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Solar Single-Effect (SE) and Single-Effect Double-Lift (SE/DL) Absorption Machines Comparison Part 1: Energy Saving

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Abstract: In this paper a comparative study between the solar powered standard Single-Effect (SE) and Single-Effect Double-Lift (SE/DL) absorption machines with identical cold output, using the same collector model is given with a special focus in solar unit part. Performance and economic analyses of the solar energy unit part of the two different cycles have been carried out for a wide range of operating conditions. Various collector types from Asian and European markets have been used as the source of energy providing hot water driving the absorption machines. The solar SE/DL allow to collecting more energy, thus saving more nonrenewable energy source, due to the mean increase in collector efficiency from 2% to 20% depending on the chosen collector. In 20 years lifetime economical analysis, the cost of this saved energy correlated to an equivalent electrical energy is more than balanced the expense at the corresponding increase in the installed collector surface area. Consequently implying a profitability by unit cooling capacity of about 2200$ for the conventional single glazed flat plate collector and about 800$ for the special designed low-cost single glazed flat plate collector, at hot water supply/return temperatures 90/65°C. The vacuum tube collector becomes profitable when the driving hot water temperature is greater than 92°C.

Key Words: Solar Refrigeration, SE and SE/DL Systems, Energy Saving, Solar Collectors Choice

Introduction

During the last few years the interest in cooling systems driven with low temperature heat has been steadily increasing. The largest potential for innovations concerning the use of low-grade heat can be attributed to the development of new cycles, which are designed to meet the special demand of low-grade heat input. The ratio of electrical energy required for providing air-conditioning to the total consumption of electrical energy is nearly one-third or even more. Among the alternative energy sources, solar energy is considered cheap, readily available, and nonpolluting which can be used in low temperature thermal applications. Solar energy systems are, therefore, promising means of reducing the consumption of nonrenewable energy sources.

It is well know that the use of solar energy for space cooling in the tropics is more attractive in principle, because the demand of refrigeration and air-conditioning becomes high, generally when the solar heat increases. This would enable the solar-assisted refrigeration and air-conditioning plants to suitable meet the power requirements with the increase in their cooling loads (Malik and Siddiqui, 1997). Of all conventional methods of refrigeration, the vapor absorption system matches well with the available solar energy, especially the SE/DL cycle due to it's specificity to use heat down 80°C.

It has been reported in a detailed analysis a solar powered standard single-effect system using different collectors models as heat source (Zhou Tonghua *et al.*, 2001). The analytical study shows that under a given conditions the system overall coefficient of performance is the highest when the solar collector temperature is 90° to 92°C.

It has been also reported an operation and performance analyses of a SE/DL absorption chiller in a district heating network. A combination of a standard single-effect and double lift process have been identified as the new cycle that can use driving heat down to return temperature of about 60°C and permits temperature glides in generation of about 30°C. Heat above 80°C can drive the Single-Effect (SE) part of the machine with the COP of 0.7 and heat at lower temperature can be supply to the Double Lift (DL) part with the COP 0.35 (Schweigler *et al*, 1996; 1998)(Ma and Deng, 1996). The study shows also that the integration of the Double-Lift (DL) into the Single-Effect (SE) process leads to a reduction of heat exchanger area and thus to smaller and cheaper machine.

With those in view, performance and economic analyses of the solar energy unit part of the two different systems with identical cooling effect have been carried out for a wide range of operating conditions.

System Modeling: To simplify the modeling of the system several assumptions are made, including the followings:

- The system operate in steady-state
- The ambient temperature T_a = 32°C,
- The solar irradiation I = 800 W/m²,
- Identical temperature glide in the DL two generators,
- The temperature difference ΔT1 into the two single-effect generators are identical.

Solar-Collector Choice: The different collectors used are listed in the Table (1). The energy absorbed by the collected fluid is calculated by:

$$Qs = \eta \text{IA} \quad (1)$$

Q_s is the heat absorbed by the collector fluid (W), A is the area of collectors (m²).

