A novel thermally-activated absorption cooling machine based on the diffusion absorption principle

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This report describes the development, investigation and simulation of a single-effect solar-heat-driven ammonia/water diffusion absorption cooling machine (DACM) with a design cooling capacity of 2.5 kW. The indirectly-heated, solar-powered generator with its bubble pump is the main new feature of this cooling machine. The results from the prototypes showed stable and continuous temperature and pressure levels. Coefficients of performance (COP) were between 0.1 and 0.45, while the continuous evaporator cooling performance was between 0.5 kW and 1.6 kW. An expanded, steady-state DACM model was also set up, based on the characteristic equation of sorption chillers.

Introduction

Over the last years, the air conditioning market has been continuously expanding. The Japan Refrigeration and Air Conditioning Industry Association (JRAIA) is expecting a worldwide rise in air conditioners for residential and commercial use from 60 422 000 units in 2005 (Europe 5 087 000 units) to 68 654 000 units in 2008 (Europe 6 118 000 units) [1]. The units that dominate the market are the small split type, with a cooling capacity of about 2 kW to 4 kW. Due to the large number of units manufactured, these systems are produced and offered at very low prices. However, the downside is that these units increase the adverse effects on local environments as a result of using primary energy such as electricity. At the same time, in many southern countries, they have been the main reason for the power shortages in electricity supply systems during the summer over the last few years. It is therefore very important to search for alternative air-conditioning units that are powered by either waste heat or solar thermal energy.

In the 1990s, a group of researchers developed a directly gas-heated diffusion absorption heat pump (DAHP) with a heating capacity between 3.0 kW and 3.5 kW at heating temperatures of 150 °C and evaporator temperatures from -15 °C to +5 °C [2,3]. Values of coefficients of performance for heating applications (COP_{heat}), were between 1.4 and 1.5. The industrial version of this DAHP is combined with a condensing boiler [4], but is not yet commercially available. Another industrial version of the DAHP has an output of 2.6 kW up to 8.0 kW heating capacity, with a COP_{heat} of about 1.5. A gas-powered DACM has a rating of 1.0 kW to 3.5 kW cooling capacity [5]. Bearing in mind that no suitable indirectly powered absorption cooling machines with small-scale cooling performance (1 kW to 5 kW) are available on the market, the Stuttgart University of Applied Sciences has developed and set up three single-effect solar-driven DACMs, each with a design cooling capacity of 2.5 kW [6-7].

Design of the prototypes

The well-known diffusion absorption technique, which was developed in the 1920s by the Swedish engineers von Platen and Munters [8], is based on the principle of pressure equilibrium between the high and low ammonia partial pressure sides of the unit through an inert auxiliary gas. A further feature of this type of absorption cooling machine is the use of a thermally-powered gas bubble pump for circulation of the solution cycle, instead of a mechanical solution pump, so that no mechanically moving parts are necessary inside the cooling machine. The core components of a DACM are the indirectly powered generator, condenser, evaporator and absorber, as shown in Figure 1.

