Performance Analysis of Evacuated Tube Collector in Hot Climate

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Abstract

Solar collectors are the major component in solar thermal systems, with flat plate and evacuated solar tube collectors the most common ones. Flat plate collectors operate efficiently at low temperatures which limits their applications to domestic water heating and space heating. The high temperatures can be achieved by adapting a vacuum between the glass cover and the absorber plate to reduce or eliminate convection losses. This paper presents an experimental and numerical study for evaluating the performance of evacuated tube solar water collector in Kuwait climate. The present paper introduces a detailed developed model for evacuated tube solar collectors where a more comprehensive optical and thermal analysis is proposed. The variation of the temperature along both the circumferential (fin) and the longitudinal (tube) directions is considered in the present model. A numerical procedure is implemented to obtain the solution for the nonlinear set of equations representing the mathematical model. A subroutine program compatible with TRNSYS is adapted to simulate the performance of ETC. The numerical model is validated by comparing simulation results with the experimental data provided by the collector manufacturer. Simulation results are found to agree well with the experimental results indicating the accuracy of the present developed model. The thermal performance of solar system adapting evacuated tube collector designed for space heating, domestic water heating, air conditioning requirements of a typical house in Kuwait is investigated. The optimum ETC area is approximately equal to 44 m^2. The total solar fraction for evacuated tube solar collector satisfies a significant portion of the load about 0.74. Finally, the value of life cycle savings is found to be \$2300 per year for the optimum conditions. These results prove the feasibility of the solar heating and cooling systems in Kuwait climate.

Keywords: Evacuated tube collector, collector efficiency, domestic hot water, space heating.

1. Introduction

Solar high temperatures applications include power generation, air conditioning systems as well as solar industrial heat processes. Evacuated tube solar collectors (ETC) are increasingly in use worldwide because of their high thermal efficiency and high working temperature compared to the flat plate solar collectors. The efficiency of ETC is substantially enhanced due to the presence of vacuum between the absorber and the cover of evacuated tube solar collector (ETC). This is mainly attributed to the reduction in heat losses by convection ad conduction. The high energy absorption increases the values of solar fraction and instantaneous efficiency. There are several configurations of evacuate tube collector. The simplest one uses a flat plate with a flow arrangement attached to an evacuated glass cylinder. Introducing a heat pipe as the absorbing element in the collector tube greatly enhances the performance of evacuated tube collector. A substantial thermal heat is transferred through the heat pipe with a small temperature difference between heat input and heat output. The heat pipe consists of a closed container filled with a capillary device and charged with small amount of working fluid suitable for the operating conditions. The incoming fluid is absorbed and then vaporized in the pipe. Heat pipes require different working fluids as fluid properties such as vapor pressure and density are temperature dependent. There are two categories of evacuated-tube solar collectors; first is the single-walled glass evacuated-tube and the other is the Dewar tube. The two basic types have a distinction differences. As an example, heat extraction can be through a U-pipe, heat pipe or direct liquid contact.

Badar et al. [1] developed an analytical steady-state model to study the thermal performance of an individual single-walled evacuated-tube with coaxial piping incorporating both single and two-phase flows. Zambolin et al [2] carried out thermal performance comparisons in two types of the flat plate and vacuum tubes solar collectors. They concluded that, in the steady-state conditions, the slope of the linear regression instantaneous efficiency with increasing heat losses in flat plate collector is greater than the water-in-glass ETCs. An improved procedure for the experimental characterization of optical efficiency in evacuated tube solar collectors has been introduced by Zambolin et al [3]. Evacuated tube collectors usually have much greater efficiencies than the conventional flat plate collectors especially at low temperature and isolation [4-6]. The performance of the heat-pipe collectors have been studied and reported before [7-10]. The thermal performance of four differently shaped absorbers of the evacuated-tube is analyzed numerically and experimentally by Kim and Seo [11].

Zhao et al. [12] conducted an experimental and theoretical research on a prototype of a looped heat pipe single walled evacuated tube water heating system. Yin and Harding [13] studied the effect of a range of tube inclinations, manifold flow rates and inlet temperatures. They concluded that for a wide range of operating conditions, buoyancy effects alone resulted in efficient heat transfer. A combination of single-walled evacuated-tubes comprising heat pipes with an external or internal concentrator is presented by Nkwetta et al. [14]. Tang et al [15,16] presented a mathematical procedure to determine the optimal choice of tilt and zenith angles. At the same environmental conditions, Ayompe et al. [17] conducted an experimental study to compare the performance of both FPC and a heat pipe ETC for domestic water heating system application. The collector efficiencies were found to be 46.1% and 60.7% and the system efficiencies were found to be 37.9% and 50.3% for FPC and heat pipe ETC, respectively.

