Pergamon

PII: S0038-092X(97)00017-0

Solar Energy Vol. 60, No. 5, pp. 245–256, 1997

0038-092X/97 $17.00+0.00

DESIGN, ANALYSIS AND PERFORMANCE OF LOW-COST PLASTIC FILM LARGE SOLAR WATER HEATING SYSTEMS

P. T. TSILINGIRIS†‡
Center for Renewable Energy Sources (C.R.E.S.), 19th Km Marathonos Ave., GR-190 09, Pikermi, Attiki, Greece

(Received 22 July 1996; revised version accepted 22 January 1997)
(Communicated by BRIAN NORTON)

Abstract—Although the use of solar energy is obvious for the energy intensive nature of low-grade heating processes, solar heating technology has not yet become commercially available even in favorable geographical locations with high solar potential. This is not surprising, taking into consideration the unreasonably high cost of solar plants relative to the level of technology of most of the commercially available components and systems. In the present work an improved low-cost large solar heating system design has been proposed, based on earlier design developments, suitable for applications in mild sunny climates where the prospects for the promotion of solar heating technology are very favorable. An analysis is developed which allows design and operational behaviour predictions of the physical system. Long-term efficiency and typical input–output performance is also investigated based on statistically processed long-term meteorological measurements for Athens, Greece. Derived results indicate that substantial performance would be expected for the proposed fractional cost system design. This may probably lead to market expansion of large solar heating plants through "commitment based" promotion schemes. © 1997 Elsevier Science Ltd.

1. INTRODUCTION

Considerable attention has recently been concentrated on the promotion of solar water heating technology, owing to the growing concern of the public with respect to the environmental hazards associated with the extensive use of conventional energy. The establishment of various incentives is being re-examined, if they are not already in use. Development of completely new or the revision of existing legislation for the mandatory installation of solar heating plants in buildings is under consideration in various countries.

Although these measures are establishing a favorable mainframe, the wide promotion of this technology in a free market environment will finally be based on its competitiveness with respect to conventional energy. The economic viability of solar heating is mainly determined by the initial cost and overall efficiency of the system, as well as by the cost of the replaced conventional energy.

Long operational experience has shown that the long-term performance of large solar heating plants is sometimes remarkably less than predicted. This is usually attributed to the complete lack of maintenance and technical support by the system user, something which considerably degrades their economic viability. When the cost of conventional energy is relatively low, the competition with solar energy may become marginal. The stabilisation of fossil fuel costs during the last decade at a relatively low level will affect the existing good prospects, inhibiting the expansion and possibly reversing the good trends for market growth, unless the initial cost of solar heating plants can be considerably reduced, while efficient maintenance schemes will ensure higher long-term system performance.

Appreciable attention has recently been paid to the establishment of commitment based promotion schemes, such as guaranteed performance and payback through energy savings. The first is based on the provision of a minimum performance guarantee to the system owner, which, if not satisfied, will impose a penalty payment on the system manufacturer and designer. The second is based on an entirely new philosophy relevant to leasing and third-party financing. In principle, it relies on a valid contract for the provision of a complete package of design, construction, financing and maintenance services for a solar heating plant, which is "leased" by an energy services company to a user, who accepts to purchase measured solar energy at a beneficial cost. Therefore, the leased system, which is no longer user property, can be paid off through the measured energy

†Correspondence address: Th. Kouri 14 str., Nea Smirni, Athens 17122, Greece.
‡ISES member.

savings, transferring in this way all technical and economic risks from the user to the specialised solar energy service company, which has every incentive to proceed to low-cost innovative design and efficient maintenance services in order to achieve the earliest pay back (Tsilingiris, 1993).

The aim of the present work is two-fold. First, to introduce a further design refinement of a large solar water heating system based on previous design developments, suitable for most domestic and process heating loads at a fractional cost and, second, the development of a generalised simple analysis for the fundamental system design and performance prediction investigations.

2. DESIGN TRENDS AND LITERATURE REVIEW

A cost effective solar system should allow capital recovery within its intended operational life, something which can be approached by two vastly different design philosophies. The first is based on the development of a sophisticated design, excessive use of expensive or even exotic materials and highly advanced manufacturing processes leading to systems of a long operational life, during which depreciation of their initial high cost would be possible.

The second refers to systems in which special attention is paid to design simplicity and the use of broadly available, low-cost and recyclable raw materials as well as simple well-proven manufacturing processes, so their fractional cost can easily be recovered even though they have a shorter operational life.

Although both approaches tend to be financially equivalent, the second appears to represent a more attractive investment due to the appreciably lower capital requirements, owing to the capital intensive nature of solar energy investments.

Among the first serious efforts to design simple low-cost, large-scale solar water heating systems were made for the Puerto Penasco pilot desalination plant in Mexico (Hodges *et al.*, 1966), where attempts have been made to use unglazed polymer film water bags on a dry sand bed in order to reduce the cost of the solar heating subsystem.

An appreciable amount of combined research, development and demonstration work on large-scale low-cost plastic bag solar collectors, the so-called shallow solar pond design, suitable for supplying large amounts of low grade heat, was performed in the U.S. almost 20 years ago (Dickinson *et al.*, 1976a,b; Guinn and Hall, 1977; Clark *et al.*, 1978; Casamajor, 1979). The system consists of a plastic film water bag which rests on a layer of thermal insulation and is covered by a UV treated fiberglass glazing, supported by arched glazing support bows. This design allows lower U values and higher operating temperatures.

The water bag is made of two layers of plastic, usually UV stabilised polyvinylchloride film sealed along the edges. The bottom and top foils are typically made of 0.3 mm clear and 0.5 mm thick black plastic films, respectively, to allow solar radiation admittance from the top and radiation absorption by the water layer and the black bottom foil, respectively.

The outcome of this remarkable development work, carried out during the 1970s mainly by a team from the Lawrence Livermore Laboratory (LLL), was the development of a practical and comprehensible manual with design and construction guidelines published by the LLL (Casamajor and Parsons, 1979). However, this technology never deeply penetrated the market. This can be attributed to the fact that it represents site built systems instead of "products", which can readily explain why it has never really attracted the attention or seriously been considered as worthy technology by the usual manufacturing–marketing organisations offering typical "turn-key" systems. Furthermore, owing to the extensive use of polymers, it is prone to rapid UV degradation unless costly UV stabilised materials are employed, which in addition to the technological risks initially involved in any relevant renewable energy investment, makes it unattractive to users. Finally, the demonstration and commercialisation efforts for these systems occurred during the early stages of the U.S. solar market collapse.

