ABSORPTION COOLING BY SUN AND WASTE ENERGY

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ABSTRACT

At present there are no thermally driven absorption cooling machines available on the market which could provide small-capacity cooling for domestic housing applications as well as offices and hotel rooms of less than 10 kW. This paper investigates the development and testing of single-stage solar or waste energy heated ammonia/water (NH_3/H_2O) diffusion-absorption cooling machines (DACM). The designed cooling capacity of the cooling machine is 2.5 kW at evaporator temperatures between -10°C and +15°C with indirect heating through commercial vacuum tube collectors. The indirectly heated, solar powered generator (bubble pump) represents the main new feature of this cooling machine. Two DACM pilot plants were built, run and data acquisition was conducted under laboratory conditions as well as simulated field conditions for vacuum tube collectors. The pilot plants were gradually analysed and stepwise improved. The second pilot plant now reaches a maximum cooling performance of 2 kW and a coefficient of performance of 0.45 (COP, ratio of cooling output to driving heat input).

Keywords: solar, waste energy, diffusion-absorption cooling, ammonia, water

1. Introduction

The diffusion-absorption technique from the Swedish engineers von Platen and Munters [11] is based on the principle of pressure equilibration between the high and low pressure side through an inert auxiliary gas, such as helium. A further special request on this type of cooling machine is the use of a thermally driven gas bubble pump instead of a mechanical fluid pump, so that inside the cooling machine no mechanically moving parts are necessary.

Conventional gas or electrically driven diffusion-absorption refrigerators (DAR) with directly powered generator/gas bubble pumps have been theoretically and experimentally investigated in numerous research works for the operative range of refrigerating as well as in part for air-conditioning [1,2,4,9,15,18]. These directly driven DARs have been available since 1925 and they are manufactured for instance by Dometic AB, Sweden (formerly Electrolux AB). The cooling power of these DARs is between 40 W and 200 W.

In the 1990s these domestic DARs were modified and improved for the use as directly heated, gas driven diffusion-absorption heat pumps (DAHP). A group of researchers [12,16,17] developed a directly gas heated 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 up to +5°C. Coefficient of performances for heating applications (ratio of heating output to driving heat input) between 1.4 and 1.5 were achieved. The industrial conversion of this directly heated, gas powered DAHP is realised in combination with a condensing boiler for a near-market unit, but is not yet commercially available. The heating capacity of the DAHP is approximately 3.6 kW (condenser) at a COP of 1.5 and it consists of 1.2 kW power input out of environmental heat through the evaporator by a solar air collector and 2.4 kW heating capacity through the gas burner/generator [3,13].

A new technology, called 3AC (advanced ammonia absorption cooling) was developed and built by another research group. The normal diffusion absorption refrigeration machine is fitted with an extra loop, called a bypass, between the evaporator, fluid cycle and absorber to achieve heating temperatures as low as 80°C for the use with flat plate collectors. Different prototypes were built with 400 W and 100 W cooling capacity and apparently a COP greater than 0.3. Evaporator temperatures for milk refrigeration at +4°C and for refrigeration at -30°C were achieved. A new prototype using a "Heronic Pump" rather than the classical bubble pump with 2.0 kW cooling capacity was set up [10,14].

To date, there are no suitable absorption cooling machines of small-scale cooling performance (1 kW to 10 kW) available on the market. Since 1998 the research team in the Department of Building Physics at the Stuttgart University of Applied Sciences has developed two single-stage solar heated ammonia/water DACMs with 2.5 kW cooling power and helium as the inert gas [5,6,7,8]. The specific objectives of this paper, therefore, are as follows: development of the solar driven DACM No.1 and No.2, analysis and experimental characterisation of the performance potential of the DACMs and the further potential of a market-ready unit.

2. Process and design

The core components of a DACM are the generator, condenser, evaporator and absorber (Figure 1). A fluid heat exchanger (FHX) in the fluid circuit and a gas heat exchanger in the auxiliary gas circuit are also components of the DACM as well as a dephlegmator for the condensation of the evaporated solvent.

At low partial pressure in the evaporator the cooling agent evaporates and is absorbed again in the absorber by the weak ammonia/water fluid from the generator. In the indirectly solar powered generator with high heating temperatures the cooling agent is driven out of the rich ammonia/water fluid and so a high cooling agent vapour pressure is generated which is enough for the condensation of the cooling agent in the condenser.

