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Optimal Sizing Of Solar Water Heating System Based On Genetic Algorithm For Aquaculture System

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***Abstract-* The most wide spread thermal use of solar energy, has been for water heating system, which have been commercialized in many countries in the world. This paper presents a model of a forced circulation solar water heating system for supplying a hot water at a required temperature for an aquaculture system. The main component of the system is flat plate collector, storage tank, and auxiliary heater. The optimization problem is carried out using genetic algorithm, which is one of the modern optimization techniques because of their evolutionary nature it can handle any kind of objective function and constraints. Genetic algorithm don't have mathematical requirements about the optimization problem, also it is very effective at performing a global search (in probability), and provide a great flexibility. The optimal design of flat plate collector area using genetic algorithm are used to optimize the objective function considering the constraints required for the system. As the genetic algorithm is a discrete optimization tool the number of variables in principle is free of choice. The economic analysis of such system is evaluated with the life cycle cost method. The collector area is equal to 63 m^2, at this value the solar fraction reached to 98%which is very high value. Also sensitivity analysis to solar radiation variation, air temperature variation, and interest rate has been carried out.**

Keywords- Solar thermal energy, Aquaculture system, Optimization, Genetic algorithm, Economic, and Optimal sizing.

I. INTRODUCTION

Proper design of solar water heating system is important to assure maximum benefit to the user, especially for a large system. Designing a solar hot water system involves appropriate sizing of different components based on predicted solar insolation and hot water demand [1]. All nations of the world depend on fossil fuels for their energy needs. However, the obligation to reduce CO2 and other gaseous emissions, in order to be in conformity with the Kyoto agreement is the reason behind which countries turn to non-polluting renewable energy sources [2]. An important issue in solar thermal system for industrial applications is the optimal sizing of the system i.e., appropriate sizing of the collectors, storage and heat exchanger [3].In recent years, some optimization methods that are conceptually different from the traditional mathematical programming techniques have been developed. These methods are labeled as modern or nontraditional methods of optimization. Genetic algorithms (GAs) are well suited for solving such problems, and in most cases they can find the global optimum solution with a high probability. Genetic algorithms are based on the principles of natural genetics and natural selection. The basic elements of natural genetics-reproduction, crossover, and mutation-are used in the genetic search procedure [4]. This paper presents the optimal sizing of solar thermal hot water system for an aquaculture system using genetic algorithm. Also sensitivity analysis is carried out.

II. MATHEMATICAL MODEL OF SOLAR THERMAL SYSTEM

Schematic diagram of a solar water heating system is shown in Fig. 1. A typical solar water heating system consists of a solar collector array connected to an insulated storage tank. Solar energy incident on the collectors is carried to the storage tank by circulating water through the collector tubes. The storage meets thermal demand of the load by supplying hot water. Cold water is supplied to the tank as soon as hot water from the tank is withdrawn to meet the load requirement. This arrangement ensures that the storage tank is always full. A biogas heater is used as auxiliary heater with a bypass is placed in series with the storage in load supply line (Fig. 1) to meet temperature requirement of the load. Storage tank temperature is an important parameter which influences the system size and performance. Energy balance of a well mixed storage tank can be expressed as [1]

$$\rho\, V_s\, c_p\, \frac{dT_s}{dt} = q_c - q_l - q_{stl} \qquad (1)$$

Where ρ water density (Kg/m3), V_s is is storage tank volume (m^3), T_s is storage tank temperature (^oC), C_p is specific heat of water (4190 J/Kg ^{o}C), q_c is actual useful energy gain, q_l is load energy, and q_{stl} is storage tank losses.

A. Flat Plate Collector Modeling

Solar useful heat gain rate (q_c) from the collector array is calculated by

$$q_c = F_R A\left[\alpha\tau\, G - U_l\left(T_i - T_a\right)\right]^{+} \qquad (2)$$

Where q_c represents actual useful energy gain (W), F_R the collector heat removal factor, G intensity of solar radiation, in (W/m^2), A collector surface area (m^2), ($\alpha\tau$) is the transmittance absorptance product, U_l is collector overall heat transfer coefficient (W/m^{2o}C), T_a is the ambient temperature (^{o}C), and T_i is the initial temperature. Where + sign indicates that only positive values of q_c is considered in the analysis.

