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Assessment of the Effectiveness of a Solar System Heating an Anaerobic Bioreactor

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Abstract The performance of a solar system designed to heat a packed bed reactor for anaerobic treatment of municipal wastewater was evaluated, and the feasibility of employing low-scale solar reactors in small settlements or enterprises was investigated. An energy balance was performed using a simple reactor model previously proposed by Yiannopoulos et al. (Bioresource Technology 99:7742–7749, 2008) to estimate the size of a solar system in Patras, Greece. The main objective is to feed the reactor with warm water produced by solar energy and achieve an increase of temperature close to 35°C for the majority of the year. Model simulations indicated that the heat demand of the reactor could be balanced practically by a number of flat plate solar collectors supplying warm water at above 20°C for over 95% of the year. Therefore, the proposed system can offer a viable alternative to enhancing anaerobic treatment in wastewater facilities.

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Keywords Solar energy · Solar heating · Solar reactor · Wastewater treatment · Anaerobic filter

Abbreviations

AF	Anaerobic filter
COD	Chemical oxygen demand
HRT	Hydraulic retention time

Nomenclature

A_c	Solar collector area (m^2)
c_p	Specific heat (J kg^{-1} K^{-1})
D	Diameter of the reactor (m)
F_R	Solar collector heat removal factor
F_R'	Modified solar collector heat removal factor
I_T	Hourly incident irradiation per unit area of a tilted solar collector (W/m^2)
$K_{\tau\alpha}$	Irradiation incidence angle modifier
L	Height of the reactor (m)
$\dot{m}$	Mass flow rate (kg s^{-1})
p	Fraction of the year that warm water with temperature greater than 20°C is delivered to the reactor (%)
q_u	Useful energy gain per unit area of solar collector (W m^{-2})
Q_L	Total heat demand by the solar reactor system (W)
$\langle Q_L \rangle$	Cumulative heat demand by the solar reactor system (W)
Q_{Lb}	Heat losses due to biogas production (W)
Q_{Lc}	Heat demand by the reactor content (W)
Q_{Lp}	Pipe heat losses (W)
Q_{Lr}	Reactor heat losses from the insulated surfaces (W)

Q_{Ls} Warm water storage tank heat losses to the surroundings (W)
Q_u Useful energy gain of solar collector (W)
r_c Energy gain correction factor
T_a Warm water temperature at the reactor outlet (°C)
T_e Ambient air temperature (°C)
T_i Warm water temperature at the reactor inlet (°C)
T_s Warm water storage tank temperature (°C)
T_s^+ Warm water storage tank temperature at the end of Δt=1 h (°C)
U_L Overall heat transfer coefficient for the collector (W m^{-2} K^{-1})
U'_L Modified overall heat transfer coefficient for the collector (W m^{-2} K^{-1})
V Reactor volume (m^3)
V_s Storage tank volume (m^3)
z Vertical coordinate (m)
a Voidage
β Slope of solar collector (deg)
Δt Time increment (s)
λ Thermal conductivity of the reactor content (W m^{-1} K^{-1})
λ_e Equivalent thermal conductivity of packed bed (W m^{-1} K^{-1})
λ_p Thermal conductivity of pebble (W m^{-1} K^{-1})
λ_w Thermal conductivity of water (W m^{-1} K^{-1})
ρ Density of fluids (kg m^{-3})
$(\tau\alpha)$ Transmittance–absorbance products of the solar collector
$(\tau\alpha)'$ Modified transmittance–absorbance products of the solar collector
$(\tau\alpha)_n$ Transmittance–absorbance product of the solar collector for irradiation perpendicular to the collector surface

1 Introduction

In countries where there is plenty of sunshine throughout the year, solar energy can easily be utilized as an alternative to the fossil fuels. Consequently, the number of specific applications that employ solar energy is growing. Some common applications that utilize solar energy are water heating for domestic use, home central heating (Ming et al. 2010), solar cooking (Prasanna and Umanand 2011), water heating for swimming pools, water desalination (Voropoulos et al. 2004; Blanco et al. 2009), water distillation (Tiwari et al. 2003), heating of reactors used for treatment of wastes (Dall-Bauman et al. 1990; Alkhamis et al. 2000; El-Mashad et al. 2003; Wu and Bibeau 2006), greenhouse heating (Kurklu et al. 2003), crop drying (Ekechukwu and Norton 1999; Akpinar 2004; Santos et al. 2005; Madhlopa and Ngwalo 2007), and drying of sludge (Haralambopoulos et al. 2002; Salihoglu et al. 2007).

The anaerobic treatment of municipal and agro-industrial wastewaters is a well-established technology (Metcalf and Eddy 2003), which is influenced by reactor temperature and hydraulic retention time (Matsushige et al. 1990; Viraraghavan and Varadarajan 1996; Zakkour et al. 2001; Manariotis and Grigoropoulos 2003). However, conventional heating of anaerobic low-strength wastewater reactors is not cost effective, because the typical volumes of wastewater treated are high. Due to the rising cost of fuel, the use of solar energy for heating anaerobic reactors has become very attractive (Axaopoulos et al. 2001; El-Mashad et al. 2004; Hou Zhi et al. 2007; Dombrovsky et al. 2007; Yiannopoulos et al. 2008). It should be noted that for the treatment of low-strength wastewaters high hydraulic loading rates are required, and reactors capable of retaining biomass, such as upflow anaerobic sludge blanket reactor (UASB) (Mahmoud et al. 2004), anaerobic filter (AF) (Manariotis and Grigoropoulos 2006), and anaerobic baffled reactor (ABR) (Manariotis and Grigoropoulos 2002), are needed.

