Design of solar cooling system

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In times of conventional energy sources depletion and excessive consumption of electricity, solutions are sought for replacement of conventional systems such as vapor compression cycle air conditioning. In this thesis a solar absorption cooling system with chilled water storage tank and peak load vapor compression cycle cooling system was considered for cooling IST Tower building in Lisbon, Portugal. In order to do this task, a dynamic simulation of the building was performed using the DesignBuilder software, then a solar collector field was designed. The next step was to build a computational model of the absorption chiller in the Engineering Equation Solver software, which allowed for further simulation of the annual operation of the system supported by the chilled water tank and the backup system with classic air conditioning system. The last stage of the work was the economic analysis of such a system in comparison with conventional air conditioning. The simulation results and economic analysis showed that the solar absorption cooling system could be a beneficial cooling solution for IST Tower building. However, it would have to operate with an energy storage system and a peak load vapor compression cycle backup system to be able to cool the building efficiently all year round. Additionally, such a solution could have a significant impact on environmental protection through huge annual savings in electricity consumption.

1. Introduction

In recent years, the search for optimal solutions for the use of renewable energy sources has been increasingly intensively sought. This is due to common problems for national energy operators problems with providing priority to renewable energy sources simultaneously ensuring full energy security of the country. Supporting the development of renewable energy sources was reflected in a number of decisions, including those of the United Nations or European Union. Activities aimed at thorough regulations and changes to protect the environment and develop the energy sector towards sustainable development began in when ”The Limits to Growth” report was issued, which indicated such problems as high rate of use of natural resources, an increase in consumption related to demographic growth or the possibility of political and social conflicts arising from natural resources depleting.

The cooling and heating energy sector is growing every year. The increase in the average temperature on earth and the increasing standard of living mean that more than 50% of electricity in the world is used for heating and cooling purposes [1]. Urban development in the world must be related to the further development of this sector, therefore, one should look for more energy-saving solutions than a typical vapor compression cycle air conditioning system, which requires relatively much electricity and has become the main energy consumer in most buildings. At the same time, scientists develop and test innovative or improved systems, which use renewable energy sources. One such installation is an absorption cooling system using solar panels. A solution whose main difference between a typical air conditioning system is the lack of a compressor (main electricity consumer). Compressor is replaced by the generator which does not need electricity but heat. Heat primarily was obtained from fuel combustion. However in recent years, the solution with obtaining heat from solar collectors is more widely used. In this case, circulation pumps are the only electricity consumers, which require a insignificant amount of electricity in relation to the compressor in conventional air conditioning system.