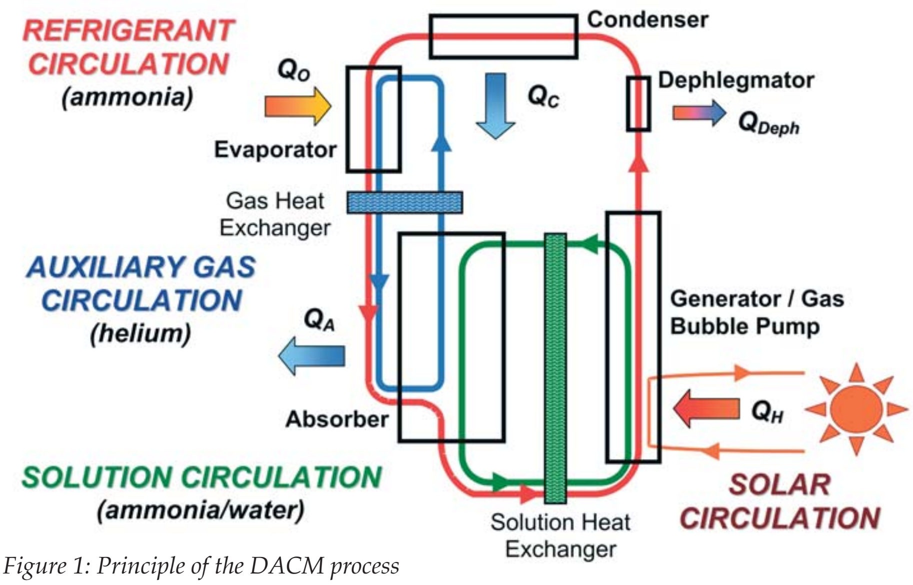

Figure 1: Principle of the DACM process

A solution heat exchanger (SHX) in the solution circuit, and a gas heat exchanger (GHX) in the auxiliary gas circuit, are also components of the DACM, together with a dephlegmator for condensation of the evaporated solvent. These components are vertical steel tubular heat exchangers or nickel-soldered plate and stainless steel coaxial heat exchangers, which are welded hermetically tight with each other. The working pair used for the solution circulation is an ammonia/water mixture. The inert auxiliary gas used is helium.

The prototypes of the DACMs are designed for air-conditioning applications as water chillers, with an evaporator temperature of 6-12 °C, and for use with cooled ceilings with an evaporator temperature of 15-18 °C. Figure 2 shows the three prototypes (Nos.1 to 3, from top to bottom), with total heights of 3.70 m, 2.40 m and 2.20 m respectively. The first prototype weighed approximately 800 kg and was in operation from November 2000 to March 2002. The second prototype was put into operation in July 2003 and ran till July 2005. With an improved, compact design, the weight of DACM No.2 was reduced to 290 kg (plate SHX) or 240 kg (coaxial SHX) was achieved. The third prototype also weighs 240 kg, and operation started in October 2005. Table 1 summarises the technical design data of the prototypes.

Operating performance

Data acquisition was conducted under laboratory conditions as well as under simulated field conditions for vacuum-tube collectors. A series of measurements were taken with the first DACM with an indirect, liquid heating system at generator heating inlet temperatures of 150 °C to 175 °C and evaporator temperatures of 25 °C down to 0 °C. The measurements were taken with and without the dephlegmator. The results showed that COP values ranged from 0.1 to 0.2 and that the evaporator cooling capacity of the pilot plant was able to reach 0.5 kW to 1.5 kW, but operation was not continuous. The lowest heating inlet temperature of the generator was 147 °C. The evaporator capacity decreased with time, due to saturation of the auxiliary gas with ammonia, as the gas circulation was insufficient. Due to the low heat recovery factors of the tubular SHXs of 39.6% and 51.1% for DACM No.1 (the low and high values correspond to the rich and weak solution sides respectively), the measured generator heating capacities were very high and so the COPs were very low.

Measured results of the second compact DACM with steady state temperature, pressure and capacity levels were obtained with variation of the heating temperatures, the cooling water temperatures and the cold brine temperatures. The heating temperature range of the generator was reduced from the 150 °C to 175 °C of the first prototype to 110 °C to 155 °C for the second prototype. This was due to the decreased lifting height

Table 1 Design data DACMs

COP (coefficient of performance, ratio of cooling output to driving heat input)		0.48
Generator	heating capacity QH	5.2 kW
	heating water in/out	130/120°C
Dephlegmator	cooling capacity QDeph	0.9 kW
	cooling water in/out	34/38°C
Condenser	cooling capacity QC	2.8 kW
	cooling water in/out	31/34°C
Evaporator	refrigerating capacity QO	2.5 kW
	cold water or brine in/out	12/6°C
Absorber	cooling capacity QA	4.0 kW
	cooling water in/out	27/31°C

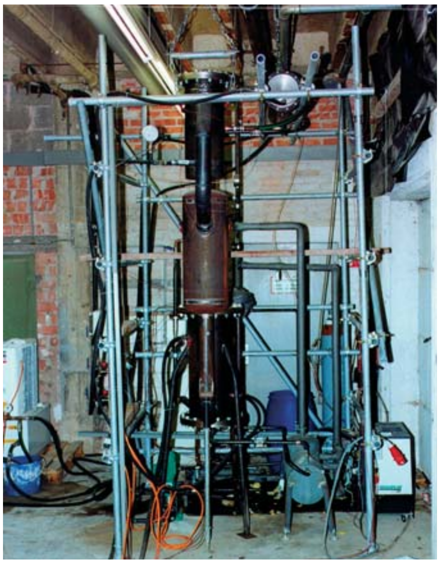

Figure 2: DACM prototypes Nos.1, 2 and 3 (from top to bottom)