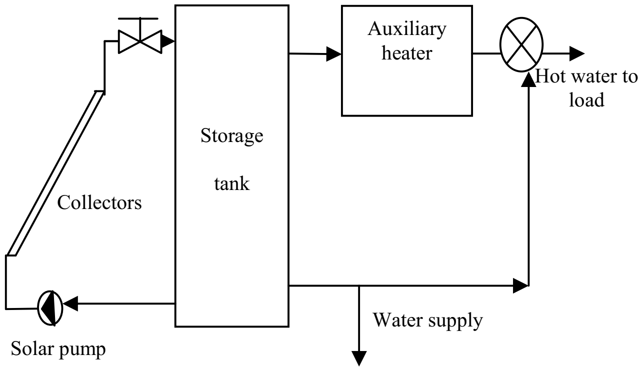

Figure 1. Schematic of a solar water heating system

This implies that hot water from the collector enters the tank only when solar useful heat gain becomes positive [1].

The collector heat removal factor, F_R, is the ratio of the actual useful energy gain of a collector to the maximum possible useful gain if the whole collector surface were at the fluid inlet temperature. It is defined as [5]

$$F_R = \frac{\dot{m} c_p}{A U_l}\left[1 - \exp\left(-\frac{A U_l F'}{\dot{m} c_p}\right)\right] \tag{3}$$

Where $\dot{m}$ is mass flow rate (Kg/s), C_p is specific heat of water (4190 J/Kg ^{o}C).

The overall heat loss from a solar collector consists of top heat loss through cover systems, back heat loss, and edge heat loss which are heat loss through back and edge insulation of the collector. With the assumption that all the losses are based on a common mean plate temperature T_{pm}, the overall heat loss from the collector can be represented as

$$U_l = U_t + U_b + U_e \tag{4}$$

Where U_l is the collector overall loss coefficient.Where the subscripts t, b, and e represent for the top, back, and edge contribution, respectively. The value of F_R and U_l used in calculation are calculated in a detailed program using Matlab software, their values are 0.6646, and 10.76 W/m^{2o}C respectively.

III. LOAD PROFILE

In solar heating system design, it is necessary to estimate the long-term (annual and/or monthly) average heating loads. The water heating load or the amount of energy required to warm water from the inlet cold water to a desired temperature is dependent on several factors such as hot water consumption rate, cold water inlet and desired hot water set temperatures, location and orientation of the system.

A. Modeling of Aquaculture Pond

A numerical model based on energy balance was developed to simulate the thermal behavior of the open-pond system. Heat losses occur mainly by evaporation, convection and radiation. Calculation of these losses can be based on simplified equations that are generally applicable to water bodies [6]. Heat gains are achieved by means of incident solar radiation and flat plate collectors. Heat exchange by conduction with the ground is normally so small as to be negligible. We assumed uniform temperature for the entire pond, although we know that there are some temperature differences through depth, and thus applied a well-mixed model [6].

B. Evaporation Losses

The evaporation heat loss is the largest loss component and is given

$$Q_e = A P_a \left[35V + 43\left(T_p - T_a\right)^{1/3}\right]\left(w_p - w_a\right) \tag{5}$$

Where Q_e is the evaporation loss (W), V is the wind speed in (m/s) in the vicinity of the pond, P_a the ambient air pressure (101.3 k Pa). T_P is the pond temperature, T_a is the ambient temperature, ω_P is the saturation humidity ratio at the pond temperature, ω_a is the humidity ratio of the ambient air above the pond, A is the area of the pond [6, 7].

C. Convection Losses

Heat losses due to convection to the ambient air can be expressed as [6, 7]

$$Q_c = Q_e \times 0.0006 \, \frac{T_p - T_a}{w_p - w_a} \tag{6}$$

D. The Net Radiation Losses

Results from the surface of the pond to the sky which can be expressed as [6, 7]:

$$Q_r = \varepsilon \sigma A \left[\left(T_p + 273\right)^4 - T_s^4\right] \tag{7}$$

Where Q_r is the radiation loss, ε is the emissivity of the surface, σ is the Stefan-Boltzmann constant, T_S is the sky temperature in degrees Kelvin, T_p is the pond temperature.

E. Solar Radiation Heat Gain

Heat gain due to the absorption of solar radiation by the pond is given by [6, 7]

$$Q_s = \alpha \, AG \tag{8}$$

Where α is pond absorptance (0.9).

F. Calculation of Pond Heating Load

The pond heating load is the total heat losses by the three mechanisms described above less any heat gain from incident solar radiation.

$$Q_l = Q_e + Q_c + Q_r - Q_s \tag{9}$$

Fig. 2 and Fig. 3 represent the three losses component and solar gain in summer and winter respectively. The evaporation loss represents the largest component of pond losses followed by the convection losses and finally the radiation losses. As the air temperature decrease the losses of the pond increase. The solar gain follows the solar radiation variation in the desired location. Fig. 3 shows the load profile of aquaculture system to keep pond temperature at the desired temperature. The energy required is inversely proportional to air temperature.