For regular flat plate collectors most of manufacturers define theirs efficiency by:

$$\eta = A - B\frac{T_{in} - T_a}{I} \quad (2)$$

A and B are the specific model constants, T_{in} is the collector inlet temperature (°C).

Solar SE/DL System

System Description: The solar powered SE/DL absorption chiller system is depicted schematically in Fig.1. Detailed description is found in (Yattara *et al.*, 2002). In this study the different elements in the cooling circuit are connected in parallel at 30/34°C. The cold output from the evaporator is expressed as:

$$Qo_{SE/DL} = COP_{SE/DL} Qg_{SE/DL} \quad (3)$$

The Solar Energy Unit Part: The total heat supplied to the three generators by means of the driving hot water, is collected by the solar collector, and express as:

$$Qg_{SE/DL} = Qg_{SE} + Qg_{DL} \quad (4)$$

$$Qg_{SE} = \eta_1 A_1 I \quad (5)$$

$$Qg_{DL} = \eta_2 A_2 I \quad (6)$$

Qg_{SE} is the total heat from the solar collector supplied to the SE generator G1 (W).

Qg_{DL} is the total heat from the solar collector supplied to the DL two generators G2 and G3 (W).

The first collector field characterized by its efficiency η_1 and surface area A_1 is used to increase the hot water supply temperature from (T_r +ΔT2) to the required hot water supply temperature T_h. The first collector field efficiency is expressed as:

$$\eta_1 = A - B\frac{(T_h - 0.5\Delta T1) - T_a}{I} \quad (7)$$

The second collector field characterized by its efficiency η_2 and surface area A_2 is used to provide a temperature boost of ΔT2 in the water return temperature T_r. It efficiency is expressed as:

$$\eta_2 = A - B\frac{(T_h - \Delta T1 - 0.5\Delta T2) - T_a}{I} \quad (8.a)$$

$$\Delta T2 = \Delta T - \Delta T1 \quad (8.b)$$

Where,

ΔT is the total temperature glide in the three generators of the SE/DL system. ΔT2 is the temperature glide in the two generators of the DL system. After rearranging the resulting equation yields:

$$\eta_2 = A - B\frac{(T_h - 0.5\Delta T1 - T_a)}{I} + \frac{B\Delta T}{2I} \quad (9)$$

The incremental collector efficiency between the two collectors fields is expressed as:

$$\delta\eta = \eta_2 - \eta_1 = \frac{B\Delta T}{2I} \quad (10)$$

The entire solar energy unit collector efficiency can be expressed as:

$$\eta_{SE/DL} = \eta_1\frac{\Delta T1}{\Delta T} + \eta_2\frac{\Delta T2}{\Delta T} \quad (11)$$

Substitution the expression for ΔT2 from eq. (8.b) and for η_2 from eq. (10) into eq. (11), and rearranging the resulting equation yields:

$$\eta_{SE/DL} = \eta_1 + \delta\eta - \delta\eta\frac{\Delta T1}{\Delta T} \quad (12)$$

The total heat supplied to the three generators is equal to the total heat absorbed by the collector fluid.

$$Qg_{SE/DL} = \eta_{SE/DL} A_{SE/DL} I \quad (13)$$

$A_{SE/DL}$ is the sum of the first and second collector field areas A_1, A_2.

Now using eq. (10) and eq. (13) the eq. (3) can be rewritten as:

$$Qo_{SE/DL} = COP_{SE/DL}(\eta_1 + \delta\eta - \delta\eta\frac{\Delta t1}{\Delta T})A_{SE/DL} I \quad (14)$$

Standard Solar SE System

System Description: The Single-Effect SE machine is identical to the single-stage Single-Effect (SE) part of the SE/DL system. Therefore the operating parameters and conditions are the same. The system cooling effect can be expressed as:

$$Qo_{SE} = COP_{SE} Qg_{SE} \quad (15)$$

Solar Energy Unit Part: The driving hot water mass flow rate must be higher as to provide the identical cooling effect as the entire SE/DL system. So the standard SE machine must operate with the first collector field in the size providing the required generator load. Its collector field efficiency is equal to the SE/DL system first collector field efficiency.

