Solar Cooling for Southern Climates, Double Effect Absorption Chillers with High Concentrating Collectors Versus Standard Single Effect Systems

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Abstract

In the present paper solar thermal cooling systems applied to office buildings in hot southern climates are analysed. The solar cooling systems are considered to be applied to a planned innovative office building in Cairo, Egypt. Dynamic building simulations with TRNSYS where used to calculate the cooling load of the analysed building. Single effect absorption chillers with vacuum tube collectors are analysed as well as double and triple effect absorption chillers with high concentrating collectors as heat source such as parabolic trough or Fresnel collectors. The dynamic simulation environment INSEL is used for the analysis of the solar cooling systems. Apart from the thermal performance of the systems also the electricity consumption of all components like cooling tower, external pumps and absorption chiller are considered in the calculated. For the double and triple effect absorption chillers additional heating provided by an external or integrated gas burner is considered if the heating energy from the solar system is not sufficient to cover the cooling load of the building. For all analysed systems additional cooling delivered by a standard compression chiller is considered to cover the remaining part of the cooling load. The primary energy consumption required to cover the whole cooling load of the building and the resulting primary energy ratio are used to compare the overall performance of the analysed solar cooling systems.

1. Introduction

The overall efficiency of solar driven absorption cooling machines (ACM) is mainly influenced by the thermal COP of the absorption chiller and the electricity consumption caused by the heat rejection system, the chiller and all connected system pumps. Single effect absorption chillers reach only quite low thermal COPs which are typically in the region between 0.55 and 0.75. In consequence, large solar collector areas and large heat rejection systems are required to reach high solar fractions and to remove the waste heat. The large heat rejection systems often cause high electricity consumptions, which significantly reduce the primary energy efficiency of the solar cooling systems [1,2]. However, the main advantage of single effect absorption and adsorption chillers is the relatively low driving temperature which varies between 65°C and 95°C. Such temperatures can be provided by efficient flat plate or vacuum tube collectors. Double effect absorption chillers reach much higher thermal COPs of 1.3 and above but typically require much higher driving temperatures of around 180°C. To provide such high temperatures highly concentrating solar systems like parabolic trough or linear Fresnel collectors are required [3-8]. In the present paper a detailed simulation based case study of a solar cooling application for an office building project in Cairo Egypt with a maximum cooling load of 800 kW and a cooling energy demand of 1,979 MWh/a is presented. Here, three different systems are regarded: Single effect (case 1), double effect (case 2 and 3) and triple effect absorption chillers (case 4). The single effect absorption chiller is considered to be combined with a vacuum tube collector field. For the water driven double effect absorption chiller both parabolic trough (case 2) and Fresnel collectors (case

3) are considered and compared. The water vapour driven triple effect absorption chiller is combined with Fresnel collectors with direct water vapour production. The single effect absorption chiller is considered to be purely solar driven. For the double and triple effect absorption chiller backup heating with a gas boiler / integrated gas burner is considered. For heat rejection all three systems are combined with an open wet cooling tower. The remaining cooling load of the building is in all analysed cases considered to be removed by a backup cooling system with an average electrical COP of 2.8 including the electricity consumption of the compression chiller, the heat rejection system and all connected pumps. For comparison of the overall system efficiency reached, within this study the primary energy consumption required to cover the cooling load of the building and the resulting average primary energy ratios are calculated and compared for all analysed cases.

2. Description of the Analysed Building and its Location

The projected office building is located in Cairo in Egypt and has a total useful floor area of 15,100 m² with a conditioned volume of 55,116 m³. It consists of a central core and three starlike adjacent 'fingers' with four office floors each. Double glazed windows with sun protecting coating are considered for the fully glazed facades with an U-Value of 1.16 W/m²K and g-value of 0.265 with 3.8% framing fraction and an U-Value of the frames of 2.04 W/m²K. Additional shading is provided by a roof overhang of 2.5 m in the upper floors of the south, southeast and southwest facing facades. For all opaque building elements like external walls, roof and floors a insulation of 20 cm is considered resulting in U-values around 0.18 W/m². According to dynamic building simulations performed with TRNSYS the maximum cooling load of the building is about 800 kW (52 W/m²) and the annual cooling energy demand is 1,970 MWh/a (130 kWh/m²a). Due to the necessity of dehumidification in summer the temperature level of the cold water distribution system is 7°C/14°C. The local weather conditions used in the dynamic simulations are taken form METEONORM weather data base. The solar radiation on the horizontal and the ambient air temperature are shown in Figure 1 and the resulting annual cooling load of the building is shown in Figure 2.

