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Solar air-conditioning designs for residential buildings in Saudi Arabia

沙特阿拉伯居住建筑的太阳能空调设计

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Abstract - **The excessive demand for air conditioning in Saudi Arabia is a direct result of the high ambient temperatures. Air-conditioning systems in residential buildings in Saudi Arabia consume approximately 46% of the total produced electrical energy. Almost air-conditioning systems used in Saudi Arabia are of the conventional (vapor-compression) type, which consumes a large amount of mechanical/electrical energy. Solar energy can be used instead to power such systems and hence help in the reduction of carbon emission, environmental pollution and global warming effects. Out of various renewable sources of energy, solar energy proves to be the best candidate for air conditioning in Saudi Arabia because of the coincidence of the maximum cooling load with the period of the greatest solar radiation input. In this paper, a solar air-conditioning system consisting of solar-powered LiBr-H_2O absorption chiller, flat plate collectors and storage tanks is investigated for a constant cooling load of 5 kW. A solar absorption air-conditioning system for a typical family living house in Saudi Arabia is studied with three storage designs (heat storage, cold storage, and refrigerant storage) to achieve full-day operation (24-hours constant cooling effect). The system performance, cost, features, energy saving and environmental pollution reduction are investigated based on the thermodynamic analysis. The results show the effect of the condenser temperature (which depends on the ambient temperature) and the evaporator temperature (which depends on the cooling load requirements) on the mass storage, energy saving and environmental pollution reduction. Based on the required storage tank capacity, the results indicate that refrigerant storage is the most suitable design for 24-hours supply of the constant cooling effect.**

Keywords - **24-hours, solar-powered, air-conditioning, residential buildings**

I. INTRODUCTION

Presently almost all the cooling produced in Saudi Arabia is by means of vapor compression systems. The compressors of these vapor compression systems are directly run by theelectrical energy that is generated by burning fossil fuel.

The building sector consumes nearly 70% of the total electrical energy produced in Saudi Arabia [1]. The air-conditioning systems in those building consume approximately 65% of the electrical energy of the building sector [2], thus, air-conditioning systems in the building sector in Saudi Arabia consume approximately 46% of the total produced electrical energy. Therefore, it is critical to consider the utilization of innovative solutions such as solar cooling.

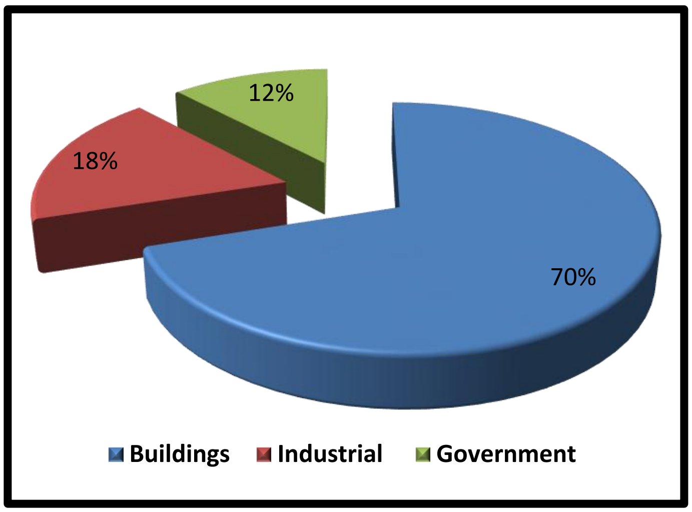

Fig. 1, Saudi Arabia Electrical Power Demand Distribution [1]

Solar energy can be used to power air-conditioning systems in two ways. First way is that, solar energy can be converted into electricity using Photo-Voltaic Cells and used to operate a conventional vapor-compression refrigeration system. Second way is that, solar energy can be used to heat the working fluid in the generator of a vapor sorption (absorption or adsorption) system. In the absorption air conditioning system, a heat source drives the cooling process, which can be considered an alternative to conventional air conditioning if excess heat is available, such as heat from the sun, which is applicable in Saudi Arabia.

