Pakistan Journal of Applied Sciences 2(9): 916-921, 2002

Theoretical Analysis on the Economico-Performance of Solar Single-Effect Double-Lift (SE/DL) Absorption Refrigeration System

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Abstract: In this paper the performance and economic analyses of solar collectors for optimizing the specific cooling cost in the Single Effect Double Lift (SE/DL) absorption cycle using aqueous solutions of LiBr, have been carried out on a wide range of operating conditions. Several kinds of collector (from two different sources) have been selected as the sources of energy for providing hot liquid in the generators of the absorption cycle. The performance of a Single Effect Double Lift (SE/DL) was calculated and analyzed theoretically. The lowest unit delivered cooling cost values and solar collector type are obtained, which will provide theoretical foundation for optimization and operation management of the solar LiBr/H_2O SE/DL absorption refrigeration systems. It is found that the honeycomb construction and the one layer glass cover (used as temperature booster) collectors type have been characterized by a high overall efficiency and a low specific unit cooling delivered cost that is suitable to operate a solar-powered SE/DL absorption plant.

Keywords: Solar Refrigeration, SE/DL Absorption Chiller, Collector Choice, Unit Cooling Delivered Cost

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Introduction

The increasing cost of the conventional sources of energy and day-to-day development of sophisticated equipment, which need comfort conditions, have resulted in a search for alternative and cheaper means of operating the refrigeration machines. Solar energy, with its abundant supply in the most parts of the world, would serve to be a premium source, especially for powering refrigeration and air-conditioning systems. It is well known that the utilization of solar energy for space cooling in the tropics is more attractive in principle, because the demand of refrigeration and air-conditioning becomes high 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 Siddique, 1997). Of all conventional methods of refrigeration, the vapor absorption system matches well with the available solar energy, especially the Single Effect, Double Lift (SE/DL) cycle due the positive proportion between sunshine and heat load and the SE/DL absorption chiller's feature to meet this load without need to an auxiliary heater.

Presently available absorption machines for air-conditioning are driven with the heat at minimum of 80^0C. 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 60^0C and permits temperature glides in generation of about 30^0C. Heat above 80^0C 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)(Ma and Deng, 1996)(Dan, 1979). Depending on the heat share supplied to the two cycles, the resulting COP of the chiller varies between 0.35-0.7. Thus a larger cooling capacity can be produced from the same heat source compared to a single-effect chiller run with the same heat carrier (Schweigler, 1998).

In the design of solar refrigeration system, selection of the heat source temperature is of a great importance (Zou Tonghua *et al.*, 2001), but for a designed solar-powered absorption chiller using low heat source temperature, the lowest unit delivered cooling cost is the most important. At present, literature investigating such problem is rare, so, the aim of this study is the selection of the collector model that powering the solar absorption refrigeration system (for low-temperature application) with the lowest specific cooling cost and a reasonable overall system efficiency. Recently, many kinds of solar collector have been developed such as plate collector and vacuum tube heat collector and the latter although it is more expensive, but it is the most promising for solar cooling that is because it can achieve higher temperature of heat source. In the specific case of the SE/DL absorption chiller using low temperature heat source, the collector field that give the lowest unit energy cost and provide a higher overall efficiency is to be selected.

(SE/DL) Cycle Description: 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 (Zhu Yuqun, 1998). 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).

In this cycle, 1-3-4-5-6-7-8-1 is a closed solution loop. Dilute solution from absorber A0 at state 1 is pumped, through the heat exchangers HEX3 and HEX1, to Generator G1 where it is heated by the heat source to the equilibrium state under the working pressure and then boiled and vapor is released at state:

1'.Then the mid-strong solution at state flows through HEX1 to Generator G3 where it releases vapor at state 3' and reaches state 7. Then this strong solution passes through HEX3 back to Absorber A0 where it absorbs refrigerant vapor from Evaporator E and reaches state 1. 12-14-15-16-12 represents the other solution loop. Dilute solution from absorber A2 flows through HEX2, G2, HEX2 and A2, in a similar way mentioned above. This time refrigerant vapor at state 2' is gained. Refrigerant generated in G1 and G2 flows into Condenser C where it is condensed and then flows to the evaporator through a throttle valve. Heat source fluidstarts from point 17, it heats solutions in G1, G2 and G3 respectively to generate refrigerant. The reasons that this flow path is adopted though there is another possible loop, (G1-G3-G2), can be explained as follows: The irreversibility losses due to large temperature difference are large. Also, the refrigerant vapor couldn't be generated smoothly with limited temperature difference in G2. Moreover, absorption effect will become worse in A2. Cooling water is connected with the system in 3 parallel ways that cool down working substances in A0, A2 and C separately. Adoption of series connection can lower the amount of cooling water and save pump power. However, this method would influence the situation of the three units and the system's working state couldn't be controlled steadily and easily. Therefore, mixed connection is adopted here: A0 and C are connected in parallel, than both in series with A2.

System Modeling: Depending on the available hot water temperature the machine can be run for a Coefficient of Performance (COP) in the range of the COPs of the two sub-cycles.

$$COP_{SE}=\frac{Q_o^{SE}}{Q_{G1}} \qquad (1)$$

$$COP_{DL}=\frac{Q_o^{DL}}{Q_{G2}+Q_{G3}} \qquad (2)$$

$$COP_{SE/DL}=\frac{Q_o}{\sum Q_G} \qquad (3)$$

Generally, manufacturer supplies collectors provided with the collector efficiency curve (η) and the installation cost of the collector per unit aperture area ($/m^2), however, thermal performance alone is not enough information for collector selection. The most desirable collector will be the one, which delivers the required amount of energy (Q_g) at specified Temperature (T_h) at the lowest cost, based one life cycle cost analysis, because the most efficient collector may not be the most economical if it costs considerably more than the less efficient one (Howell, 1982., and Sodha, 1983). For a given values of the Insolation (I), ambient Temperature (T_a), and the required operating Temperature (T_h), a good criteria for collector selection is lowest cost per unit of energy delivered rate (UEC) expressed as:

$$UEC=\frac{Cost/m^2}{\eta.I} \qquad (4)$$

For a specific collector design and ambient conditions, collector efficiency is linearly related to the solution inlet Temperature (T_i) as follows:

$$\eta = A - B\frac{(T_i - T_a)}{I} \qquad (5)$$

Where *A* and *B* are constant depend on the collector design and operating conditions.

Thus, equation (4) can be rewritten as:

$$UEC=\frac{Cost/m^2}{A.I - B(T_i - T_a)} \qquad (6)$$

Keeping T_a and I fixed, Equation (6) becomes

$$UEC=\frac{Cost/m^2}{C - B.T_i} \qquad (7)$$

Where $C\ (= A.I + B.T_a)$ is a constant.

For solar-assisted absorption chiller, cooling capacity (Q_o) can be expressed as:

$$Q_o = COP_{SE/DL}.Q_G \qquad (8)$$

Where Q_G is the total load of the three generators given by:

$$Q_g = \eta.A.I \qquad (9)$$

And *A* is the collector area. Thus, Equation (8) becomes

$$Q_o = \psi.A.I \qquad (10)$$

Where ψ is the refrigeration plant overall Coefficient of Performance ($=COP_{SE/DL}.\eta$).

The Unit of Cooling delivered Cost (UCC) is expressed as:

$$UCC=\frac{Cost/m^2}{COP_{SE/DL}(C-B.T_i)} \qquad (11)$$

For specific Temperature (T_h), equation (11) gives the lowest cost of unit cooling capacity delivered by different kinds of collectors.

Table 1 shows different kinds of solar collectors with their characteristics constants (*A, B, C*) and cost per unit area.

It is rather difficult task to model the dynamic operation of absorption cooling systems. To avoid the complexity involved, a steady-state computer modeling is developed that can be latter extended to the actual dynamic solar operation of the system. 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, effectiveness of the solution heat exchangers, and fixed refrigerant concentration and mass flow rate coming out of the condenser. These values are chosen from the actual ranges over, which the machine could be expected to operate. The computer modeling is based on mass, material, and heat balances for each component, including generators, absorbers, condenser, and evaporator.