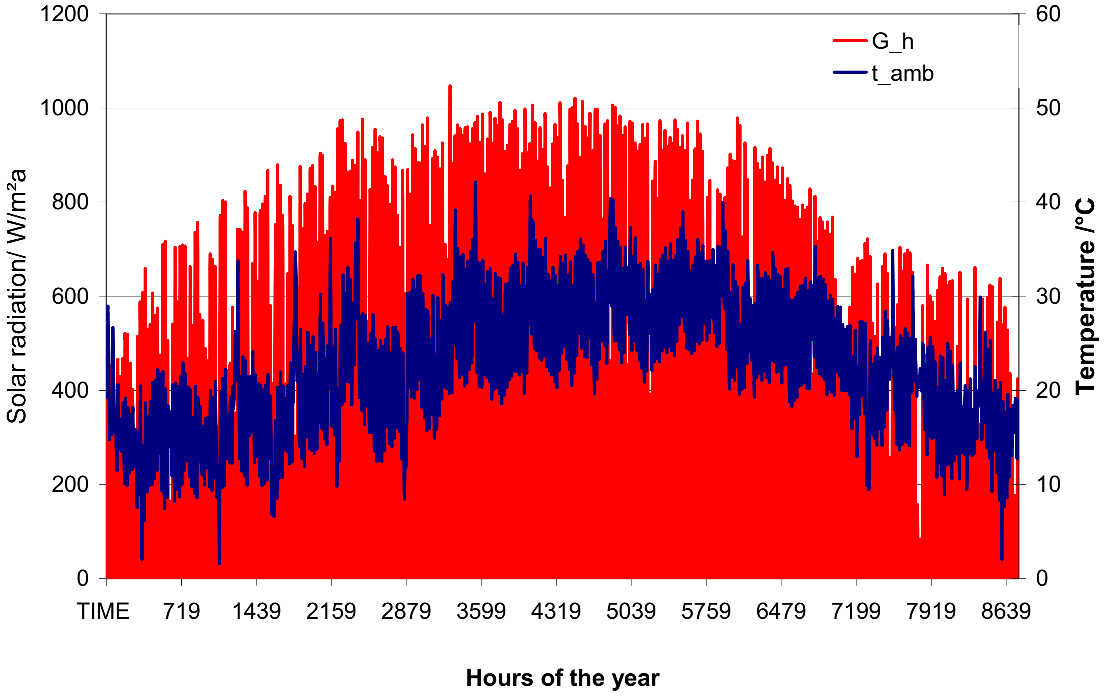

Figure 1: Annual distribution of the global solar radiation on the horizontal and of the ambient air temperature in Caro, Egypt