The main difference between vapor compression (conventional) and absorption system is that absorber, generator and pump replace the compressor. In term of performance, absorption system can be categorized into the following three types:

- Single Effect: COP 0.6 to 0.8
- Double Effect: COP 1.0 to 1.2
- Triple Effect COP 1.4 to 1.6

COP is the coefficient of performance used to measure the performance of cooling systems. Higher COP, larger than one, means higher efficiency of the equipment which equates to lower operating costs. The main benefits of absorption systems are:

- Vibration-free
- Longer life-time
- High reliability
- Low maintenance
- Energy Saving

The major working pairs employed for solar absorption systems are LiBr-H_2O and H_2O-NH_3. Most researches confirm that LiBr-H_2O has a higher COP than for the other working fluids, the low cost and excellent performance of this working fluid combination make it the favorable candidate for use in solar air conditioning cycles. However, it cannot be used in sub-zero cooling application. The ammonia-water system has the following disadvantages when compared to LiBr-H_2O system [3].

- The coefficient of performance (COP) for the H_2O-NH_3 system is lower than that for the LiBr-H_2O system.
- It requires a higher generator inlet temperature, which results in the H_2O-NH_3 cooling systems achieving a lower COP.
- It requires higher pressures and hence higher pumping power.
- A more complex system requiring a rectifier to separate ammonia and water vapor at the generator outlet is required.
- There are restrictions on in-building applications of ammonia-water cooling units because of the hazards associated with the use of ammonia.

For these reasons, the lithium bromide-water system is considered better suited for most solar absorption air-conditioning applications. The storage can be used in an absorption cooling system to increase the effectiveness of the system.

The two main storage systems are (Hot storage tank and Cold storage). These two storage systems can be used individually or in combination. The hot storage is accomplished using a hot water storage tank, in order to reduce losses in conversion of thermal energy. The cold storage can be integrated in order to store energy at times of high radiation for use at times when the available solar energy is not sufficient to meet the cooling demand.

II. ENERGY SAVING

The developed designs systems operate 24-hour a day (continuous operation) using three methods of storage systems (heat, cold and refrigerant). During the full day (24-hour), for a constant hourly cooling load of five kWh for typical house in Saudi Arabia, the only electrical energy used is the pump consumption, which is less than 0.01% of the total energy produced by electricity. Using simulation software, engineering equation solver (EES), Table 1 shows the amount of energy saved using solar air-conditioning with storage systems. It indicates that for one house, 56.3 MWh of electrical energy can be savedon annual basis.

Table 1: Energy Saving

Period	**Energy Saving**
Hourly	6.43 kWh
Daily	154.2 kWh
Annually	56.3 MWh

III. ENVIRONMENTALIMPACT

The environmental effects of carbon dioxide are currently of significant interest. The increase of carbon dioxide emission has major negative impact on the environment. According to the World Bank for 2014, Table 2 shows the carbon dioxide emission in Saudi Arabia and United Kingdom [4, 5]. In both countries, the rate of CO2 emissions is high; however, in Saudi Arabia the rate per capita is higher than UK.

Table 2: CO2 emissions in Saudi Arabia and United Kingdom [4, 5]

Country	Annual CO2 Emissions (kt)	Per Capita (t) 1 t =1,000 kg	% of World Total
SaudiArabia	464,481	17.04	1.38%
United Kingdom	493,505	7.863	1.47%

The use of solar air-conditioning system can save such emission of carbon dioxide in order to have positive impact on the environment. The average amount of CO_2 that can be saved when using solar energy is 392 g CO_2/kWh [6]. For typical house in Saudi Arabia of 5 kW cooling power, using solar air-conditioning can save major amount of CO_2 emission as shown in Table 3.

