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Solar Single-Effect (SE) and Single-Effect Double-Lift (SE/DL) Absorption Machines Comparison
Part 2: Economic Assessment

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Abstract: In the first paper energy saving rate of the solar SE/DL vs. solar SE systems has been analyzed, and it was found that using a low-cost special designed single-glazed flat-plate solar collector with selective surface as heat source it can be saved 800$/kW at heat source supply/return temperature 90/65°C in 20 years lifetime of the system. In the present paper we present the computer simulation results of a full comparative study between the two systems with identical cold output at 14/9°C using the above mentioned solar collector model as heat source. It is found that the SE/DL is profitable when the supply temperature is less than 100°C at return temperature 65°C. For T_h = 90°C the profitability will be 490$/kW at T_r = 75°C and drop to 298$/kW at T_r = 60°C in 20 years system life. The profitability depends also on the system lifetime, the working-hours per year and the chiller unit cost per Ton.

Key Words: Solar Refrigeration; SE and SE/DL Systems; SE/DL System Profitability

Introduction

The common energy sources for cooling systems are electricity and some natural gas. The increasing demand for air-conditioning and the increasing costs of energy and electricity demand have caused us to seek alternative energy sources. Other the past few years, solar energy has received increasing attention as an alternative energy source for driving a cooling system. This is because the need for energy to drive cooling systems usually occurs when solar energy is most available. The use of solar energy promises to reduce the energy use and peak demand on conventional energy sources.

Solar-powered cooling implies the use of solar through several mechanical components to produce a cooling. The solar energy flows from the sun to a solar collector, where the energy is transferred to a flowing fluid that is than usually stored in a storage tank. A cooling cycle uses this stored energy to produce a cooling effect by removing heat from a cold storage reservoir. The resulting energy is rejected through a heat rejecter.

Various technologies are available for air conditioning using a solar energy as the main energy input. However performance comparisons of several cooling systems using solar energy as the external energy input shows that chiller with higher Coefficient of Performance (COP) yields relatively higher performance compared to the other systems. Although this high COP is an advantage because low collector cost is need, the first part (Yattara *et al.*, 2002) analysis shows that solar SE/DL unit part is more profitable than the solar SE one.

The aim of this present study is to investigate the economic and performance of the whole two systems with identical cold output in a wide range of operating conditions.

The single glass honeycomb construction performs as well as a low-cost special designed single-glazed flat-plate solar collector with selective surface. But for technical considerations the latter one will be use as heat source.

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/m^2,
- Identical temperature glide in the DL two generators,
- The temperature difference ΔT1 into the two Single-Effect generators are identical.

Chiller Systems Modeling: The solar powered SE/DL absorption chiller is depicted schematically in Fig.1. The SE/DL machine is a combination of a single-stage Single-Effect (SE) and a double-stage Double-Lift (DL) absorption chiller integrated into a single machine as developed in the first part. Compared to a single-stage machine consisting of the mains components of evaporator (E), Absorber (A0), Condenser (C) and Generator (G1), it includes additional heat exchangers generators (G2, G3), and Absorber (A2).

The coefficient of performance of the SE/DL chiller is expressed as:

$$COP_{SE/DL} = \frac{Q_o}{Q_{G1} + Q_{G2} + Q_{G3}} \tag{1}$$

The coefficient of performance of the SE chiller running for an identical cooling capacity is expressed as:

$$COP_{SE} = \frac{Q_o}{Q_{G1}}, \tag{2}$$

In computer modeling of the SE/DL absorption chiller, the system is assumed to be in steady state at each operating point with given values for the temperature of the main components and fixed refrigerant concentration and mass flow rate coming out of the condenser. Therefore, the supply temperature or the return temperature or the temperature glide in generation is allowed to vary while the parameters listed in Table (1) are kept constant.

The computer modeling is based on mass, material, and heat balances for each component. The model includes also the economic parameters for each element.