The influence of the component temperature on the cooling effect and the COP can be studied from this computer modeling. In the parametric study undertaken, one of the input parameters is allowed to vary while keeping others constant. Thus the operating zones of the entire cycle can be established, and system operation feasibility can be studied under steady-state conditions.

In solar cooling system, the influence of solar heat sources on COP for absorption cycles is paid more attention to. Therefore, the generating temperature is allowed to vary while other parameters are kept constant. These constant parameters and their values are shown in Table 2.

Results and Discussion

The variations of the Coefficient of Performance ($COP_{SE/DL}$), collector efficiency (η), the overall coefficient of performance (ψ), the Unit delivered Energy Cost (UEC) and the Unit delivered Cooling Cost (UCC) with the collector temperature (= generating temperature, T_h) for each model of collector chosen are shown in Figs. 2-6.

In Fig. 2 it can be seen that the $COP_{SE/DL}$ increases gradually with increasing collector temperature from the values of the double-lift COP_{DL} to the single-effect COP_{SE}. Also, it can be seen that the SE/DL had a COP

Table1: Selected Collector Models

No	Collector Models	Absorber Types	A	B	C	$\$/m^2$**
		Group A				
c1	SRE-29 Single glass non selective.	Rubber	0.6972	8.0864	816.53	224
c2	SG33-F06-4 single glass non selective.	Copper tube/ Al finish	0.7826	6.5289	835.01	146
c3	98C Single glass non selective.	Copper	0.7230	6.2949	779.84	183
c4	SG L10206 Single glass selective.	Stainless steel	0.7274	4.696	732.19	247
c5	D-477 Single glass selective.	Copper	0.7362	4.0202	717.61	164
c6	AF-24-DG Two glass non selective.	Copper tube/ Al finish	0.7076	4.1991	700.45	140
c7	Single glass Mylar honeycomb.	Black paint-Al	0.8170	4.5767	800.05	160
c8	Two glass Mylar honeycomb.	Black paint - Al	0.7350	2.8821	678.16	250
		Group B				
c9	C 151 Single glass.	Black Chrome	0.698	3.56	657.92	180
c10	C 482 Single glass.	TiNOX	0.733	4.19	720.48	150
c11	C 256 Single glass (multipass).	Black Chrome on Nickel on Copper	0.696	3.73	676.16	250
c12	C 200 Single glass.	Black Chrome on stainless steel	0.765	3.97	737.44	350
c13	C 477 Single glass (serpentine absorber).	NiOX on Al	0.698	3.32	664.64	350
c14	C 286 Single glass with anti Reflector	TiNOX	0.748	3.82	720.64	250
c15	C 123 Two glass	M40 LI	0.624	3.45	609.60	150
c16	C 264 Heat-pipe vacuum tube.	Black Chrome on Nickel on Copper	0.601	1.44	483.68	700
c17	C 444 Glass vacuum tube.	Al/Al/Ni	0.543	0.94	464.46	500

** The average unit area collector cost.
Group A was taken from (Military Handbook, 1985) except C7 and C8 from (Simon, 1976).
Group B was taken from (SPF Collector-Catalog Online, 2000).

Table 2: Cycle Operating Parameters

Cold production at (°C)	14/9
Cooling water inlet outlet Temp. (°C)	30/36
Absorber A22 out solution concent. %	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 A22 inlet outlet temperature difference (°C)	2
Evaporator outlet temperature difference (°C)	2
Hot water return temperature (°C)	65
Identical heat input in both double lift generators	

between 0.35-0.7, when the solar powered absorption system's overall coefficient of performance is suitable to be greater than 13% (Yeung *et al.*, 1992), therefore, the collector efficiency must be greater than 0.37. In the expected generator temperature range, (75-92°C), the vacuum tube, honeycomb construction and selective single glass collectors is suitable to be used as main collector field and the non selective single glass as temperature booster.

