SOLAR INDUSTRIAL PROCESS HEAT POTENTIAL IN KHARTOUM, SUDAN

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Abstract—The main objective of the present paper is to investigate the economic viability of the solar domestic hot water systems for industrial processes in Khartoum. Sudan. The industries covered in this study are soft drinks and vegetable oil. The economic viability investigation is based on life-cycle savings calculations. The economic analysis and the performance of the solar domestic hot water systems were predicted using the *f*-chart design method. Monthly average meteorological data are used to calculate both the annual solar fraction and the life-cycle savings. The results showed that the solar energy systems have a great potential in industrial process, and significant life-cycle savings can be achieved with solar heating systems.

INTRODUCTION

In most African countries where the price of fuel is very high, solar heating may be economically competitive with conventional heating systems. This paper investigates the possibility of using solar heating systems in the food industry in Khartoum. Sudan instead of the conventional heating systems. A survey has been made of 25 factories to determine the hot water demands. The industries covered in this study are soft drinks and vegetable oil. Results of the study showed that there is a high demand for hot water at temperatures approximately equal to 80°C. The average hot water consumption loads are 3000 and 2000 kg/day for soft drinks and vegetable oil industries, respectively.

In the soft drinks industry, the consumption of hot water is mainly in the preparation of the syrup (water and sugar) and washing of the bottles. Steam is used in both processes to give the heating effects (Fig. 1). In the preparation room a mixture of water, sugar and syrup is heated together in a tank with steam passing in a coil around the tank. The temperature of the mixture ranges between 50 to 60°C. The washing process includes two steps. The first step is to wash the bottles with a mixture of sodium hydroxide and water. The second step is to rinse the bottles with water only. These processes are done in the washing machine which consists of a series of tanks. Most of the energy consumed in the soft drinks industry is used

to produce hot water at temperature approximately equal to 80 C. In the vegetable oil industry (Fig. 2), the hot water at 80–90 C is used for washing the oil from the remains of soda and other chemical residuals.

The economic feasibility of solar domestic hot water (SDHW) systems will be investigated in this paper. SDHW systems are simple, easily maintained, and relatively inexpensive. In addition, in this type of thermal energy storage, heat is added and removed from the storage unit by transport of the storage medium itself, thus eliminating the temperature drop between transport fluid and storage medium. Unlike conventional hot water systems, SDHW system performance is dependent on local climatic conditions, such as solar radiation and ambient temperature.
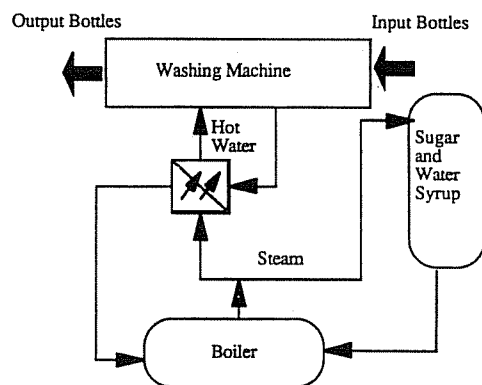
The main objectives of the present paper are :

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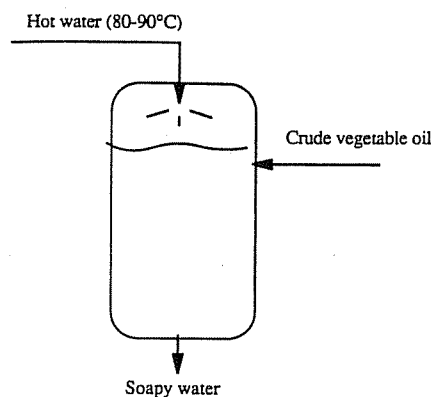
Fig. 1. Steam and water process in soft drinks industry.

Fig. 2. Washing the vegetable oil from the remains of soda and other chemical residuals using hot water.

(1) to investigate the economic viability of a solar domestic hot water system designed to provide the hot water needs for industrial processes in Khartoum, Sudan based on life-cycle savings calculations;
(2) to determine the optimum domestic solar hot water system parameters.