Morrison et al. [18] presented a numerical study on a 45° inclined evacuated tube collector. They found the possible presence of a stagnant region at the bottom of very long tubes. Evacuated tube collectors is preferably used for high temperature applications such as desalination of sea water, air conditioning, refrigeration, and industrial heating processes since their performance is better than that of FPC [19]. The effects of thermal flow and mass rate on forced circulation solar hot water system are experimentally investigated by Gao etal. [20]. Two types of ETC namely water in glass and U pipe evacuated collectors was adapted. Results showed that U pipe evacuated collectors have 25–35% higher energy storage than water in glass. In addition, they concluded that the energy storage and also pump operations are influenced by the flow rate and fluid thermal mass. It is noted that the performance of energy collection will be reduced for higher flow rate.

Mangal [21] stated that ETC are strong and long lasting. If any tube is broken, it is just replaced which is considered as a cheaper option compared to flat plate collector (FPC) which require the replacement of the whole collector. Optical and heat loss characteristics of water in glass evacuated tube solar heaters is investigated by Budihardjo and Morrison [22].The domestic water heating system was compared with FPC and the performance of 2 panel flat plate arrays was found to be higher than 30 evacuated tube arrays. Shukla et al. [23] mentioned in the review of recent advances in the solar water heating system that the performance of an ETSC is better than mostly used FPC due to its ability to produce high temperature but ETSCs are not widely used because of its high initial cost.

Louise and Simon [24] studied heat transfer and flow structure employing computational fluid dynamics and an optimum inlet flow rate of 0.006–0.015 kg/s has been recommended. The thermal performance of single-phase ETCs with different tilt angles was carried out by Selvakumar et al [25]. They found that the daily efficiency of inclined solar water heater at 22°C is relatively equal to that of inclined solar water heater at 46°C. So, they concluded that the result shows that the thermal performance of water-in-glass solar domestic hot water system is independent of the collector slope.

Ayompe and Duffy [26] analyzed the thermal performance of solar water heating system using heat pipe evacuated tube collector. Measurement data are collected over one year period from a forced circulation solar water heating system. Water was used as the working fluid in the system and the maximum outlet temperature of water was recorded as 70.3° while 59.5° was recorded at the bottom of the hot water tank. Measurements obtained revealed that the heat pipe ETCs are more efficient than FPCs of a solar water heating system. The characteristics and the performance of different types of ETSCs for solar water heating system sthrough out the year was investigated by Arefin et al. [27]. They evaluated the system feasibility by calculating the payback time. They also reported that all glass evacuated tubes are the cheapest and simplest and the heat loss is less than heat pipe collectors as the glass tube collectors are directly connected with the tank. In addition, they determined the operating temperature of the system to be 50° C which is good enough for domestic purposes and their cost analysis showed that the solar water heater using an ETSC is more cost effective than the electric water heater. Pappis et al. [28] conducted economical and environmental comparison between FPC and ETC. They stated that the ETC are the best choice from the environmental point of view because of the least impact generated during the manufacturing process. On the other hand, FPC is preferable from the economic point of view as it is much cheaper than ETC.

Active solar heating systems are now widely used in many applications, while, active solar cooling systems are not. Many publications studied the performance of the solar heating systems [29-31]. On the other hand, there are fewer publications discussing the performance of solar cooling and air conditioning systems. Absorption chiller systems are considered as the most suitable option for solar cooling; because they are compact, reliable and can be easily integrated into different building energy systems. An absorption air conditioner or refrigerator does not use an electric compressor to mechanically pressurize the refrigerant. Instead, the absorption device uses a heat source, such as natural gas or a solar collector, to evaporate the already-pressurized refrigerant from an absorbent/refrigerant mixture. Breesch et al. [32] studied passive cooling in a low-energy office building in Belgium in which natural night ventilation and an earth-to-air heat exchanger are applied. The overall thermal comfort in the office building is evaluated by means of measuring and simulation results.

The objective of this paper is to investigation thermal performance of evacuated tube solar water collector in hot and harsh climate like Kuwait climate. The present paper introduces a detailed nonlinear model for evacuated tube solar collectors where a more comprehensive optical and thermal analysis is proposed. The numerical developed model is validated by the experimental data provided by the collector manufacturer. The variation of the temperature along both the circumferential and the longitudinal directions is considered in the present model. The second goal of the present study is to investigate the thermal performance of solar system designed for space heating, domestic water heating, and cooling requirements of a typical house in Kuwait. TRNSYS [33] is adapted to simulate the thermal performance of different solar heating and cooling system components.

