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Design, construction and operation of a solar powered ammonia–water absorption refrigeration system in Saudi Arabia

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ABSTRACT

This study presents an experimental investigation of a solar thermal powered ammonia–water absorption refrigeration system. The focus of this study lies on the design of the components of the absorption chiller, the ice storages and the solar collector field as well as the integration of the data acquisition and control unit. An ammonia–water (NH_3/H_2O) absorption chiller was developed in the laboratory of the Institute of Thermodynamics & Thermal Engineering (ITW) at the University of Stuttgart (Germany). A demonstration plant was built in the laboratory of the CoRE-RE at King Fahd University of Petroleum & Minerals (KFUPM – Saudi Arabia). The whole system was tested successfully. The results of the experiments indicated a chiller coefficient of performance (COP) of 0.69 and a cooling capacity of 10.1 kW at 114/23/−2 (°C) representing the temperatures of the generator inlet, the condenser/absorber inlet and the evaporator outlet respectively. Even at 140/45/−4 (°C), the chiller was running with a cooling capacity of 4.5 kW and a COP of 0.42.

Conception, construction et fonctionnement d'un système frigorifique solaire à absorption à ammoniac-eau en Arabie Saoudite

Mots clés : Ammoniac-eau (NH3-H2O) ; Refroidisseur à absorption ; Système frigorifique ; Energie solaire ; Stockage de glace ; Collecteurs solaires tubulaires à vide

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Nomenclature

A	area [m^2]
C	capacity [kWh]
COP	coefficient of performance
FCU	fan coil unit
I_{Glob}	global solar irradiance [W m^{-2}]
$\dot{Q}_C$	cooling performance [kW]
m	mass [kg]
P	power [kW]
V	volume [m^3]
$\vartheta_{Gen,in}$	generator inlet temp. [°C]
$\vartheta_{Cond,in}$	condenser inlet temp. [°C]
$\vartheta_{Abs,in}$	absorber inlet temp. [°C]
$\vartheta_{Evap,out}$	evaporator outlet temp. [°C]
×	concentration [%]

1. Introduction

The technological advancement and economic growth of any country rest on the availability of utilizable forms of energy. For the last centuries, fossil fuel has been considered and utilized as the main source of energy. However, the negative impacts of burning fossil fuel on the environment have forced energy research to consider renewable sources of energy seriously. Renewable energy sources include biomass, geothermal, hydropower, wave, wind, solar and tidal energy sources. Among all of these naturally available and environmentally friendly sources, solar energy (Afshar et al., 2012; Balaras et al., 2007) stands on top of the list due to its enormous potential and natural availability.

In the Gulf Region, air-conditioning and refrigeration represent one of the sectors with the highest energy consumption. About 65% of the electrical energy produced in the Kingdom of Saudi Arabia (KSA) is consumed by the residential sector whereas more than 65% of this residential energy consumption is used for comfort air-conditioning (Said et al., 2003). Furthermore, the energy consumption for the air-conditioning sector is increasing each year (Faisal, 2008). Solar energy is considered as the most appropriate option among other renewable energy sources since the peak of solar irradiance coincides with the peak of the air-conditioning demand.

There are many ways to convert solar radiation into cooling. Henning (2007) gives an overview of solar cooling technologies. The two main processes are solar electric and solar thermal cooling. Kim and Infante Ferreira (2008) compared the two systems focusing on energy efficiency and economic feasibility. The results indicated that solar electric refrigeration systems appear to be more expensive than solar thermal absorption systems. There is a wide range of solar thermal absorption technologies depending on intermittent and continuous absorption systems and a variety of working pairs. Hassan and Mohamad (2012) and Fan et al. (2007) give an overview of this topic.

In intermittent absorption systems, both the generation and the absorption process do not take place simultaneously. They follow each other in an intermittent manner. The most common working pair for these systems is NH3/H2O. However, certain other working pairs have also been used (El-Ghalban, 2002; Hernández et al., 2012; Rasul and Murphy, 2006). Intermittent systems operate in a cyclic behavior with a cycle time of one complete day (24 hours). The pressurization process in the intermittent operation systems is carried out by isochoric heating of the solution in the generator. El-Shaarawi and Ramadan (1986) developed an experimental setup for testing an intermittently operating solar powered NH3/H2O refrigeration system in the Egyptian climate. Although the experimental setup was designed to produce cooling energy at an evaporator temperature of –13 °C, the experimental results indicated cooling energy at –2 °C with a COP of 0.5. The low performance of the system was due to water being transferred into the condenser.

In continuous operating systems, both the desorption and the absorption process take place simultaneously. Continuous absorption cycles eliminate the need of an electrical compressor by replacing it with a solution circuit consisting of an absorber, a solution pump, a generator and an expansion valve (Afshar et al., 2012). The advantage of absorption systems compared to vapor compression systems is the fact that less electric power is required to pressurize the refrigerant in the order of absorbing, pressurizing and desorbing (Chidambaram et al., 2011). However, such absorption systems require heat input to desorb the refrigerant vapor. One way of providing the heat input at the desorber/generator are solar thermal collectors (Wang and Wang, 2005). The most common absorbent–refrigerant working fluid pairs are NH_3/H_2O and H_2O/LiBr. In the following, the focus lies only on absorption systems, which are driven by solar thermal collectors.

Agyenim et al. (2010) performed an experimental analysis of a domestic-scale 4.5 kW solar-powered H_2O/LiBr absorption system equipped with a 1000 liters cold storage and vacuum tube solar collectors with a collector area of 12 m^2. Balghouthi et al. (2012) installed and tested a 16 kW double effect H_2O/LiBr absorption system in Tunisia. In addition to that, solar-powered H_2O/LiBr pilots with a higher cooling capacity are shown in Darkwa et al. (2012), Bermejo et al. (2010), Praene et al. (2011) and Sumathy et al. (2002). Some of them are operating as gas/solar-hybrid-systems.

The two main problems with H_2O/LiBr absorption systems are their inability to operate at a condensation temperature higher than 40 °C due to crystallization and at evaporation temperatures below 0 °C due to the freezing of the refrigerant water (Izquierdo, 2004). These limitations of H_2O/LiBr systems are overcome by working pair NH_3/H_2O in absorption systems (Hassan and Mohamad, 2012). Research projects with a solar thermal powered NH_3/H_2O absorption chiller can be found in Boudéhenn et al. (2012) and Arias-Varela et al. (2000). Boudéhenn et al. (2012) developed a 5 kW solar-powered NH_3/H_2O absorption chiller that resulted in a COP of 0.65. However, it was reported that their solution heat exchanger, designed to operate at an efficiency of 0.83, showed a poor efficiency of only 0.16. Arias-Varela et al. (2000) designed a solar powered NH_3/H_2O absorption chiller to preserve seafood and analyzed the feasibility of the system economically that resulted in a COP of 0.426.

Recently, ITW developed an experimental setup for a small-scale solar-powered 10 kW absorption system with the working pair NH_3/H_2O (Brendel et al., 2010). This absorption system was unique on account of its compact design of the generator and incorporated an additional waste heat recovery from