$$\eta_{SE} = \eta_1 \quad (16)$$

The total heat supplied to the SE generator by means of the driving hot water is express as:

$$Qg_{SE} = \eta_{SE} A_{SE} I \quad (17)$$

System Comparison: The two systems are designed for the unit cold output:

$$Qo_{SE} = Qo_{SE/DL} (= 1kW) \quad (18)$$

Substitution of the expressions for Qo_{SE} and $Qo_{SE/DL}$ from eq. (14) and (15) into eq. (18), and using eq. (17), after rearranging the resulting equation yields an expression for the collector surface area ratio:

$$A_{SE/DL} = \frac{COP_{SE}\eta_{SE}}{COP_{SE/DL}(\eta_{SE} + \Delta\eta)} A_{SE} \quad (19)$$

Where,

$$\Delta\eta = \delta\eta - \delta\eta\frac{\Delta t1}{\Delta T} \quad (20)$$

is the mean incremental collector efficiency, which is proportional to the energy saving rate from the solar system, when operates a solar SE/DL system instead of a standard solar SE system, producing the same cooling effect.

Figures of Merit: How quantity of nonrenewable energy can be saved, when using the solar SE/DL instead of solar SE systems. The Cost of Saved Energy (SEC) can be determined by correlated it with the cost of electricity giving the same amount of energy. Using 3500 hours operating time per year, a 20 years system lifetime, annual interest rate 10% and inflation 12%, the cost of heat input can be calculated as:

$$SEC = idr\Delta\eta A_{SE/DL} IC_e \quad (21)$$

idr is the inflation-discount rate [9],
C_e is the electricity cost per kWh (0.55¥ or 0.0668$ or 0.04€).
Substituting the expression of $A_{SE/DL}$ from eq. (14) into eq. (21) yields:

$$SEC = idr\frac{\Delta\eta Qo_{SE/DL}}{(\eta_{SE} + \Delta\eta)COP_{SE/DL}}C_e \quad (22)$$

The more collected energy implies an additional collector surface area for the solar SE/DL system. Its cost (AAC) is determined as:

$$AAC = \frac{df}{mf}(A_{SE/DL} - A_{SE})C_c \quad (23)$$

C_c is the collector surface area cost per square meter ($/m^2 or €/m^2),
mf is the mortgage factor (9%), df is the discount factor (10%).
Substitution of the expression of A_{SE} and $A_{SE/DL}$ from eq. (17) and eq. (19) into eq. (23) and using eq. (15) yields after rearranging

$$AAC = \frac{df}{mf}\left(\frac{COP_{SE}\eta_{SE}}{COP_{SE/DL}(\eta_{SE} + \Delta\eta)} - 1\right)\frac{Qo_{SE}}{COP_{SE}\eta_{SE}1}C_c \quad (24)$$

Which system is profitable under which conditions can be determined using the expression of the eq. (22) and eq. (24), by the degree of profitability:

$$\Pr d = 3500(SEC - AAC) \quad (25)$$

Results and Discussion

The mean incremental collector efficiency increase rate (Δη%), the collector surface area ratio ($A_{SE/DL}/A_{SE}$) and the degree of profitability (Prd) depend on two main factors:

1 The total temperature glide in generation ΔT depending at T_h and T_r.
2 The SE generator G1generating temperature glide ΔT1.

Fig. (2) shows the Δη% variation against the driving hot water temperature T_h, the hot water return temperature T_r, the generating temperature glide ΔT1 respectively for the various Asian collector models. When decrease T_r or increase T_h, or decrease ΔT1, Δη% increases linearly with different slopes and different magnitudes. Δη% is slightly sensitive to the temperature change for the vacuum tube collectors (A3 and A5) models. From Fig.(2) at constant supply/return temperature it can be seen the magnitude of Δη% per unit cooling capacity, they are about 13 to 20% for the conventional single glazed flat plate collectors, about 6 to 8.5% for the special designed single glazed flat plate collector and about 2 to 4% for the vacuum tube collectors. Consequently when running solar SE/DL chiller instead of the solar SE one with identical cooling capacity, the collected solar energy is more, thus saving more nonrenewable energy resource.