2. Theoretical Modeling of ETC

Evacuated tube collector receiver consists of a copper U-tube inside a glass vacuumed tube. The copper tube is surrounded by a cylindrical aluminum fin pressed on it. This fin enhances the heat transfer area between the inner glass absorber surface and the U-tube. The working fluid enters the collector inlet pipe, then it is evenly distributed to the U-tubes, absorbs heat and, at the end, it is returned to the outlet header pipe. The outer cylindrical glass transmits the rays to the inner glass tube, which conducts the energy to the absorber fin. The energy transformed into heat is conducted by the fin to the copper U-tube and finally absorbed by the working fluid, which is water in this case. Figure 1 shows a detailed schematic diagram of the evacuate tube and its cross section view.

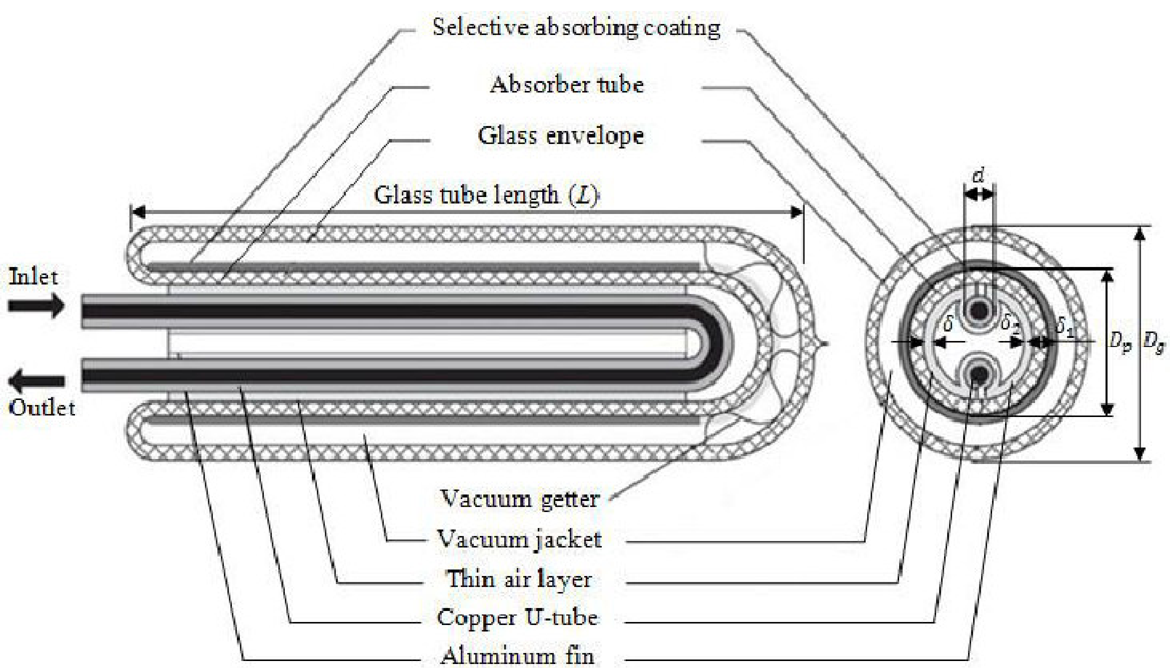

Figure 1. Schematic diagram of the glass evacuated tube solar collector with U-tube

One dimensional analysis for the fin of a single unit of the glass evacuated tube solar collector is carried out. To simplify the model, the following assumptions are considered: i) steady-state conditions are considered with normal incidence angle of solar radiation; ii) thermal resistance of the outer glass tube thickness is negligible; iii) perfect vacuum is assumed between the two glass tubes, thus gas conduction is neglected; iv) an air layer of small thickness is considered between aluminum fin and the absorber glass tube. The absorbed solar power (S), is equal to the incident solar power times the optical losses and can be expressed as:

$$S = (\tau\alpha)GA_a \qquad (1)$$

where τ is the glass cover transmittance, α is the glass cover absorptance, G is the global solar irradiance on the collector surface and A_a is the collector aperture area. The theoretical model is based on the heat balance equations for each part of the collector as follows:

i) Outer glass tube

$$h_{r-g}L_{r-g}(T_r - T_g) + h_{g-a}L_g(T_a - T_g) = 0 \qquad (2)$$

where T_r, T_g, T_a are the inner glass tube temperature, outer glass tube temperature and ambient temperature; h_{r-g} is the heat transfer coefficient between the inner and outer glass tubes; and h_{g-a} is the heat transfer coefficient between the outer glass tube and the ambient environment. Heat conduction can be ignored because the space between the inner and outer tubes is a very narrow vacuum layer, in which the vacuum level is 10^{-4} Pa and the heat conduction coefficient is less than 0.27 x 10^{-5} W/m °C [34]. Considerin $h_{r-g} = h_{r-g,rad} + h_{r-g,cond}$, where $h_{r-g,rad}$ and $h_{r-g,cond}$ are the radiation and conduction heat transfer coefficients between the outer and inner glass tube Also, $h_{g-a} = h_{g-a,rad} + h_{g-a,conv}$, where $h_{g-a,rad}$ and $h_{g-a,conv}$ are the radiation and convection heat transfer coefficients between the outer tube and the ambient environment, and $h_{g-a,conv}$ is a function of the wind velocity. $L_{r-g} = (L_r + L_g)/2$, where L_r and L_g are the perimeters of the inner and outer glass tubes.

ii) Inner glass tube

$$h_{r-g}L_{r-g}(T_g - T_r) + h_{r-Al}L_{r-Al}(T_{Al} - T_r) + Q_e + \tau_g\alpha_r d_g G = 0 \qquad (3)$$

where T_{Al} is the aluminum fin temperature; and h_{r-Al} is the total heat transfer coefficient between the inner glass tube and the aluminum fin, and $h_{r-Al} = h_{r-Al,rad} + h_{r-Al,cond}$, where $h_{r-Al,rad}$ and $h_{r-Al,cond}$ are the radiation and conduction heat transfer coefficients between inner glass tube and aluminum fin, τ_g is the transmission coefficient of the outer glass tube; τ_r is the absorption coefficient of the selective coating on the inner glass tube; d_g is the diameter of the outer glass tube; G is the total solar irradiance on the collector aperture surface; $L_{r-Al} = (L_r + L_{Al})/2$, where L_{Al} is the perimeter of aluminum fin, and Q_e is the heat loss of the tube edge to the manifold.

iii) Aluminum fin

$$h_{r-Al}L_{r-Al}(T_r - T_{Al}) + h_{Al-Cu}L_{Cu}(T_{Cu} - T_{Al}) = 0 \qquad (4)$$

where T_{Cu} is the U copper pipe temperature; and h_{Al-Cu} is the total heat transfer coefficient between the aluminum fin and U copper pipe, $h_{Al-Cu} = h_{Al-Cu,rad} + h_{Al-Cu,cond}$, where $h_{Al-Cu,rad}$ and $h_{Al-Cu,cond}$ are the radiation and conduction heat transfer coefficients between the aluminum fin and U copper pipe, and L_{Cu} is the perimeter of the copper pipe.

iv) U copper pipe

$$h_{Al-Cul}L_{Cu}(T_{Al} - T_{Cu}) + h_f L_{Cu}(T_f - T_{Cu}) = 0 \qquad (5)$$

where h_f is the fluid convective heat transfer coefficient inside the U copper pipe and it varies with flow velocity.

v) Working fluid

$$h_f L_{Cu}(T_{Cu} - T_f)\, x + \dot{m} c_p (T_{in} - T_{out}) = 0 \qquad (6)$$

where T_{in} and T_{out} are the inlet and outlet temperatures of working fluid in the U copper pipe and x is the interval of the fluid along the tube axis. $\dot{m}$ and c_p are the mass flow rate and specific heat capacity of the working fluid.

The radiation heat transfer coefficient ($h_{r-g,rad}$) between the outer and inner glass tube is given by:

$$h_{r-g,rad} = \frac{\sigma\left(T_r^2 + T_g^2\right)\left(T_r + T_g\right)}{\frac{1}{\varepsilon_r} + \frac{1}{\varepsilon_g} - 1} \qquad (7)$$

where ε_r and ε_g are the emission coefficients of the inner tube selective coating and glass of the outer glass tubes, respectively. Under the conditions given by the industrial temperature range, the ambient air can be treated as a transparent body of heat radiation, so that $h_{g-a,rad}$ can be ignored.
The convection heat transfer coefficient (h_f) between the fluid and the U-pipe wall is given by [35]:

$$h_f = \frac{\lambda_f Nu}{D} = \frac{\lambda_f}{D} 1.75 \left[Gz + 5.6 \times 10^{-4}\left(GrPr\frac{L_T}{D}\right)^{0.7}\right]^{\frac{1}{3}} \left(\frac{\mu_{av}}{\mu_{wall}}\right)^{0.14} \qquad (8)$$

where Nu is Nusselt number, Gz is Graetz number, Pr is Prandtl number, L_T is the length of the tube, D is equivalent diameter for the theoretical model, μ_{av} and μ_{wall} are the viscosity of fluid at average fluid temperature and wall temperature.

