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An Efficient and Reliable District Heating and Cooling Supplier

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***Abstract*—In this study, by employing solar parabolic trough collectors, the supply of the thermal energy demand of an absorption chiller, as well as a portion of the local district heating demand, is proposed for a case study. The case study already uses the local district heating system to support the chiller which makes problems during the warm months of the year. The results show that the system totally resolves the technical problem of the case study, offers a great contribution to providing the district heating demand and leads to a more favorable economic index compared to the old design. It is observed that the heat demand of chiller is zero for one-third of the year. For a quarter of the year, the system feeds district heating over 1 MW heat and the IRR value of the system is 5.7% for 8 years of operation.**

Keywords— Absorption Chiller, District Heating Systems, IRR Analysis

I. Introduction

District energy systems, i.e. district heating and district cooling systems, are getting globally more and more popular every day [1]. Paving the bed for the utilization of waste energy resources around, facilitating the further use of renewable energy technologies, decreasing the costs and increasing the efficiency of energy supply is of the most important advantages of district energy systems [2]. By 2015, about 63% of Danish citizens had been served by district heating while this value has been over 93% for Iceland in the same year. Although district cooling, in general, must be as important as district heating, it has not been that developed in practice yet. Sweden is a forerunner of developed district cooling systems with 40% of households supplied while this number is only about 4% for Denmark [3].

An absorption machine is a device that receives heat and generates cold. Although it is not as efficient as a heat pump with an energy output a few times larger than its electricity input, it is still highly of interest because it provides the opportunity of using a waste heat flow (if any) or renewable energy technologies. The solar-powered absorption chiller is one of the interesting systems that is widely used for cold production from small- to large-scale modules. The literature on solar absorption systems is quite rich with numerous engrossing articles. In the literature, different types of solar collectors are introduced and utilized for different applications. Flat plate collectors (FPC), evacuated tube collectors (ETC), compound parabolic collectors (CPC) and parabolic trough collectors (PTC) are many well-known types of collectors which are utilized for supplying water to a wide range of temperature [4-9], which could be used for driving absorption chillers as well.

Shirazi et al. [10] did a systematic parametric study and feasibility assessment of solar-assisted single-, double- and triple-effect absorption chillers for heating and cooling applications. Bellos et al. [11] presented a thorough dynamic energetic, exergetic and financial evaluation of a solar-driven absorption chiller. Marc et al. [12] accomplished the dynamic modeling of a solar-driven absorption machine and validated their results through experimental work. Xu et al. [13] carried out an experimental study to evaluate the performance of a variable effect LiBr–water absorption chiller designed for high-efficient solar cooling systems. Weber et al. [14] proposed a linear concentrating Fresnel collector to drive two absorption chillers, achieving a solar system efficiency of 50–60% and observing a sound operating behavior and promising results for industrial process integration. Gonzalez et al. [15] made an evaluation of thermal parameters and simulation of a solar-powered, solid-sorption chiller with a compound parabolic concentrator solar collector. Lu et al. [16] proposed and analyzed a novel solar adsorption cooling system and a solar absorption cooling system with new compound parabolic concentrator collectors.

In this article, the application of PTC-powered absorption chillers for co-supply of district heating and cooling is considered. The case study is an absorption chiller supporting a hospital in Denmark. The hospital absorption cooling system is supplied by local district heating which is not efficient enough during the warm seasons. The proposed scheme provides heating for both absorption chiller and district heating and makes the cold production system efficient during the hot season as well. The proposed system is designed, sized and analyzed thermodynamically for the case study and the results are presented and discussed.

II. Information Of The Case Study

According to the yearly cooling demand of Aarhus hospital, maximum cooling demand of 3.5 MW and a base-load of over 1.5 MW is for the system during the year. The cooling equipment which is used to provide the required cooling is an absorption chiller. The required heat is provided via the local district heating. Waste incineration CHP plants provide the base-load of the district heating networks. This method of energy provision has a problem. During summer when the cooling system demands are in its maximum value, district heating produces its minimum load. Therefore, the baseload of this configuration is that in the summer, when the cold demand of hospital is at its peak level and the district heating network at its lowest demand, other heat preparation units need to come into the inefficient condition of partial load operation for supplying the extra demand of heating of the chiller. According to the maximum cooling demand occurs in the warmest months of the year with a total monthly value of 2.6 GWh in June and the hourly averaged value of 3.5 MW sometime in July. There is always a base load of 1.4 GWh/month and 1.5 MW cooling demand during the winter [17].