Solar Unit Modeling: The solar unit supplying energy to the designed SE/DL absorption machine is characterized by a large temperature glide in the generation. A storage tank with this kind of temperature difference provides a substantial heat loss. One way to overcome this problem is to lower the storage tank temperature difference by boosting the load return temperature before it enter the tank trough a second collector field with respect to the generators mass flow rate. Then the second collector field will heat the hot water to the required temperature.

For the heat supply of the solar SE and SE/DL systems, a low-cost specially designed single-glazed flat-plate solar collector with selective surface is used (Huang *et al.*, 2000). At steady-state thermal performance curves are expressed as follows:

For SE machine only:

$$\eta_{SE} = 0.8 - 3.5\frac{(\mathrm{T}_h - 0.5\Delta T1 - \mathrm{T}_a)}{\mathrm{I}} \qquad (3)$$

For DL machine only:

$$\eta_{DL} = 0.8 - 3.5\frac{(\mathrm{T}_r + 0.5\Delta T2 - T_a)}{I} \qquad (4)$$

For SE/DL machine:

$$\eta_{SE/DL} = \eta_{SE}\frac{\Delta T1}{\Delta \mathrm{T}} + \eta_{DL}\frac{\Delta T2}{\Delta \mathrm{T}} \qquad (5)$$

Mathematical Modeling: The computation equations for the SE/DL profitability analysis are presented in Table (2).

The SE/DL chiller unit cost is about 20% much than the SE unit. The storage tank is assumed to provide heat source energy after the sunset for 3 hours. The element installation cost is assumed as percent of it capital cost: 25% for the absorption chiller unit, 50% of the solar collector, 4% for the storage tank, 50% for the cooling tower. The cooling tower cost is assumed 20\$/kW. The solar collector maintenance cost is assumed 1% of it capital cost.

C_{ch} = 350\$/Ton for Qo = 90 - 1600 Tons (TRANE, 2000), C_{sc} = 136\$/m^2, C_{st} = 500\$/m ^{3} (Tsilingiris, 1993), EC_{ct} = 0.04 kWh/m^3 (Dai Yongqing, 1999), $\eta_p = 0.6$, P_{ab} = 80e-6 kW/m^2 (Frederick, 1976), C_e = 0.0668\$/kW.h.

The SE/DL solar unit part is designed in such way that the return temperature is first boosted to ($T_r + \Delta T2$) before it enter the storage tank, than heated to the required temperature.

The present worth of the variable part of the system first cost is determined for different lifetime periods (20, 15, 10 years) at 10% interest rate and 9% mortgage rate. The present worth of the variable part of the system running cost during different lifetime periods (20, 15, 10 years) at different operating hours per years (1000, 3500, 6000 working-hours) at 10% interest rate and 12% inflation rate is calculated.

Results and Discussion

Solar SE/DL system is assumed to be profitable when its total cost is less than that of the SE one.

Fig.2 shows the variation of the theoretical profitability of the solar SE/DL system at various heat source Temperature T_h and load return temperatures T_r for 20 years system lifetime at different working-hours per year. It is seen that for a constant heat source temperature T_h = 90°C (3500hr/a) the profitability decreases with decreasing return temperature from 490\$/kW at 75°C to 298\$/kW at 60°C. For a constant return temperature T_r = 65°C the profitability decreases with increasing heat source temperature from 491\$/kW (3500hr/a) at 86°C to zero profitability at 100°C. Also it can be seen that at constant T_h or constant T_r the profitability increases slightly with increasing working-hours per year, becomes equal at 98/65°C for the different working-hours per year and then inverse. It can be noted that the same amount of profitability can obtained for two different operating conditions, for example the profitability 435\$/kW corresponds to the operating conditions T_h = 90°C at T_r = 71.5°C and T_h = 88°C at T_r = 65°C. It is interesting to see that there is only one operating condition (90/65°C) at constant T_h and variable T_r or vice versa corresponding to the profitability 366\$/kW.