The thermal efficiency of ETC (η) is given by:

$$\eta = F_R(\tau\alpha) - F_R U_L \frac{(T_{in} - T_a)}{G} \qquad (9)$$

where $(\tau\alpha)$ is the transmittance-absorptance product, T_{in} is the working fluid inlet temperature, T_a is the ambient temperature, U_L overall heat loss coefficient. The 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.
The previous equations are employed to develop a theoretical model to predict the performance of evacuated tube collector under different climatic conditions.

3. System Description and Control Strategy

A schematic diagram of the system studied is represented in Figure 2.

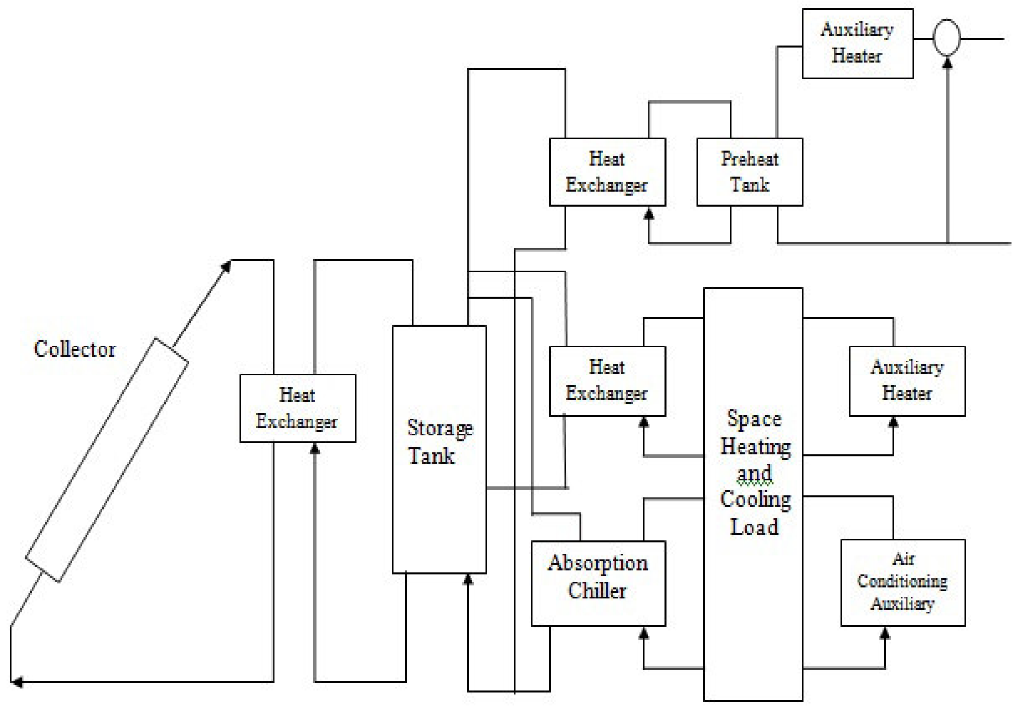

Figure 2. Schematic diagram of the solar heating and cooling system

The system consists of evacuated tube solar collector, a storage tank, an absorption chiller, heat exchanger, and auxiliary units. The main components of the absorption unit are; generator, condenser, evaporator, absorber, and low temperature heat exchanger. The lithium bromide solution is pumped from the absorber to the generator where the water is boiled off. The heat source is passed in a counter-flow arrangement through the generator to boil off water vapor from the LiBr-H_2O solution. A cooling water loop is needed to condense the water vapor boiled off from the generator and to aid in the absorption of water vapor back into the LiBr-H_2O solution. This cooling water is passed first through the absorber and then the condenser. The evaporator takes in low-pressure cold water and produces a cooling effect by evaporating the water and passing it to the absorber. Hot water is supplied to the air conditioner at a temperature of 87°C (minimum), 93°C (maximum) and leaves this unit 10°C cooler than the supply and returns to the storage (or to the auxiliary heater if storage is below 77°C). Whenever hot water from storage is cooler than 87°C, the auxiliary heat is supplied to raise its temperature to 87°C. When storage is cooler than 77°C, it is not used, and the auxiliary heater carries the full cooling load. The performance of air conditioning systems is expressed by their coefficient of performance (COP). COP determines how many units of cooling/heating one gets for every unit of energy he puts.