During the following years a few publications and reports, mainly on design and demonstration work on compact low-cost or portable plastic film solar water heaters, appeared sporadically in the international literature (Kudish and Wolf, 1978; Forbes, 1983; Garg and Datta, 1984; Abtahi, 1993). Their design varies from unglazed versions of the previous designs to designs with very simple glazing systems consisting, for example, of a clear polyethylene bubble-film, commonly used for protection of breakable goods during shipment, which have been tested to simplify even more an already simple and low-cost design.

A certain amount of demonstration and comparative evaluation work of the original shallow solar pond design has also recently been performed by Schwarz *et al.* (1990) using very simple polymer film glazing systems such as multiple clear plastic films, films similar to those proposed by Forbes (1983), and transparent insulation materials (TIM). To overcome the possible restrictions imposed by more stringent sanitary hot water regulations, integral copper tube coil heat exchangers inside the water bag have also been tested.

It appears that any further design improvement and reassessment of the long-term performance of such systems would be vital at this critical stage of international solar market development.

3. PROPOSED DESIGN AND SYSTEM MODELLING

The proposed design of the horizontal solar collector modules is very similar to that proposed earlier by Casamajor and Parsons (1979), and mainly differs in the design of the glazing system and collector enclosure which can be made of hard structural thermal insulation material.

The use of ordinary glass panes of 3 to 5 mm thickness is believed to resolve the problems associated with the UV degradation of polymer glazing. Apart from its weight and fragility, glass is an excellent and low-cost solar material, which substantially improves the protection of the polymer water bag against UV degradation owing to its superior spectral characteristics.

The solar collector field can be made of several parallel collector modules of an appropriate length-to-width ratio as shown in Fig. 1, the width possibly being determined by the size of widely available glass panes.

Water bags can either be factory or in-situ built products. They are basically watertight tubes made of two polymer layers of clear and dark plastic films of proper width, sealed along the edges and cut to a length suitable for the collector module. The use of a clear plastic film at the top allows the development of negative temperature gradients, induction of thermal instability and convecting mixing at the fluid layer, eliminating in this way thermal stratification effects leading to the reduction of top loss coefficient.

The water bag sits on a modular in-situ assembled modular container in direct contact

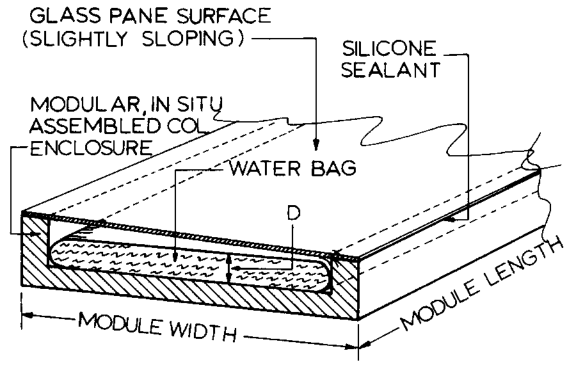

Fig. 1. Schematic representation of the typical design of the solar system module, showing the insulating collector enclosure, water bag and top glazing.

with the soil or horizontal roof, made of hard cellular polymer thermal insulation material of the appropriate cross-sectional design and dimensions, sealed at the top with the glass panes which are supported by the edges of the container. These in-situ assembled insulating containers are factory made and designed to allow easy assembly of solar modules of any size at fractional time.

Owing to the very low profile of the horizontal modules they can very easily be concealed on the roofs of buildings, presenting an appropriate solution to the problem of the integration of large conventional collector fields in buildings situated in architecturally protected areas. The proposed solar water heaters can, when necessary, be used either with or without a load heat exchanger.

The use of simple, mostly polymer pre-fabricated components and structural parts, produced remotely in mass quantities and at low cost for easy in-site assembly of large collector fields within a few hours, leads eventually to the erection of large solar heating plants at a fractional overall cost.

The pre-fabricated plastic bag container made, for example, from cellular, moisture-proof, construction-grade thermal insulation material, is readily fixed in place (for example, in horizontal roofs) and forms the basic structural part of the system, on which the pre-fabricated water bag is unfolded and connected through standard fixtures with the piping, before applying and sealing the top glazing at the rim of the container.

System cost estimates are usually based on experience gained through the construction of full size models and demonstration plants. Although there is a complete lack at the moment of any practical system of the design under consideration, attempts towards system cost estimates have been carried out, based on the market cost of materials and labour. It is estimated that the unit cost of the system will possibly be as low as about 30 U.S.$ m^{-2}, based on a labor cost of about 6 U.S.$ m^{-2}, which is far lower than the estimated average unit cost of solar water heaters of about 350 U.S.$ m^{-2}.

Although the cost of the copper will be completely recoverable, the cost of an integral copper tube heat exchanger with a heat transfer area of about 0.5 m^{-2} per square metre of collector area will add about another 15 U.S.$ m^{-2}. Therefore, a possible unit cost lower than 50 U.S.$ m^{-2} is estimated for the same system with an integral heat exchanger, a figure which is still far lower than the average cost of the current design systems. It should also be noted that the estimated unit cost is strongly dependent on system size and substantial economies could be expected for scaling up the system size.

The physical system is modelled by a horizontal and isothermal fluid layer of water or antifreeze solution of uniform thickness D, heated by the incident solar radiation which is admitted through the single glass pane top glazing.

In ordinary glazed flat plate solar collectors the incident solar radiation, after striking the absorber, undergoes a sequence of absorption and reflection processes before its complete extinction and the transmittance absorbance product is calculated through conventional ray-tracing procedures.

In water heaters of the present design, the incident solar radiation, after passing through the glazing system, strikes the clear upper polymer layer of the water bag where it undergoes successive reflection and refraction at the air–polymer and polymer–water layer interfaces. Although reflection is expected to be partly diffuse and partly specular, Fresnell reflection losses at the water–polymer interface are considered to be relatively low, owing to the corresponding similar refractive index figures for both media (1.33 for water compared to around 1.45 for polymers).