From (Fig.3) it can be seen the installed collector surface area ratio change, when change T_h, T_r ΔT1 respectively for the various collector types. When increase the hot water return temperature for a fixed driving hot water temperature (90°C) or decrease the driving hot water temperature for a fixed the hot water return temperature (65°C) or increase ΔT1 for a constant supply/return temperature the installed collector surface area ratio increase gradually having a maximum value for each collector model; they are 1.15 for the collector A2, 1.30 for the collector A4, 1.35 for the collector A1 and about 1.45 for the collectors A3, A5. Theses values correspond to a minimum return temperature 75°C at T_h = 90°C or the minimum hot water supply temperature is 86°C at T_r = 65°C or when ΔT1 is equal to one third of the total temperature glide in generation ΔT. It means that that for a return temperature 65°C the minimum hot water supply temperature is 86°C or for a hot water supply temperature 90°C the minimum return temperature is equal to 75°C or for a constant hot water supply/return temperature, ΔT1 is equal to one third of the total temperature glide in generation ΔT. So when designing a solar SE/DL system the generators temperature distribution must be carefully checked.

From Fig. (4) it can be seen the degree of profitability variation with T_h, T_r and ΔT1 respectively for the various collectors. When decrease T_r or increase T_h, the degree of profitability value increases linearly with different slopes and different magnitudes for the various collector types. It is slightly sensitive to the change in ΔT1. From theses figures it can be seen the magnitude of the profitability per unit cooling capacity. At T_h = 95°C and T_r = 65°C the profitability values at different lifetimes at different running hours per year are listed in the Table (2) and (3). It is interesting to see that the vacuum tube collector becomes profitable for T_h > 92°C or ΔT1< 6° C at T_h = 90°C.

Fig. (5) shows the overall coefficient of performance ($\psi_{SE/DL}$) variation. At low return temperature value, $\psi_{SE//DL}$ increases with increasing T_h, decreasing T_r or decreasing ΔT1. For a fixed T_h (90°C), $\psi_{SE/DL}$ are highest in case of vacuum tube collector (A5) and lowest for the conventional single glazed flat plate collector A2. It means that for a better overall performance the solar SE/DL absorption chiller had to be run with the vacuum tube collector, which become profitable only for T_h > 92°C.

From Table (3), the above mentioning discussions are also true when using the European market collector models. For example at constant T_h (102°C) there exist a minimum installed collector surface area ratio corresponding to a minimum T_r. Whereas one note, that the profitability magnitude is less than 300€ for any chosen collector model except the flat-plate collector with 1700€. This is due the higher market