An earlier work for the selection and design of solar systems producing hot water for domestic use was made by Panteliou et al. (1996) who developed an expert system using a software tool. Also, a computer model suitable for solar system performance predictions and operational behaviour investigations was developed by Tsilingiris (1996). Later Nafey (2005) made an overview of the simulation techniques used in solar heating systems and gave an outline of some simulation programs and the corresponding numerical procedures. Also, Badescu (2006) proposed a procedure for sizing and optimizing the structure of solar collection systems, where proper economical indices for several applications were considered by replacing conventional energy sources of heat with solar energy.

A theoretical and experimental investigation of solar thermal systems was made by Belessiotis et al. (2010) based on the input–output approach. They considered a solar system as functionally integral set and analysed the main energy quantities during a daily cycle assuming a pseudo-steady state. The proposed modelling method allows the prediction of the energetic performance of a solar thermal system by means of two approaches, which are mutually related in their underlying theory and may be used in a complementary fashion even though they differ in their practical implementation. Yiannopoulos et al. (2008) developed a mathematical model for the estimation of the heat demand or dissipation, and temperature distribution within a solar heated anaerobic reactor under steady state conditions. Preliminary results showed that the reactor was maintained at a desired operational temperature of 35°C during the majority of the year.

The aim of the present investigation was to assess the effectiveness of a solar system that feeds with warm water an anaerobic bioreactor for the treatment of municipal wastewater with the mathematical model previously developed by Yiannopoulos et al. (2008). Model simulations were performed for the meteorological conditions of Patras, Greece, in order to assess the effectiveness of the proposed design in achieving a desired temperature level of 35°C. It was demonstrated that the designed solar reactor for anaerobic treatment of low-strength wastewaters at elevated temperatures could lead to improved process performance and stability.

2 Materials and Solar System Design

A schematic layout of the proposed solar reactor system is shown in Fig. 1. The system consists of flat plate solar collectors, a heat exchanger, a warm water storage tank, and an anaerobic filter (AF) reactor. Warm water from the storage tank and recirculated water from the reactor are mixed in appropriate volumetric fractions with the aid of a three-way tempering valve, so that the resulting mixture is maintained at a steady, pre-specified temperature. The liquid mixture is pumped into the twin walls of the AF reactor. The liquid that circulates through the solar collectors is a mixture of water and ethylene-glycol of about 40% by weight to avoid freezing in the winter. The solar collectors are coated with an absorptive surface and oriented to the south. A counter-flow heat exchanger unit is located between the collectors and the storage tank to separate the liquid mixture of ethylene-glycol from the water of the tank. The main purpose for using a storage tank is to store excess of heat for utilization during time periods with low or no sun radiation. The reactor energy demands are time dependent, so stored energy is used only when there is a demand for heat in the reactor. The capacity of the storage tank and the area of the solar collectors were designed to accommodate the needs of selected reactor size under the local weather conditions.

The AF reactor is a cylindrical tank with a metallic twin-wall enclosure. A network of inlet ports located at the bottom of the reactor distributes evenly the influent wastewater. The packing material is pebble. The bottom and cylindrical surfaces are well insulated. Heat dissipation to the ambient air is allowed from the upper circular surface of the reactor. The warm water enters the reactor from a set of distributed inlets located at the base periphery and flows through the void space of the twin wall. The warm water exits the reactor from the upper periphery and flows back to the storage tank. The flow rate of circulating warm water is kept quite high, so that a very small temperature variation occurs

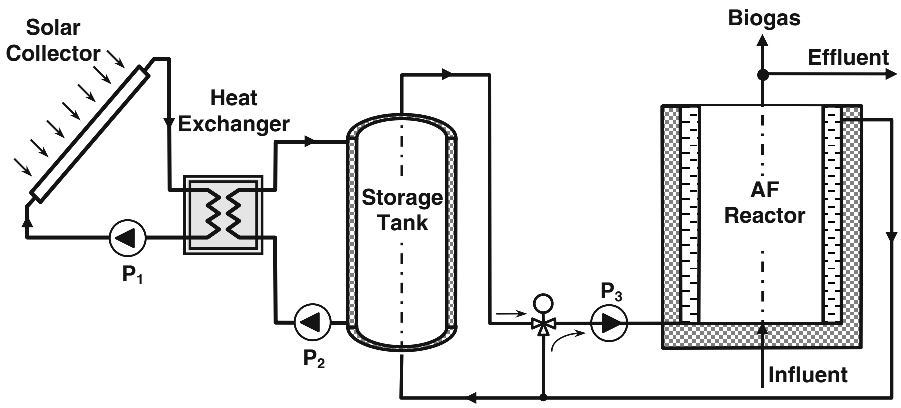

Fig. 1 Schematic diagram of the solar heated reactor system

within the twin walls. The AF reactor size as well as the type of packing material affects considerably the heat demand and size specifications of the solar system. In this work, only two different AF reactor sizes are examined (i.e. V=2 m^3 and 20 m^3). Furthermore, the AF reactors are classified into four categories depending on the assumed thermal conductivity coefficient of their combined packing-wastewater material. The equivalent thermal conductivity, λ_e, of a packed bed consisted of pebble can be determined by the following equation (Rohsenow et al. 1998):

$$\log_{10}\left(\frac{\lambda_e}{\lambda_w}\right) = \left[0.280 - 0.757\log_{10}(\alpha) - 0.057\log_{10}\left(\frac{\lambda_p}{\lambda_w}\right)\right] \times \log_{10}\left(\frac{\lambda_p}{\lambda_w}\right) \quad (1)$$

where α is the voidage, λ_w is the thermal conductivity of water, and λ_p is the thermal conductivity of pebble. Taking for example λ_w=0.6 Wm^{-1} K^{-1}, λ_p=3.0 W m^{-1} K^{-1} and α=0.4, the thermal conductivity of the combined packing-wastewater material is: λ_e=1.5 W m^{-1} K^{-1}. Thus, the various AF reactor systems considered in this study are classified using these values as listed in Table 1.