(48 %) of the bubble pump. With the same heat transfer surface, the efficiency of the bubble pump increased and temperature levels dropped. COPs were between 0.2 and 0.45, and the continuous evaporator cooling capacity between 1.0 kW and 1.6 kW at evaporator outlet temperatures for air-conditioning between 22 °C and 15 °C (Figure 3). The lowest logged external evaporator outlet temperature was –5 °C, with a generator heating inlet temperature of 145 °C. The first version, with a plate SHX, was replaced by a coaxial SHX due to very low heat recovery factors of 11.4 % and 31.2 % for the rich and weak solution sides respectively. The heat recovery factors of the coaxial heat exchanger of DACM No.2 were within an acceptable range of 76 % and 92 % (values of the rich and weak solutions respectively). Due to the low solution mass flow rates, the coaxial SHX provided better heat exchange performance than did the plate heat exchanger.

The developed bubble pump worked over a wide operation range at varied temperatures and external mass flows. A theoretically possible evaporator cooling capacity was determined for the evaporator, based on the evaluated liquid ammonia mass flow of the experimental data. A comparison of the resulting theoretically possible and the actual measured cooling capacity of the existing DACM No. 2 evaporator shows that, with a generator heating inlet temperature of 125 °C, the evaporator could not evaporate all of the available liquid ammonia into the helium gas atmosphere, not even with high external evaporator inlet temperatures of around 25 °C. The evaporator therefore needs more or longer evaporation tubes in order to increase the heat transfer surface, which would reduce the film thickness and so give a longer delay time.

The first experimental results from DACM No. 3 show evaporator cooling capacities up to 1.4 kW and COPs up to 0.3. Further investigations of the performance potential will be carried out.

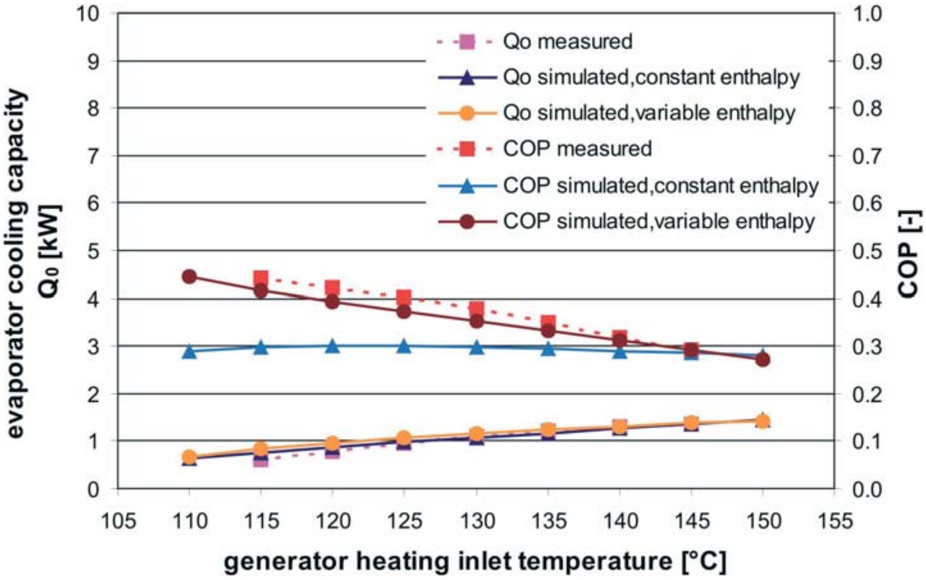

Figure 3: Comparison of measured and simulated values of DACM No.2 (design evaporator temperature is 22.5°C at 1.3 kW cooling capacity, with generator, absorber and condenser temperatures of 140°C, 29°C and 32°C respectively, and SHX and GHX efficiencies of 0.76 and 0.30 respectively)