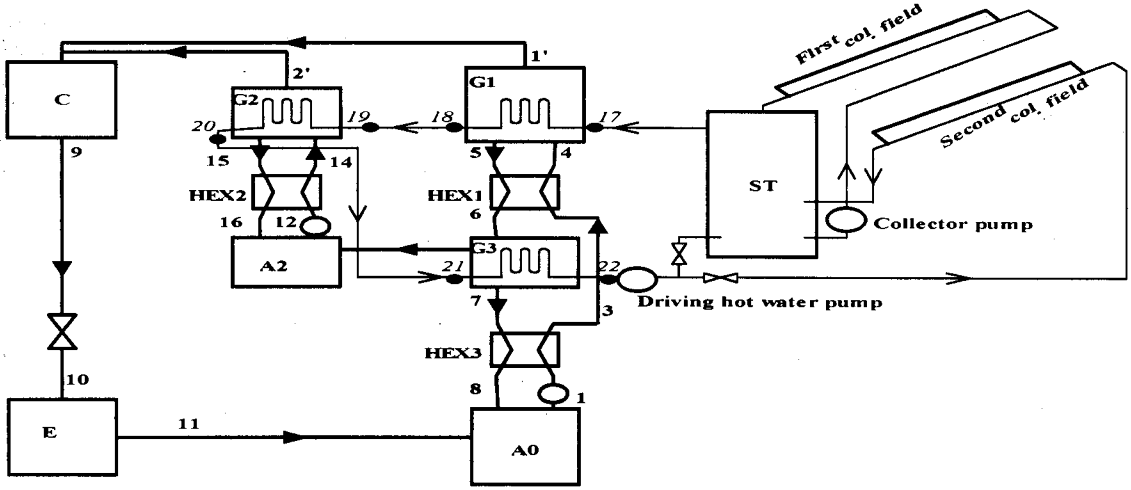

Fig.1: Schematic of Solar Powered SE/DL Absorption Chiller System

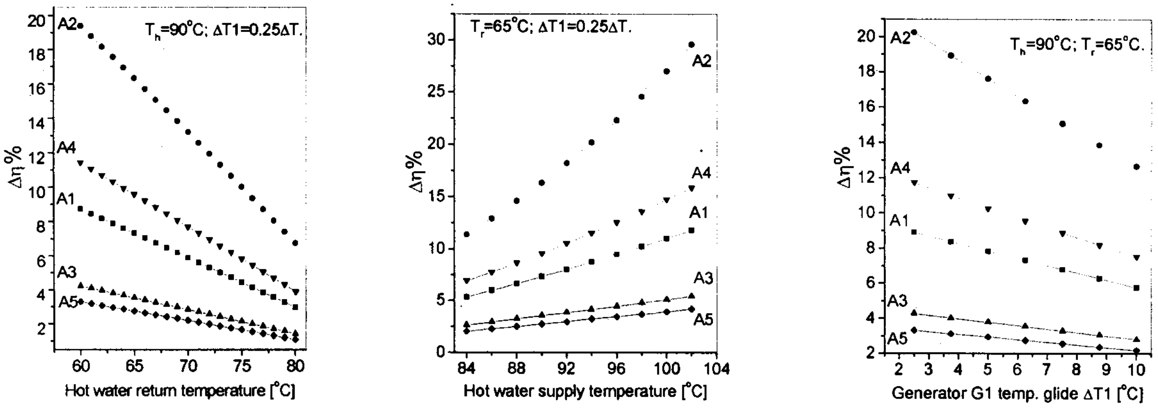

Fig.2: Mean Incremental Collector Efficiency Increase Rate