IV. OPTIMAL SIZING USING GENETIC ALGORITHM

The optimization technique with genetic algorithm is used to find mainly the optimal size of flat plate collector and auxiliary heater based on minimum cost of the system. A life-cycle analysis is performed in order to obtain the total cost (or life-cycle cost). The period of economic analysis is taken as 20 years (i.e., life of the system), whereas the auxiliary heater has been sized to satisfy the whole load without solar radiation.

GAs differs from the traditional methods of optimization in: A population of points (trial design vectors) is used for starting the procedure instead of a single design point. GA uses only the values of the objective function. The derivatives are not used in the search procedure. In GA the design variables are represented as strings of binary variables that correspond to the chromosomes in natural genetics. Thus the search method is naturally applicable for solving discrete and integer programming problems. For continuous design variables, the string length can be varied to achieve any desired resolution. The objective function value corresponding to a design vector plays the role of fitness in natural genetics. In every new generation, a new set of strings is produced by using randomized parents selection and crossover from the old generation (old set of strings) [4].

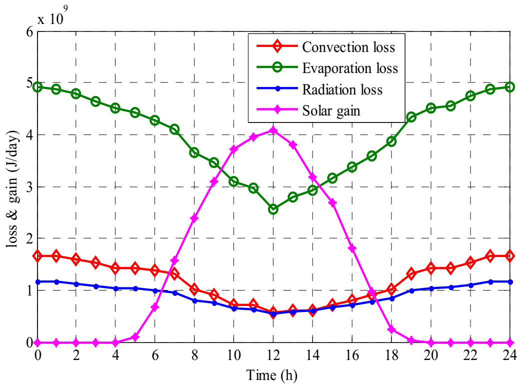

Figure 2. The solar gain and losses of the pond during the summer.

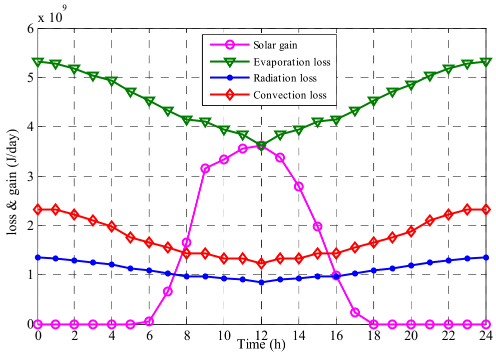

Figure 3. The solar gain and losses of the pond during the winter.

The solar cost represents by the annualized life cycle cost method is as below:

$$C_s = CI + CM\ \&\ O + CR - CS \tag{11}$$

$$CI = CF + C_a\ A \tag{12}$$

Where C_s is the solar system cost, *CI* is initial system cost, *CM&O* represents cost of maintenance and operation equal to 2% of initial value, *CR* represents replacement cost, *CS* is salvage value equal to 20% of initial cost, where *CF* is the collector area independent cost (4000$) and *Ca* is the collector area dependent cost (333$/m^2) [8, 9]. The auxiliary system cost is given by [10]

$$C_{aux} = I + F + V \tag{13}$$

Where *I* is initial cost equal to 450$/KW, *F* is fixed cost has the value of 2.7% of initial cost, and *V* variable cost equal to 1.2 $/MW$_h$. Total system cost is

$$TC = C_s + C_{aux} \tag{14}$$

To convert to annualized value of money two factors have been used which are capital recovery factor (*crf*) and sinking fund deposit factor (*sdfd*) respectively [8]

$$crf = \frac{i}{1 + (1 + i)^{-n}} \tag{15}$$

$$sdfd = \frac{i}{(1 + i)^n - 1} \tag{16}$$

A. Problem Description and Sizing Procedures

The flowchart of genetic procedure which is used in sizing calculation is depicted in Fig.6. The economic minimization model is as below:

Minimize

$$LCC = \sum_{i=1}^{n} CIi + CRi + CMOi - CSi \qquad (17)$$

The system constraint is the energy balance which must be satisfied during the year. The energy balance insures continuity for feeding the load demands along the year.

