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Comprehensive Analysis of Cold and Heat Supply via Solar-Powered Absorption Chillers

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Abstract— In warm seasons, supplying the heat demand for large-scale absorption chillers is extremely challenging when supported by district heating systems. The objective of this study is to assess the performance of an absorption chiller integrated with solar parabolic trough collectors and a district heating system to address this challenge. Indeed, the parabolic trough solar collectors are considered here to co-supply the required heat of the chiller and supply further heat to the district heating system. This system is studied energetically, exergetically, economically and environmentally. The results show that the proposed system removes the supply problem of the chiller heat demand during the summer. As such, the payback period of the system is 7.5 years based on the net present value approach. And finally, a huge amount of CO₂e emission reduction is made by the proposed system.

Keywords—district heating, district cooling, absorption chiller, parabolic trough collector

I. INTRODUCTION

The heating and cooling process of buildings consumes approximately half of the world's energy [1]. In addition to this great contribution, the depletion of fossil fuels, their environmental impacts, and the need for long-term energy sources have brought considerable attention to the building energy production issue. District heating is a common heating system for transferring heat for space and water heating through insulated pipes. District heating could take principal act in the future of energy systems and in the project of efficiency increasing. In the 1970s, the third generation of systems was introduced. The heat carrier was pressurized water is still the heat carrier, with supply temperature often below 100 °C [2]. This generation of district heating systems is still in operation. Today in Denmark, where more than 60% of households get their heat supply through district heating till 2016, the further growth of this rate is a serious target of the energy planners. This value is over 93% for Iceland. Besides district heating, district cooling is another general topic about the energy demand of buildings. In spite of being similar to district heating systems in principles and the techno-economic advantages, district cooling has not yet been developed that much in practice [3].

Many district cooling systems are supplied by large-scale absorption chillers. An absorption chiller is a cooling production machine that is driven by heat. Although it does not have a high coefficient of performance, due to the possibility of integrating with renewable energy or waste heat flows, it is highly of interest for large-scale applications. In the energy systems with both district heating and cooling systems, the heat demand of absorption chillers is mainly supplied by the heat flow coming from the local district heating systems. However, in the summer, when the load of the district heating system is very low, the cold demand for district cooling is high

and this mismatch of the production and demand is extremely challenging in terms of techno-economic aspects [4].

On the other hand, solar-powered absorption chiller is one of the most mature technologies in this framework. In the literature, different types of solar collectors are introduced and utilized for different applications. Flat plate collectors, evacuated tube collectors, compound parabolic collectors and parabolic trough collectors (PTC) are the well-known types of solar collectors that could be used for such an application. The integration of solar-powered absorption chiller with district heating systems is an excellent idea to address the aforementioned challenge of district cooling systems. Arabkoohsar and Andresen [5] proposed a solar assisted absorption chiller with evacuated tube solar collectors. Although they found their own proposed solution much effective, meanwhile, they perceived a solar-powered solution that could supply further heat to district heating as well might be much more of techno-economic advantages for such a system. Therefore, in this study, solar PTCs are employed for co-supplying the heat demand of the chiller and the local district heating system. The case study of this work is a hospital absorption chiller located in Aarhus city, Denmark. A thorough energetic, exergetic, economic and environmental analysis is accomplished on this work to assess the impacts of employing this system.

II. SYSTEM AND COMPONENTS

The system consists of three basic sections; parabolic

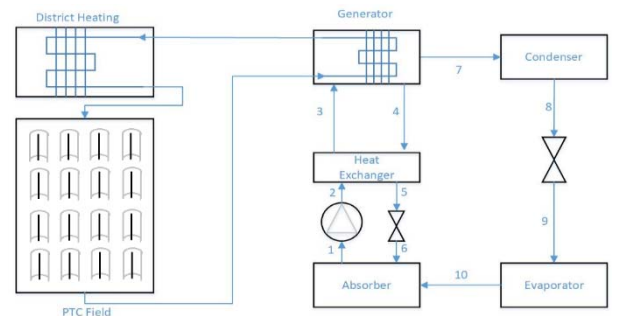


Fig. 1. Schematic of the proposed system, absorption chiller integrated with PTC field and district heating

trough collectors, district heating system and an absorption chiller. The PTC are collectors that profit by direct normal irradiances [6]. Figure 1 clarifies the proposed system in detail. The hot water after the PTC enters the generator. Here the input and output temperature of the target stream is considered 15 °C and 8 °C.

In this study, LS2 parabolic trough solar collectors are selected as the energy collecting device. This kind of collector is one of the most accepted kinds of solar technologies for a wide range of applications. Information about solar collectors

being used in the proposed system is presented in [6]. For the considered single-effect 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 calculated to be 0.208 W, 13.16 kW, 13.76 kW, 9.841 kW, 10.44 kW, 3.134 kW and 0.715, respectively.