The angle of the solar collector inclination is important because it affects the amount of solar energy that can be collected. For a solar system operated throughout the year, the optimum solar collector inclination angle results from the maximum absorption of incident solar energy during the time period that the heat demand by the solar AF reactor is most crucial. In the present study, the sum of the solar energy collected during the time period November through April is calculated based on hourly values of irradiation provided by the METEONORM meteorological dataset (Remund et al. 1999) as a function of solar collector inclination angle for the selected location. This software is essentially a meteorological database for climatology and solar energy and can be used to perform simulations for systems located at any region with distinctly different meteorological conditions. The results are shown in Fig. 2 and suggest that the estimated optimum value of the inclination angle is β=45°.

Table 1 Classification of AF reactor types

Reactor type	Reactor dimensions			Thermal conductivity λ (W m^{-1} K^{-1})
	D (m)	L (m)	V (m^3)	
A_1	1.20	1.80	2	0.6
A_2	1.20	1.80	2	1.5
B_1	2.50	4.00	20	0.6
B_2	2.50	4.00	20	1.5

The effect of temperature on AF reactor performance treating low-strength wastewater was examined by Manariotis and Grigoropoulos (2006) and Matsushige et al. (1990). Their experimental data show that the removal of chemical oxygen demand (COD), from the operation of AF reactors treating raw municipal wastewater, increases considerably with increasing temperature and follows a variation as presented in Fig. 3. The results indicate that at 20°C the COD removal efficiency is 59%, whereas at 35°C the removal efficiency increases to 80%. Therefore, the recommended optimum temperature range for the present investigation may be 30 to 35°C.

3 Mathematical Modeling

In the present work, a simplified reactor model is employed, where the temperature of the incoming wastewater is in general unknown but varies in the vicinity of the daily mean ambient air temperature (Yiannopoulos et al. 2008). The simplifications of the model are as follows: At a given instant the amount of feed that enters the reactor per unit time is too low,

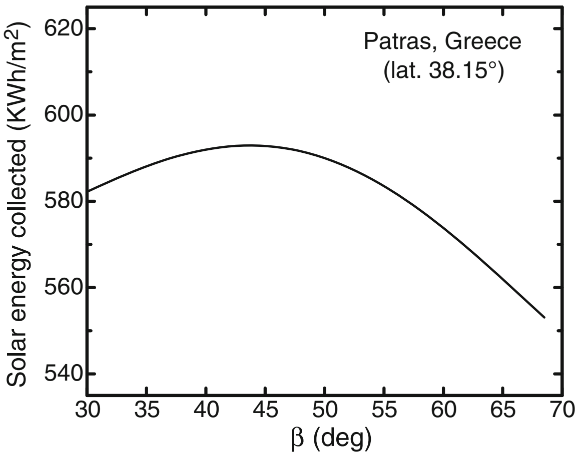

Fig. 2 Solar energy received during the time period November through April as a function of the solar collector inclination angle

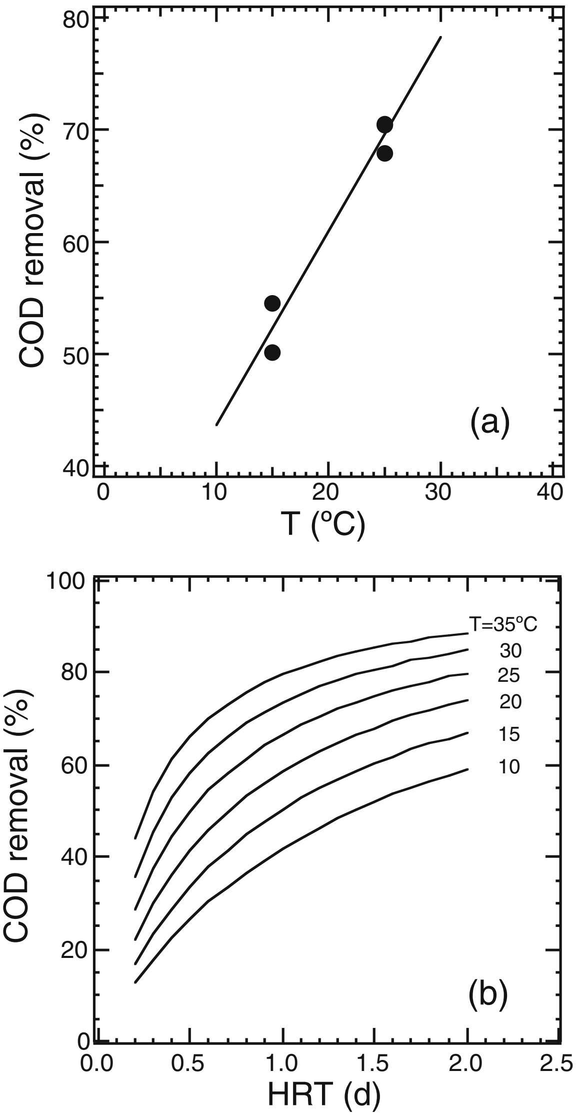

Fig. 3 COD removal in an AF reactor as a function of (**a**) temperature shown by the experimental data (*symbols*) collected by Manariotis and Grigoropoulos (2006) and fitted line (*solid line*), and (**b**) hydraulic residence time for various temperatures