Calculation of radiation absorption through the solid partially transparent media employed, requires the evaluation of their spectral characteristics. Fortunately, a single average shortwave absorption coefficient can be assigned for most polymers, since they exhibit an almost uniform transparency in the visible and near-infrared region of the solar spectrum. Although this coefficient for polymers is appreciably higher than that for glass, the absorption losses are not remarkably high, owing to the small thickness of the polymer layers employed.

Refracted radiation is further transmitted downwards through the strongly attenuating water slab to the lower black polymer layer where it is mostly absorbed, although a small fraction is diffusely reflected and retransmitted upwards, undergoing subsequent attenuation through the water slab. The same process is repeated with the reflected beam being further attenuated through reflection and absorption before its complete extinction.

It is clear that solar radiation attenuation in the water determines the transmittance absorbance product of the system. Pure water is a strongly selective absorber and exhibits a narrow transmittance window at around 0.46 μm, while it absorbs strongly towards the near-IR region of the solar spectrum. Solar radiation attenuation is due to the combined effects of absorption and scattering which are both spectrally dependent phenomena; it is proportional to the optical path length in the water and depends strongly on the optical water quality. Spectral attenuation is not only determined by the absorption characteristics of pure water, but also strongly by complex scattering mechanisms caused by suspended and dissolved matter, very sensitive to the nature, concentration and size of scattering centres (Tsilingiris, 1991).

It has been demonstrated that, although the upper theoretical transmission limit for an extremely pure water layer 0.1 m thick is as high as 64%, it becomes about 54% for the clearest natural waters (Tsilingiris, 1988). The presence of impurities, bacteria and colloidal matter, which are frequently found in stagnant waters, dramatically degrades the transmission, typically below 10%, something which is strongly desirable and should seriously be considered in the calculation of the transmittance–absorbance product.

Heat losses occur in a time varying temperature heat sink, corresponding to the ambient temperature. The isothermal fluid layer sits on a thermal insulation layer bed, which is always mounted directly on the soil or on building roofs. Owing to this, heat losses almost always occur at a higher than the ambient temperature heat sink, which leads to a rather conservative evaluation of thermal performance.

4. THEORETICAL ANALYSIS AND PERFORMANCE

The basic heat balance of the solar collector module is given by the expression

$$A_c D\rho c\left(\frac{dT_w}{d\tau}\right) - Q_u = 0 \quad (1)$$

where the first term corresponds to the sensible heat storage in the water bag and the second the useful heat gain of the collector, which is given by the expression

$$Q_u = A_c F_R \gamma [S - U_t(T_w - T_a) - U_{pb}(T_w - T_a)] \quad (2)$$

with γ the integral heat exchanger effectiveness, if there is any, and the collector heat removal factor F_R being fixed at a numerical value equal to unity.

Evaluation of the transmittance–absorbance product for the system of the proposed design could be carried out by consideration of all the combined complex effects of multiple transmission, reflection absorption and scattering in the sequence of transparent interfaces and strongly absorbing and scattering water slab, employing conventional ray-tracing procedures. However, validation measurements of the normal transmittance–absorbance product and investigation of the incidence angle modifiers indicating the angular response and directional properties of the system are also considered necessary in practical models, following existing collector testing procedures, something which is beyond the scope of the current investigation.

Testing results from previous field measurements carried out by Clark and Dickinson (1980) on single glazed systems with a corrugated fiberglass pane with a second thin film of tedlar bonded at the top for UV protection revealed a normal transmittance–absorbance figure of about 0.75. Taking into account the appreciably lower absorption and reflection losses at the glass pane glazing, it was found reasonable to assume a corresponding figure fixed at 0.85 with an angular response similar to single glazed collectors for the system of the proposed design.

The modified top loss coefficient for a horizontal orientation of the air gap is given by the following semiempirical expression developed by Klein (1975)

$$U_t = \left[\frac{(273+T_w)}{520[(T_w-T_a)/(1+f)]^e} + \frac{1}{h_{wc}}\right]^{-1} + \frac{\sigma(546+T_w+T_a)[(273+T_w)^2+(273+T_a)^2]}{(\epsilon_{ab}+0.00591h_{wc})^{-1}+(1+0.133\epsilon_{ab}+f)/\epsilon_g - 1} \quad (3)$$

with parameters f and e given by the expressions

$$f = 1.07866(1+0.089h_{wc} - 0.1166h_{wc}\epsilon_{ab}) \quad (4)$$

$$e = 0.43[1 - 100/(273+T_w)] \quad (5)$$

and h_{wc} the convective heat transfer coefficient due to the wind. The conduction heat loss coefficient for the back cover and periphery is

$$U_{pb} = (A_p/A_c)h_p + (A_{bc}/A_c)h_{bc}. \quad (6)$$

The solar energy absorption, S, is given by

$$S = (\tau\alpha)_n[I_b R_b K_b + I_d K_d] \quad (7)$$

where $(\tau\alpha)_n$, I_b and I_d are the transmittance–absorbance product for normal incidence and the instantaneous value of direct and diffuse solar radiation, respectively, while the geometric factor R_b is assumed to be equal to unity. It is assumed that for the purpose of the present analysis the incidence angle modifiers for the direct and diffuse components of solar radiation K_b and K_d are given respectively by

$$K_b = 1 + b_0(1/\cos\theta_{eb} - 1) \quad (8)$$

$$K_d = 1 + b_0(1/\cos\theta_{ed} - 1) \quad (9)$$

with b_0 taken as for single glazed collectors, $b_0 = -0.1$, θ_{eb} the incidence angle for the beam solar radiation and θ_{ed} the equivalent angle for the sky diffuse radiation, fixed at $\theta_{ed} = 59.68$.

It is assumed that, in the early morning, the water inside the polymer bags follows the hourly ambient temperature. Incident solar radiation causes a rapid temperature build-up of the water bag up to its maximum level, a few hours after the solar noon. According to extensive computer simulations, which have been carried out for a wide range of practical fluid layer thicknesses up to 20 cm, it has been found that the maximum temperature depends on the layer thickness and occurs 4 h after the solar noon for a layer thickness of 5 cm, up to 6 h for a water layer thickness of 20 cm.

The water is then drawn off either to supply the load directly or to be stored for later use. Draw off flow begins when the water layer is at its maximum temperature and the calculation of the daily collected energy is based on this temperature and the overall mass of heated water

$$Q_{da} = \rho_w A_c D c_w (T_{wm} - T_{wi}) \quad (10)$$

where T_{wi} is the initial fluid temperature which is assumed to be equal to the ambient temperature at sunrise. The process is then repeated throughout all the subsequent days of the month and the monthly energy collection is derived as the sum of the daily collected energy.