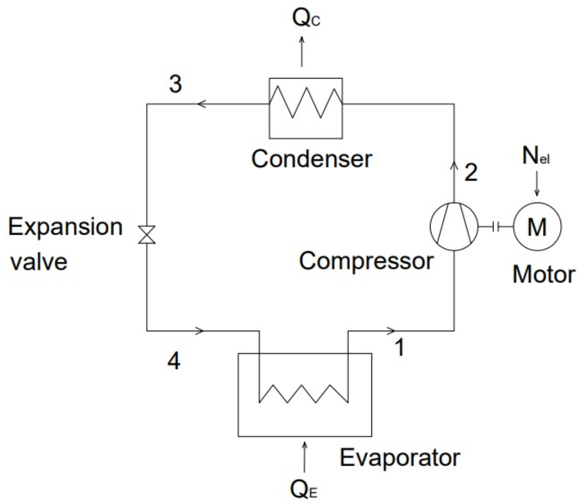

Figure 1. Conventional cooling system

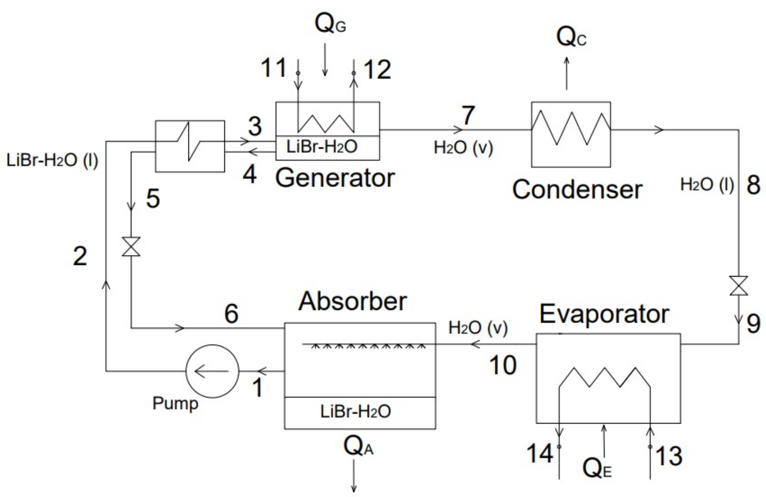

Figure 2. Single effect absorption chiller

2. Aim and scope of thesis

The aim of the thesis was to investigate whether solar absorption cooling system would be advantageous solution in comparison with conventional vapor compression cycle air conditioning system for utilisation in the IST Tower in Lisbon, Portugal. In order to check it, the annual simulation of the solar absorption cooling system for the IST Tower in Lisbon was carried out and economic analysis in comparison to vapor compression air conditioning system was prepared. Firstly, the model of the university building was designed. The purpose of that model was to obtain cooling capacity demands of the building throughout a whole year. Then simulation of the solar collector field was prepared to calculate possible heat output. The crucial part of the calculation was to prepare the design parameters absorption chiller model. This simulation with the use of correction curves and data from the building and solar field simulation allowed to perform an annual simulation of the installation. Additionally, in order to ensure effective year-round operation of the system, the chilled water storage and back-up cooling system was calculated and simulated. The final purpose of the work was to analyze the installation from an economic point of view. For this purpose, several economic indicators have been calculated (net present value (NPV), net present value rate (NPVR), internal rate of return (IRR), discounted payback period (DPB) and simple payback time (SPB)).

3. Literature review

Although the utilisation of an absorption chiller unit is still rare, especially with solar collectors as heat source, there are many articles, theses and texts analyzing these systems in various configurations.

The article [2] discusses the problems of today's energy, presents the possibilities and needs. Additionally, presents the operation of the absorption chiller and environmental aspects using the Life Cycle Assessment (LCA) technique. The conclusions of the article were that an absorption chiller could be a very beneficial, future-proof solution for cooling systems, especially when it comes to large buildings, e.g. skyscrapers. The possibility of easy connection with renewable energy sources is a huge advantage and this technology should be developed and used in the future.

The thesis [3] was focused on the introducing solar cooling system for underground mine in Queensland, Australia. Various configurations of a classic cooling system with PV panels as electricity supplier and absorption cooling system with solar collectors as heat source were analyzed.The conclusions were that solar-powered absorption cooling system with heat storage would be a viable solution for mines in Australia.

Ph.D. thesis [4] was significant because the simulations were carried out on a real research position in Arlon, Belgium and showed the differences between the results of computer simulations and tests on a real installation. The comparison, among other things, showed that the consumption of electricity in the thermal system was twice as high as simulation shows.

The article [5] presented technological and economic analysis of solar absorption cooling for commercial buildings in Chennai, India. The solar absorption cooling system was simulated in the TRNSYS software. Conclusion were that solar absorption cooling system will achieve full payback time after 15.5 years. However, the analysis also highlighted very high initial installation costs.

4. Case study

4.1 The IST Tower model simulation

The model of the IST Tower was designed in the DesignBuilder software. Dimensions of the building were determined using Google Maps and the Google Earth application, therefore, some dimensions may be slightly different from the reality.

As a result of the simulation, the necessary hourly data was obtained on:

- weather conditions, simulated for Lisbon, Portugal,
- cooling capacity of the building,
- heating capacity,
- electricity needs for heating system, classic air condition installation, domestic heating water.

Key input data:

- lightweight concrete clad wall as a external walls material,
- light office work as occupation scenario,
- office area as activity profile,
- cooling setpoint temperature = 24°C.