Fig.3 shows the profitability increase trend with decreasing system lifetime period. This is due to the fact that the running cost influences the profitability more than the first cost. It is interesting to see that the SE/DL system is not profitable at T_r = 65°C at 3500 working-hours when T_h is greater or equal 100°C. This is logic because the SE/DL chiller is a low-temperature application chiller, while the SE chiller is more efficient when the supply temperature is higher, as can be seen in Fig.4 and 5.

From Fig.2 and 3 it can be concluded that the profitability depends strongly on the working-hours per year than on the system lifetime. The SE/DL system is suitable for a longtime lifetime and working-hours.

From Fig.5 it can be seen the confirmation that the overall coefficient of performance of a SE system is the highest when the solar collector temperature is between 90° to 92°C and the increase of the SE/DL collector efficiency compared to the SE one. The main characteristics of the systems at chiller unit cost per unit cooling capacity 350\$/Ton (100\$/kW) and heat source temperature 90°C are presented in Table (4). The overall coefficient of performance of a SE/DL system increases linearly with increasing heat source temperature. This is because when increasing heat source temperature the DL share is reduced and tends to zero and the chiller operates as a pure SE machine at T_h = 100°C with a COP = 0.702, (Fig.4).

Other factor that influences the profitability of the SE/DL system is the absorption refrigeration unit cost per unit cooling capacity. From Table (3) it can be seen the increasing trend of the profitability with increasing chiller unit cost per unit cooling capacity. Also when the storage tank cost increases from 170\$/m^3 to 500\$/m^3 the profitability increases by about 25-30%.

Conclusion

The present computer simulation shows that solar SE/DL system is profitable in the expected operating range, the low-temperature application (t_h < 100°C). It must be designed with a low-cost high efficiency medium-temperature collector. Its profitability depends on operating and economical conditions, which at the design stage had to be checked. At heat source supply/return temperatures 90/65°C for 20 years