because the volume of the reactor is relatively quite large depending on the retention time of wastewater. This in turn leads to a small change in the reactor temperature. Consequently, we can assume that the sensible heat of the feed to and effluent from the reactor are approximately zero. As the reactor is a relatively large packed bed with a very low wastewater inflow rate, it can be assumed further that the fluid in the packed bed is almost motionless, and consequently the contribution of the radial and axial convection to heat transfer can be neglected. In addition, we assume that the flow rate of the warm water circulating within the twin walls of the reactor may be taken quite high, so the temperature difference between the inlet and outlet of the warm water will be very small. Therefore, a linear decrease in temperature along the vertical coordinate z can be considered without a significant error. Based on the above simplifications the heat flux from the warm water to the reactor content can be assumed constant and obtained by the following equation:

$$\dot{q}_0 = \frac{\dot{m} c_{\mathrm{p}}}{\pi D L}\left(T_{\mathrm{i}} - T_{\mathrm{a}}\right) \tag{2}$$

where $\dot{m}$ is the mass flow rate of the warm water, c_{p} is the specific heat of the warm water under constant pressure, D is diameter of the reactor, L is the height of the reactor, and T_{i} and T_{a} are the warm water temperatures at the reactor inlet and outlet, respectively. Note that the heat flux is independent of the vertical coordinate z.

According to previous considerations, the total heat demand, Q_{L}, required by the solar reactor system can be estimated by the following relationship:

$$Q_{\mathrm{L}} = Q_{\mathrm{Lc}} + Q_{\mathrm{Lr}} + Q_{\mathrm{Ls}} + Q_{\mathrm{Lp}} + Q_{\mathrm{Lb}} \tag{3}$$

where Q_{Lc} is the heat demand by the reactor content, Q_{Lr} is the reactor heat losses from the outer surfaces, Q_{Ls} is the warm water storage tank heat losses to the surroundings, Q_{Lp} is the total heat losses from the pipe loop that circulates warm water between the storage tank and the AF reactor, and Q_{Lb} is the loss of heat transferred out by biogas (Yiannopoulos et al. 2008).

The last term of Eq. 3 is the heat losses due to released biogas during biological process, which consists mainly of three gases, i.e. CH_4, N_2, and CO_2, where the percentage of CH_4 is about 70%. Experimental results showed that biogas production varies considerably in reactors treating low-strength wastewater. The CH_4 production rate within an AF reactor treating medium-strength wastewater (COD of 500 mg L^{-1}) at an HRT of 1.0 days, measured at normal conditions, is estimated to be 140 L [CH_4] per m^3 of wastewater treated at 35°C and 38–45 L [CH_4] per m^3 at 25°C. It has been estimated that 50% of the CH_4 produced leaves with the liquid effluent (Manariotis and Grigoropoulos 2002). These values indicate that a relatively small quantity of biogas is produced, so the sensible heat loss through the total biogas production can be assumed negligible. Despite of this small amount of heat, the chemical energy of released biogas is more significant and can be exploited.

The change of temperature of a fully mixed warm water storage tank over a time increment of Δt=1 h is estimated by the following expression:

$$T_s^+ = T_s + \frac{\Delta t}{\rho V_s c_p}(Q_u - Q_L) \quad (4)$$

where T_s and T_s^+ are the temperatures of the warm water in the storage tank at the beginning and end of a time increment Δt=1 h, respectively, Q_u is the useful energy gain of the solar collector, ρ is the water density, and V_s is the volume of the storage tank. Using Eq. 4, the warm water storage tank temperature, T_s, is calculated incrementally on an hourly basis (Δt= 1 h). It should be noted that if T_s<20°C the warm water flow is interrupted because it offers no useful energy. If T_s>35°C the temperature of the warm water entering the AF reactor is tempered by a three-way valve so that its temperature is maintained at the specified upper limit of 35°C. Therefore, the warm water inlet temperature to the reactor, T_i, can be expressed by the following formula:

$$T_i = \begin{cases} 20^\circ\mathrm{C}, T_s < 20^\circ\mathrm{C} \\ T_s, \quad 20 \le T_s \le 35^\circ\mathrm{C} \\ 35^\circ\mathrm{C}, T_s > 35^\circ\mathrm{C} \end{cases} \quad (5)$$

The useful energy gain of the solar collector, Q_u, is estimated by the known procedure (Sukhatme 1984; Duffie and Beckman 1991), taking into account that:

$$Q_u = A_c r_c \frac{F_R'}{F_R}\left[I_T K_{\tau\alpha}\frac{(\tau\alpha)'}{(\tau\alpha)}F_R(\tau\alpha)_n - \frac{U_L'}{U_L}F_R U_L(T_s - T_e)\right] \quad (6)$$

where A_c is the solar collector area, r_c is the energy gain correction factor, F_R and F_R' are the typical and modified solar collector heat removal factors, respectively, I_T is the hourly incident irradiation per unit area of a tilted solar collector, $K_{\tau\alpha}$ is the irradiation incidence angle modifier, $(\tau\alpha)$ and $(\tau\alpha)'$ are the typical and modified transmittance–absorbance products of the solar collector, respectively, $(\tau\alpha)_n$ is the transmittance–absorbance product of the solar collector for irradiation perpendicular to the collector surface, U_L and U_L' are the typical and modified overall heat transfer coefficients for the collector, respectively, and T_e is the ambient air temperature. The values for the energy loss product, $F_R U_L$, and energy absorption product, $F_R(\tau\alpha)_n$, are usually provided by the solar collector manufacturers. Note that for the reactor system proposed in this study, the parameters involved in the preceding equation account for the specific features of the system, as the use of the glycol solution, the heat losses from the solar collector pipe network, the effect of the heat exchanger, and the correction of solar radiation incidence angle between the direction of radiation and the normal to the collector surface.