Obtained data allowed to calculate annual electricity consumption for classic cooling system and hourly cooling capacity demands.

4.2 Design and characteristics of solar collectors and solar field

The solar collectors field was designed on roofs of the Instituto Superior Tecnico university buildings. The calculations of available area were based on Google Earth satellite images. The calculations showed that it would be possible to place 112 panels. Arcon-Sunmark A/S HT-SolarBoost 35/10 collectors were adopted as solar collectors for the entire installation.

For calculation of available heat from solar collectors field, the following formula was used:

$$A \cdot (\eta_0 \cdot G - a_1 \cdot \Delta T_{sol} - a_2 \cdot \Delta T_{sol}^2) \tag{1}$$

where:

- A - total aperture area $[m^2]$,
- η_0 - zero loss efficiency,
- G - irradiation $[\frac{W}{m^2}]$,
- a_1 - first order coefficient,
- a_2 - second order coefficient,
- ΔT_{sol} - temperature difference between average temperature of solar fluid and ambient temperature [°C].

4.3 Characteristic of solar absorption cooling system

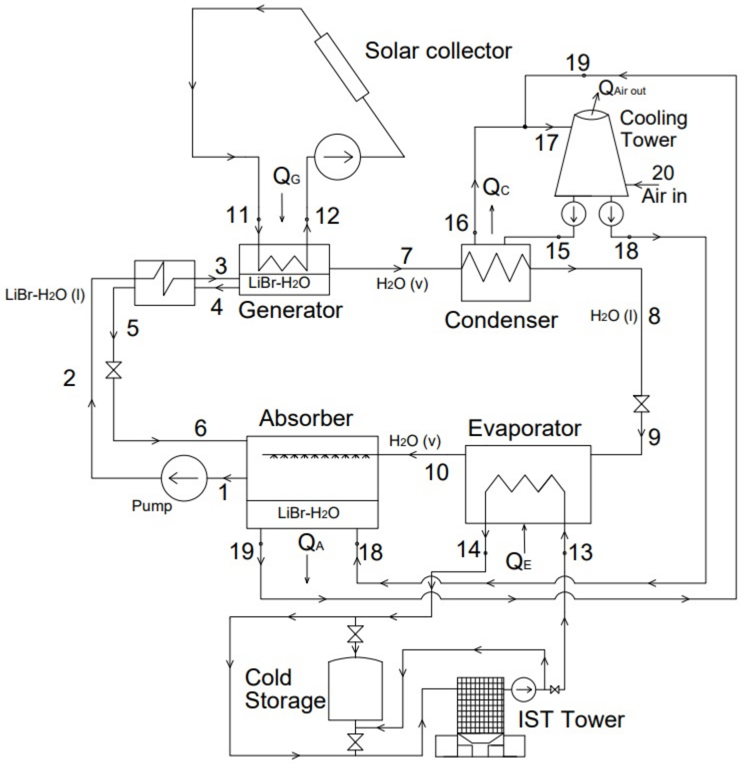

Figure 3. Technological scheme of solar absorption cooling system with cold storage

The main part of the installation was an absorption chiller in which the absorption phenomenon takes place. LiBr/H_2O was chosen as cooling fluid and working fluid. In the absorber, working medium, due to its strong hygroscopic properties, absorbs the evaporating cooling medium from the evaporator. Subsequently, the solution of two fluids is directed to the generator where the refrigerant (cooling medium) is evaporated due to the supplied heat from solar field [2]. The evaporated water from the generator moves towards the condenser where the steam become liquid by cooling with water from the cooling tower. Then, collected liquid is gravity fed through an expansion valve, where temperature drops below vaporisation temperature and pressure drops near vacuum. Finally, into evaporator the cooling effect occurs. Additionally, the system required a solar fluid cycle as well chilled water cycle with chilled water storage.

5. Model and simulation of integrated cooling system

The model was prepared in the Engineering Equation Solver (EES) software.