The heating demand of the whole city is just above 100 MWh/day during summer while its annual peak is at about 730

MWh/day. Taking into account the logical coefficient of performance of 0.7 for the chiller, and the maximum cooling demand of 77 MWh/day of the hospital, the district heating system is imposed on a sharp extra load of around 110 MWh/day. It should be mentioned that for providing the requested heat of the cooling system of the hospital, the other heat plants of the network should come into operation [18].

III. The Proposed Configuration

In this section, the configurations and the technical characteristics of the proposed solar heat-district heating driven absorption chiller are explained. As a primary solution for the mentioned technical problem of the case study (which is a common issue for all district heating connected chillers), Arabkoohsar and Andresen [19] designed a solar assisted single effect LiBr-water absorption chiller with evacuated tube solar collectors. Next, the same team proposed the parallelization of this solar-assisted chiller with a power-cold productive gas station near the hospital site [20]. In this work, however, the same problem is addressed by proposing an absorption machine powered by PTC collectors capable to provide not only a major portion of the required heat demand of the chiller during sunny days but also a large amount of excess heat to further decrease the base load of the local district heating system.

Figure 1 depicts the configuration of the introduced solution. According to this configuration, the system includes a single-effect absorption cycle and a farm of solar PTC. In this system, the heat collected by the solar set is first used to drive the chiller through the solar heat exchanger. Then, the high-temperature flow passes through a heat exchanger, then it is implemented for heating the local district heating system. As the return line of district heating has a temperature of about 40 °C, the temperature of the solar working fluid after the district heating heat exchanger will be quite low (about 50 °C with respect to the mass flow rate of the solar working fluid. The effectiveness factor of both of the solar and the district heating heat exchangers are considered to be 0.8 here. On the other hand, if there is not enough solar energy to provide all the heating demand of the chiller, the extra heat demand of the chiller will be provided by the district heating system. The approach for sizing the solar system will be performed by the maximum annual solar availability. In this time, the maximum heat demand of the chiller occurs. On many occasions, there will be always some heating duty for the district heating for the chiller. Note that, the district cooling return line enters the evaporator at 15 °C to be cooled to 8 °C. The mass flow rate of this line in every moment specifies the instantaneous capacity of the evaporator (absorption chiller load) and the other supplementary components of the system regulate their working load and conditions based on this cooling demand.

For an absorption chiller, the values of pump power, heat transfer rates in the absorber, the generator, the evaporator, the condenser, the solution heat exchanger and the COP are considered to be 0.208 W, 13.16 kW, 13.76 kW, 9.841 kW, 10.44 kW, 3.134 kW and 0.715, respectively. For LS2 PTC collectors are supposed to be used in the proposed system. A parabolic trough collector is one of the most common types of solar concentrating technologies for a wide range of applications. The device comprises a reflector with a parabolic shape to reflect solar radiations on a receiver line, and a receiver that is usually covered with a glass enclosure to minimize the heat losses and carries the solar working fluid.

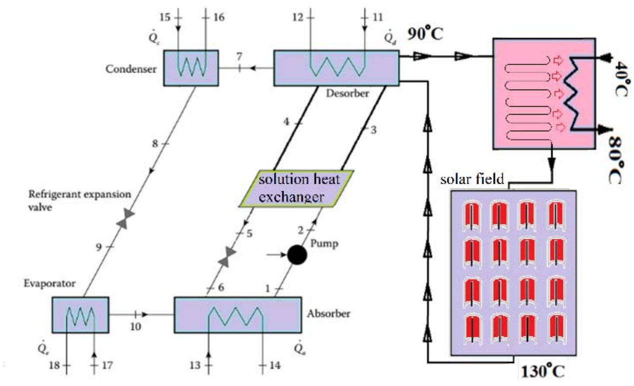

Fig. 1. Schematic diagram of the designed PTC powered chiller for co-supply of district heating and cooling systems.

IV. Energy and Economic Equations

Here, the governing equation of the proposed subject is presented. Then to assess the viability of the system, the economic equation is introduced.