SOLAR SYSTEM DESCRIPTION AND CONTROL STRATEGY

Figure 3 shows a schematic representation of the direct two-tank SDHW system chosen for the present study. This system was chosen because it is one of the standard system configurations used in the development of the *f*-chart design method. It consists of a preheat tank containing water which is circulated through the solar collectors when the incident solar radiation is sufficient to provide thermal energy. When solar radiation is not enough to satisfy the load, water is taken from the auxiliary tank. This water is replaced by solar heated water from the preheat tank.

The water in the auxiliary tank is maintained at a specified set temperature by an internal heater. The system also contains a tempering valve which limits the temperature of the delivered water to the set temperature by mixing with mains water as needed. The circulation of water is controlled by a differential controller. When water temperature at collector outlet exceeds the water temperature in the bottom of the preheat tank (deadband upper limit) the circulation pump is activated. When this temperature difference falls below a certain value (deadband lower limit) circulation of the water is stopped. Relief valve is used for dumping excess energy.

ANALYSIS

In the present study, the weather data for Khartoum, Sudan (latitude 15) was used. The data file of Khartoum [1] contains monthly average values of daily radiation on a horizontal surface, clearness index, ambient temperature, wind speed, and relative humidity.
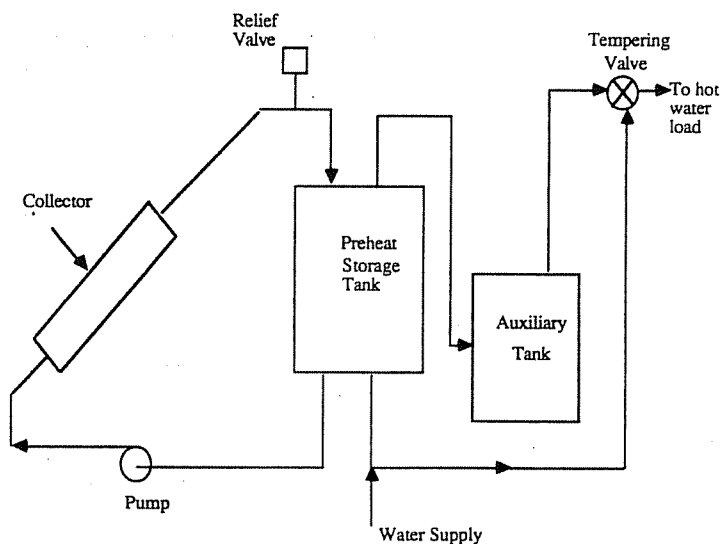

Fig. 3. Solar water heating system.

The economic calculations for this study are based on life-cycle savings calculations developed by Brandemuehl et al. [2]. The life-cycle savings (LCS) of a solar heating system over a conventional heating system can be defined as the difference between the reduction in fuel costs and the increase in expenses resulting from the additional investment for the solar system.

$$LCS = P_1 C_1 LF - P_2(C_1 A + C_E) \qquad (1)$$

where P_1 is the factor relating life cycle fuel cost savings to first year fuel cost savings, and P_2 is the factor relating life cycle incurred by additional capital investment to the initial investment. C_1, C_E, and C_F are the solar energy system investment costs which are directly proportional to collector area (A), the solar energy system investment costs which are independent of collector area, and the unit cost of delivered conventional energy for the first year of analysis, respectively. L is the hot water load. F is the annual solar fraction which is defined as the fraction of the water heating load met by solar energy.

Detailed computer simulation programs, such as the transient simulation program (TRNSYS), developed by Klein et al. [3] at University of Wisconsin-Madison, can be used to estimate the long-term annual thermal performance of solar domestic hot water systems (i.e. the annual solar fraction). The advantages of detailed simulations are flexibility and accuracy. Simulations, however, are not convenient. They require a high computer cost, hourly meteorological data, and a lot of experience. So, the detailed simulation programs are impractical as a long-term performance design tool. An interesting alternative to the use of detailed simulation programs is the f-chart design method [4, 5], which provides estimates of monthly average system performance using monthly average weather data. Ammar et al. [6] have made a comparison between the annual solar fraction predicted by both f-chart method and TRNSYS. Their results showed a great resemblance between both predictions.