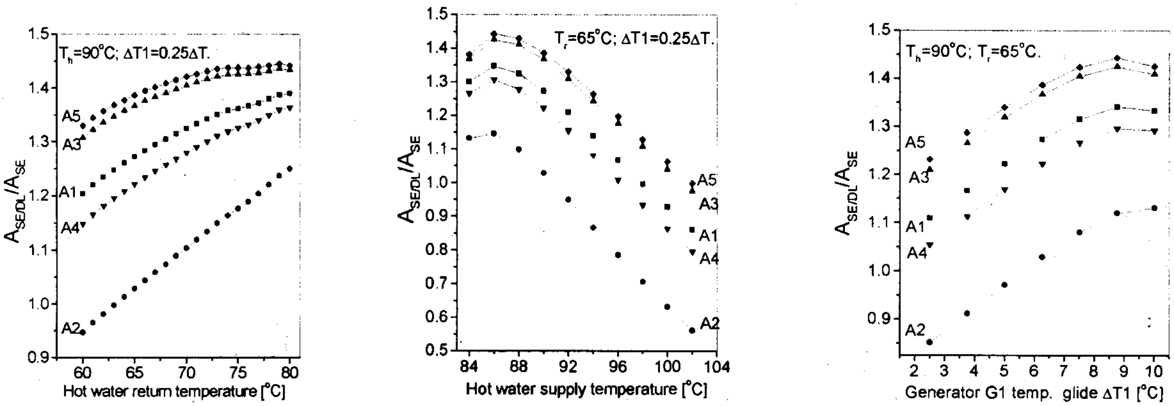

Fig.3: Installed Collector Surface Area Ratio

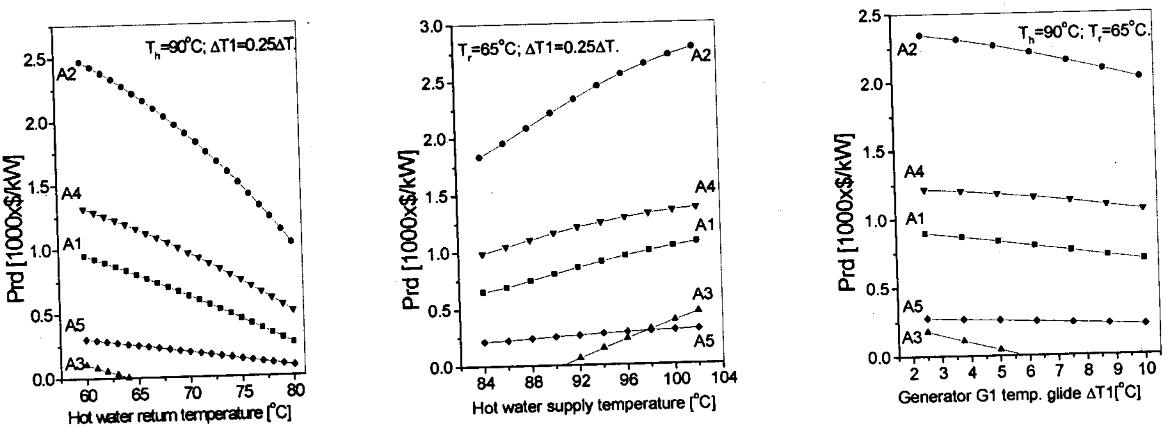

Fig. 4: The Profitability Degree of the Solar SE/DL Compared to the Standard Solar SE Systems