A. Thermodynamic model

To assess the performance of the absorption chiller, energy equations and basic assumptions for all the components must be considered. the assumptions are considered as: the refrigerant being pure water, no pressure changes in pipes and installations except pumps and valves, pumps being isentropic and expansion occurring in an adiabatic condition. Following, the energy balance of each component of the chiller is presented. The mass balance on the evaporator is:

$$\dot{m}_9 = \dot{m}_{10} \quad (1)$$

The energy balance on the evaporator is:

$$\dot{Q}_{eva} = \dot{m}_{10} h_{10} - \dot{m}_9 h_9 \quad (2)$$

The mass balance on the absorber could

$$\dot{m}_1 = \dot{m}_{10} + \dot{m}_6 \quad (3)$$

and

$$\dot{m}_1 x_1 = \dot{m}_6 x_6 \quad (4)$$

The energy balance on the absorber could be written as:

$$\dot{Q}_a = \dot{m}_{10} h_{10} + \dot{m}_6 h_6 - \dot{m}_1 h_1 \quad (5)$$

The mass balance on the desorber could be written as:

$$\dot{m}_3 = \dot{m}_4 + \dot{m}_7 \quad (6)$$

The energy balance on the desorber could be written as:

$$\dot{Q}_{des} = \dot{m}_4 h_4 + \dot{m}_7 h_7 - \dot{m}_3 h_3 \quad (7)$$

The mass balance on the absorber could be written as:

$$\dot{m}_3 = \dot{m}_4 + \dot{m}_7 \quad (8)$$

The energy balance on the desorber could be written as:

$$\dot{Q}_c = \dot{m}_7 (h_7 - h_8) \quad (9)$$

The other component is the heat exchanger that is a medium to transfer thermal energy from the solar PTC set to the solution in the absorption chiller. For this heat exchanger, the rate of energy that must be exchanged between the solar working fluid and the solution could be easily calculated as:

$$\dot{Q}_{shx} = \dot{m}_F c_F (T_{shx,i} - T_{shx,e}) = \dot{m}_S c_S (T_3 - T_2) \quad (10)$$

c is specific heat capacity and the subscriptions f and s refer to the solar working fluid (ethylene glycol) and absorption chiller solution (LiBr-water). The specific heat capacity of the solution could be presented as a function of X, the concentration of LiBr in the solution [21] :

$$c_S = 0.0976X^2 - 37.512X + 3825.4 \tag{11}$$

It is necessary that the performance criteria should be defined for the system.

$$COP = \frac{\dot{Q}_{eva}}{\dot{Q}_{shx} + \dot{Q}_{des}} \tag{12}$$

By conserving energy at each surface of the receiver, the following energy balance equations are presented:

$$q'_{12Conv} = q'_{23Cond} \tag{13}$$

$$q'_{3SolAbs} = q'_{34Conv} + q'_{34Rad} + q'_{23Cond} + q'_{Cond,bracket} \tag{14}$$

$$q'_{34Conv} + q'_{34Rad} = q'_{45Cond} \tag{15}$$

$$q'_{45Cond} + q'_{5SolAbs} = q'_{56Conv} + q'_{57Rad} \tag{16}$$

$$q'_{HeatLoss} = q'_{56Conv} + q'_{57Rad} + q'_{Cond,bracket} \tag{17}$$

In equations 13-17, q'_{12Conv} , q'_{23Cond}, q'_{34Rad}, q'_{45Cond}, q'_{56Conv} and q'_{56Rad} , are parameters related to the solar collector modeling and in order to prevent the article from being unnecessarily too long, the readers are invited to see the energy models of such collectors presented in [22].

B. IRR Analysis Method

In this section, the economic formulation of the proposed system is presented. This method is called the internal rate of return (IRR). To calculate this parameter, one first needs to know the definition of net present value (NPV). The NPV is defined as the difference between the present value of cash inflows and outflows. The value of NPV is calculated as [23]:

$$\mathrm{NPV} = \sum_{j=1}^{n} \frac{(B_j - C_j)}{(1+r)^j} \tag{18}$$

where B_j and C_j are the benefit, and the cost of the project during the j^{th} year, respectively, and r refers to the discount rate. For calculating the IRR of a system, one has the following equation [24]:

$$\sum_{j=1}^{n} \frac{(B_j - C_j)}{(1+\mathrm{IRR})^j} = 0 \tag{19}$$

Indeed, the IRR of a system is the value of interest rate that makes the NPV of the given system equal to zero over a specific number of years (here 8 years).

V. Results and Discussion

In this section, the results of simulations, carried out on the proposed system, will be presented. Figure 2 shows the effect of the solution heat exchanger on the proposed hybrid cycle performance. An increase in the effectiveness causes an increase in heat transfer of the solution heat exchanger and a decrease in heat demand of the absorber. Totally, it could be said that an increase in the effectiveness factor causes an increase in the COP.