III. ENERGY EQUATIONS

In steady-state conditions, the mass balance and energy balance on the components are as follows:

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

$$\dot{Q}_{eva} = \dot{m}_{10}h_{10} - \dot{m}_9h_9 \quad (2)$$

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

$$\dot{m}_1x_1 = \dot{m}_6x_6 \quad (4)$$

$$\dot{Q}_a = \dot{m}_{10}h_{10} + \dot{m}_6h_6 - \dot{m}_1h_1 \quad (5)$$

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

$$\dot{Q}_{des} = \dot{m}_4h_4 + \dot{m}_7h_7 - \dot{m}_3h_3 \quad (7)$$

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

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

$$\dot{m}_4c_4(T_4 - T_5) = \dot{m}_2c_2(T_3 - T_2) \quad (10)$$

For PTC, we have these energy equations:

$$q'_{12Conv} = q'_{23Cond} \quad (11)$$

$$q'_{3SolAbs} = q'_{34Conv} + q'_{34Rad} + q'_{23Cond} + q'_{Con,bra} \quad (12)$$

$$q'_{34Conv} + q'_{34Rad} = q'_{45Cond} \quad (13)$$

$$q'_{45Cond} + q'_{5SolAbs} = q'_{56Conv} + q'_{57Rad} \quad (14)$$

$$q'_{HeatLoss} = q'_{56Conv} + q'_{57Rad} + q'_{Cond,bracket} \quad (15)$$

In equations 11-15, q'_{12Conv} , q'_{23Cond} , q'_{34Rad} , q'_{45Cond} , q'_{56Conv} and q'_{57Rad} , are convective heat transfer between the solar working fluid and the absorber, conductive heat transfer through the absorber wall, heat transfer from the absorber to the glass envelope, conductive heat transfer through the glass envelope, convective heat transfer from the glass envelope to the atmosphere and radiative heat transfer from the glass envelope to the atmosphere. The terms $q'_{5SolAbs}$ and $q'_{3SolAbs}$ are respectively the rate of solar energy absorption in the glass envelope and by the absorber. The mathematical model of solar PTC is quite extensive yet frequently available in the literature. For more detailed information about PTC collectors, the readers are invited to see [6, 7]. For Exergy analysis by considering the dead state with the subscript o , the exergy be presented as

$$EX = m((h - h_o) - T_o(s - s_o) + ex^{ch}) \quad (16)$$

Where ex is specific exergy and h , and s are respectively specific enthalpy and specific entropy. The kinetic and gravitational potential energies are considered insignificant and we neglect the chemical exergy. The rate of exergy destruction in a system is defined as the difference between the actual work of the system and its maximum producible work in a reversible process, which is simply equal to the multiplication of the dead state temperature by the rate of entropy generation:

$$\dot{EX}^{De} = \dot{W}_{rev} - \dot{W}_{act} = T_o\dot{S}_{gen} \quad (17)$$

The exergy efficiency (ε) is also defined as the rate of net exergy output to the input exergy of the system:

$$\varepsilon = \frac{\dot{EX}_{out}}{\dot{EX}_{in}} = \frac{\dot{EX}_{in} - \dot{EX}^{De}}{\dot{EX}_{in}} \quad (18)$$

It should be stated that exergy losses of PTC are caused by optical error and heat transfer losses from the solar receiver and the exergy destruction occur because of the heat transfer between the absorber and the solar working fluid.

There are four parameters for analysis of the system performance: the overall energy performance of the system, the energy efficiency, exergetic coefficient of performance and overall exergetic efficiency:

$$COP = \frac{\dot{Q}_{Eva}}{\dot{Q}_{Gen}} \quad (19)$$

$$EnEff = \frac{\dot{Q}_{Eva}}{\dot{Q}_{Gen} - \dot{Q}_{Sol}} \quad (20)$$

$$ECOP = \frac{\dot{EX}_{Eva}}{\dot{EX}_{Gen}} \quad (21)$$

$$ExEff = \frac{\dot{EX}_{Eva}}{\dot{EX}_{Gen} - \dot{EX}_{Sol}} \quad (22)$$

Next, we study economically the proposed system with the well-known indicator Net Present Value (NPV) which is defined as below:

$$NPV = \sum_{j=1}^n \frac{(B_j - C_j)}{(1+r)^j} \quad (23)$$

In this equation, B and C are the benefits and the cost of project and j is the year of operation, respectively, and r indicates the discount rate.