The efficiency curves of different collector models are shown in Fig. 3A and 3B. The collector group(A)is taken from the American market and group (B) from the German market. The difference in performance between the main kinds of collector: the vacuum tube, the selective and non-selective single or two glasses cover flat-plate collectors is clear.

The overall Coefficient of Performance of the different kinds of collector, obtained for operating the SE/DL absorption cycle at various collector temperatures have been exhibited in Fig.4 A-4B.

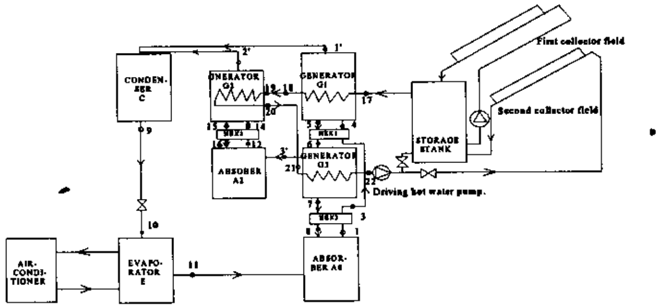

Fig. 1: Schematic of the Solar-Powered (SE/DL) Absorption Chiller

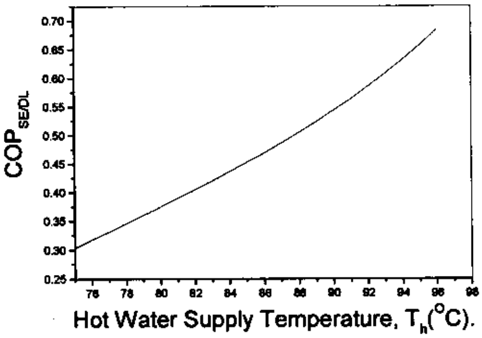

Fig.2: Variation of the Coefficient of Performance with the Hot Water Supply Temperature

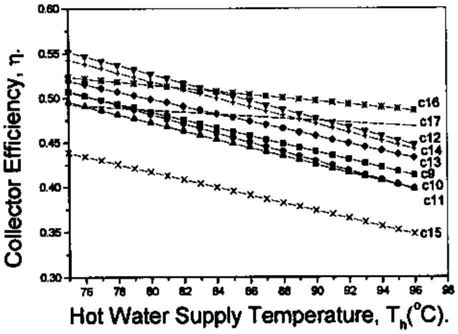

Fig. 3B: Variation of the Collector Efficiency with the Hot Water Supply Temperature (B)

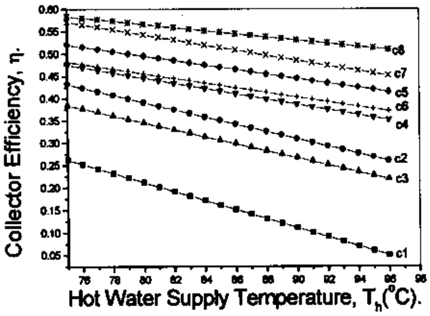

Fig.3A: Variation of the Collector Efficiency with the Hot Water Supply Temperature (A)

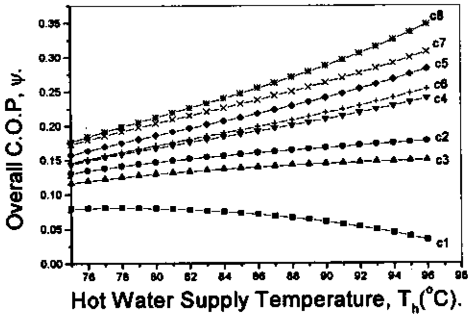

Fig. 4A: Variation of the Overall Coefficient of Performance with the Hot Water Supply Temperature (A)

At the given conditions, for each collector model the overall coefficient of performance increases either linearly or almost gradually with the collector temperatures, except for the model 1 which has it's maximum efficiency at 80°C. This is because, the expressions of the overall efficiency is the product of the collector efficiency and the COP. And since the equation of the collector efficiency shows a straight line decreasing with the increasing collector temperatures, the rapid increase of the COP with the increasing collector temperatures dominates and hence of the overall efficiency always increases. The COP's are higher for the two glass honeycomb construction in group A; for the heat pipe vacuum tube at $T_h>84°C$, and selective single glass (with black chrome steel absorber) at $T_h<84°C$ in group B. The OCP of the evacuated tubular is higher than the flat-plate one only above 90°C. It is interesting to see that in both case, change in the OCP with change in collector temperature is very significant; except for the non-selective single glass collectors that are slightly sensitive to the change in T_h.