Figure 3 shows the effect of the solution temperature entering the solution heat exchanger on the COP. There is this potential that the temperature of this point will be influenced by the other energy resources. The other thing that one should consider in Figure 3, is this assumption that the variation of T_3 is independent of the refrigerant temperature and the returning solution temperature. An increase in this temperature causes that the coefficient of performance improves. To see why COP increases by increase in T_3 can be found in Figure 4. The amount of heat in the desorber decreases by increasing the temperature of the solution. This decrease in heat transfer in the desorber is the main reason for the COP improvement.

The total mass flow rate of hot water produced in the solar fields is seen in Figure 5 in a duration curve format. The hourly annual mass flow rate for one LS2 PTC is known. To deliver the maximum heat demand of chiller, one would have 53 sets of LS2 PTC. According to 53 sets, the total mass flow rate of the solar field will be calculated. About 1% of the time and at the maximum irradiation, the maximum flow rate occurs, about 80 kg/s. In more than 20% of cases during the year, the mass flow rate of hot water supplied to the chiller is more than 45 kg/s and in more than 40% of cases during the year, the chiller gets 14 kg/s from the solar field. About 60% of cases, solar PTC set has no contribution in providing heat demand of chiller due to the very small values of solar radiation.

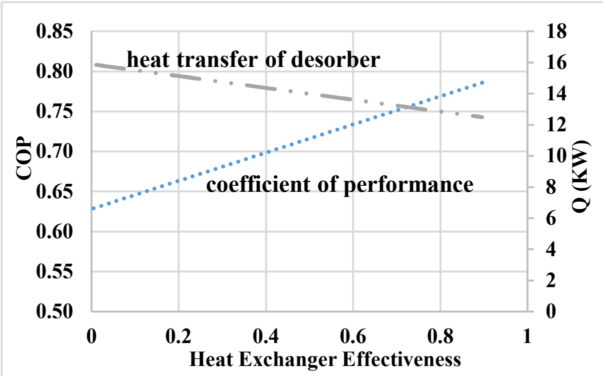

Fig. 2. The impact of the solution heat exchanger on the performance of the chiller cycle.

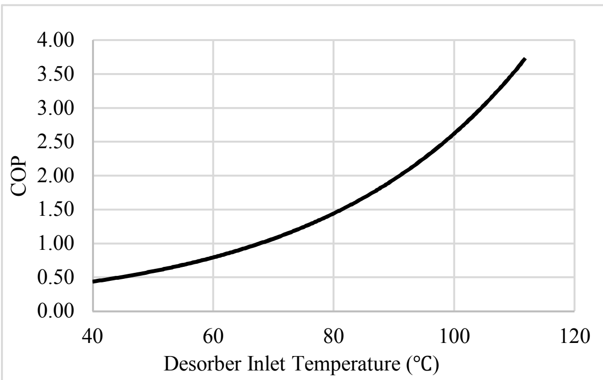

Fig. 3. Effect of desorber solution inlet temperature on COP, evaporative capacity and heat transfer rates

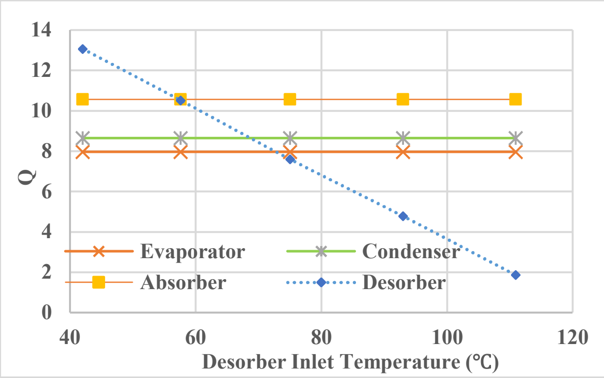

Fig. 4. Desorber solution inlet temperature effects

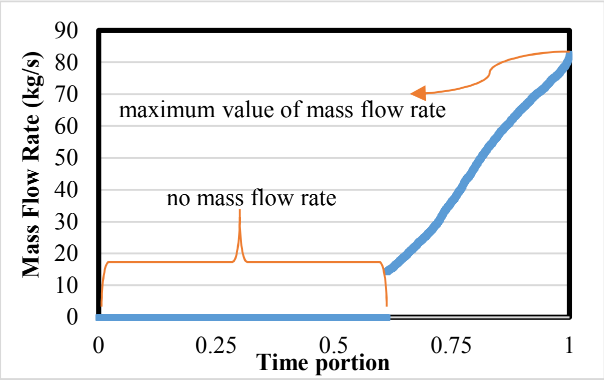

Fig. 5. Hourly mass flow rate for 53 collectors.