Finally, to calculate the total emission in the form of equivalent CO₂ (CO_{2e}), we first need to have the amount of required fuel to supply the chiller. For example, in this part, the required heat of chiller first is supposed to be provided throughout district heating and the heat demand of district heating is supplied by Municipal Solid Waste (MSW). We consider that by burning a tonne of MSW, 415 kg of CO_{2e} is produced [6].

IV. CASE STUDY AND VALIDATION

A. Case Study

The case study of the work is Aarhus University Hospital which is a large hospital in Aarhus city, Denmark. We have for the summer, maximum cooling demand of 3.5 MW and for the winter, a baseload of over 1.5 MW. The cooling is supplied by an absorption chiller for which the required heat is provided via the local district heating.

B. Data Validation

Table 1 and Table 2 present the validation of PTC modeling with the experimental data of Dudley et. Al [8] and the validation of LiBr absorption chiller with the experimental data of Lizarte et. Al [9].

TABLE I. validation of the PTC SIMULATION RESULTS

G _b	T _{amb} (K)	T _{in} (K)	V (m ³ /s)	T _{out} Exp. (K)	T _{out} (K)	Error (%)
933	294	375	47.7	397	397	0.073
982	297	470	49.1	492	492	0.012

TABLE II. VALIDATION OF THE ABSORPTION CHILLER SIMULATION RESULTS

T_{Eva}	T_{Con}	T_{Abs}	T_{Gen}	COP (Exp)	COP (Model)	Error (%)
11.1	42.7	39.2	96.5	0.6	0.614	1.9
10.8	45.2	43.5	102.8	0.7	0.716	2.1

V. RESULTS AND DISCUSSION

In this section, the results are presented. In the first section, the results of the energy analysis are presented. In Figure 2, the COP and average energy efficiency of the whole cycle are reported for 365 days of the year.

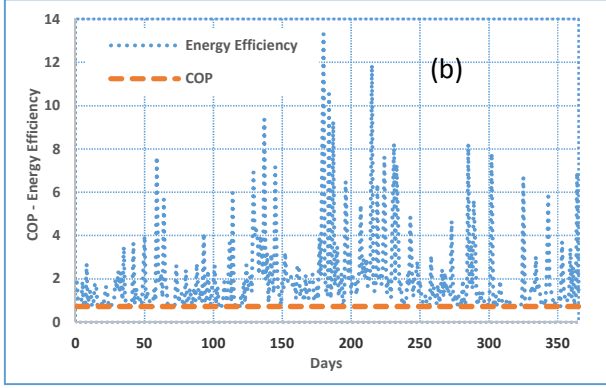


Fig. 2. COP and Energy Efficiency of the proposed system

Before entering the discussion of exergy analysis in the chiller, it is necessary to discuss the exergy analysis of one LS2 PTC set. According to Figure 3, with increasing temperature, first, the exergy efficiency increases, but this trend does not increase steadily, and with increasing temperature, the amount of exergy efficiency decreases due to the increase in irreversibilities caused by the increase in temperature. It can be said that four parameters cause exergy destruction in a PTC set, the optical losses of PTC equipment, heat transfer losses from the solar receiver to the environment, exergy destruction due to heat transfer from the sun to the absorber and exergy destruction due to heat transfer from the absorber to the solar working fluid.

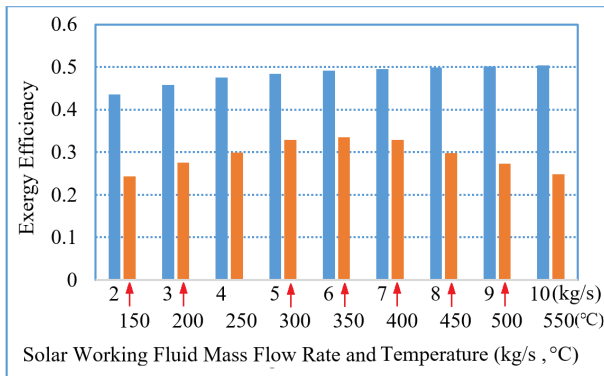


Fig. 3. Mass flow rate effect and temperature effect on exergy efficiency

In Figure 4, the ECOP and the average exergy efficiency of the whole cycle are presented for that period. The COP and ECOP of the system are constant and equal to 0.724 and 0.16, while average energy efficiency and average exergy efficiency of the proposed system increasing as the solar share increases in the cycle.