The monthly and yearly solar energy collection is given by eqns (11) and (12), respectively

$$Q_m = \sum_{d=1}^{N} Q_{da} \quad (11)$$

$$Q_y = \sum_{m=1}^{12} Q_m \quad (12)$$

where N is the number of days for each successive month of the year. The daily solar incident energy in the horizontal plane is given by

$$H_{da} = \sum_{i=1}^{24} I_0 P \quad (13)$$

where P is the time period over which the instantaneous value of the solar incident energy is referred to ($P = 3600$ s).

The monthly and yearly values of solar radiation incident in the horizontal plane are then defined by eqns (14) and (15), respectively

$$H_m = \sum_{d=1}^{N} H_{da} \quad (14)$$

$$H_y = \sum_{m=1}^{12} H_m. \quad (15)$$

The yearly solar collection efficiency of the system is calculated by the expression

$$\eta_y = \frac{\sum_{m=1}^{12} Q_m}{\sum_{m=1}^{12} H_m A_c}. \quad (16)$$

5. THE COMPUTER MODEL

The developed model, suitable for long-term system performance investigations based on hourly computer simulations, requires access to extensive hourly meteorological data or test reference years in a computerised form. Such data are usually either lacking or costly, while collection of a lengthy sample of hourly measured data for an adequately long period of time and for a given geographical location is cumbersome and expensive. In addition to this, a lengthy sample of hourly measurements of solar radiation and ambient temperature data for a single year and a given site may not be representative, since statistically significant deviations from the typical weather conditions possibly owing to weather extremes may lead to significant errors in the calculation of typical yearly performance.

Therefore, in order to filter out the effect of such unusual meteorological phenomena, some kind of statistical processing of these data is necessary prior to their introduction into the computer model and before their use as meteorological driving functions in the thermal calculations.

The present work is based on a statistical treatment of a long sampling period of some 25 years of solar radiation data from the National Observatory of Athens and over 20 years of ambient temperature measurements from the National Meteorological Service for the Athens, Greece, area. Hourly solar insolation measurements were integrated over all hours of the day to derive the daily values of solar insolation incident on the horizontal surface, as is also reported in greater detail by Tsilingiris (1996). In a similar way, calculation of long-term daily average temperatures is made possible by integration of the corresponding long-term hourly measurements.

The results are employed for the derivation of long-term daily range, maximum and average temperatures for each day of the year. The derived average daily data of solar radiation and ambient temperature can be fitted with good accuracy by harmonic functions which can very easily be introduced into the computer model by the introduction of a certain number of amplitudes as well as phase angle terms of the necessary orders to obtain a sufficient level of fit accuracy.

Daily solar radiation data are subsequently split by the computer model into daily direct and diffuse components according to the Liu and Jordan (1960) procedure. Then, hourly direct and diffuse components are calculated according to relevant standard procedures as discussed by Duffie and Beckmann (1980), while the calculation of hourly ambient temperatures, based on daily range, maximum and average daily temperatures, is performed by the computer model according to the model proposed by ASHRAE (1981).

As soon as the hourly values of meteorological variables along with incidence angles for the beam radiation θ_{eb} have been evaluated by the computer model, they are temporarily stored for the calculation of the temperature of the water bag throughout the successive hourly steps during the day and the calculation of the daily heat collection. The calculation procedure is repeated during each successive day of the given month for the derivation of the monthly heat collection which is the sum of the corresponding calculated daily energy collection.

6. RESULTS AND DISCUSSION

The derived results are referred to the typical parametric presentation of the short- as well as long-term operational behaviour and performance, to comparisons with earlier field measurements on heaters of relevant design and to the investigation of the typical input–output characteristics of the system.

6.1. *Typical thermal behaviour and performance*

Typical daily results are shown in Fig. 2 corresponding to a near equinox day (16 March); the water bag temperature along with the total incident solar radiation on the collector plane and ambient temperature throughout the day are shown. The water bag temperature is plotted with its thickness as a parameter ranging between 5 and 20 cm, which appears to be the practical water layer thickness for most applications.

It can be seen that the final water temperature before draw off is inversely proportional to the water layer thickness, varying for this particular day between about 20 and 40°C for a corresponding range of layer thicknesses between 20 and 5 cm, respectively. Similar results corresponding to a midsummer day (17 July) are shown in Fig. 3, in which the final water temperature before draw off becomes appreciably higher, ranging between 42 and 77°C for the same range of water layer thicknesses. It is clear that, at these temperatures, the system can either directly satisfy most domestic or process heating loads or can also be combined with an appropriate afterheater for further boosting the water supply temperature. Therefore, the proposed system can either be employed during the summer as an autonomous solar heating plant or as a solar preheating system for the rest of the year, something which depends mostly on the particular load requirements.

The monthly average daily maximum temperature, which is defined as the average daily maximum temperature before draw-off throughout the given month, determines the suitability of the plant as an autonomous solar heater for the particular load. In Fig. 4 the calculated monthly average maximum temperature is plotted throughout the year, with the fluid layer thickness ranging between 5 and 20 cm. It can be seen that there is an appreciable interseasonal variation of this quantity, irrespectively of the water layer thickness, with maximum and minimum values occurring in July and January, respectively. The monthly average maximum temperature depends strongly on the water layer thickness, both quantities being inversely proportional. This strong dependence

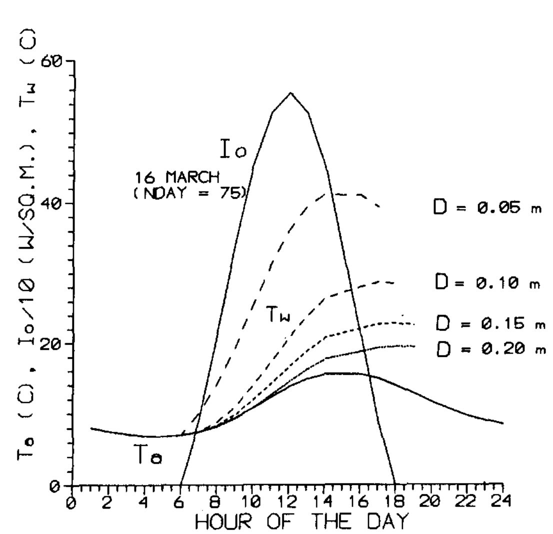

Fig. 2. Typical daily results corresponding to 16 March. Incident solar radiation, ambient and water temperature are plotted with the layer thickness *D* ranging between 0.05 and 0.2 m as a parameter.

