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Simulation and performance of diffusion absorption cooling machines for solar cooling

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Abstract

Solar thermal driven or assisted absorption cooling machines are gaining increasing importance due to the continually growing demand for air-conditioning in residential houses as well as office and hotel buildings. Considering these circumstances, the Stuttgart University of Applied Sciences has developed and set up three single-effect hot-water driven, solar powered diffusion absorption cooling machines (DACM) each with a design cooling capacity of 2.5 kW. The first DACM prototype showed that the values of COP ranged from 0.10 to 0.20, and the evaporator cooling capacity could reach 1.5 kW. However, the auxiliary gas circulation of the first prototype was not high enough, leading to fast saturation of evaporated ammonia. The second compacted prototype showed stable and continuous temperature and pressure levels. The reached COPs were between 0.2 and 0.45 and the continuous cooling performance was between 1.0 kW and 1.6 kW. A third prototype with marketable dimensions was set up in October 2005. The first results showed cooling capacities between 0.7 kW and 2.3 kW. The reached COPs are between 0.12 and 0.30. An expanded, steady-state model of the DACM based on the characteristic equation of sorption chillers showed a good accordance of the compared experimental and simulated data. Efficient evaporation with high surface wetting factors is essential for high performance.

Keywords: absorption cooling machine, solar cooling, bubble pump, simulation

Introduction

In 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 62970000 units in 2006 (Europe 5382000 units) to 68654000 units in 2008 (Europe 6118000 units) [1]. The units that dominate the market are the small split-units with a cooling capacity of around 2 kW up to 4 kW. Due to the large number of manufactured units, these systems are produced and offered at very low prices, however, such systems increase the adverse effects on local environments as a result of using primary energy such as electricity. Therefore, it is important to search for alternative air-conditioning units that are driven by either waste heat or solar thermal energy.
Up to now, some prototypes of commercial absorption refrigerators with indirectly solar powered generators have been experimentally and theoretically investigated. In these studies, COPs of 0.2

to 0.3 and cooling capacities between 16 W and 62 W were reached at heating temperatures between 160°C and 230°C and evaporator temperatures of -6°C down to -18°C [2-5]. One research group used a diffusion absorption heat pump (DAHP), which is not yet commercially available, and modified it by substituting the direct gas fired generator by an indirectly heated one [6,7]. The solar thermal heating capacity of 1.8 kW is provided by vacuum tube collectors. The cooling capacity is approximately 1 kW and the COP is 0.59 at a heating temperature of 175°C and an evaporator temperature of 2°C.
Considering the circumstances that no suitable indirectly driven 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 diffusion absorption cooling machines (DACM) each with a design cooling capacity of 2.5 kW [8-10].

Prototype design

The well-known diffusion absorption technique which was developed in the 1920s by the Swedish engineers von Platen and Munters [11] is based on the principle of pressure equilibration between the high and low ammonia partial pressure sides of the unit through an inert auxiliary gas. A further peculiarity of this type of absorption cooling machine is the use of a indirectly driven gas bubble pump for the circulation of the solution cycle, instead of the mechanical solution pump, so that inside the cooling machine no mechanically moving parts are necessary. The core components of a DACM are the generator, condenser, evaporator and absorber, as shown in Figure 1. 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 as well as a dephlegmator for the 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 used working pair for the solution circulation is an ammonia/water mixture. The inert auxiliary gas used is helium.

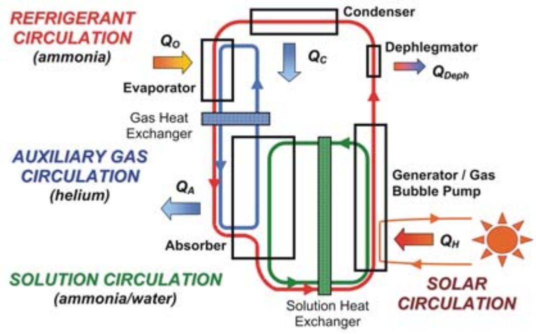

Figure 1: Principle of the DACM process

The prototypes of the DACMs are designed for the application area of air-conditioning as water chiller with an evaporator temperature of 12/6°C as well as for the operation of cooled ceilings with an evaporator temperature of 18/15°C. 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 run till July 2005. Due to the compacted design of DACM No.2 a weight reduction down to 290 kg (plate SHX) and 240 kg (coaxial SHX) was achieved. The third prototype also weighs 240 kg and the operation started in October 2005. Figure 2 shows the third prototype which had a total height of 2.20 m. The technical design data of the developed prototypes are:

- COP: 0.48
- generator water in/out: 130/120°C
- dephlegmator water in/out: 34/38°C
- condenser water in/out: 31/34°C
- evaporator cold brine in/out: 12/6°C
- absorber water in/out: 27/31°C

Figure 2: DACM prototype No.3

Performance Prototypes

Data acquisition was conducted under laboratory conditions as well as under simulated field conditions for vacuum-tube collectors. A series of measurements were taken at the first DACM with an indirect liquid heating system and obtained evaporator temperatures of 25°C 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 the operation was not continuous. The lowest reached heating inlet temperature of the generator was 147°C. The evaporator capacity decreased with time, which is due to saturation of the auxiliary gas with ammonia, as the gas circulation was insufficient.

Measuring results of the second compacted DACM with stationary temperature, pressure and capacity levels were obtained with variation of the heating temperatures, the cooling water temperatures and the cold brine temperatures. The achieved 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 6).

The first previous 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 had a better heat exchange than the plate heat exchanger.

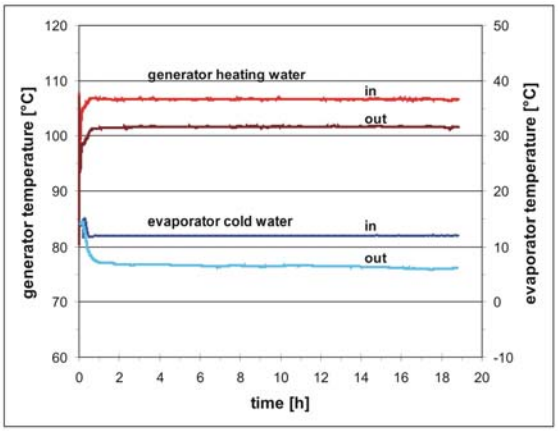

Figure 3: Measured generator and evaporator inlet and outlet temperatures of the DACM No.3 at a continuous cooling capacity of 0.7 kW and COP of 0.19

The experimental investigations of the third DACM with marketable dimensions are focused to the combined evaporator-GHX-absorber unit and the new designed generator. The first measurements were carried out at stationary pressure and temperature levels. The heating temperature range of the generator was reduced from 150°C to 175°C of the first prototype to 110°C to 155°C for the second prototype and now to 100°C to 150°C of the third prototype (Figure 3). This is due to the decreased lifting height of the bubble pump. With a same heat transfer surface the efficiency of the bubble pump increased and temperature levels dropped. The first experimental results show evaporator cooling capacities from 0.7 kW (Figure 4) up to 2.3 kW (Figure 5) and COPs between 0.12 and 0.30. The usually obtained evaporator temperatures are 12/6°C and 18/15°C. The lowest logged external evaporator outlet temperature was –15°C at a generator heating inlet temperature of 135°C.

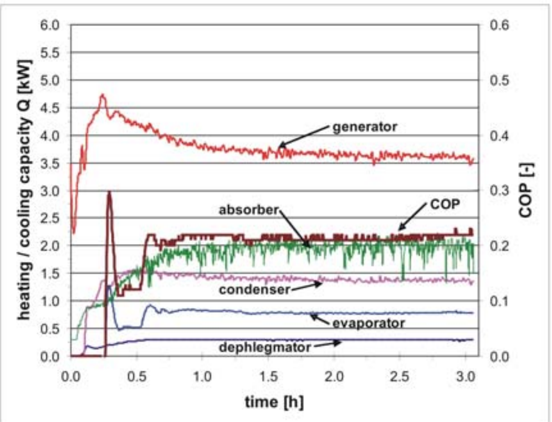

Figure 4: Measured heating and cooling capacities of the single components and COP of the DACM No.3 at heating inlet temperature of 105°C and evaporator temperatures of 12/6°C

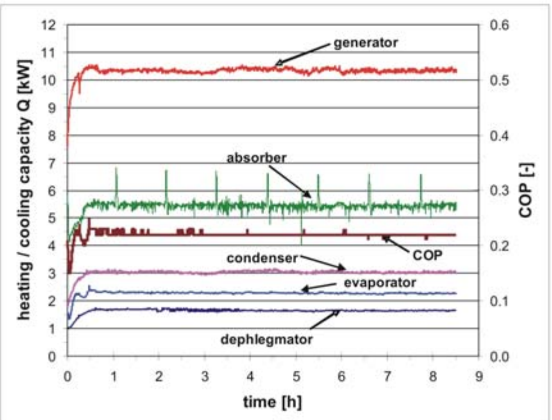

Figure 5: Measured heating and cooling capacities of the single components and COP of the DACM No.3 at heating inlet temperature of 150°C and evaporator temperatures of 18/15°C

The analysis of the heat recovery factors of the GHX, values >1, showed, that partly liquid ammonia evaporates inside the GHX, which could not be converted in cooling capacity inside the evaporator. In order to reach the design cooling capacity, the ammonia distribution and with that the wetting of the evaporator tubes and tube conditions, respectively, have to be further optimised.