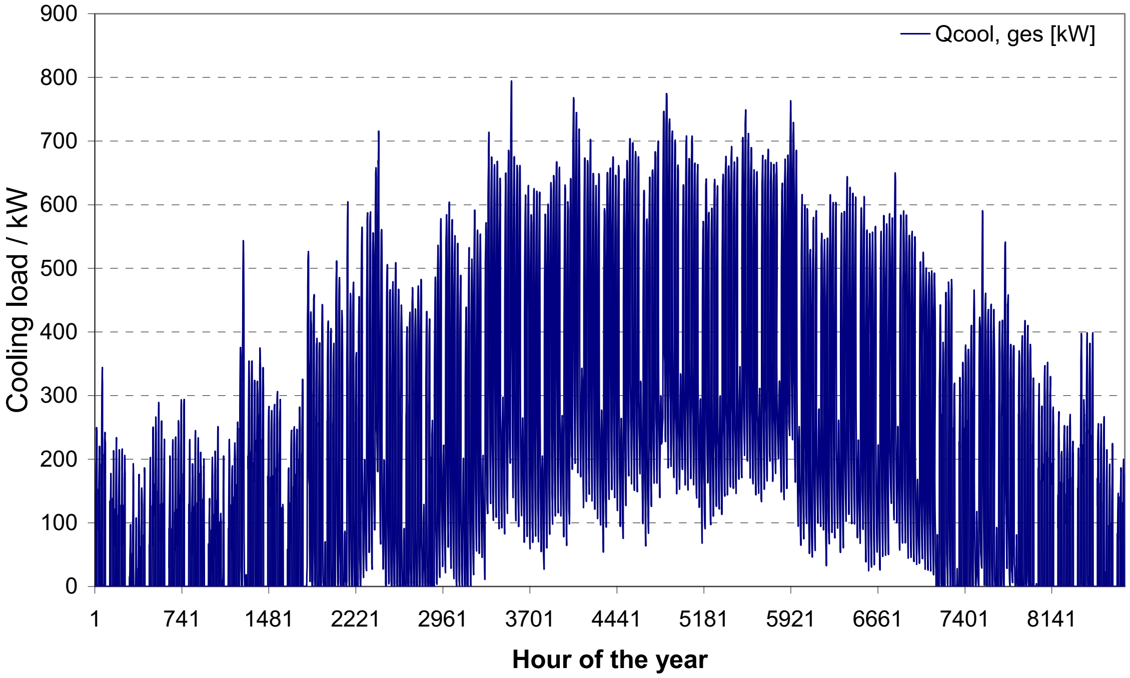

Figure 2: Annual distribution of the resulting cooling load of the analysed office building

3. Analysed Solar Cooling Systems

The limiting factor for the size of the solar cooling systems is the available and usable roof area for the solar thermal system, which is 2,000 m² only. For the system design several simulations were performed for single effect, double effect and triple effect absorption chillers. The single effect absorption chiller was combined with efficient vacuum tube collectors (Jiangsu Sunrain TZ47/1500-10U) with an optical efficiency of 0.65, a linear heat transfer coefficient of 1.585 W/m²K and a temperature dependent quadratic heat transfer coefficient of 0.002 W/m²K². The maximum possible collector size at horizontal orientation is 2,050 m² brut collector area which is equal to a collector aperture area of 1,350 m² (1,500 collectors). For the double effect absorption chiller high concentrating parabolic trough collectors 'PolyTrough 1200' of NEP Solar with a row distance of 2.3 m (low self-shadowing) and linear concentrating Fresnel collectors of MIRROXX are considered. The optical efficiency of the parabolic trough collectors is typically 68.5% with a linear heat transfer coefficient of 0.4 W/m²K and a temperature dependent quadratic heat transfer coefficient of 0.0015 W/m²K². The Fresnel collectors reach a slightly lower optical efficiency of 62% with a linear heat transfer coefficient of 0.1 W/m²K and a temperature dependent quadratic heat transfer coefficient of 0.00043 W/m²K². For the parabolic trough collectors a row distance of 2.3 m and a collector aperture area of 1 267 m² (44 collectors, each 24 m long) are possible on the available roof area. For the linear Fresnel collectors the maximum collector aperture area is 1,320 m² (60 collectors; length 4 m; width 8 m).

To evaluate the optimum system configuration the size of the hot water storage and the capacity of the absorption chillers were varied. The optimum configurations found are 422 kW cooling power for the single effect absorption chiller and 500 kW for the double effect absorption chiller. Larger chillers do not significantly increase the annual cooling energy production since not enough heating energy is available from the solar system. The optimum size of the hot water storage tank is in both cases 20 m³ (pressurised in case of the double effect chiller). Larger hot water storage tanks only slightly increase the ACM fraction on the overall cooling energy demand by around 0.4 % per 10 m³ in case of the single effect system and by around 2% in case of the double effect chiller. The energy savings obtained therefore do not justify the additional invest. Apart from the single effect and double effect chiller also a steam driven triple effect absorption chiller (Kawasaki Sigma Ace CF01-10-0001) with a nominal cooling power of 564 kW is analysed. Linear concentrating Fresnel collectors are used for the water steam production at a temperature of 250°C and 3.9 MPa pressure. The optimum collector aperture area found for this chiller is 880 m^2 (1,280 m^2 brut collector area). Since no storage is implemented in this system larger collector areas do not significantly increase the solar contribution on the heating energy demand of the triple effect absorption chiller. For the comparison of single, double and triple effect absorption chillers the described optimised system design of the solar system was selected. Dynamic annual simulations were performed for the following four system configurations:

Case 1: **Single effect ACM** 422 kW, 7°C/12.2°C cold water, wet cooling tower (29.4 °C/36.6°C), vacuum tube collector field for hot water supply

- **Vacuum tube collectors**, horizontal placement

  Brut collector area: 2,025 m^2
  Collector aperture area: 1,350 m^2
  Electricity consumption solar pump: 3.3 kW

  (20 m^3 hot water storage and 10 m^3 cold water storage)

Case 2: **Double effect ACM** 500 kW, 7°C/12°C cold water, wet cooling tower (37°C/42°C), parabolic trough collectors for hot water supply, collector row distance 2.3 m

- **Parabolic through collectors** (NEP Solar, PolyTrough 1200), row distance 2.333 m (typical installation)

  Brut collector area including spaces between the rows: 2,171 m^2
  Collector aperture area: 1,257 m^2
  Electricity consumption solar pump: 3.6 kW

  (20 m^3 pressurised hot water storage (max. 200°C) and 10 m^3 cold water storage)

Case 3: **Double effect ACM** 500 kW, 7°C/12°C cold water, wet cooling tower (37°C/42°C), linear Fresnel collectors for hot water supply

- **Linear concentrating Fresnel collectors** (Mirroxx) ,

  Brut collector area including spaces between the rows: 2,050 m^2
  Collector aperture area: 1,320 m^2
  Electricity consumption solar pump: 3.2 kW

  (20 m^3 pressurised hot water storage (max. 200°C) and 10 m^3 cold water storage)

Case 4: **Triple effect ACM** 563 kW vapour driven (250°C), 7°C/15°C cold water, wet cooling tower (32°C/36.6°C), linear concentrating Fresnel collectors for water steam supply (max. 250°C at 3.9 MPa)

- **Linear concentrating Fresnel collectors** with direct evaporation (Mirroxx)

  Brut collector area including spaces between the rows: 1,280 m^2
  Collector aperture area: 880 m^2
  Electricity consumption solar pump: 1.8 kW

  (No hot water storage, 10 m^3 cold water storage)

Additional cooling is considered to be provided by an efficient compression chiller with an average electrical COP of 2.8 including the electricity consumption of the compression chiller, of the heat rejection system and of all connected pumps. The technical data of the absorption chillers and of the cooling tower applied to the system are shown in

Table 1.

Table 1: Technical Data of the Single, Double and Triple Effect Absorption Chiller

	THERMAX Cogenie LT12C **Single Effect**	**Jiangsu Shuangliang** **Double Effect**	**Kawasaki Sigma Ace CF01-10-0001** **Triple Effect**
Cooling power	422 kW	500 kW	563 kW
Cold water inlet	12.2°C	12°C	15 °C
Cold water outlet	6.7°C	7°C	7°C
Cold water volume flow rate	65.8 $m^3 h^{-1}$	86 m^3/h	60.5 $m^3 h^{-1}$
Nominal pressure loss	19.6 kPa	42.0 kPa	34 kPa
Total pressure drop evaporator circuit *)	47.3 kPa	71.7 kPa	63.5 kPa
Electric power demand evaporator pump *)	1.73 kW	3.43 kW	2.14 kW
Heating power	593 kW	358 kW	299 kW
Hot water / steam supply temperature	90.6 °C	180°C	250°C
Hot water return temperature / steam pressure	85 °C	160°C	3.9 MPa
Hot water volume flow rate	91 $m^3 h^{-1}$	4.27 $m^3 h^{-1}$	624 $kg\ h^{-1}$
Nominal pressure loss	43.1 kPa	34 kPa	42 kPa
Total pressure drop generator circuit *)	74.2 kPa	61.5 kPa	69.7 kPa
Electric power demand generator pump *)	3.78 kW	0.53 kW	0.10 kW
Heat rejection power	1,014 kW	857 kW	862 kW
Cooling water supply	29.4 °C	37°C	32 °C
Cooling water return	36.6°C	42°C	36.6°C
Cooling water volume flow rate	121 $m^3 h^{-1}$	148 $m^3 h^{-1}$	160 $m^3 h^{-1}$
Nominal pressure loss	38.2 kPa	92 kPa	71 kPa
Total pressure drop abs. / cond. circuit *)	170.2 kPa	220 kPa	204 kPa
Electric power demand abs. / cond. pump *)	11.44 kW	18.05 kW	18.3 kW
Electrical power consumption ACM	2.55 kW	6.5 kW	5.0 kW
Thermal COP	0.71	1.4	1.88