5.1 Assumptions of the model

Assumptions of the model:

- two levels of pressures. High pressure - $P_{sat}(T_{cond})$ (saturation pressure depended on the condenser temperature), low pressure - $P_{sat}(T_{evap})$ (saturation pressure depended on the evaporator temperature),

- constant temperature of working medium from solar collectors and on the return (90/80 °C),
- constant efficiency of heat exchanger in the absorption chiller between absorber and generator,
- temperatures of cooling water at inlet (29.4°C) of absorption chiller set according to the catalogue characteristic of absorption chiller [6],
- constant chilled water temperature (inlet: 12.2°C; outlet: 6.7°C) set according to the catalogue specification [6],
- difference between temperature of the cooling water before/after condenser set as 6 K,
- temperature difference in absorber set as 3 K,
- temperature difference in generator set as 3 K,
- pinch in the condenser set as 3 K,
- pinch in the evaporator set as 3 K.

5.2 Main model calculation equations

Energy balances for the absorber:

$$Q_A = \dot{m}_{10} \cdot h_{10} + \dot{m}_6 \cdot h_6 - \dot{m}_1 \cdot h_1 \tag{2}$$

$$Q_A = \dot{m}_{19} \cdot h_{19} - \dot{m}_{18} \cdot h_{18} \tag{3}$$

Energy balance for the generator:

$$Q_G = \dot{m}_4 \cdot h_4 + \dot{m}_7 \cdot h_7 - \dot{m}_3 \cdot h_3 \tag{4}$$

Energy balances for the condenser:

$$Q_C = \dot{m}_7 \cdot h_7 - \dot{m}_8 \cdot h_8 \tag{5}$$

$$Q_C = \dot{m}_{16} \cdot h_{16} - \dot{m}_{15} \cdot h_{15} \tag{6}$$

Energy balance for the evaporator:

$$Q_E = \dot{m}_{10} \cdot h_{10} - \dot{m}_9 \cdot h_9 \tag{7}$$

The coefficient of performance of the absorption chiller (COP) and heat pump (COP$_{hp}$):

$$COP = \frac{Q_E}{Q_G} \tag{8}$$

$$COP_{hp} = \frac{Q_C + Q_A}{Q_G} \tag{9}$$

The Engineering Equation Solver calculation model results of design parameters of the absorption chiller were as follows:

Table 1. Main design parameters of the absorption chiller.

Parameter	Symbol	Unit	Value
Cooling capacity from the evaporator	$Q_{E\ design}$	kW	331.9
Heat discarded from the absorber to the cooling tower	$Q_{A\ design}$	kW	482.4
Heat discarded from the condenser to the cooling tower	$Q_{C\ design}$	kW	352.8
Heat obtained from solar collectors field transfered to the generator	$Q_{G\ design}$	kW	503.2
Design coefficient of performance of the absorption chiller	COP	-	0.66

5.3 Correction curve of the absorption chiller

In order to make annual simulation realistic correction curve of the chiller was used. For chosen absorption chiller (WFC-M100 Yazaki Energy absorption chiller) manufacturer correction chart was adopted [6].

The use of diagrams facilitated the calculation of the equations computing the parameters involved:

$$FCF = 0.0051 \cdot z + 0.4922 \tag{10}$$

where:

- z - hot medium flow rate [$\frac{kg}{s}$].

Referring to the equation (10), it was possible to calculate hourly cooling capacity obtained from absorption chiller:

$$Q_E = FCF \cdot Q_{E\ design} \tag{11}$$

6. Results and findings

6.1 Atmospheric and solar condition simulation

The hourly weather and solar condition results was obtained through EnergyPlus software data for Lisbon, Portugal area.

6.2 Simulation of the annual system performance

The key parameters determining the efficiency as well as the legitimacy of using solar absorption cooling system were the COP and the generated cooling effect which should meet the building's demand. Simulation was performed for every hour in the year. Cooling effect obtained from solar absorption chiller system was fairly even during the year which resulted from absorption chiller configuration, and considering only the hours when the refrigerator was producing any cooling effect the average was 265.38 kWh.