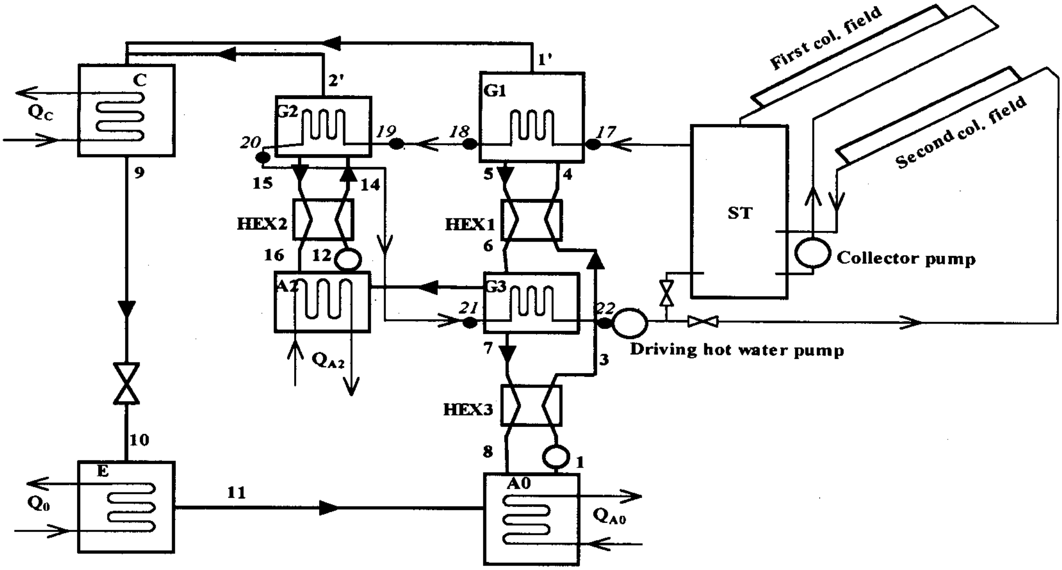

Fig. 1: Schematic of Solar Powered SE/DL Absorption Chiller System

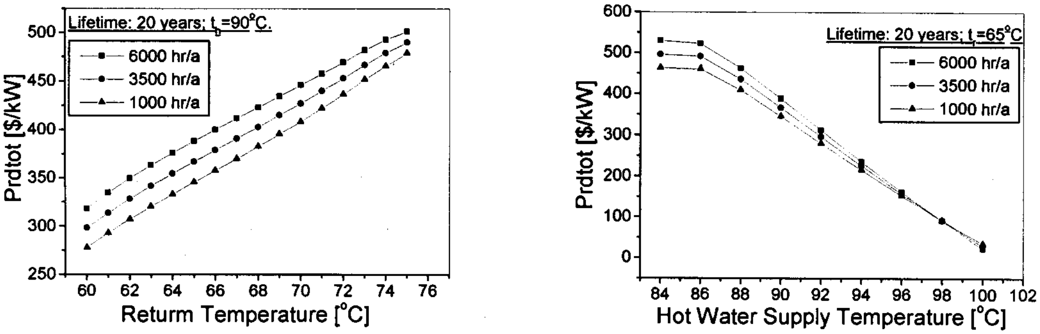

Fig. 2: Variation of Solar SE/DL vs. SE Systems Profitability, at 20 Years Lifetime Period at Different Working Hours per Year

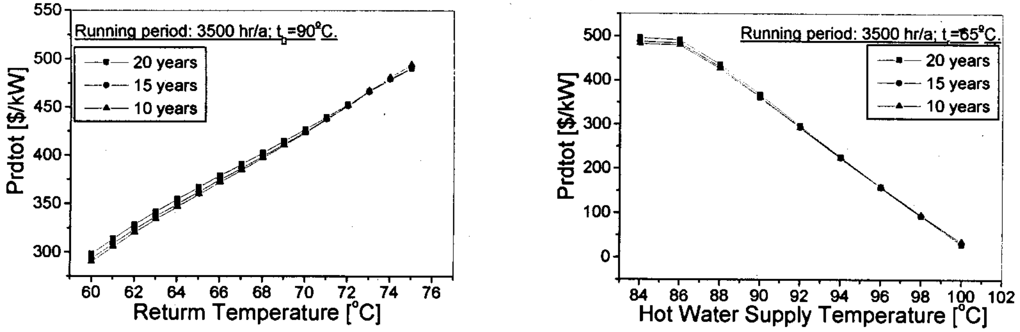

Fig. 3: Variation of the Solar SE/DL vs. SE Systems Profitability at 3500 Working Hours per Year at Different System Lifetime Periods

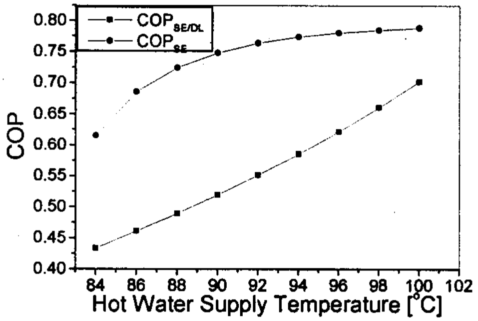

Fig. 4: Variation of the SE/DL and SE Coefficient of Performance

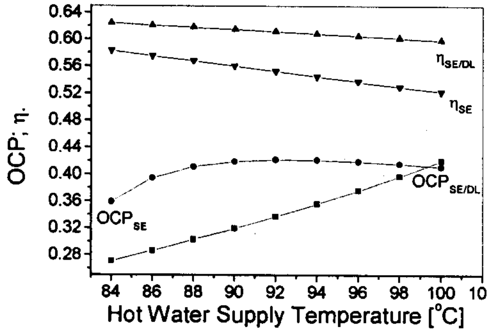

Fig. 5: Variation of System Overall Coefficient of Performance and Collector Efficiency