Table 3: CO_2 Emission Saving

Period	CO2 Emission Saving
Hourly	2.544 kg of CO2
Daily	61 kg of CO2
Annually	22,289.5 kg (21.9 UK ton) of CO2

IV. SYSTEM DESIGNS

Solar air-conditioning systems can meet continuous operation (day and night) based on different types of thermal energy storage systems. The designs for 24-hour solar air-conditioning systems are categorized based on the storage techniques in use, as follows: (heat, cold and refrigerant).

In the heat storage system, the stored hot thermal energy is supplied to the generator when the incident solar radiation is insufficient to produce therequired generator temperatures. In the cold storage system,the cold storage tank is introduced after the evaporator. The losses to the environment in thissystem can be expected to be lower than in heat storage system because of the lower temperature difference betweenworking and ambient temperatures. In the refrigerant storage system,the refrigerant storage tank is associated withthe condenser where the storage tank accumulates therefrigerant during the hours of high solar insolation. Then,this stored liquid refrigerant can be regulated at other times(e.g., nighttime) to meet the required cooling loads.

The refrigerant (water) is released from the absorbent (LiBr) when the refrigerant-absorbent solution is heated in the generator. The refrigerant vapor travels to the condenser while the weak absorbent-refrigerant solution moves to the absorber. The refrigerant experiences a throttling process as it passesfirst to the evaporator and then to the absorber, and it isreabsorbed by the weak solution to create a strong refrigerantsolution. The solution is then pumped to the generator to complete the cycle. The heat exchanger between thegenerator andabsorber is used to increase the efficiency of thesystem.

Several valves that are configured with the storage systems direct the flow for nighttime and daytime operation for the three systems. For the three systems, the heat is rejected to the environment by natural convection or forced fan. The total electricity requirement for any of the three systems is limited to that needed by the solution pump.

The advantages and disadvantages for each of designs are summarizedin Table 4. The heat storage system has the highest storage capacity (1,896 kg) and the cold and refrigerant storage systems have the lowest storage capacity (100.6 kg and 108.5 kg, respectively), with a slight difference between the two.Based on thermodynamic analysis, the refrigerant storage found to be the most suitable design due to mass storage size and collector area.

The systems are designed to meet a constantcooling load over the 24 hours under the steady-state operationmode.

Table 4: Comparative Analysis of the Three Designs

Design	Advantages	disadvantages
Heat Storage	Higher COP in nighttime operation	• Larger solar collectors area • Components of the system operate day & night. • Storage tank requires thick insulation.
Cold Storage	• Less complexity in the controlrequirements • Components of the systemoperate only in daytime.	Large evaporator and generator size.
Refrigerant Storage	• Smaller solar collector area • Strengthrequirements are notcritical. • Storage tank has thin insulation.	Evaporator operates day and Night.