Table 2 Parameter values for model simulations

System component	Parameter	Value and units
Solar collector	β	45°
	$F_R(\tau\alpha)_n$	0.75
	$F_R U_L$	4.13 $\mathrm{Wm^{-2}\,K^{-1}}$
Heat exchanger	UA, for reactors A_1 and A_2	320 $\mathrm{WK^{-1}}$
	UA, for reactors B_1 and B_2	540 $\mathrm{WK^{-1}}$
Ethylene-glycol solution	ρ, at 60°C	1030 $\mathrm{kg\,m^{-3}}$
	c_p, at 60°C	3650 $\mathrm{Jkg^{-1}\,K^{-1}}$
Water	ρ, at 60°C	985 $\mathrm{kg\,m^{-3}}$
	c_p, at 60°C	4184 $\mathrm{Jkg^{-1}\,K^{-1}}$
	λ_w	0.6 $\mathrm{Wm^{-1}\,K^{-1}}$
Pebble	λ_p	3.0 $\mathrm{Wm^{-1}\,K^{-1}}$

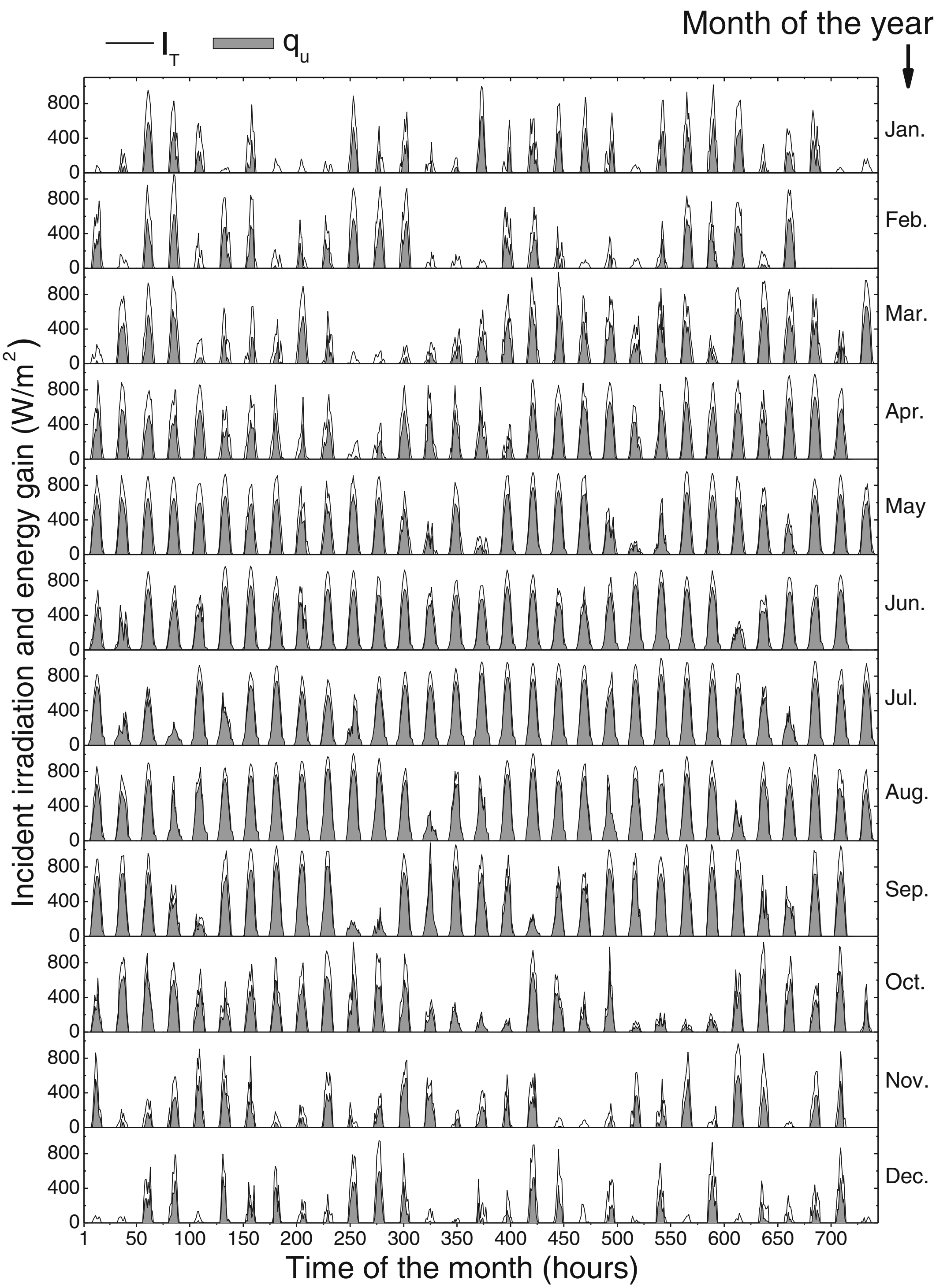

Fig. 4 Hourly average of incident irradiation I_T (*clear areas*) and useful energy gain q_u (*shaded areas*) per unit solar collector area as a function of time, for a full year

4 Model Simulations and Discussion

The proposed solar heated reactor system is located in Patras, Greece, with latitude 38.15°, and it is designed to accommodate any type of bioreactor. However, the greater part of the simulations presented in this study, in order to validate the proposed simulation method, are based on the AF reactor types listed in Table 1 accompanying with the model parameter values of Table 2. The other parameters employed here are according to solid and realistic assumptions or they are obtained directly from our analysis of the solar energy received at the selected location.