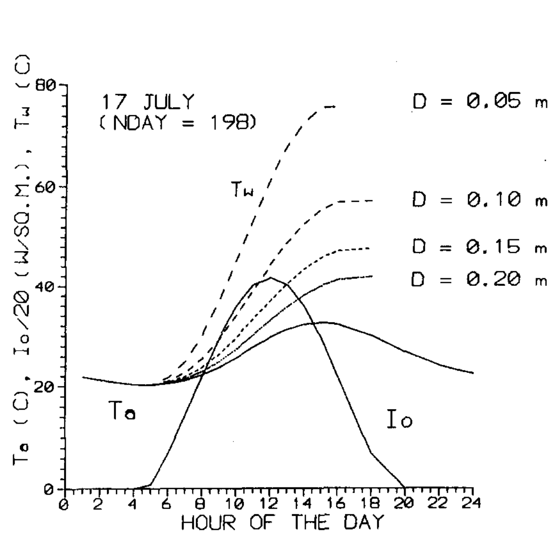

Fig. 3. Typical daily results corresponding to 17 July. Incident solar radiation, ambient and water temperature are plotted with the layer thickness *D* ranging between 0.05 and 0.2 m as a parameter.

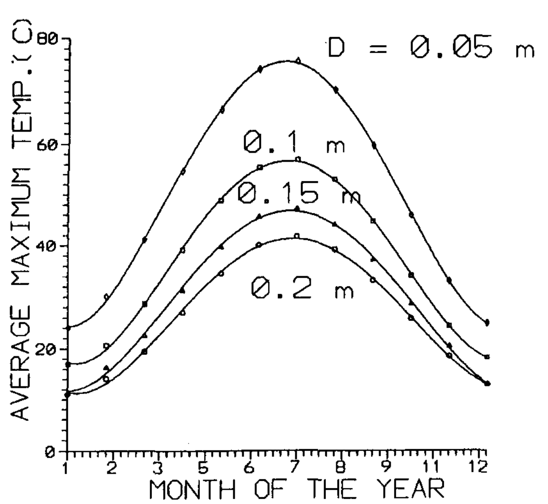

Fig. 4. Monthly average daily maximum temperature throughout the year with the layer thickness D as a parameter ranging between 0.05 and 0.2 m.

suggests means for monthly water temperature control through appropriate control of the fluid layer thickness. According to the plotted results the system is capable of supplying the load with water at temperatures higher than 45°C between May and September for the range of the investigated layer thicknesses and for the geographical location under consideration.

The calculated monthly heat collection throughout the year ($\mathrm{kWh\,m^{-2}\,month^{-1}}$) is shown in Fig. 5 with the layer thickness ranging between 5 and 20 cm. It can be seen that reduction of this parameter leads to a remarkable reduction in heat collection, owing to the corresponding appreciably higher operating temperatures.

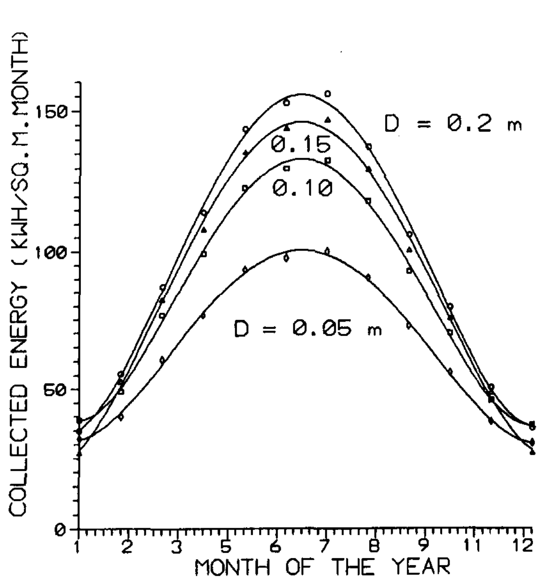

Fig. 5. Calculated monthly heat collection per collector unit area ($\mathrm{kWh\,m^{-2}\,month^{-1}}$) throughout the year with the layer thickness D as a parameter ranging between 0.05 and 0.2 m.

Both Figs 4 and 5 can be employed as fundamental system design tools, since a rough definition of the load supply temperature and the time duration of demand throughout the year leads to approximate selection of a layer thickness from Fig. 4. For the given layer thickness, prediction of the monthly energy collection per unit area can be made using Fig. 5, which will roughly determine the approximate size of the solar plant.

The calculated performance does not take into consideration heat losses from the intermediate water storage tank, if present, and it is valid for direct systems without an intermediate heat exchanger between solar collectors and load. This is a standard design philosophy for most systems operating in mild climatic conditions where freezing temperatures and ground frost are both unusual phenomena.

However, certain restrictions imposed by local health and sanitary water quality standards may sometimes make the use of a heat exchanger between solar collector field and load necessary. This device can either be of the ordinary external shell and tube type or of an integral type, consisting of a simple multiturn flat copper tubing coil placed inside the plastic bag.

The latter type of heat exchanger is usually more preferable, since it allows pumping through the heat exchanger coil instead of the polymer bag directly, where the fluid motion is now entirely due to natural convection. Several technical problems can easily be resolved or eliminated in this way, possibly leading to a polymer bag of even more simple design and lower cost. Although copper is a readily recyclable material, its relatively high initial cost may add considerably to the overall cost of the system and therefore selection of the heat exchanger size through its effectiveness should possibly be based entirely on technicoeconomic grounds.

The typical all-year-round performance penalty due to the installation of a heat exchanger is shown in Fig. 6. In this figure the yearly average heat collection efficiency is plotted against heat exchanger effectiveness ranging between 50 and 100% with the fluid layer thickness as a parameter. It is clearly shown that the performance loss due to the installation of a heat exchanger is remarkably lower at thinner fluid layer thicknesses owing to the corresponding remarkably higher operating temperature differences.