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The usual mechanical fluid pump of absorption cooling machines is replaced in a DACM by a thermal gas bubble pump. The circulation of the fluid between the generator and absorber is maintained by vapour bubbles which are generated at nucleation cells at the lower part of the lifting pipes and forms at best a slug flow regime to push up a liquid column. So the processes of desorption of the cooling agent and lifting the fluid are combined in one component. The pressure compensation between high and low pressure level is achieved by the inert auxiliary gas helium. The auxiliary gas circulates between the evaporator and absorber because of the temperature and density differences. There are no mechanical moving components inside the cooling unit and total pressure is constant at all points inside the cooling unit.

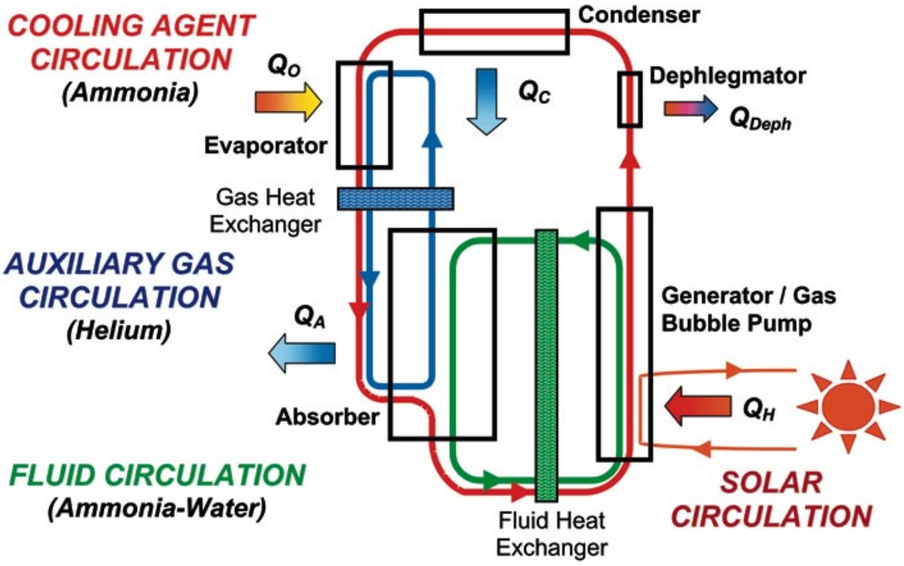
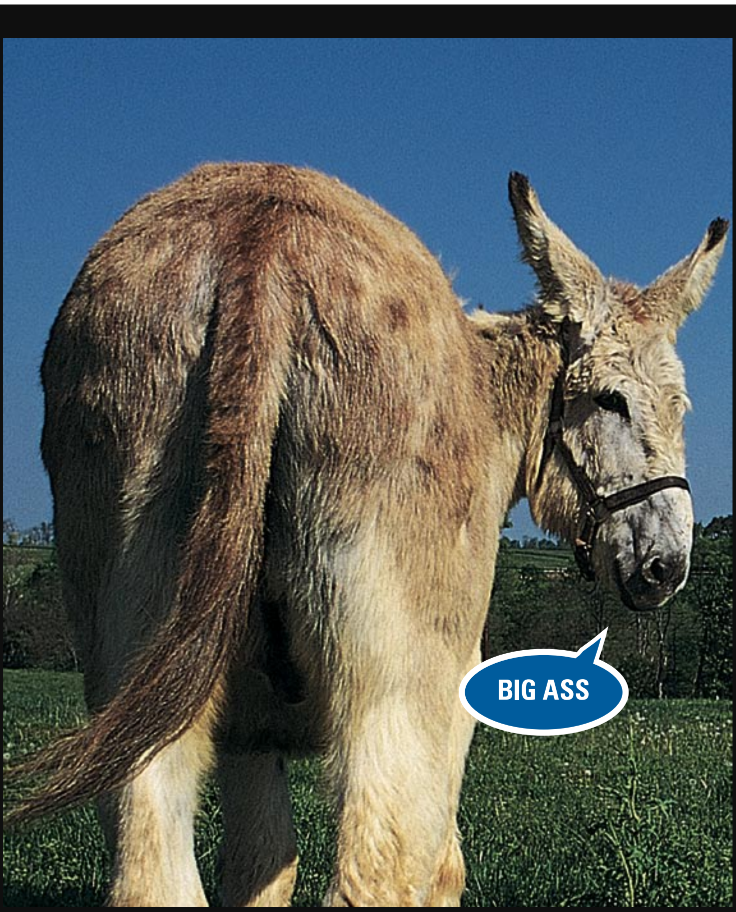