Figure 4 illustrates the relationship between the incident irradiation per unit area on a tilted solar collector, I_T, and the useful energy gain per unit area of a solar collector, q_u, as a function of time, where q_u is defined as: $q_u=Q_u/A_c$. The meteorological data used correspond to the selected region, where the values of I_T and q_u are calculated on an hourly basis for each month of a year. The I_T values are produced by the METEONORM software, and the q_u values are determined through Q_u values by Eq. 6 for a solar collector with area A_c=1 m^2 and slope β=45°. The other parameter values needed for the calculation of q_u are given in Table 2. It is evident from Fig. 4 that the q_u values follow closely the time-dependent behaviour of the corresponding I_T values, and there are only just a few days per year without useful energy.

The cumulative heat demand $\langle Q_L \rangle$ for a total year and two types of solar reactors (i.e. type A_1 with A_c= 10 m^2 and V_s=0.75 m^3, and type B_1 for A_c=20 m^2 and V_s=1.5 m^3) is calculated using Eq. 3, and the results are illustrated in Fig. 5. The graph shows that the heating energy needed to meet all heat losses for type B_1 is about 60% greater than type A_1.

The variation of warm water storage tank temperature, T_s, the useful energy gain per unit area of the solar collector, Q_u, and the total heat demand, Q_L, for two randomly selected weeks of the year, one in January and the other in July, are shown in Fig. 6.

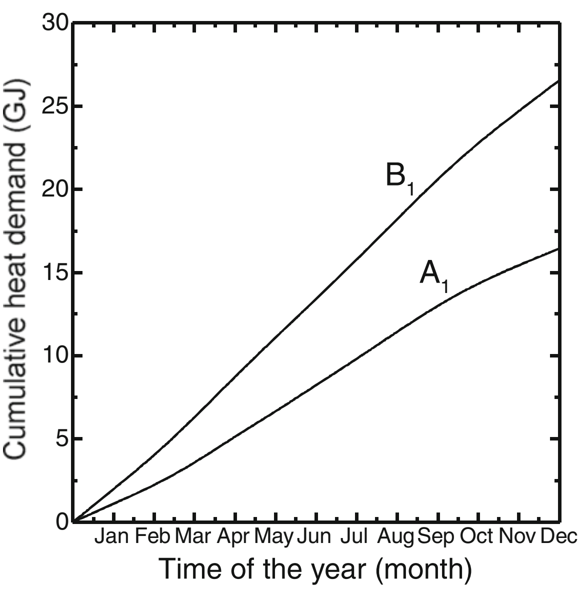

Fig. 5 Cumulative heat demand $\langle Q_L \rangle$ as a function of time, for a full year, calculated for reactor types A_1 and B_1

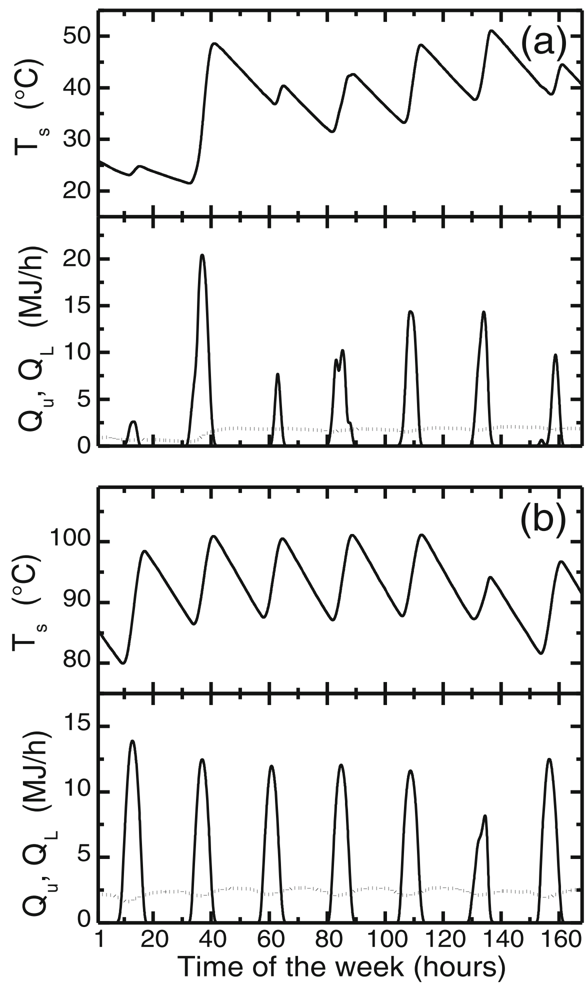

Fig. 6 Variation of T_s, Q_u (*solid curve*) and Q_L (*dotted curve*) for the weekly periods: (**a**) third week of the year, and (**b**) 29th week of the year. Here A_c=10 m^2, V_s=0.75 m^3, and reactor type A_1