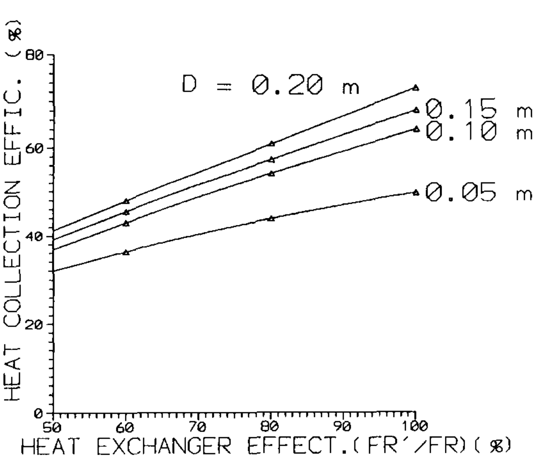

Fig. 6. Typical yearly performance penalty due to the installation of a heat exchanger as a function of the heat exchanger effectiveness ranging between 50 and 100%, with the layer thickness D as a parameter ranging between 0.05 and 0.2 m.

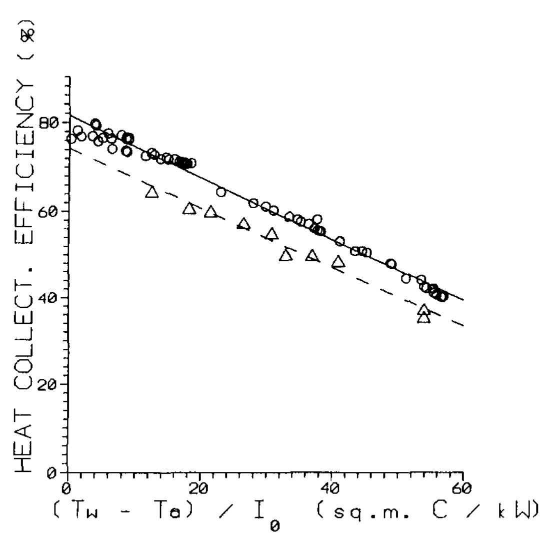

Fig. 7. Calculated instantaneous collection efficiency (○) at solar noon plotted as a function of the ratio $(T_w - T_a)/I_0$. The solid line corresponds to the best linear regression fit $y = -0.7025x + 81.5392$. Comparative results from field tests of shallow solar ponds are also shown (△) along with their best fit linear regression broken line $y = -0.6803x + 74.2299$. Both groups of data correspond to July.

6.2. Comparisons with earlier field measurements

A calculation of instantaneous heat collection efficiency of the proposed collectors has been made based on noon data which have been selected from extensive hourly calculated results mainly from many mid-summer as well as from several randomly selected spring, autumn and winter days throughout the year. These data cover the whole range of layer thicknesses between about 3 and 20 cm.

For this purpose, the calculated ratio $(T_w - T_a)/I_0$ has been plotted against the quantity $\eta = \rho_w c_w D(\Delta T_w)/I_0$, where ΔT_w is the water temperature rise between the two successive hourly steps of 12 and 11 a.m., for all the variables corresponding to solar noon.

The results are shown in Fig. 7 and the discrete data are fitted by the solid straight line $y = -0.702575x + 81.5392$. The indicated lower than assumed normal transmittance–absorbance product through the intercept of the above linear fit expression of plotted data and their slight scatter suggesting a trend of lower efficiency at less than about 15 m^2 °C kW^{-1} of the parameter $(T_w - T_a)/I_0$ corresponds entirely to systems with the thickest fluid layers of 20 cm. This may be attributed to violation of the thermal equilibrium assumption, which may no longer be valid owing to the remarkably increased thermal inertia of the system.

To allow comparisons with published field measurements carried out in test shallow solar pond modules during July 1975, published data by Clark and Dickinson (1980) have been compiled and transferred to the same plot.

These measurements were carried out on modules of 3.5 m width by 15 m length with a single pane glazing made of a corrugated fiberglass sheet with a thin film of Tedlar or acrylic bonded at the top, under conditions of average total daily insolation of 30 MJ m^{-2}, average ambient temperature of 23°C and wind speed between 2 and 7 m s^{-1}, and they correspond to a slightly different range of fluid layer thicknesses between 2 and 15 cm. The best fit broken line $y = -0.680362x + 74.2299$ of these data is also shown in Fig. 7.

It can be seen that although the intercept representing the normal incidence transmittance–absorbance product is appreciably higher for the collectors of the proposed design, there is fairly good agreement in the slope of both lines, representing the numerical figure of the collector loss coefficient. This is clearly attributed to the higher normal transmittance–absorbance product of the proposed design, due to the superior optical qualities of glass versus the corrugated fiberglass glazing of the earlier shallow solar pond heaters. The daily maximum temperature and the corresponding daily collection efficiency has been plotted in Fig. 8 as a function of fluid layer thickness. Several calculated mid-July data, corresponding to the maximum daily incident solar radiation of

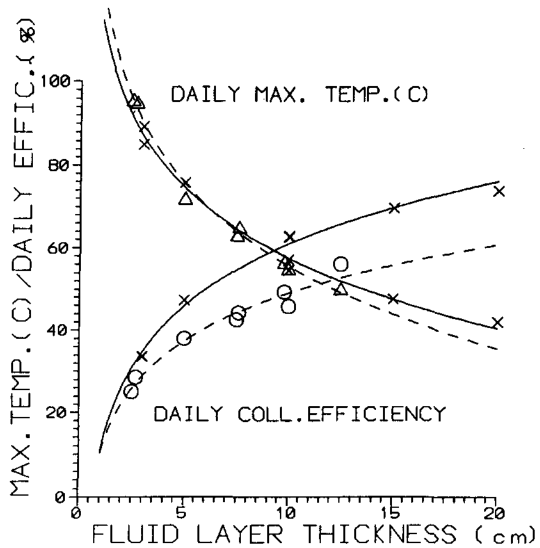

Fig. 8. Daily maximum temperature and collection efficiency data as a function of layer thickness. Calculated data are shown (×) along with their non-linear regression fit solid lines. Comparative results from field tests of shallow solar ponds are also shown (○, △) along with their non-linear regression fit broken lines. Both groups of data correspond to July.

about 25 MJ m^{-2}, have been collected and plotted along with their best fit solid line. It can be seen that daily collection efficiencies of typically up to 60% can be expected for a fluid layer thickness of 10 cm at a maximum draw-off temperature of about 55°C, while excessively high temperatures would possibly develop for fluid layers thinner than 3 cm.

