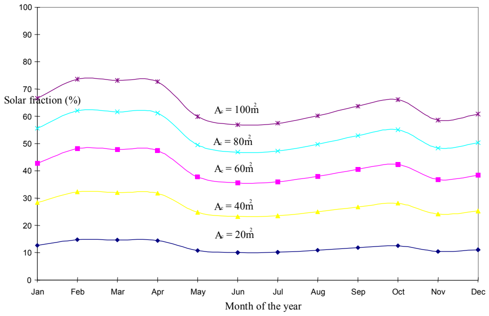

Fig. 9 The Monthly Solar Fraction for Kuala Lumpur with 3 tons Cooling Capacity and s = 10^0

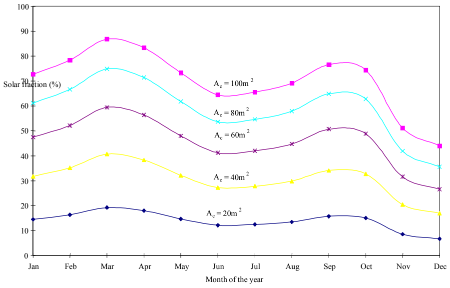

Fig. 10 The Monthly Solar Fraction for Kota Bharu with 3 tons Cooling Capacity and s = 10^o

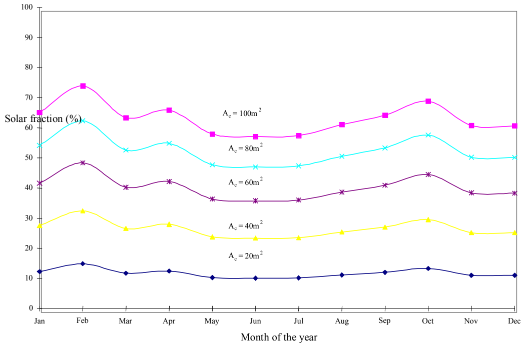

Fig. 11 The Monthly Solar Fraction for Petaling Jaya with 3 tons Cooling Capacity and s =10^o

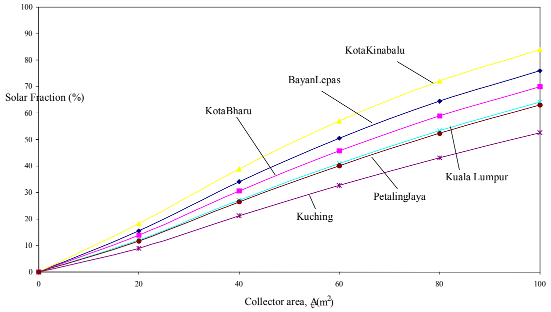

Fig. 12 The Annual Solar Fraction

A. The Monthly Fraction

Figures 6 through 11 shows the monthly fraction of the solar energy delivered to the air conditioning obtained for each month for each city. The highest monthly solar fraction was obtained at Kota Kinabalu. More than 90% of the energy is provided by the solar energy for the month of March and April with a collector size of 100 m^2 and are always above 75% throughout the year for the same collector area. Bayan Lepas obtained its highest monthly solar fraction in January, February and March which corresponds to the sunniest season for a collector size of 100 m^2 and are always above 65% throughout the year. Kota Bharu obtained its highest monthly solar fraction in February, March and April. However, during the monsoon season, a drastic drop in solar fraction is obvious. The solar fraction reaches above 80% for the sunniest season, however during the monsoon season, it reaches only 45% for a collector area of 100 m^2. The solar system in Kuala Lumpur experiences a high monthly solar fraction ranging between 60% to 75%. Highest solar fraction obtained in February, March and April for a collector area of 100 m^2. At Petaling Jaya, the same system behaves similarly at Kuala Lumpur except for the early of the year. Kuching experience the lowest solar fraction in April and May with only 40% solar fraction with a collector area of 100 m^2. Its highest monthly solar fraction is 60% with the same collector area.

B. The Annual Solar Fraction

The variation of the annual solar fraction of solar energy delivered to the absorption cooling system as a function of collector area is shown in Figure 12. The annual solar fraction increases with the collector area but at a decreasing rate. The reason for this is that the larger the collectors size, will give higher losses. Moreover, the higher the collectors size the higher will be the collector inlet temperature and will decrease the collector efficiency hence illustrating the law of diminishing return. Kota Kinabalu has the highest yearly solar fraction followed by Bayan Lepas and then Kota Bharu. Kuala Lumpur and Petaling Jaya almost have the same yearly solar fraction and Kuching has the lowest yearly solar fraction.

IV. CONCLUSIONS

The conceptual design and the long term performance of a solar assisted absorption air conditioning system using thermal solar collector was presented. Six cities namely, Bayan Lepas, Kota Bharu, Kota Kinabalu, Kuala Lumpur, Kuching and Petaling Jaya were chosen representing different locations within Malaysia. The ϕ-f-*chart* design was used to predict the long terms performance of a solar absorption air conditioning system. The system is technically feasible. Kota Kinabalu has the best performance on both monthly and yearly solar fraction, followed by Bayan Lepas and then Kota Bharu. Kuala Lumpur and Petaling Jaya almost have the same performance on yearly solar fraction. Although Kuching has the lowest solar fraction, its contribution to the system is still valuable. An economic analysis must be carried out to determine the economic feasibility of such system in Malaysia.

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