As for the average annual COP values, during the operation of the chiller they ranged between 0.34 and 0.76. however, the system works by far the most intensively during the summer period - 728 hours, and only 276 hours during the winter.

6.3 Simulation of the cold storage with backup system

The chilled water storage system simulation was performed in the Excel. The solar absorption cooling system was not able to cool the building every hour of the year. Therefore, chilled water storage reservoir and a vapor compression cycle cooling backup unit were used to solve this problem. Three different sizes of the energy storage tank were considered - 2500 kWh - 392 m^3, 5000 kWh - 784 m^3, 125000 kWh - 1958 m^3.

The system with the 392 m^3 storage tank, on average, did not use 32.24 kWh of solar energy per hour. Subsequently, on average system hourly need 65.62 kWh of cooling capacity from backup system, which need to work 1378 hours per year.

Regarding the system with 784 m^3 storage tank, on average, this system needed 60.36 kWh per hour of support from the backup cooling system and annually 21.11 kWh per hour was unused from solar collectors field. The backup cooling system was needed for 1255 hours per year.

Finally, the system with the biggest reservoir, on average, did not use 12.83 kWh of solar energy from solar collector field. At the same time, it needed a reserve system to a much lesser extent (on average, hourly 57.63 kWh). Additionally annual extra consumption of the electrical energy was reduced to 168 277.55 kWh per year and this installation would efficiently use 170 110.53 kWh of thermal energy from solar field more than systems with 392 m^3 chilled water tank and 72 549.77 kWh than 784 m^3 storage system.

7. Economic analysis of solar absorption cooling system

Despite the fact that the initial costs of absorption cooling systems are high, savings in electricity consumption due to the innovative cooling system could be so significant that, with a long-term investment, the absorption solar cooling system can turn out to be a profitable investment, especially for a large building. The economic analysis of the solar absorption cooling system was carried out with reference to the conventional vapor compression cycle air conditioning system.

In order to check the economic justification of the innovative solar absorption system net present value (NPV), net present value rate (NPVR), internal rate of return (IRR), Simple payback time (SPB), Discounted Payback Time (DPB) were calculated.

Table 2. Economic indices for the solar absorption system with 784 m^3 storage reservoir

Profitability indices		
1	NPV [€]	**189 770.04**
2	NPVR	**0.37**
3	IRR	**0.09**
4	SPB [years]	**9.1**
5	DPB [years]	**12.5**

Table 3. Economic indices for the solar absorption system with 392 m^3 storage reservoir

Profitability indices		
1	NPV [€]	**242 821.10**
2	NPVR	**0.55**
3	IRR	**0.11**
4	SPB [years]	**8.1**
5	DPB [years]	**10.6**

Table 4. Economic indices for the solar absorption system with 1958 m^3 storage reservoir

Profitability indices		
1	NPV [€]	**- 11 057.07**
2	NPVR	**-0.02**
3	IRR	**0.05**
4	SPB [years]	**12.7**
5	DPB [years]	**20.6**

8. Conclusions, remarks and recommendations

In conclusion, the innovative solar absorption cooling system with chilled water storage tank could be an interesting solution for IST Tower cooling. This system is able to meet the needs of the building most days of the year. However, to be effective every hour of the year, a back-up system was needed to ensure the needs in times of excessive demands. Another solution could be the use of an absorption chiller with a greater nominal cooling capacity along with the use of a backup heat source.

The net present value was negative only for configuration with 1958 m^3 storage tank. Other economic indicators for systems with 392 m^3 and 784 m^3 chilled water reservoirs (NPVR, IRR, SPB, DPB) also met the conditions that a profitable investment should achieve. It was difficult to clearly define which solution (in terms of the size of the chilled water reservoir) under consideration would be the best. Decision would depend on the primary purpose of the investor and the possibilities of the initial investments, as the system with the 784 m^3 tank in economic terms would be less favorable. However, if the selection depended on the independence of the installation in relation to conventional air conditioning system and electricity savings, the larger system would have been more beneficial solution.

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