Relevant field measurements carried out in July 1975 were also selected from the same source, compiled and transferred to the same plot. These are shown as discrete data points along with their best fit broken line in Fig. 8, to allow comparisons with the calculated results.

It is clearly seen that daily collection efficiency is appreciably higher for the collectors of the proposed design, owing to the use of glass versus polymer glazing materials. Fairly good agreement is shown in the same plot between calculated and measured daily maximum temperatures. This can mainly be attributed to the counterbalancing effects of the improved collection efficiency of the proposed collector along with the slightly lower July insolation level for Athens which is about 25 MJ m^{-2} as compared to 30 MJ m^{-2} in Livermore, California.

6.3. Investigation of the input–output characteristics of the system

It has long been clear that although a large number of parameters influence the performance, only a very few significantly affect the time averaged solar energy collection of a solar water heater. This is confirmed by extensive field measurements and is supported by the development of a fundamental theory based on the integral form of the Hottel–Willier–Bliss equation and several crude, although reasonable, assumptions usually justified in practice, as discussed, for example, by Lunde (1980).

The time averaged energy collection from a solar heating system can be expressed with adequate accuracy by a simple linear expression as a function of a few fundamental variables, completely ignoring the effect of numerous other less significant parameters. The most significant variables, as proposed, for example, by the ISO 9452-2 standard, are the time averaged values of solar incident radiation and the ambient and initial water temperature; the energy collection is given by the general relationship

$$Q_{da} = C_1 H_{da} + C_2(T_{wi} - T_a) + C_3 \quad (17)$$

where C_1, C_2 and C_3 are numerical constants, with the daily incident energy the dominating variable.

To derive the input–output characteristics of the proposed solar water heaters, it was necessary to calculate the monthly energy collection Q_m and the monthly incident solar energy H_m, given by eqns (11) and (14), respectively. Such data, derived by the present model for the range of fluid layer thicknesses between 5 and 20 cm, have been calculated along with values of monthly average daily total incident energy on the horizontal plane and monthly average daily energy collection, given respectively by the expressions

$$H_{ma} = \frac{1}{N} \sum_{d=1}^{N} H_d \quad (18)$$

$$Q_{ma} = \frac{1}{N} \sum_{d=1}^{N} Q_{ud}. \quad (19)$$

Plotted results are shown in Fig. 9, in which the daily average heat collection is given as a function of the daily incident solar energy for the layer thickness as a parameter.

Each of the 12 data points corresponding to a fixed layer thickness represents the daily average conditions for each month of the year and the drawn broken lines correspond to the best linear regression fit of the calculated data. The derived monthly average daily output energy of the solar heater is given by the

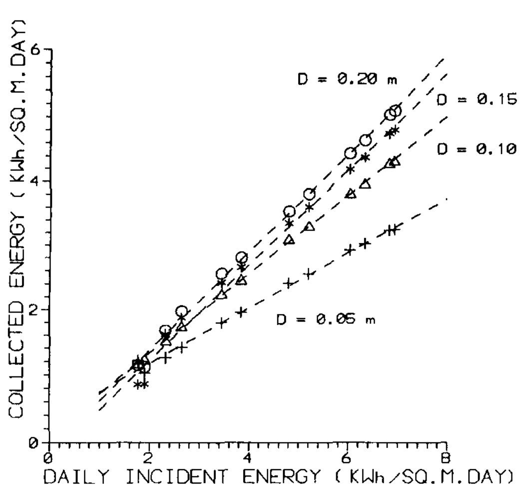

Fig. 9. Calculated monthly daily average heat collection (kWh m^{-2} day^{-1}) as a function of the total daily incident solar energy for the layer thickness D as a parameter ranging between 0.05 and 0.2 m. Broken lines correspond to the linear regression best.

following simple linear regression expressions

$$Q_{ma} = 0.426H_{ma} + 0.323 \quad \text{for } D = 0.05 \text{ m} \tag{20}$$

$$Q_{ma} = 0.612H_{ma} + 0.109 \quad \text{for } D = 0.10 \text{ m} \tag{21}$$

$$Q_{ma} = 0.739H_{ma} - 0.262 \quad \text{for } D = 0.15 \text{ m} \tag{22}$$

$$Q_{ma} = 0.759H_{ma} - 0.145 \quad \text{for } D = 0.20 \text{ m} \tag{23}$$

according to which the calculated daily collection efficiency of the system may vary between about 45 and 70% for the corresponding range of fluid layer thickness between 5 and 20 cm.

It can clearly be seen that the derived analytical input–output results from the presented model are in very good agreement with the familiar linear input–output behaviour of solar water heaters. It is remarkable that at medium and relatively high insolation levels there is a rapid improvement of energy collection for an increase of fluid layer thickness up to 10 cm, while further layer thickness growth has a relatively small effect on energy collection efficiency. It is also worth noting that at low insolation levels of about 2 kWh m^{-2} day^{-1} the effect of the fluid layer thickness is insignificant for energy collection efficiency.

7. CONCLUSIONS

In the present article a low-cost, large solar heating system of improved design has been presented. Design modularity and standardisation of a few factory made polymer structural parts will eventually allow the easy in-situ assembly and maintenance of large solar heating plants at a substantially lower cost. It is expected that the use of low-cost, widely available and completely recyclable polymer materials combined with glass will ensure a longer operational life and better protection against UV degradation.

The system can be used in the "BTU saver" mode either as a preheater or as an autonomous heater for large heating loads, especially when supply temperature control requirements are not critical.

Although the system could be used for year round loads, it would also be particularly suitable for seasonal loads, offering an effective solution to the architectural integration problems of large solar water heating plants in buildings.

A generalised analysis suitable for the investigation of the performance and operational behaviour predictions of the system has also been developed. This computer model allows calculation of the short- and long-term energy output of the system, draw-off temperature predictions as well as analyses leading to the evaluation of the fundamental design parameters, based on very easily introduced, long-term average meteorological data for Athens, which are typical for a sunny Mediterranean country.