The system operates in four different modes. When solar energy is available for collection and there is a load demand, heat is supplied directly from the collector to the heating or cooling unit. When solar energy is available for collection and there is no heat or cooling demand, heat is stored in the storage unit. On the other hand, if solar energy is not available for collection and there is a load demand, storage then supplies heat to the heating or cooling unit. However, if storage temperature is not sufficient, the heating or cooling load is supplied by the auxiliary source. The control strategy and the multistage room thermostat used is shown in Table 1.

Table 1. Control Strategy for Room Thermostat

	On Temperature (°C)	Off Temperature (°C)
Solar- AC	$T_R > 24.9$	$T_R < 24.1$
Auxiliary I- AC	$T_R > 25.5$	$T_R < 25.0$
Auxiliary II-AC	$T_R > 26.6$	$T_R < 26.0$
Solar- Heat	$T_R > 19.7$	$T_R < 21.2$
Auxiliary – Heat	$T_R > 18.2$	$T_R < 19.6$

4. Results and Discussions

The following sections present the results of the current study.

4.1 Evacuated Tube Collector Performance

A comparison between the ETC performance predicted by the present model and the corresponding performance provided by the collector manufacturer is presented in Figure 3 for reduced temperature, $(T_{in}-T_a)/G$, ranging from 0 to 0.08 m^2 K/W. Simulations are carried out under different test conditions to obtain the collector efficiency curve shown in Figure3.

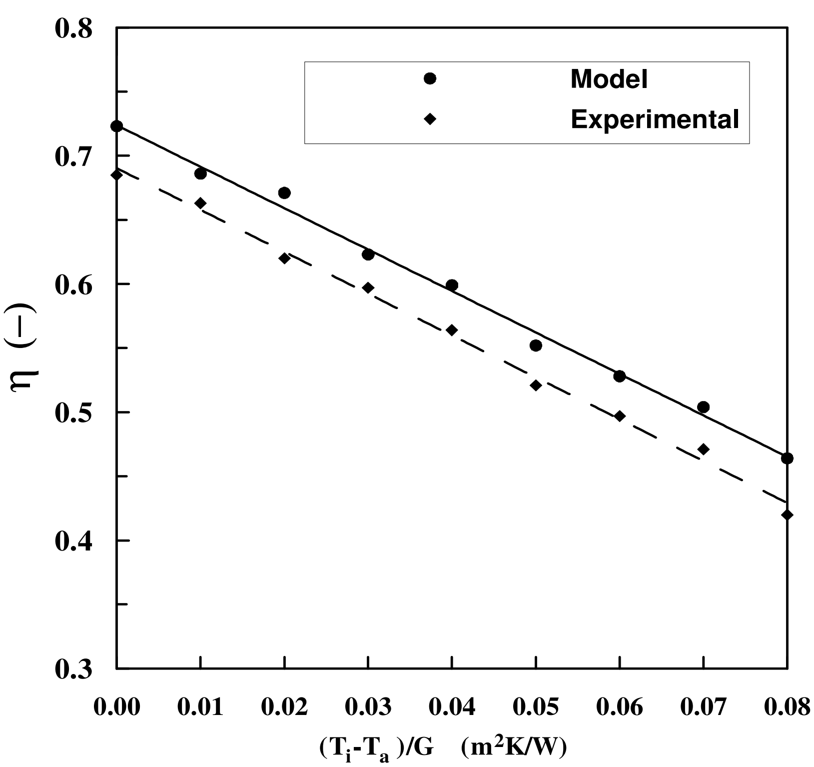

Figure 3. Comparison between simulated and experimental ETC thermal efficiency

The efficiency curves obtained from the present model and experimental data provided by manufacturer are:

$$\eta_{\mathrm{model}} = 0.718 - 3.17\frac{(T_{in} - T_a)}{G} \tag{10}$$

$$\eta_{\mathrm{experiment}} = 0.696 - 3.31\frac{(T_{in} - T_a)}{G} \tag{11}$$

Error analysis revealed that the maximum deviation between model and experimental optical efficiency is about 2.9% while the maximum deviation between model and experimental overall heat loss coefficient is approximately 3.8%. The above graph and these predictions clearly demonstrate the reliability of the present developed ETC numerical model.