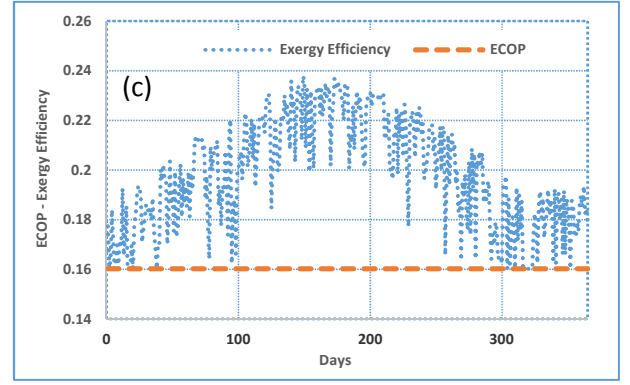


Fig. 4. ECOP and Exergy Efficiency of the proposed system

Figure 5 shows the variation of NPV in a range of discount rates for 8, 10 and 12 years from the start of the project. The NPV helps us decide if it can bring a fairly large income or not. In this form of NPV presentation, one would simply discover the values of IRR. This shows that for 8, 10 and 12 years of operation, IRR would be 5.7%, 10.6%, and 13.2%, respectively to indicate the potential for the economic viability of the proposed system. For a discount rate of 4% [13], the payback period of the system is about 7.5 years.

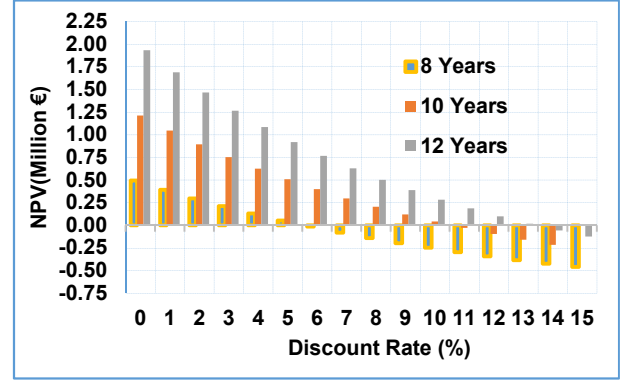


Fig. 5. NPV variation for various discount rates.

Figure 6 shows that the amount of CO₂e produced in each month if the energy required to supply a chiller is provided from an incineration power plant. After the contribution of solar energy in supplying the required energy of the chiller, the CO₂e emission reduction rate is shown in this figure. It is clear that in the summer when we have the highest solar radiation, 85% CO₂e emission reduction occurs by applying the proposed system. In addition, 58% overall CO₂e emission reduction was calculated during the year.

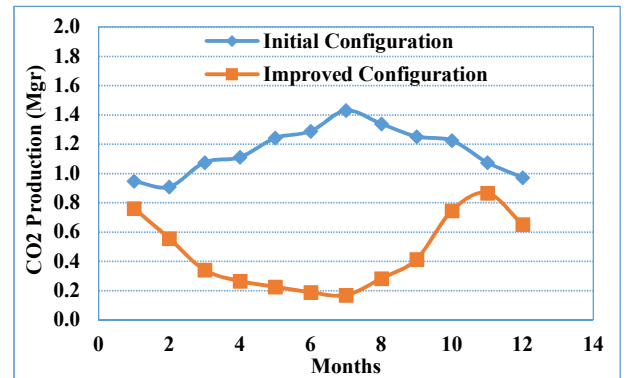


Fig. 6. NPV variation calculated in different years

VI. CONCLUSION

In this article, we considered an absorption chiller integrated with district heating and a PTC field. This type of cooling has problems in the summer when heat demand is low and consequently, the absorption chiller supply encounters difficulty. To address this problem, a new integration of solar PTC with absorption chiller and district heating was proposed. Here, a 4E analysis was applied to investigate the viability of such a system in eliminating the problem. First, the LS2 PTC set and then single-effect absorption chiller were investigated from an energy and exergy point of view. Then, the integration of LS2 PTC set with an absorption chiller is studied in which 53 sets of collectors were implemented to provide the solar energy for heat supply. It is shown that for 53 LS2 PTC sets, 29% of the time, from zero to 6.4 MW heat is provided for district heating. In the exergy analysis, it was displayed that an increase in mass flow rate results in an increase in the exergy efficiency, although for higher values of mass flow rates, exergy efficiency was relatively constant. Exergy efficiency went up and then down over a defined range of inlet temperature. In its usual practice, the absorption chiller cycle has an exergy efficiency of 0.16, but in the case that the solar exergy is added to the generator as a free source of energy, an increase in exergy efficiency occurs. The higher the amount of radiation, the greater the amount of exergy output of the cycle. In economic analysis, it was observed that for 8, 10 and 12 years of operation, IRR would be 5.7%, 10.6%, and 13.2%, respectively to indicate the potential for the economic viability of the proposed system. After supplying a portion of the required heat of chiller by solar energy, 58% overall CO₂ emission reduction is achieved during the year.

ACKNOWLEDGMENT

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