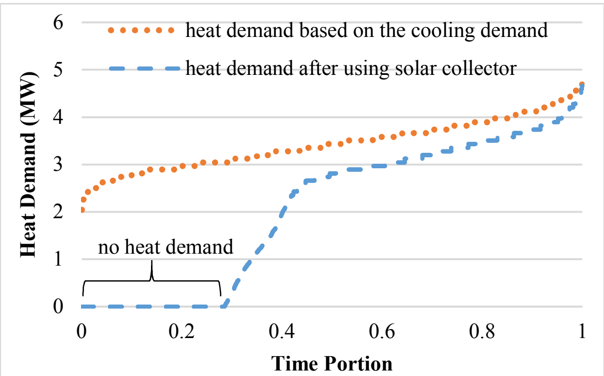

Fig. 6. Heat demand for chiller before and after employing the PTC set

Figure 6 shows the heat demand of chiller before and after employing the PTC set. The difference between the two graphs shows the contribution of solar LS2 PTC set in providing the heat demand of chiller. About 30%, demand will be zero. It means at this time, the solar system will be able to provide all heat demand. The amount of demand decrease will be about 35% cases of the year between zero and 3MW. For the rest of the year, it is not very effective during the year because the demand will remain above 3 MW. After employing the PTC set and supplying the absorption chiller, extra heat will be provided for DH. This extra heat is presented in Figure 7. About 70% of cases of the time, no heat is supplied to DH. For about 25% of the time, the supplied heat is more than 1 MW.

To assess the economic value of the proposed configuration, one would decide to calculate IRR. For 8 years of operation, the IRR of the system is presented in Figure 8. The capital cost of the chiller is set 300 $/kW. The capital cost of PTC arrays, HTF and hydraulic circuit and heat exchanger will be 250 $/m2. The O&M is set as 5% of the initial investment. The IRR values of 5.7% and above are considered to indicate the potential for the economic viability of the proposed system for 8 years of operation. By assessing the presented data, the proposed system has quickly been recognized as a cost-effective solution for supplying cooling and heating for such a kind system.

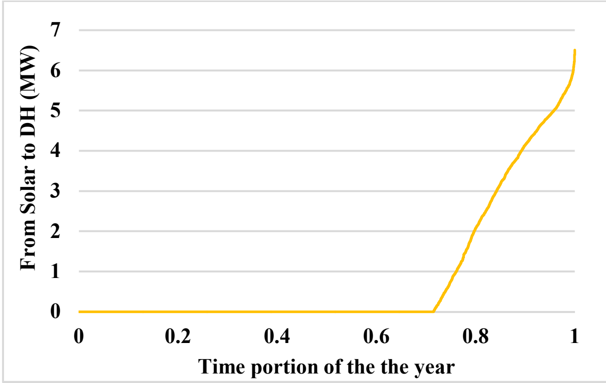

Fig. 7. Heat supplied to DH after employing the PTC set

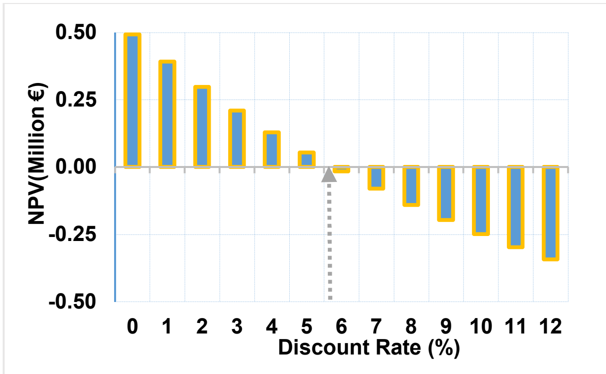

Fig. 8. The IRR of the system for the 8th year of operation

Conclusion

In this article, the effect of employing a solar PTC Powered absorption chiller for co-supply of district heating and cooling systems was investigated. In this regard, we studied first the effects of different internal thermophysical parameters on the performance of the absorption chiller. Then, to provide some part of the chiller heat demand, an LS2-PTC set is considered as an additional heat source of the chiller. It was shown that in the highest solar radiation, the mass flow rate of the solar working fluid supplied to the chiller is approximately 80 kg/s. It is also shown that for more than 40% of cases during the year, the solar PTC set is able to provide 14 kg/s hot water for chiller. The results show that for 30% of cases, no heat demand is required by the other source of energies and solar system is able to provide all the demand and for about 25% time, the supplied heat is more than 1 MW and solar the LS2-PTC set plays a significant role in supplying heat for the local district heating system. The economic performance of the proposed solution was found interesting with the IRR=5.2% for a payback period of 8 years.

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