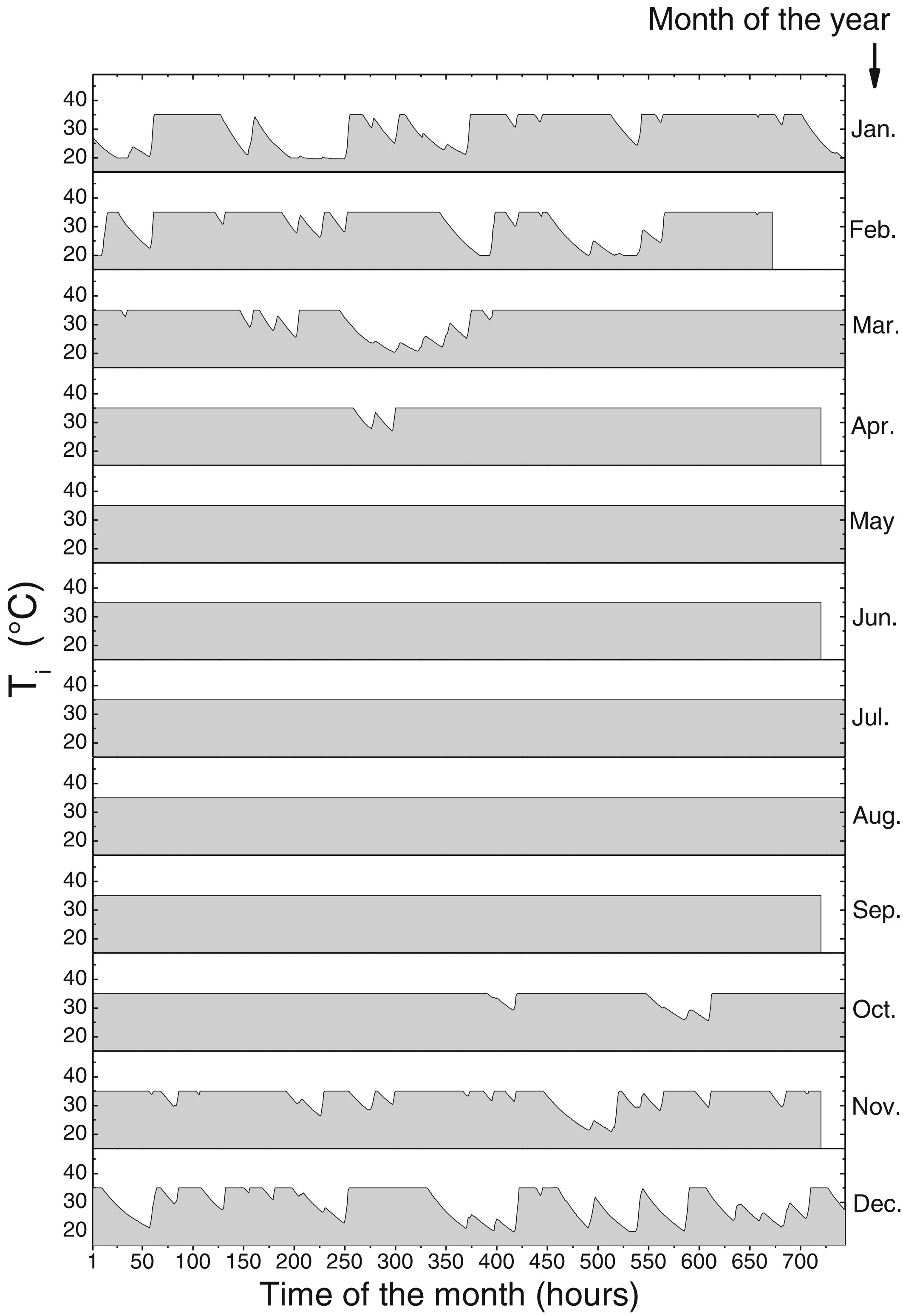

Fig. 7 Hourly calculated water temperature T_i at the reactor inlet as a function of time for a full year. Here A_c=10 m^2, V_s=0.75 m^3, and reactor type A_1

The T_s values are calculated from Eq. 4, whereas the Q_L and Q_u values from Eqs. 3 and 6, respectively. Note that for both of the weeks considered here, T_s and Q_u exhibit significant daily fluctuations, whereas Q_L remains practically flat.

Figure 7 presents the water temperature at the reactor inlet, T_i, calculated hourly from Eq. 5 for a reactor type A_1 over the time period of a full year. The results show that T_i is kept at the upper limit of 35°C through most of the year. There is only a small fraction of the year that T_i is below 35°C and just a few hours that remains close to 20°C.

Figure 8 presents the fraction of the year, p, during which warm water from the storage tank with temperature higher than 20°C is supplied to the reactor as a function of storage tank volume for various solar collector sizes and reactor types. The remaining time of the year the warm water supply is interrupted. Clearly, p increases with increasing A_c and V_s, for all reactor types considered. For the ratio V_s/A_c=75 L m^{-2}, which is frequently used in practical applications (Duffie and Beckman 1991), or equivalently for a system with A_c=10 m^2 and V_s=0.75 m^3, p=99 and 98% for reactor types A_1 and A_2, respectively (see Fig. 8a). Furthermore, for A_c=20 m^2 and V_s=1.5 m^3, p=97 and 96% for reactor types B_1 and B_2, respectively (see Fig. 8b). Higher p values represent more continuous operation (fewer interruptions) of the solar reactor system.