Comparisons with measured performance in many other places have shown that f-chart design method provides reliable estimates of long-term performance for SDHW systems. Fanney and Klein [7] have measured the performance of six different types of domestic hot water systems at the National Bureau of Standards (NBS) in Gaithersburg, Maryland. Their measurements were conducted over a 1 year period and compared to the performance predicted by the f-chart method. The annual solar fraction estimated by the f-chart design method was within 5% of the measured value for five active heating systems (the sixth system was a thermosyphon system, to which

the f-chart method does not apply). Duffie and Mitchell [8] stated that there is a general agreement between the measured performance and the performance predicted by the f-chart method for systems with configurations close to the standard configuration used in developing the f-chart correlations. For these reasons, the following results were generated using the f-chart design method to predict both the performance of solar domestic hot water system and the life-cycle savings to take advantage of its huge reduction in computer cost over the detailed simulation programs.

The f-chart design method [4] provides a fast means of estimating the fraction of the heating load that will be supplied by solar energy for a specified standard system configuration. The f-chart method has been developed for three standard system configurations, air and liquid-based systems for space and domestic water heating, and domestic hot water system only. It suggests that f (the fraction of the monthly heating load met by solar energy) is empirically related to the two dimensionless groups:

$$X = A_c F_R' U_L (T_{ref} - \bar{T}_a) \Delta t / L \qquad (2)$$

$$Y = A_c F_R'(\tau\alpha) \bar{H}_T N / L \qquad (3)$$

where

A_c is the area of the solar collector, (m^2)

F_R' is the collector-heat exchanger efficiency factor

U_L is the collector overall energy loss coefficient. (kJ h m^2 K)

Δt is the total number of seconds in the month

T_{ref} is a reference temperature determined to be 100 C

$\bar{T}_a$ is the monthly average ambient temperature, (C)

L is the monthly total heating load, (kJ)

$(\tau\alpha)$ is the collector monthly average transmittance-absorbtance product

$\bar{H}_T$ is the monthly average daily radiation incident on the collector surface per unit area, (kJ m^2)

N is the number of days in the month.

These dimensionless groups have some physical meaning. Y is proportional to the ratio of the total energy absorbed on the collector plate surface to the total heating load during the month. X is proportional to the ratio of a reference collector energy loss to the total heating load during the month. The equations for X and Y can be rewritten in a more convenient

form for calculations:

$$X = F_R U_L (F_R' F_R)(T_{ref} - \bar{T}_a) A_c \Delta t / L \quad (4)$$

$$Y = F_R(\tau\alpha)_n (F_R' F_R)[(\overline{\tau\alpha})/(\tau\alpha)_n] A_c \bar{H}_T N / L \quad (5)$$

where F_R is the collector heat removal factor, and $(\tau\alpha)_n$ is the collector monthly average transmittance-absorptance product at normal incidence. The detailed calculations of the parameters on the right hand side of eqs (3), and (4) can be found in [3]. For domestic water heating system, the mains water supply temperature (T_{main}) and the set point temperature of the hot water (T_{set}) affect the collector energy losses. So, the dimensionless group X, which is proportional to the collector energy losses must be corrected to account for this effect. The corrected dimensionless group X_c becomes

$$X_c = F_R U_L (F_R' F_R)(11.6 + 1.18 T_{set} + 3.86 T_{main}$$

$$- 2.32 \bar{T}_a) A_c \Delta t / L. \quad (6)$$

The correlation between X_c, Y, and f for domestic hot water is

$$f = 1.029 Y - 0.065 X_c - 0.245 Y^2 + 0.0018 X_c^2$$

$$+ 0.0215 Y^3 \quad (7)$$

for $0 < Y < 3$ and $0 < X < 18$.

Also, the life-cycle savings calculations are built in the *f*-chart method.