*) These values are roughly calculated from the expected system size and configuration

For heat rejection wet cooling towers are considered with frequency inverters for fan speed control at part load conditions. The single effect and triple effect absorption chillers are combined with an AXIMA EWK 680/9 and the double effect chiller with an AXIMA EWK 450/9 cooling tower. Compared to the single effect absorption chiller, the required heat rejection energy is much lower for the triple effect chiller but due to the high mass flow rate in the absorber/condenser circuit the bigger cooling tower is required.

4. Results and Discussion

The main simulation results found for the analysed solar cooling systems are shown in Figure 3 to Figure 5. The fraction of the absorption chiller on the overall cooling energy demand of the building is shown in Figure 3 together with the solar system efficiency. The lowest absorption chiller fraction of 37% is reached for the single effect absorption chiller, since no backup heating is used in this case. This system reaches compared to the high concentrating systems the highest overall solar thermal system efficiency of 40%. The much lower solar system efficiency of the systems with high concentrating collectors result mainly from the fact, that these system can only use the direct solar radiation and not the diffuse part. The direct beam radiation part is in the annual average in Cairo only 60% of the total solar radiation. The systems with the double effect absorption chiller and high concentrating collectors reach 91% ACM fraction on the cooling load, since only the peak loads above 500 kW need to be covered by the compression chiller. The triple effect absorption chiller reaches a higher maximum cooling power of 563 kW and is therefore able to cover 93% of the annual cooling load of the building.

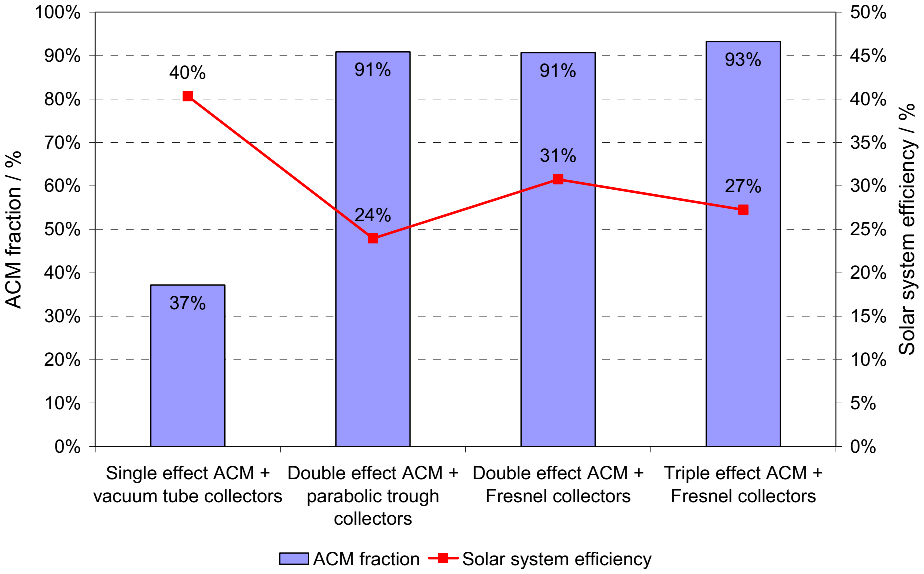

Figure 3: Fraction of the ACM on the cooling load and solar system efficiency

The solar heating energy and the additional heating energy provided to the absorption chillers is shown in Figure 4 together with the average thermal COP of the chillers which are 0.7 for the single effect, 1.31 for the double effect and 1.83 for the triple effect chiller. Due to the higher thermal COP the double effect and triple effect chillers require much lower heating energy than the single effect system. Although the double effect systems covers 91% instead of 37 % (single effect) of the annual cooling energy demand the required heating energy demand is only 30% higher than the heating energy demand of the single effect chiller. The triple effect chiller requires even 4 %