Figure 1 - principle of the DACM process



		DACM No.1	DACM No.2
Dimensions	w x d x h	1.5 x 1.5 x 3.7 m	0.8 x 0.8 x 2.4 m
Weight		800 kg	290 kg Plate-FHX 240 kg Coaxial-FHX
COP		0.48	
Generator	heating capacity Q_H	5.2 kW	
	heating water in/out	130/120°C	
Dephlegmator	cooling capacity Q_{Deph}	0.9 kW	
	cooling water in/out	42/47°C	
Condenser	cooling capacity Q_C	2.8 kW	
	cooling water in/out	32/35°C	
Evaporator	chilling capacity Q_O	2.5 kW	
	chilled water in/out	12/6°C	
Absorber	cooling capacity Q_A	4.0 kW	
	cooling water in/out	27/32°C	

Table 1 - site and design data of DACM No.1 and No.2

The two pilot plants of the single-effect DACMs were designed for air conditioning and refrigeration. The design and site data of the pilot plants is summarised in Table 1.

3. Development and construction

3.1 DACM No.1

The development of the first pilot plant of the solar driven DACM was completed in October 2000 within a European JOULE-CRAFT program at the Stuttgart University of Applied Sciences. The designed performance range of the cooling machine of 2.5 kW led to the development of a newly constructed generator with indirect heating, an efficient bubble pump as well as new heat exchanger geometry.

3.1.1 Standard components

The standard components (condenser, evaporator, gas heat exchanger, absorber and fluid heat exchanger) were constructed as a vertical or horizontal tubular heat exchanger (Figure 2). The condenser and the absorber were water-cooled and cold brine was used for the refrigeration circuit of the evaporator.

3.1.2 Newly developed components

The usual mechanical fluid pump of absorption cooling machines is replaced in a DACM by a thermal gas bubble pump. By indirect heat input, vapour bubbles are generated which, at best, produce a two-phase slug flow in several lifting tubes pushing liquid upwards

Figure 2 - first DACM pilot plant

Figure 3 - second DACM pilot plant

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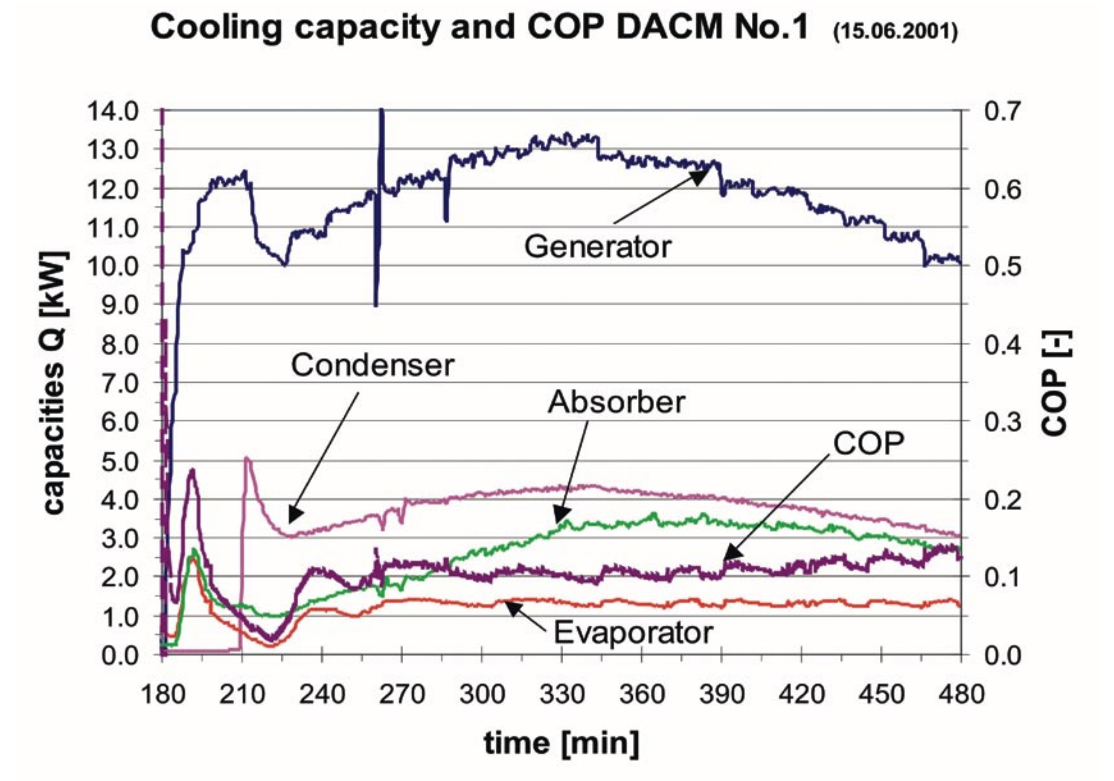