4.2 Solar Heating and Cooling Performance

The solar heating and cooling system is designed to satisfy the needs of space heating, water heating and air conditioning loads for a family in a typical Kuwaiti house. The weather data file for Kuwait is measured and recorded for two years at the College of Technological Studies, Kuwait. The weather file contains monthly average values of daily radiation on horizontal surface, clearness index, ambient temperature, and wind speed. The weather data generator subroutine included in TRNSYS package is used to generate hourly data from the available average monthly data for Kuwait. Figure 4 shows the variation of the solar fraction of space heating (F_s), domestic water heating (F_D), and cooling load (F_{Ac}) as well as the total solar fraction (F_t) with collector area. As seen from the figure, a significant portion of the solar fraction for space heating and domestic water heating is satisfied at areas around 44 m^2. Conversely, the space cooling requires much greater areas.

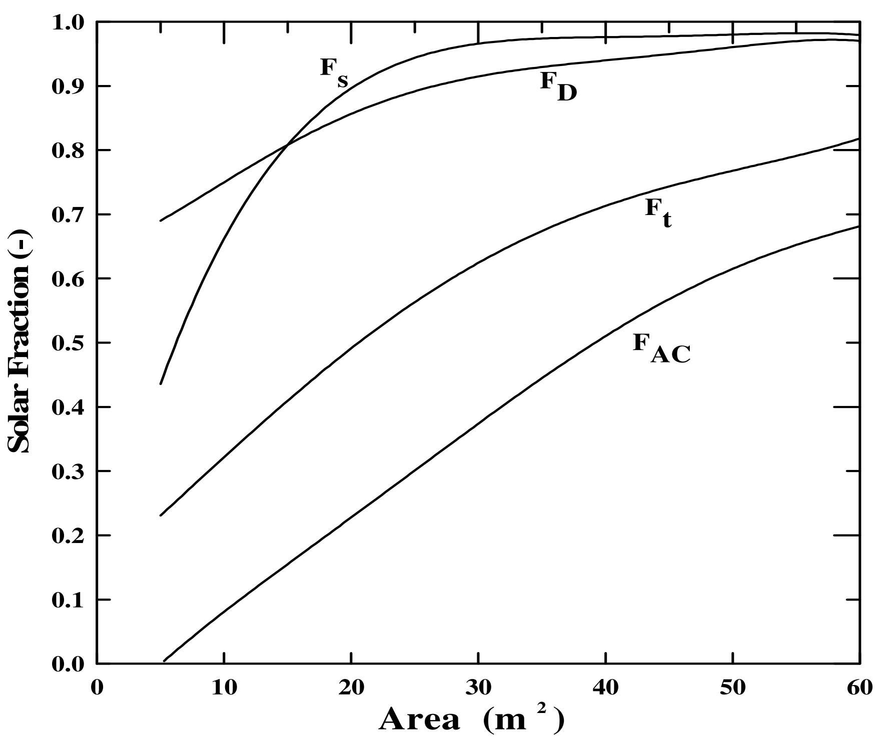

Figure 4. Solar fraction variation with collector area

The variation of total solar fraction, life cycle savings, and overall system efficiency (ratio of solar energy provided to the total incident radiation) with collector area is presented in Figure 5. This typical figure shows the choice of optimum collector area which is approximately equal to 44 m^2 in this case. It is clear from this figure that this optimum area neither corresponds neither to maximum system efficiency nor to the maximum solar fraction. Also, the total solar fraction (F_t) for evacuated tube solar collector satisfies a significant portion of the load about 0.74. Finally, the coefficient of performance (COP) of the absorption chiller is approximately 0.62 which is within the accepted practical values of the conventional lithium bromide system. The life cycle cost of the conventional and the solar system varies significantly due to the corresponding variation of the total load. The value of life cycle savings (LCS) is found to be \$2300 per year for the optimum conditions. These results prove the feasibility of the solar heating and cooling systems in Kuwait climate.