less heating energy compared to the single effect chiller although it covers 93% instead of 37% of the annual cooling load. Therefore, the size of the solar collector system could be reduced by 33% from 1,320 m² to 880 m² (aperture area) of linear concentrating Fresnel collectors compared to the double effect absorption chiller.

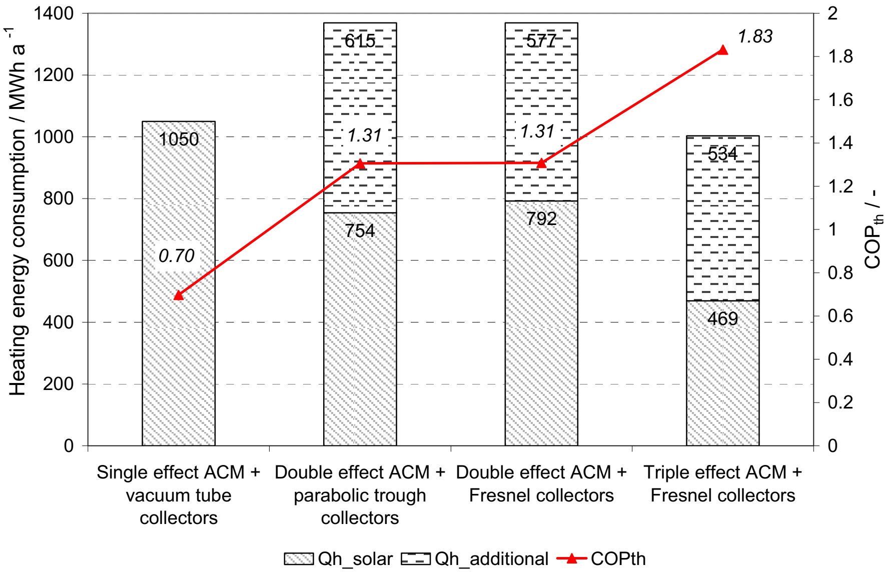

Figure 4: Solar heating, additional heating and average thermal COP

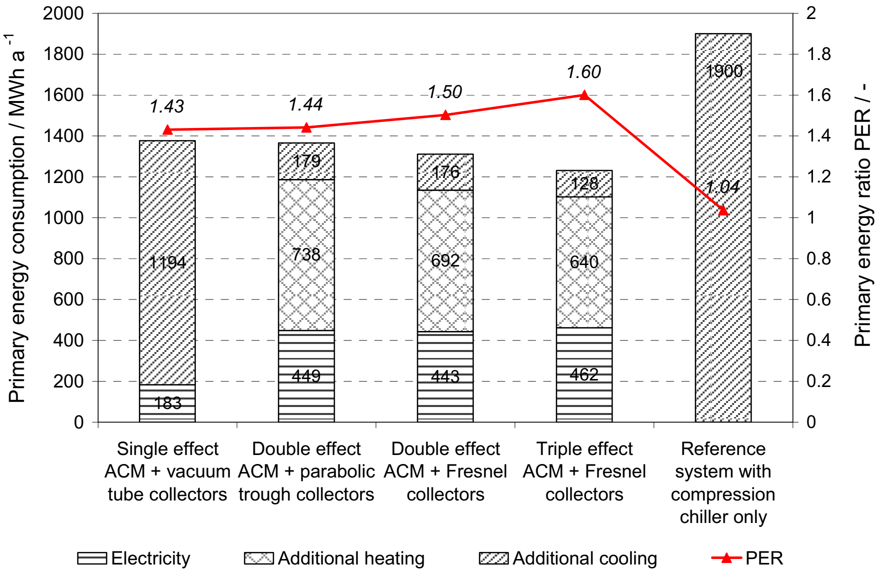

Figure 5: Primary energy consumption and average primary energy ratio (PER)