Figure 4 - measured, supplied and dissipated power and COP of the DACM No.1 based on a simulated irradiation gradient

through columns for the circulation of the fluid between the generator and absorber. This is necessary to attain good heat transfers, because of the low heat flux densities in the solar heating section of the generator.

There were three newly developed, constructed and built generator prototypes all with a different design. The generator prototype No.1 led the ammonia vapour inside the generator through a central tube from the top downwards out of it. Due to the welding difficulties, further development was stopped.

After that, generator prototype No.2 was constructed with smaller dimensions and with a direct ammonia outlet on the top of the generator head. A simpler construction was selected to avoid the previous problems. This second generator was separately investigated with methanol and methanol/water fluid. An additional third generator was developed and built to achieve an improvement of the heat transmission in the solar heating section by suitable constructive steps.

The constructive fluids of the generator were difficult because of the required high pressure level at operating conditions of 18x10^5 Pa. In particular, the tube design and fixation led to leakages of the first prototype construction. Finally two prototypes of the generator indirectly heated through a solar thermal collector field would be manufactured for the first pilot plant of the DACM.

3.2. DACM No.2

A second optimised pilot plant based on the experiences and results of the first pilot plant was built in July 2003 at the Stuttgart University of Applied Sciences. For the designed and realised cooling capacity range of the second cooling machine of 2.5 kW, a further improved indirectly heated bubble pump was developed. The auxiliary gas circuit construction was also reworked. This resulted in weight reduction down to 240 kg and height reduction to 2.40 m which are important for a later market-ready unit.

3.2.1 Standard components

Figure 3 (previous page) shows the second pilot plant of the DACM with standard commercial condenser and fluid heat exchanger (nickel soldered plate heat exchanger). The heat transfers in the previously used horizontal tubular heat exchangers between rich and weak ammonia/water fluid in the fluid heat exchanger and between the condensed cooling agent and the external cooling liquid in the condenser were insufficient.

In the starting phase of the cooling machine helium is always in the condenser, which is normally subsumed into the evaporator by ammonia vapour coming from the generator. In the first pilot plant helium partly remained in the condenser, so the maximum heat transfer surface was not available and the condenser capacity was reduced. Due to this reduction, higher generator temperatures and a higher condenser pressure were necessary to condense the ammonia vapour that entered.

The fluid heat exchanger for this part had included a reservoir for the ammonia/water fluid with approximately 60 litre capacity. That led to a very long preheating phase of the whole fluid heat exchanger and therefore to a sluggish heat exchange between the cold and concentrated fluid from the absorber and the hot and weak fluid from the generator. The preheating of the concentrated fluid was not sufficient, so instead of 100°C generator inlet temperature, the maximum temperature was only 50°C to 60°C after three hours of operation. In the second pilot plant the reservoir