Modelling and Simulation

The diffusion absorption cycle has been modelled starting from the constant-characteristic equation of sorption chillers, which give an exact solution of the internal mass and energy balances of each component, as well as the heat transfer between external and internal temperature levels, for only one given design point (constant enthalpy). An expanded, steady-state DACM model was developed, based on changing internal enthalpies (variable enthalpy) and changing rich solution mass flow rates due to the characteristics of the bubble pump for each time step [9]. Figure 4 shows the data reduction

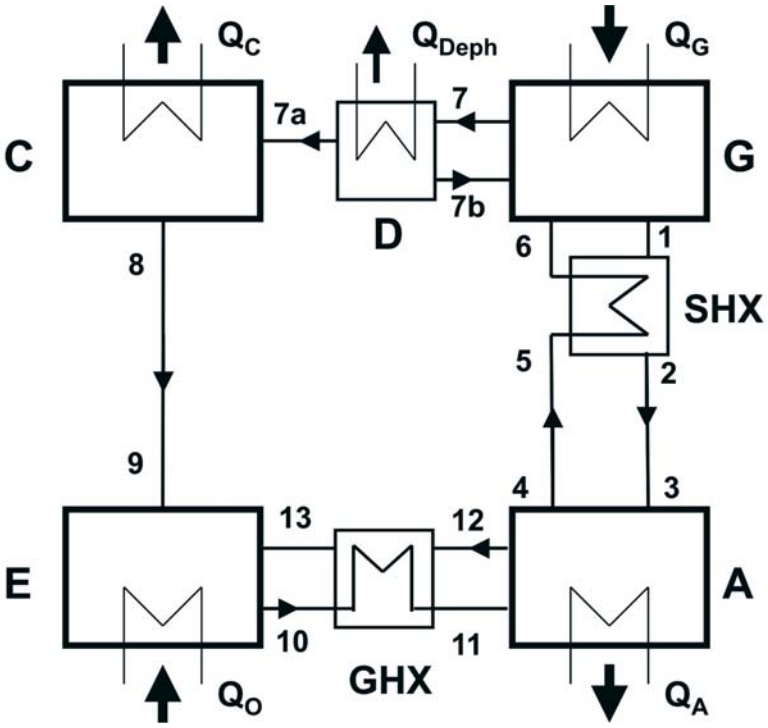

Figure 4: Ammonia/water/helium DACM data reduction model

model for the DACM. The model was implemented in the INSEL simulation environment, and validated by experimental data from DACM No.2. The results of the simulation runs showed that the performance of the DACM, with variable enthalpy, describes the experimental data of the measured performance well (Figure 3). For the constant enthalpy model case, the performance deviated from the measured data.

A parameter study was also carried out to determine how to improve the performance of the DACM at different evaporator inlet and cooling water temperatures, together with evaporator surface wetting factors and GHX heat recovery factors. As expected, the COP and the evaporator cooling capacity decrease at lower evaporator temperatures. In addition, the lower the absorber cooling inlet temperature, the higher is the resulting evaporator cooling capacity. The surface wetting factor and the heat recovery factor have a considerable influence on the cooling capacity. With a higher surface wetting factor, and a better evaporation efficiency, the cooling capacity and the COP increase by a factor of 2 for a surface wetting factor of 0.50 to 1.00. If the heat recovery factor increases from the measured value of 0.30 to 0.60, both cooling capacity and COP increase by a factor of 1.1 to 1.2. To achieve this improvement, it is necessary to optimise the heat transfer inside the GHX using constructive steps to reach higher heat recovery factors.

Conclusions

The first DACM prototype showed that COP values ranged from 0.10 to 0.20, and that the evaporator cooling capacity could reach 1.5 kW. However, the auxiliary gas circulation was not high enough, leading to fast saturation of evaporated ammonia. The second compacted prototype showed stable and continuous temperature and pressure levels. COPs were between 0.2 and 0.45, and the continuous cooling performance was between 1.0 kW and 1.6 kW. A maximum cooling capacity of 2.0 kW could be reached if the evaporator temperature was set to a value of 25 °C. A third prototype, DACM No.3, was built in October 2005, and now has marketable dimensions.

An expanded, steady-state model of the DACM based on the characteristic equation of sorption chillers showed good accordance of the compared experimental and simulated data. Efficient evaporation with high surface wetting factors are essential for high performance.

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