Figure 5 shows the primary energy consumption of the four analyses solar cooling systems compared to the primary energy consumption of reference system with efficient compression chiller. The resulting average primary energy ratio of all analysed systems is also shown in this graph. From this graph it becomes clearly obvious, that the single effect absorption chiller with vacuum tube collectors and additional cooling reaches nearly the same primary energy ratio as the double effect absorption chiller with parabolic trough, additional heating and additional cooling. Since the Fresnel collectors deliver slightly more heating energy to the system, the primary energy consumption decreases and the primary energy ratio increases from 1.44 to 1.5. The overall best energetic performance is reached for the triple effect absorption chiller which reaches a primary energy ratio of 1.6 which is 12 % higher than in case of the single effect system. However, compared to a standard system all analysed cooling systems reach significantly higher primary energy ratios of +38% in case of the single effect absorption chiller up to +54% in case of the triple effect chiller with Fresnel collectors. This highlights the main advantage of efficient designed and controlled solar cooling systems.

5. Conclusions

For the application in an office building in Cairo in the present work different types of solar cooling systems have been analysed and compared to a standard compression chiller system. A single effect absorption chiller with vacuum tube collectors and a hot water driven double effect chiller with both high concentrating parabolic trough and Fresnel collectors were analysed. Furthermore a high efficient water steam driven triple effect absorption chiller was analysed with highly concentrating Fresnel collectors. The results clearly demonstrated that double effect absorption chillers with backup heating (1st choice) and backup cooling (2nd choice) are from the primary energy point of few not necessarily better than single effect absorption chillers with backup cooling only. The overall best performance with a primary energy ratio of 1.6 was reached for the triple effect chiller with backup heating (1st choice) and backup cooling (2nd choice). However, it could be shown that all analysed solar cooling systems reach 38% to 54% higher primary energy efficiencies than standard systems with compression chillers.

References:

[1] Albers, J., Kemmer, H., Ziegler, F. "Solar driven absorption chiller controlled by hot and cooling water temperature",in Proceedings of the 3rd International Conference Solar Air-Conditioning, 30th September – 2nd October, Palermo, Sicily, Italy, pp 338-343, 2009

[2] Pietruschka, D., Jakob, U., Eicker, U. and Hanby, V., "Simulation based optimisation and experimental investigation of a solar cooling and heating system", in Proceedings of the 2nd International Conference Solar Air-Conditioning, Tarragona, Spain, 2007

[3] Rubio, H., "Solar cooling systems and natural gas; experiences and results", in Proceedings of the 7th European Forum Gas, Madrid, Spain, 2009

[4] Lokurlu, A., Müller, G., "Experiences with the worldwide first solar cooling system based on parabolic trough collectors (Solitem PTC 1800) combined with double effect absorption chillers", in Proceedings of the 1st International Conference Solar Air-Conditioning, 6th – 7th October, Bad Staffelstein, Germany, pp 298-302, 2005

[5] Epp, B., "Australia: First solar-cooled shopping centre", www.solarthermalworld.org/node/810, 2nd September, 2009

[6] Zahler, C., Häberle, A., Schwind, T., Berger, M. Louw, J.W., "Mirroxx Fresnel process heat collectors for industrial applications and solar cooling", in Proceedings of the 3rd International Conference Solar Air-Conditioning, 30th September – 2nd October, Palermo, Sicily, Italy, pp 271-276, 2009

[7] Kohlenbach, P., Dennis, M., "Solar Cooling in Australia: The Future of Air-Conditioning?", in Proceedings of the 9th IIR Gustav Lorentzen Conference, 12th – 14th April, Sydney, Australia, 2010

[8] Bermejo, P., Pino, F.J., Rosa, F. "Solar absorption cooling plant in Seville", Solar Energy, Vol. 84, Issue 8, pp 1503-1512, 2010