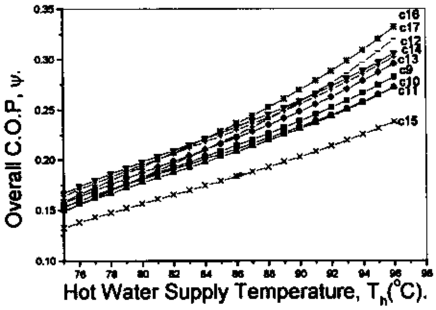

Fig.4B: Variation of the Overall Coefficient of Performance with the Hot Water Supply Temperature (B)

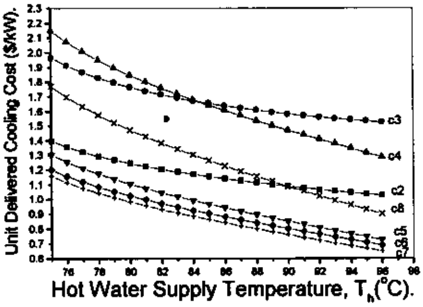

Fig. 6A: Variation of the Unit Delivered Cooling Cost with the Hot Water Supply Temperature (A)

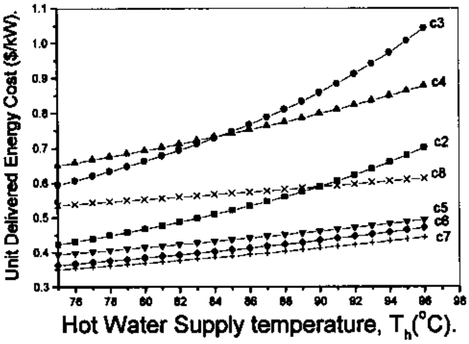

Fig. 5A: Variation of the Unit Delivered Energy Cost with the Hot Water Supply Temperature (A)

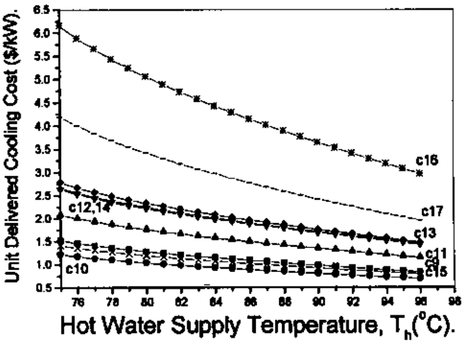

Fig. 6B: Variation of the Unit Delivered Cooling Cost with the Hot Water Supply Temperature (B)

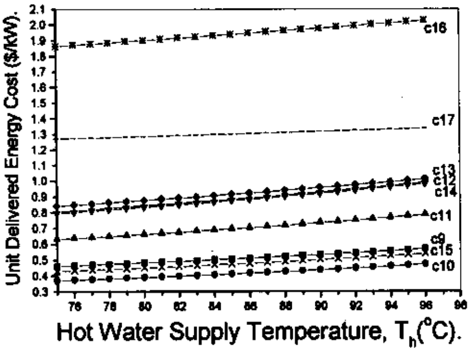

Fig. 5B: Variation of the Unit Delivered Energy Cost with the Hot Water Supply Temperature (B)