The constraint model is as follows:

Subject to

$$\begin{aligned}&Load\ demand \geq \\ &Energy\ of\ solar\ thermal + Energy\ of\ auxiliary\ heater\end{aligned} \qquad (18)$$

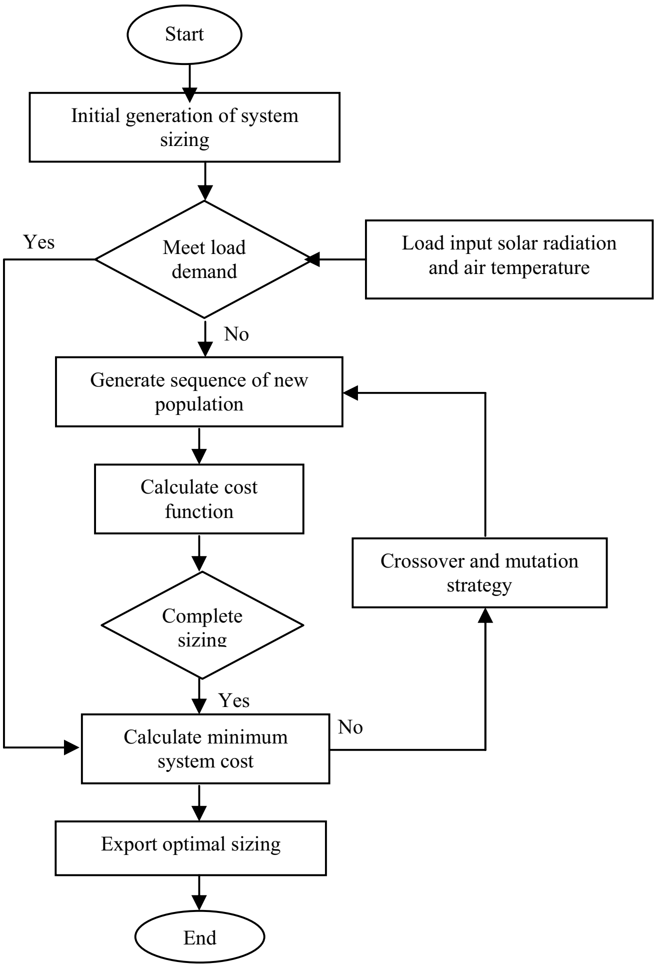

Figure 4. The flow chart of genetic algorithm.

V. RESULTS AND DISCUSSION

The genetic algorithm parameters used in the present work are as follows, Population size (=20). Crossover rate (=80%). Crossover rate determines the probability that the crossover operator will be applied to a particular chromosome during a generation. The program give the area of flat plate collector is equal to 63 m^2, at this area the solar fraction is equal to 98% which satisfy the load. The aquaculture system has two operating seasons during the year (summer and winter).

The solar fraction, *f*, is defined as the ratio of the useful solar energy supplied to the system to the energy needed to heat the water if no solar energy is used. In other words, *f* is a measure of the fractional energy savings relative to that used for an auxiliary system. Fig. 5 and Fig. 6 show the variation of solar fraction with different collector areas and solar radiation in summer and winter respectively. As collector area increase solar fraction increase but it depends on system cost. The average value of solar fraction in summer is higher than in winter due to high value of solar radiation in summer. For a 63 m^2 collector is able to supply 90–99% of the hot water demand from May to September.

Fig. 7 and Fig. 8 present the variation of air temperature effect on solar fraction in summer and winter respectively. January has the minimum value of solar fraction due to the low values of air tempeature and solar radiation over the winter season. The value of solar fraction in winter is in range of 44.9% - 92.8%, and in summer is 68.1% - 99%.

The senstivity analysis are carreied out by varying the input parameters (solar radiation, air temperature, and interest rate). Fig. 9 and Fig. 10 present the solar radiation variation over the year on cost function. In winter season the auxiliary heater give more energy to heat water to the desired temperature so the variation of cost are increase depends on the value of auxiliary heater energy. Table I shows the effect of interest rate variation on cost, as interset rate incease the system cost incease. In Egypt the value of interest rate equal to (=11.6%.)

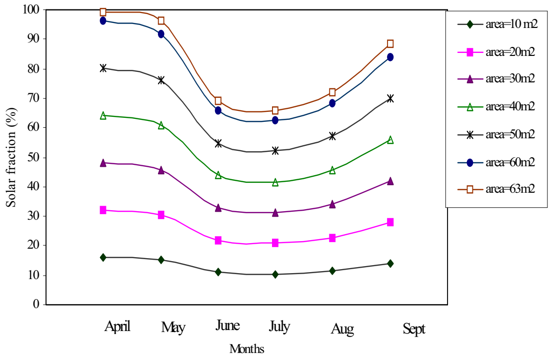

Figure 5. Solar fraction variation with solar radiation in summer.