Modelling and Simulation

The diffusion absorption cycle has been modelled starting from the constant characteristic equation of sorption chillers, which are 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 [12].

The characteristic equation (1) for the evaporator cooling capacity Q_0 [kW] of the DACM with the considered cooling losses of the auxiliary gas circuit Q_{AUX} [kW] is a simple function of a slope and the characteristic double temperature difference:

$$\dot{Q}_O = s_E \left(\Delta\Delta t - \Delta\Delta t_{\min,E}\right) - \dot{Q}_{AUX} \quad (1)$$

The double temperature difference $\Delta\Delta t$ [K] between the mean external generator and absorber temperatures t_G [°C] and t_A [°C] on the one hand and the external condenser and evaporator temperatures t_C [°C] and t_E [°C] on the other, is given in equation (2).

$$\Delta\Delta t = \left(t_G - t_A\right) - \left(t_C - t_E\right)\ B \quad (2)$$

The Dühring factor B [-] is usually for ammonia/water chillers between 1.6 and 2.4. The intersection $\Delta\Delta t_{min,E}$ [K] in equation (3) is determined with the efficiency of the SHX and thereby with the dissipated energy which results from the solution circulation between the absorber Q_{Ax} [kW] and the generator Q_{Gx} [kW]. The slope s_E [kW/K] given in equation (4) contains the enthalpy differences between the inlet and outlet of each component and the heat transfer coefficient UA [kW/K] between the external and internal circuits.

$$\Delta\Delta t_{\min,E} = \left(\frac{\dot{Q}_{Ax}}{UA_A} + \frac{\dot{Q}_{Gx}}{UA_G} \right) \qquad (3)$$

$$s_E = \begin{pmatrix} \left(\frac{C_E}{UA_C} + \frac{1}{UA_E} \right) B \\ + \left(\frac{G_E + G_{E,deph}}{UA_G} + \frac{A_E + A_{E,aux}}{UA_A} \right) \end{pmatrix}^{-1} \qquad (4)$$

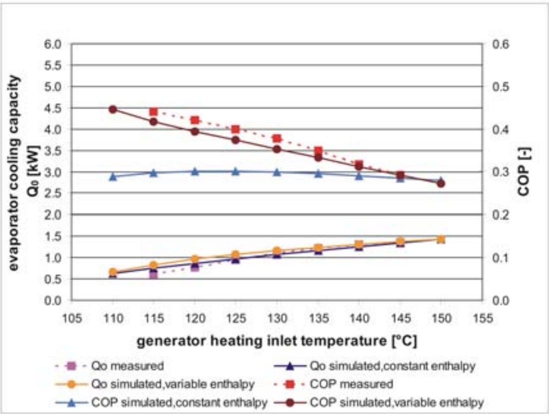

Figure 6: Comparison of measured and simulated values of the DACM No.2 (design evaporator temperature is 22.5°C at 1.3 kW cooling capacity as well as generator, absorber and condenser temperature of 140°C, 29°C and 32°C, respectively with SHX and GHX efficiency of 0.76 and 0.30, respectively)

The model was implemented in the simulation environment INSEL and validated by experimental data of the 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 6). For the case of constant enthalpy, the performance deviated from the measured ones.

Furthermore a parameter study was 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. Furthermore, the lower the absorber cooling inlet temperature, the higher is the resulting evaporator cooling capacity. A strong influence on the cooling capacity is given by the surface wetting factor as well as the heat recovery factor. With a higher surface wetting factor as well as a better evaporation efficiency, the cooling capacity and the COP increase by a factor 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 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 the values of COP ranged from 0.10 to 0.20, and 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. The reached 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, which has now marketable dimensions, showed cooling capacities between 0.7 kW and 2.3 kW at evaporator temperatures of 12/6°C and 18/15°C with COPs from 0.12 to 0.30.
An expanded, steady-state model of the DACM based on the characteristic equation of sorption chillers showed a good accordance of the compared experimental and simulated data. Efficient evaporation with high surface wetting factors is essential for high performance.

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