The dependence of the reactor volume V on the collector area A_c at three different p levels and two

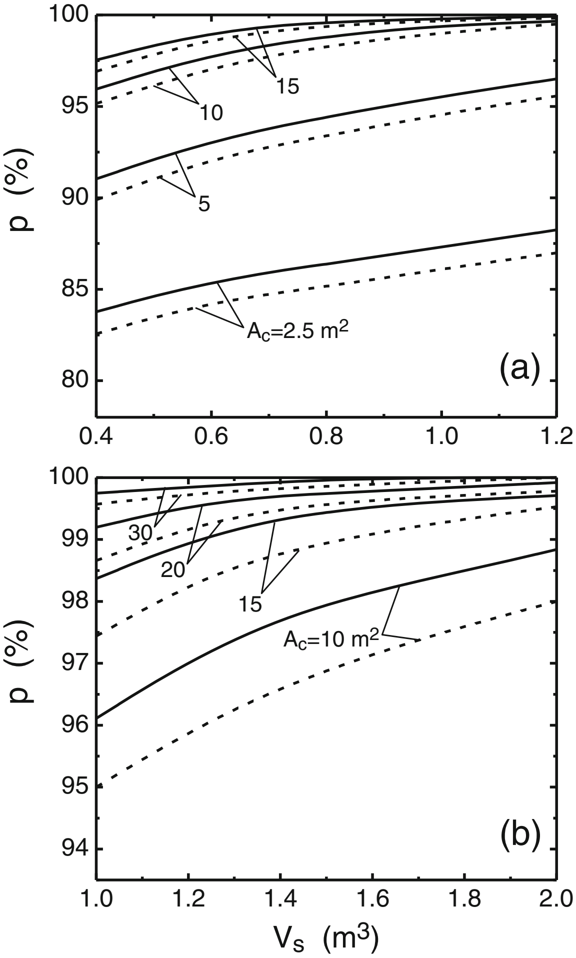

Fig. 8 Fraction of the year with warm water supply to the reactor as a function of V_s, and various values of A_c for (**a**) reactor type A_1 (*solid curves*) and A_2 (*dashed curves*), and (**b**) reactor type B_1 (*solid curves*) and B_2 (*dashed curves*)

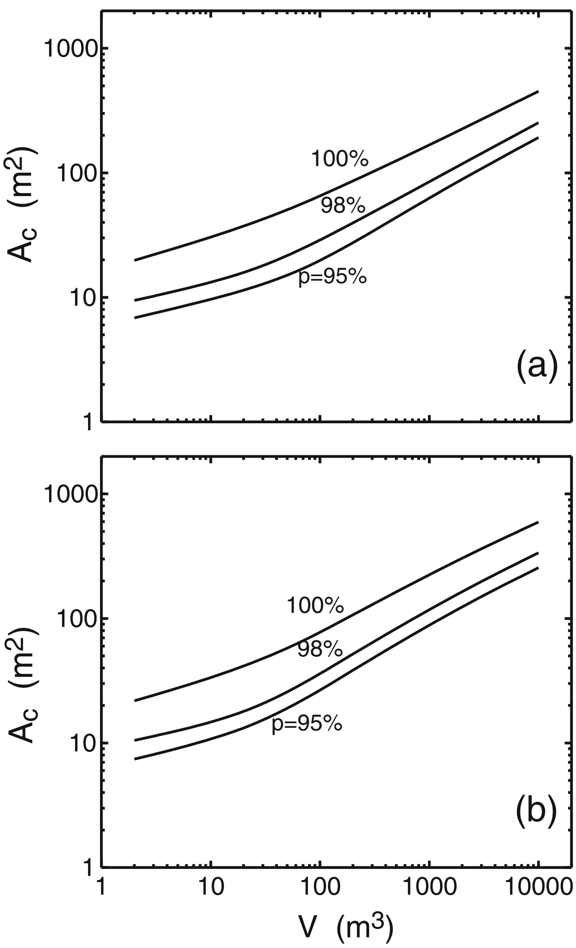

Fig. 9 Solar collector area A_c as a function of reactor volume V at three different p levels for reactant thermal conductivity (**a**) λ=0.6 Wm^{-1} K^{-1} and (**b**) λ=1.5 Wm^{-1} K^{-1}

different types of reactant thermal conductivities is illustrated in Fig. 9. The results presented in Fig. 9 provide practical information on the required solar collector size for a given AF reactor size and desired level of system operation interruptions. We think that the graphs of Fig. 9 are the main contribution of the present work and indicate that it is possible to construct a solar system in the aforementioned region, where it is plenty of sunshine throughout the year, with a reasonable solar collector size even for optimum continuous operation (p=100%).

5 Summary and Conclusions

The performance of a solar reactor system capable to treat municipal wastewater was evaluated. The solar system consisted of a flat plate solar collector, a heat exchanger, and a storage tank for the warm water. Based on the design proposed by Yiannopoulos et al. (2008), the reactor is a cylindrical tank heated with the warm water. The water temperature at the reactor inlet was regulated by a three-way valve, so as never exceeds 35°C. The heat demand and dissipation of the solar reactor system were estimated using a simple mathematical model. The solar heating energy was transferred to the reactor, which raised the temperature of the reactant up to 35°C. The warm water at the reactor inlet is kept at the desired limit of 35°C through most of the year. The fraction of the year that warm water with temperature greater than 20°C is delivered to the reactor increases with the solar collector area and the storage tank volume. Model simulations for different reactor volumes provide practical information for the application of the solar system in areas with similar meteorological conditions of Patras, Greece. Clearly, the solar reactor system proposed here is environmentally friendly and technically attractive because it uses free cost energy.

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