RESULTS AND DISCUSSION

There are many parameters which affect the solar system performance and consequently the life-cycle savings. The results of optimizing these parameters for soft drinks and vegetable oil industries are discussed below. Table 1 indicates the water storage system parameters, flat plate collector parameters, and economic parameters which have been fixed during this study. The economic parameters used in this study are taken from Solaron Corporation catalog [9].

Soft drinks industry

The main solar heating system design parameter is the collector area. The variation of both annual solar fraction and life-cycle savings with collector area is shown in Fig. 4. As the collector area increases the solar fraction increases. This increase is not so pronounced for collector areas higher than 140 m². Also, as the collector area increases, the LCS increases until reaching a maximum at the optimum collector area which is approximately 84 m² in this case. As the collector area is further increased the excessive system costs

Table 1. Solar domestic hot water system parameters

Water storage system	
City	Khartoum
Latitude	15
Water volume collector area	37.5 liters m²
Fuel	Oil
Efficiency of fuel usage	70%
Daily hot water usage	3000 liters
Water SEt temperature	80 C
Environmental temperature	25 C
UA of auxiliary storage tank	4.0 W C
Inlet pipe UA	1.20 W C
Outlet pipe UA	1.30 W C
Relative load heat exchanger size	2.0
Tank-side flowrate area	0.018 kg sec-m²
Heat exchanger effectiveness	0.75
Flat plate collector	
Collector panel area	2.77 m²
$F_R(U_L)$ (test slope)	4.650 W m²- C
$F_R(\tau\alpha)$ (test intercept)	0.74
Collector azimuth	0
Incidence-angle modifier calculation	Glazings
Number of glazings	2
Collector flowrate area	0.018 kg sec-m²
Collector fluid specific heat	4.20 kJ kg- C
Economic parameters	
Cost per unit area	250S m²
Area independent cost	1200S
Price of electricity	0.06S kW-hr
Annual % increase in electricity	10%
Price of fuel oil	0.32S liter
Annual % increase in fuel oil	10%
Period of economic analysis	20 years
% Down payment	50%
Annual mortgage interest rate	10%
Term of mortgage	10 years
Annual market discount rate	9.2%
% Extra insurance and maintenance in year 1	1.3%
Annual increase in insurance and maintenance	4%
Effective state income tax rate	10%
% Resale value	50%
Commercial depreciation schedule	10%

force the solar savings to decrease as shown from the figure. The results indicate that with solar heating system a life-cycle savings of approx. $22,500 can be achieved (i.e. about $1125 year). The following results are generated using the optimum collector area (84 m²) since the collector area is the most important factor affecting the performance of solar heating system, and hence the LCS.

Figure 5 shows the variation of annual solar fraction and life-cycle savings with collector slope (orientation). Collector orientation affects performance in two ways. Most importantly, it directly affects the
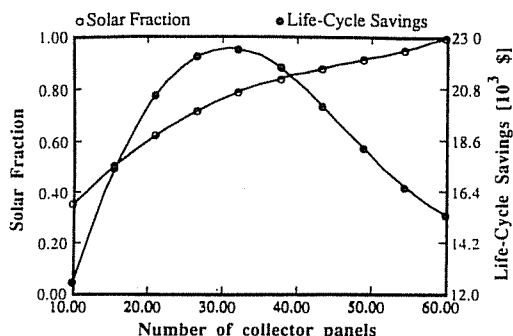
Fig. 4. Solar fraction and life cycle savings vs number of collector panels (2.77 m^2 panel) for 3000 kg day hot water consumption.
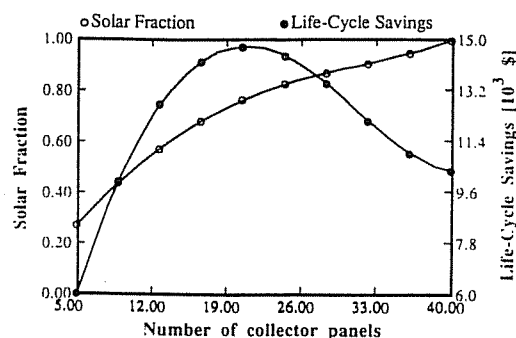

Fig. 6. Solar fraction and life cycle savings vs number of collector panels (2.77 m^2 panel) for 2000 kg day hot water consumption.

transmittance of the transparent covers and the absorbance of the collector plate since both are functions of the angle at which radiation strikes the collector surface. The optimum collector orientation from Fig. 5 is approx. equal to the latitude (15). However, the collector orientation is not critical. Deviation from the optimum by as much as 10 has little effect on both the solar system performance and the life-cycle savings.