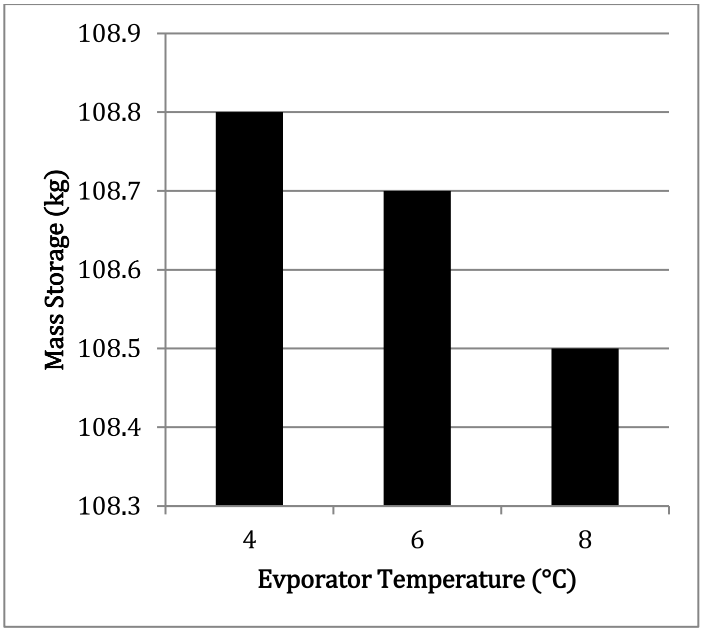

Fig. 2, Mass Storage by Evaporator Temperature

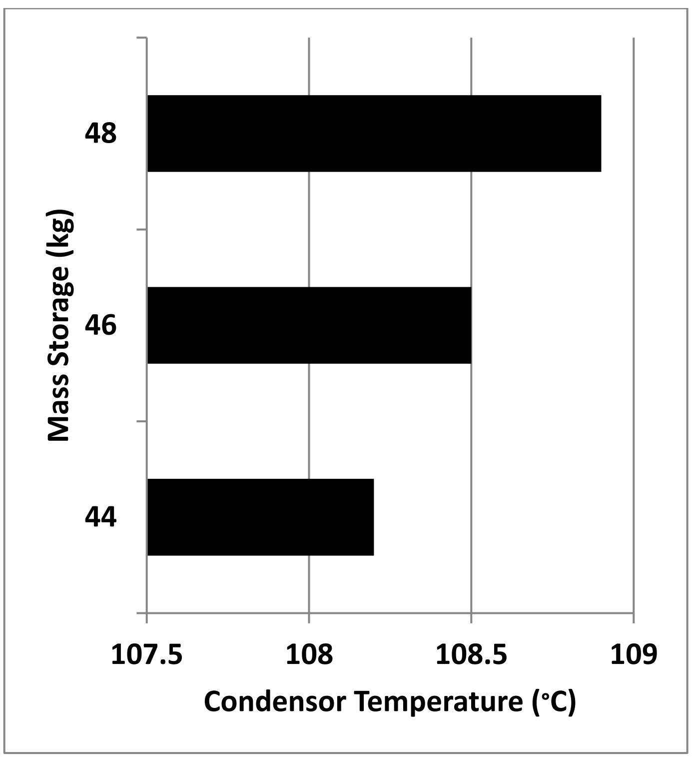

Fig.3. Mass Storage by Condenser Temperature

Using simulation software, engineering equation solver (EES), Fig. 2 shows the effect of evaporator temperature on the mass storage for the refrigerant storage system. The mass storage decreases when the evaporator temperature is higher which indicates that increasing the evaporator temperature will result in cost savings due to the reduction in storage tank. Similarly, Fig. 3 compares the mass storage for the refrigerant storage system versus condenser temperatures using simulation software, engineering equation solver (EES). It shows that the mass storage increases as the condenser temperature increases.

The analysis results show that as the solar available time for the refrigerantstorage system increases, which is applicable for summer,the mass storage capacity decreases. This indicates thata location featuring longer solar availability is highly suitablefor this system. For locations where the solar available time is 14.5h, the storage capacity is decreased to less than 75 kg.

V. Cost of collector IN three systems

The cost of individual components depends on the heat capacity of the components. Higher heat capacity corresponds to a higher heat exchange area required for each component, which further corresponds to a higher cost for that component. The collector rate for flat plate collector is $230/m^2, as stated by the Intelligent Energy-Europe (IEE) program). The collector cost for cold storage system is the most expensive one ($12,259) while it is the cheapest for the refrigerant storage ($5,106). For the heat storage system, the collector cost is $10,143.

VI. Conclusion

The development of solar air-conditioning system has major advantages towards energy saving and carbon dioxide emission elimination. In this paper, three solar-air-conditioning designs for 24-hour a day based on storage methods have been discussed. The features and benefits for each design in term of storage capacity and collector cost have been analyzed. The best storage design is the refrigerant storage as the collector cost is small compared to the other. Moreover, non-insulated storage tanks are required for refrigerant storage systems. These twofactors indicate that the cost of the refrigerant storage system is lower than the other two systems.The improvement of mass storage by condenser and evaporator temperatures will positively affect the design parametersand system selection.

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