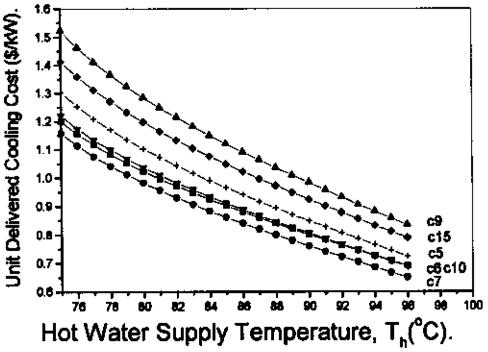

Fig. 7: Variation of the Unit Delivered Cooling Cost With the Hot Water Supply Temperature (A, B)

This evidently due to their lowest heat loss at high temperature compared to the non-selective single glass collectors. It can be seen that all collectors, except the non-selective single glass ones have a gradually increasing overall coefficient of performance with different slopes and different magnitudes. As a result the vacuum tube collectors are not suitable to be used when running a solar powered SE/DL system; the selective single glass collectors are better compared to the non-selective single and two glass collectors. It means that from the performance analysis, the best collector to operate a solar-powered SE/DL absorption chiller is the single glass honeycomb or selective single glass collector models, and the less efficient one is the non-selective single glass collector model.

The variation of the Unit delivered Energy Cost, using different kinds of collector, at various collector temperatures are shown in Figs. 5A and 5B. For the low collector temperatures the energy (low quality) cost is low but provides a very low COP and consequently an expensive cooling. The UEC values increases almost linearly but less sensitive to T_h, being higher for vacuum tube collectors and lower for the single glass honeycomb construction, the non-selective two glass and the selective single glass (copper absorber).

The variation of the Unit delivered Cooling Cost (UCC), using different kinds of collector, at various collector temperatures are shown in Figs. 6A, and 6B. The UCC values decreases gradually with increasing T_h. In group A, the lowest UCC are observed for the single glass honeycomb construction. The second and third lowest UCC are noted for the non-selective two glass and the selective single glass (copper absorber). The three collector models perform in similar way with different magnitudes. The non-selective single glass collectors are less sensitive T_h; the two glass honeycomb and the selective single glass (steel absorber) collectors perform good for the high collector temperature' so they can be used to run a single-effect absorption machine.

In group B, the lowest UCC is observed for the single glass (TiNOX absorber). The second and third lowest UCC are noted for the non-selective two glass and selective single glass (black chrome absorber) collectors. Compared to the other collectors these three collectors are less sensitive to the collector temperatures. Superimposing the two groups in Fig. 7, the lowest UCC are observed for the single glass honeycomb construction, which is also sensitive to the collector temperature increasing change. The two glass non-selective and the single glass (TiNOX absorber) collectors perform in the same. For any selected model collector, the Unit Cooling delivered Cost becomes constant beyond 94°C collector temperature, except for the collector model 1.

Conclusion

The performance and economic analyses of solar collectors for optimizing the Specific Cooling Cost in the Single Effect Double Lift (SE/DL) absorption cycle using aqueous solutions of LiBr, have been carried out on a wide range of operating conditions and the following conclusions were drawn:

1. When the performance and economic analyses for different models of collectors for cold production in the Single Effect Double Lift (SE/DL) cycle, that can use hot water down to return temperatures of about 60°C and permits temperature glides in generation of more than 30oC, and when unit delivered cooling cost paid more attention, the single glass honeycomb or selective single glass (TiNOX absorber) collectors model are suggested to be used to optimize the cold production cost under a better overall efficiency of the entire plant.
2. When using the same collector model as the main and the booster fields-collectors, the specific cooling cost is lower for the main field collector.
3. As expected, the vacuum collectors (the more expensive collectors) are not suitable to run a SE/DL absorption chiller system because their specific cooling cost is low only at a generating temperatures more than 100°C. The two glass honeycomb and the selective single glass (steel absorber) collectors perform good for the high collector temperature, so they can be used to run a Single Effect absorption machine.
4. In group A, except the non-selective two glasses and the selective collector models, the specific cooling cost of the non-selective collector models' are more expensive for low generating temperature and are less sensitive to the increasing collector temperature. Also, their overall system performance are lower than 0.16, so they are not suitable to run a SE/DL absorption cycle system.

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