Vegetable oil industry

The variation of both annual solar fraction and life-cycle savings with collector area is shown in Fig. 6. The optimum collector area in this case is 55 m^2. The collector area in this case is smaller than the optimum collector area required by soft drinks because the hot water load in this case (2000 kg/day) is smaller than the hot water load required for soft drinks industries

(3000 kg day). The results indicate that with a solar heating system a life-cycle saving of approx. $14.500 can be achieved (i.e. about $725 year). Figure 7 shows the variation of annual solar fraction and life-cycle savings with collector slope (orientation). The results and conclusion obtained for the soft drinks industry are obtained again for the vegetable oil industry.

In conclusion the solar domestic hot water system is a preferable alternative to the conventional heating systems currently used in the food industry in Sudan. Significant life-cycle savings can be achieved with solar heating systems. Solar heating systems seem to be more favorable for factories with a problem of fuel shortage, which is a common problem among the factories covered in the survey. Great attention should be paid to install real solar systems in food industries and examine the economic viability predicted in this paper.
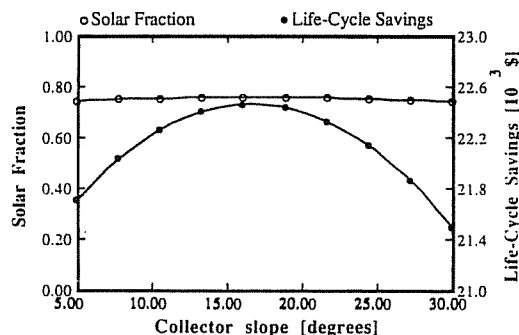

Fig. 5. Solar fraction and life cycle savings vs collector slope for 3000 kg day hot water consumption.
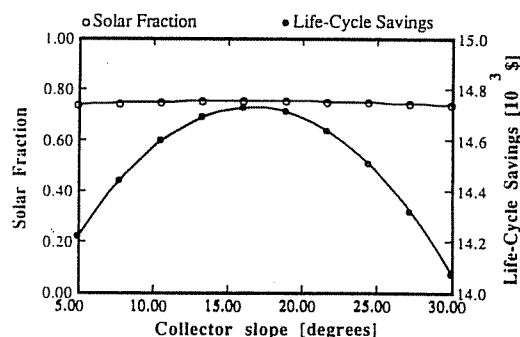

Fig. 7. Solar fraction and life cycle savings vs collector slope for 2000 kg day hot water consumption.

NOMENCLATURE

A collector area
C_1 the solar energy system investment costs which are directly proportional to collector area (A)
C_L the solar energy system investment costs which are independent of collector area
c specific heat of circulating fluid
C_F the unit cost of delivered conventional energy for the first year of analysis
f monthly solar fraction
F annual solar fraction
F' collector efficiency factor
F_R collector heat removal factor
$\bar{H}_T$ monthly average daily radiation incident on the collector surface per unit area
L hot water load
$\dot{m}$ mass flow rate
N number of days in the month
P_1 factor relating life cycle fuel cost to first year fuel cost savings
P_2 factor relating life cycle incurred by additional capital investment to the initial investment
T_{ref} reference temperature (100 C)
$\bar{T}_a$ monthly average ambient temperature
U_L collector overall loss coefficient
Δt total number of seconds in the month
ρ fluid density
$(\tau\alpha)_n$ transmittance-absorbance product
$(\tau\alpha)$ collector monthly average transmittance-absorbance product.

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