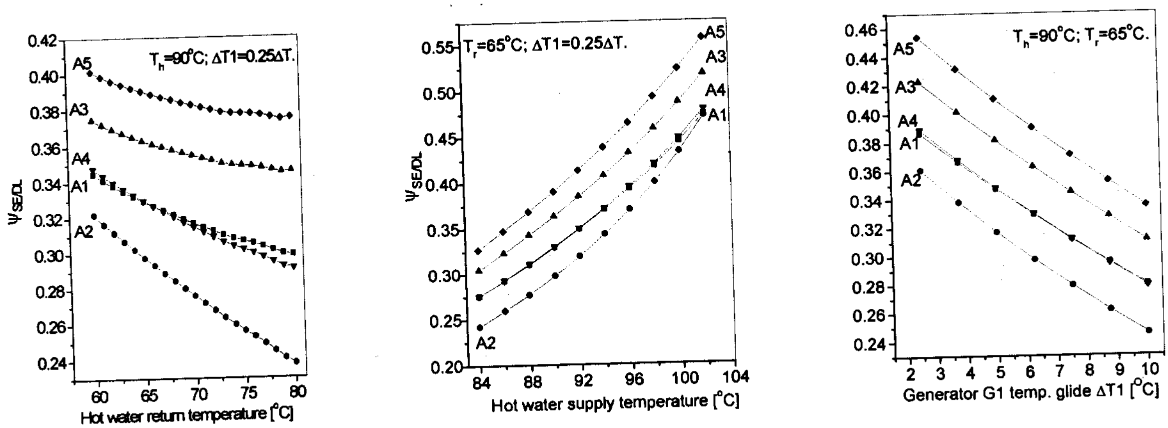

Fig.5: The SE/DL System Overall Coefficient of Performance

Table 1: Several Kinds of Solar Collector Models

No.	Collector types	A	B	Cost/m²
	Collector models from Asian market (Taiwan, China)(Huang *et al.*, 2000)			
A1	Low-cost special designed Single glazed flat plate	0.80	3.5	$136
A2	Conventional Single glazed flat plate	0.80	5.7	$121
A3	Vacuum tube	0.80	2.0	$485
A4	Single glazed Honeycomb construction	0.84	4.4	¥300
A5	Evacuated tube	0.84	1.7	¥350
	Collector models from European market (Hans Schweiger *et al.*, 2000)			
C1	Flat-plate collector	0.6603	3.2736	<= €250
C2	Evacuated flat-plate collector	0.6645	1.0260	<= €350
C3	Evacuated Tube collector	0.5978	0.7546	<= €500
C4	Evacuated Tube collector with external CPC-reflector.	0.6008	0.8526	<= €400

Table 2: Asian Market Collector Models Profitability [$/KW] at Different System Lifetimes

		A1	A2	A3	A4	A5
20 years	6000 hrs	1445.66	3807.13	260.33	1999.79	455.59
	3500 hrs	800.27	2215.34	-22.30	1156.80	251.01
	1000 hrs	154.92	623.56	-304.73	313.79	46.42
15 years	6000 hrs	1003.41	2719.16	62.36	1423.42	315.27
	3500 hrs	541.81	1580.63	-139.72	820.46	169.04
	1000 hrs	80.20	442.10	-341.81	217.50	22.71
10 years	6000 hrs	598.83	1725.02	-120.29	896.68	187.10
	3500 hrs	305.19	1000.63	-248.87	513.05	93.99
	1000 hrs	11.50	276.25	-377.44	129.42	0.89
5 years	6000 hrs	228.71	816.42	-289.17	415.19	69.70
	3500 hrs	88.47	470.51	-350.57	232.01	25.24
	1000 hrs	-51.77	124.61	-411.91	48.82	-19.21

Table 3: European Market Collector Models Figure of Merits Values and Profitability [€/KW] At Different System Lifetimes

		C1	C2	C3	C4
T_h / T_r [°C]		96/65	102/65	102/65	102/65
$\Delta\eta$%		8.502	3.064	2.441	2.7838
$A_{SE/DL}/A_{SE}$		1.1974	1.005	1.0115	1.005
$\psi_{SE/DL}$		0.272	0.4573	0.4193	0.4181
15 years	1000 hrs	-17.96	29.22	12.94	27.60
	3500 hrs	383.45	112.39	85.20	110.25
	6000 hrs	784.87	195.58	157.46	192.89
20 years	1000 hrs	47.95	42.51	24.63	40.83
	3500 hrs	609.05	158.80	125.66	156.37
	6000 hrs	1170.15	275.10	226.68	271.92

price of collector and electricity in Europe. In the same table are also listed the other figure of merits values at constant T_h and T_r.

Conclusion

Under the same ambiance and conditions, for an identical cooling effect, the solar powered SE/DL absorption chiller system compared the standard single-effect one, in addition to the electrical energy saving (4 times) by the driving hot water pump, have several advantages:

1 The solar SE/DL allow to collecting more solar energy, thus saving more nonrenewable energy source, due to the mean collector efficiency increase of about 2% to 20% depending on the chosen collector model.

2 Consequently the installed collector surface area increases about 15% to 45% depending on the used collector model, at the generators temperature distribution. It has a maximum value that must be checked for each collector model when designing a solar SE/DL system.

3 In 20 years (3500 hours-year) lifetime economical analysis, the cost of this saved energy correlated to an equivalent electrical energy is greater than the expense at the corresponding installed collector surface area implying a profitability per unit cooling capacity of about 2200$ for the conventional single glazed flat plate collector and about 800$ for the special designed low-cost single glazed flat plate collector. The vacuum tube collector becomes profitable when $\Delta t1$ is less than 6° C at T_h = 90°C or T_h greater than 92°C at T_r = 65°C.

4 For a better system overall performance the solar SE/DL absorption chiller had to be run with the vacuum tube collector at less profitability.

5 The use of solar cooling is more benefit in Asian (China) than in Europe due the lowest collector cost.

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