Table 1: Computation Equations for the SE/DL System Profitability Analysis

Elements of comparison	SE/DL system	SE system
FISRT COST		
Absorption chiller unit:	$1.25[1.2(Q_0.C_{ch})]$	$1.25[Q_0.C_{ch}]$
Solar collector:	$1.51[1.2(\frac{Q_0}{COP_{SE/DL}.\eta_{SE/DL}.I})C_{sc}]$	$1.51[1.2(\frac{Q_0}{COP_{SE}.\eta_S.I})C_{sc}]$
Storage tank:	$1.04[3(\frac{3600.Q_0}{COP_{SE/DL}\rho.c.\Delta T1})C_{ST}]$	$1.04[3(\frac{3600.Q_0}{COP_{SE}\rho.c.\Delta T1})C_{ST}]$
Cooling tower:	$1.5[20(Q_C+Q_{A0}+Q_{A2})C_e]$	$1.5[20(Q_C+Q_{A0})C_e]$
RUNNING COST		
Heat source pump energy:	$m_{GSE/DL}.\Delta P.C_e/\rho.\eta_p$	$m_{GSE}.\Delta P.C_e/\rho.\eta_p$
Collector pump energy:	$(Q_0/COP_{SE/DL}.\eta_{SE/DL}.I)P_{ab}.C_e$	$(Q_0/COP_{SE/DL}.\eta_{SE/DL}.I)P_{ab}.C_e$
Cooling water pump energy:	$EC_{ct}.V_{SE/DL}.C_e$	$EC_{ct}.V_{SE}.C_e$
System total cost:	(First cost)$_{SE/DL}$+(Running cost)$_{SE/DL}$	(First cost)$_{SE}$+(Running cost)$_{SE}$
SE/DL system profitability:	(System total cost)$_{SE/DL}$ – (System total cost)$_{SE}$	

Table 2: Cycle Operating Parameters

Cold production at [°C]	14/9
Cooling water inlet outlet temperature [°C]	30/34
Absorber A2 out solution concentration [%]	50
Identical closest approach in the three generators [°C]	4
Condenser inlet outlet temperature difference [°C]	4
Absorber A0 inlet outlet temperature difference [°C]	4
Absorber A2 inlet outlet temperature difference [°C]	2
Evaporator outlet temperature difference [°C]	2

Table 3: Variation of Profitability vs. Chiller Cost per Unit Cooling Capacity

Chiller cost [$/Ton]	350	365	430	520	800
Profitability [$/kW]	366.88	367.88	372.21	378.20	396.86

Table 4: Performance Parameters of the Solar SE/DL vs. Solar SE Systems

	Solar SE/DL	Solar SE
Inlet/outlet temperature of heat source [°C]	90/65	90/83.75
COP [-]	0.52	0.748
MRC [kg/kW·h]	66.175	183.9
Flow rate of cooling water per kW [m³/h]	0.7694	0.6693
System profitability [$/kW]	366.88	0.0

system lifetime (3500 working-hours per year) a profitability of 366$ per unit cooling capacity is expected which is very significant.

Nomenclature

Variables:

T	temperature, °C
ΔT1	generator G1 temperature glide, °C
ΔT2	double-lift generators G2 and G3 temperature glide, °C
ΔT	SE/DL generators temperature glide, °C
Q	heat capacity, kW
I	solar radiation, W/m²
Prdtot	system profitability, $/kW
P	pumping power, kW
M	mass flow rate, kg/s
C	condenser or element costs, $
C	water specific heat, kJ/kg °C
MRC	mass flow rate per cooling capacity, kg/kW·h
EC	energy consumption per cubic meter of cooling water, kW.h/m³
V	cooling water volume rate, m³/h
ΔP	hot water pressure drop, kPa
Hr.a-1	hours per years
H	solar collector or pump efficiency
p	water density, kg/m³

Subscripts:

r	load return water
h	heat source
a	ambient
Gn	generators (n=1,2,3.)
ch	absorption chiller
sc	solar collector
ST	storage tank
Ct	cooling tower
P	pump
E	electricity
Ab	collector absorber area
SE	single-effect
SE/DL	single-effect double-lift
O	cooling capacity

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