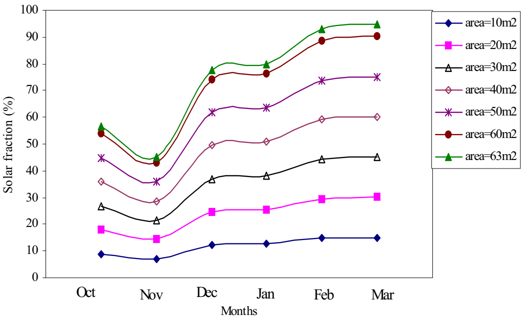

Figure 6. Solar fraction variation with solar radiation in winter.

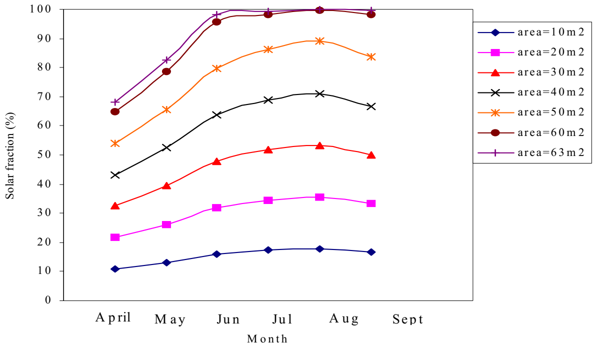

Figure 7. Solar fraction variation with air temperature in summer

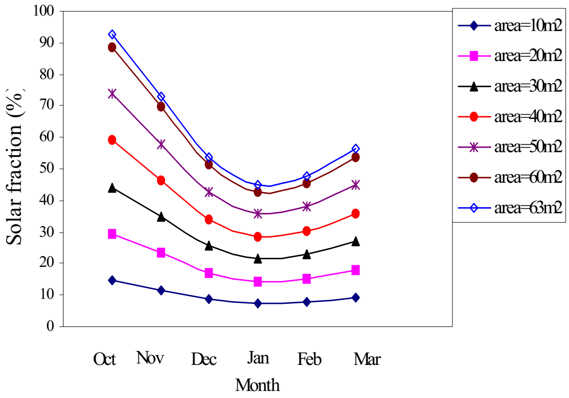

Figure 8. Solar fraction variation with air temperature inwinter.

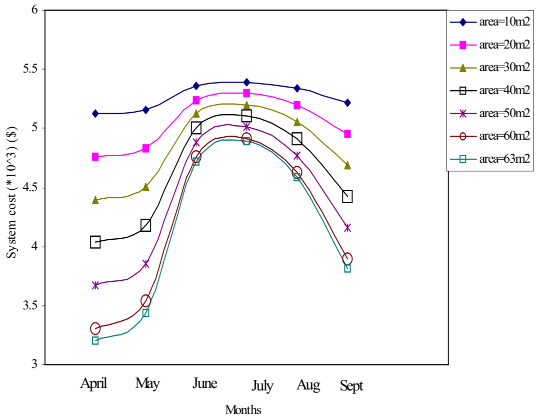

Figure 9.System cost variation with different collector areas

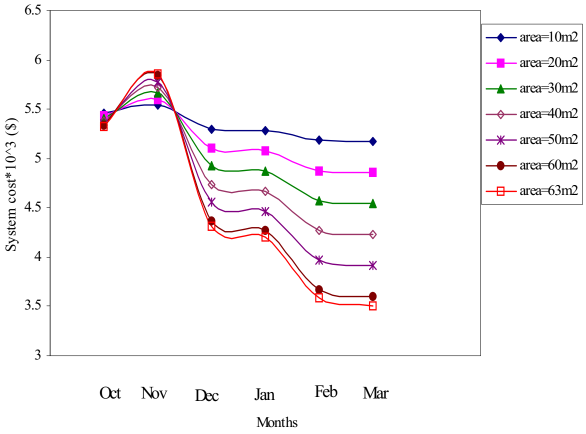

Figure 10. System cost variation with different collector areas

TABLE I. COSTVARIATION WITH INTEREST

Interest rate (%)	Cost $(10^3\$)$
5	2.6012
8	3.3821
10	3.9336
12	4.3522
15	5.3284
20	6.6868

VI. CONCLUSION

Optimum sizing of system components is important in design a large solar thermal water heating system. In this paper a design of a solar thermal water heating system for supplying an aquaculture system with the required hot water demand was presented. A methodology of sizing solar thermal water heating system using genetic algorithm is proposed. Genetic algorithm has been suggested in order to determine the optimal sizing of solar thermal system according to minimize the objective function considering the different constraints and give the optimal area of flat plate collector. The collector area is equal to 63 m^2, at this value the solar fraction reached to 98%which is very high value. The solar radiation has obvious effect on the solar fraction and system cost specially when collector area increase. The senstivity analysis are carreied out by varying the input parameters (solar radiation, air temperature, and interest rate).

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