For these typical meteorological conditions, very simple input–output regression expressions have also been derived, allowing direct prediction of the energy output for a system of a given design. According to the derived results it is shown that depending on the average load temperature, the system may be operated at remarkably high collection efficiencies, particularly for evening peaking loads.

Finally, theoretical results from the present model were successfully compared with earlier measurements carried out in field test facilities of a similar design.

It is therefore concluded that, at least as far as certain fields of practical applications are concerned, systems of the proposed design can resolve the problems associated with the enormous capital requirements of large solar heating plants, which still strongly inhibit their market promotion. The low-cost design may eliminate the need for government incentives, which in the past usually had only a temporary favorable effect on the solar market. It would also very possibly open up new prospects for "commitment" based promotion schemes through the development of solar energy service companies aiming to supply solar heat to energy users under the provision of a complete package of design, construction and maintenance services.

NOMENCLATURE

- A surface area, m^2
- b_0 numerical constant
- c specific heat capacity, J kg^{-1} $°C^{-1}$
- C numerical constant
- d day number of the month
- D fluid layer thickness, m
- e parameter
- f parameter
- F_R collector heat removal factor
- h heat transfer coefficient, W m^{-2} $°C^{-1}$
- H daily average solar incident radiation, J m^{-2}
- i hour number of the day
- I instantaneous incident solar radiation on the horizontal plane, W m^{-2}
- K incidence angle modifier
- m number of month
- N number of days per month
- P time period ($P = 3600$ s)
- Q energy, J or kWh
- R geometric factor
- S solar energy absorption rate, W m^{-2}
- T temperature, °C
- U heat loss coefficient, W m^{-2} $°C^{-1}$
- V velocity, m s^{-1}

Subscripts

- a ambient
- ab absorber surface
- b beam
- bc back cover
- c collector
- d diffuse
- da daily
- eb effective beam
- ed effective diffuse
- g glass
- ma monthly average daily
- m monthly
- n normal
- t top
- p periphery
- pb conduction loss
- u useful
- w water
- wc wind
- wi water, initial
- wm water, maximum
- y yearly
- 0 total incident at the horizontal plane

Greek letters

- γ heat exchanger effectiveness, $\gamma = (F'_R/F_R)$
- ϵ emissivity
- η collection efficiency, %
- θ incidence angle
- σ Stefan–Bolzman constant ($\sigma = 5.6697 \times 10^{-8}$ W m^{-2} K^{-4})
- τ time, s

REFERENCES

ASHRAE (1981) Air conditioning cooling load. In *The Handbook of Fundamentals*. ASHRAE, New York, pp. 26.1–26.46.

Abtahi A. (1993) Low-cost solar water heating: the bread-box heater made with recycled plastics. In *Proc. I.S.E.S. Solar World Conf.*, Budapest, Hungary, Vol. 5, Kaboldy E. (Ed.), pp. 347–352.

Casamajor A. B. and Parsons R. E. (1979) Design guide for shallow solar ponds. Lawrence Livermore Laboratory Report UCRL 52385 Rev. 1 to U.S. Dept. of Energy.

Casamajor A. B. (1979) The application of shallow solar ponds for industrial process heat: case histories. In *Proc. A.S./I.S.E.S. Silver Jubilee Congress*, Atlanta, GA, pp. 1029–1032.

Clark A. F., Casamajor A. B. and Hewett L. D. (1978) Shallow solar ponds with mirrors on the north sides. In *Proc. I.S.E.S. Conf.*, New Delhi, pp. 1078–1079.

Clark A. F. and Dickinson W. C. (1980) Shallow solar ponds. In *Solar Energy Technology Handbook*, Part A, Dickinson W.C. and Cheremisinoff P.N. (Eds). Marcel Dekker, New York, pp. 377–402.

Dickinson W. C., Clark A. F. and Iantuono A. (1976a) Shallow solar ponds for industrial process heat: the ERDA-SOHIO project. In *Proc. Joint A.S./I.S.E.S. and Solar Energy Soc. Canada Conf.*, Winnipeg, Canada, Vol. 5, pp. 117–141.

Dickinson W. C., Clark A. F., Day J. A. and Wouters L. F. (1976) The shallow solar pond energy conversion system. *Solar Energy* **18**, 3–10.

Duffie J. A. and Beckmann W. A. (1980) *Solar Engineering of Thermal Processes*. Wiley, New York, pp. 67–83 and 505–506.

Forbes R. E. (1983) Design and testing of a plastic bubble-film covered shallow solar pond. *J. Solar Energy Engng* **105**, 382–384.

Garg H. P. and Datta G. (1984) Studies on an all-plastic solar hot water bag. *Energy Res.* **8**, 291–296.

Guinn G. R. and Hall B. R. (1977) Solar production of industrial process hot water using shallow solar ponds. In *Proc. Solar Industrial Process Heat Symp.*, pp. 161–169.

Hodges C. N., Thompson T. L., Groh J. E. and Frieling D. H. (1966) Solar distillation utilizing multiple-effect humidification. United States Department of Interior, Research and Development Progress Report No. 194.

Klein S. A. (1975) Calculation of flat-plate collector loss coefficients. *Solar Energy* **17**, 79–80.

Kudish A. I. and Wolf D. (1978) A compact shallow solar pond hot water heater. *Solar Energy* **21**, 317–322.

Liu B. Y., Jordan R. C. (1960) The interrelationship and characteristic distribution of direct diffuse and total solar radiation. *Solar Energy* **4**, 3, 1–19.

Lunde P. J. (1980) *Solar Thermal Engineering*. Wiley, New York, pp. 280–310.

Schwarz M., Muhlbauer W. and Boettcher A. (1990) Application of plastic foil storage collectors for domestic use in hotels. In *DGS Conf.*, Frankfurt, pp. 755–761.

Tsilingiris P. T. (1988) An accurate upper estimate for the transmission of solar radiation in salt gradient ponds. *Solar Energy* **40**, 1, 41–48.

Tsilingiris P. T. (1991) The radiation transmission across a salinity gradient. *Energy Convers. Manage.* **32**, 4, 333–345.

Tsilingiris P. T. (1993) Third party financing for active solar systems in Greece. Presented at the 1st European Solar Industry Federation (E.S.I.F.) Meeting, Marseilles, France. Centre for Renewable Energy Sources, Athens.

Tsilingiris P. T. (1996) Solar water heating design—A new simplified dynamic approach. *Solar Energy* **57**, 1, 19–28.