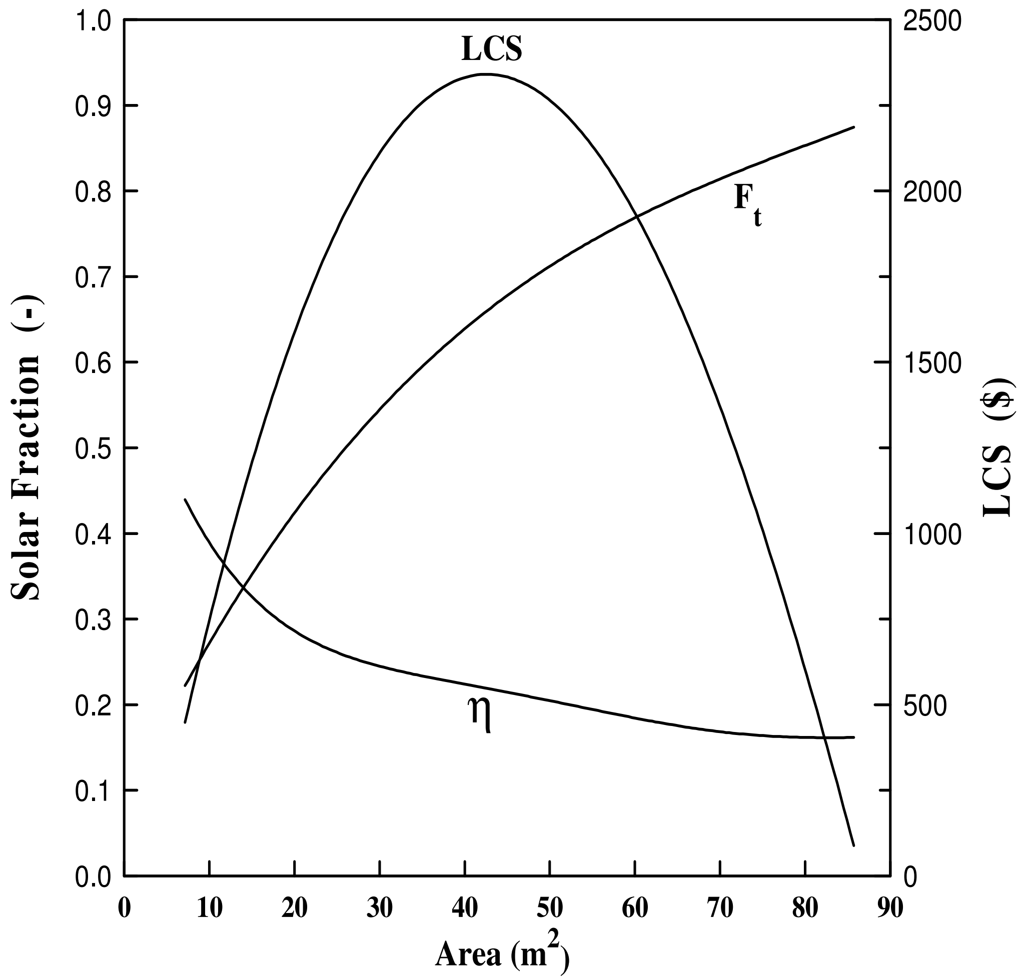

Figure 5. Variation of system parameters with collector area

5. Conclusions

The present paper introduces a detailed nonlinear model for evacuated tube solar collectors. The numerical developed model is validated by the experimental data provided by the collector manufacturer. Also, the present study investigates the thermal performance of solar system designed for space heating, domestic water heating, and cooling requirements of a typical house in Kuwait. Based on the present results, the following conclusions can be drawn:

- The reliability of the present developed model is validated by the experimental data and the two predictions agree well.
- The maximum energy is attained with a solar collector area of 44 m^2.
- An annual solar savings of about $2300 is achieved at these optimum conditions which confirm the feasibility of solar heating and cooling systems in Kuwait climate.
- The results of the present study should encourage wide utilization of solar energy systems which will help in keeping our environment healthy and clean.

Nomenclature

A_p	collector Aperture area (m^2)
c_p	specific heat of the water (J/kg K)
F_D	solar fraction of domestic water heating
F_s	solar fraction of space heating
F_t	total solar fraction
F_R	heat removal factor
G	incident radiation on horizontal surface (W/m^2)
G_r	Grashof number
Gz	Graetz number
h	heat transfer coefficient (W/m^2 K)
L	perimeter (m)
LCS	life cycle savings ($)
$\dot{m}$	mass flow rate of water to the collector (kg/s)
Nu	Nusselt number
Pr	Prandtl number
S	absorbed solar power (W)
T_a	ambient temperature (°C)
T_{in}	inlet collector temperature (°C)
T_{out}	outlet collector temperature (°C)
U_L	collector overall heat loss coefficient (W/m^2 K)
α	absorptance
η	collector efficiency
λ	thermal conductivity coefficient (W/m°C)
μ	kinematic viscosity (Pa s)
τ	transmittance
$(\tau\alpha)$	transmittance-absorptance product

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