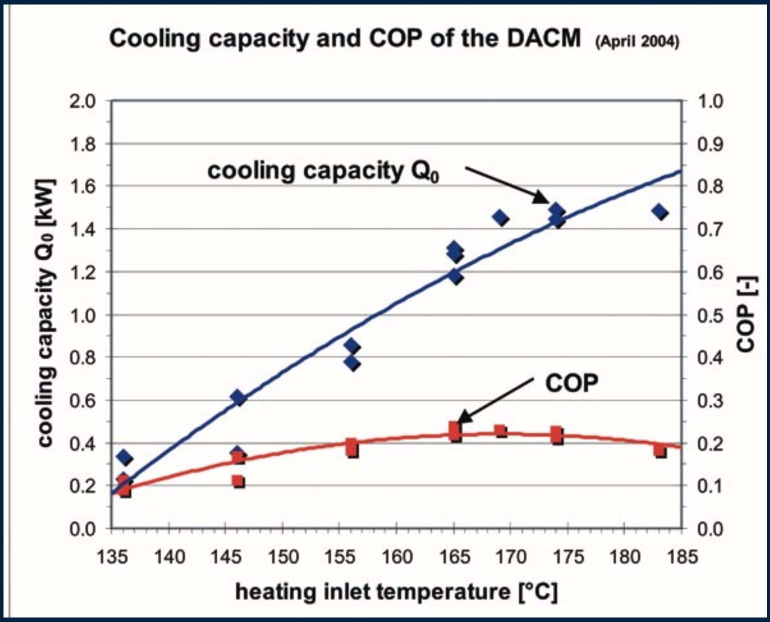

Figure 5 - measured cooling capacity and COP of the DACM No.2 before the latest improvements

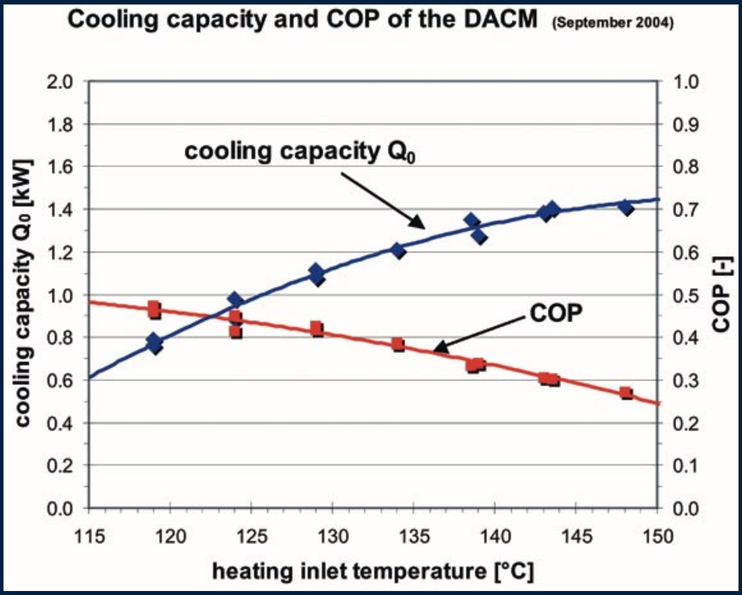

Figure 6 - measured cooling capacity and COP of the DACM No.2 after the latest improvements

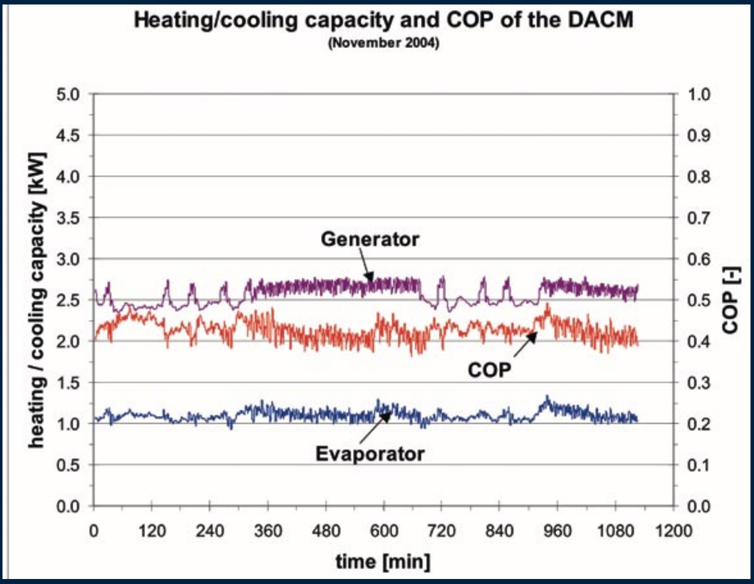

Figure 7 - long-term measured heating/cooling capacity and COP of the DACM No.2 after the latest improvements

is uncoupled from the fluid heat exchanger and integrated below the absorber. By the use of plate heat exchangers the pressure drop of both components was slightly increased.

In the second pilot plant the components of the auxiliary gas circuit evaporator, gas heat exchanger and absorber were again constructed as vertical tubular heat exchangers, but compacted in size (Figure 3).

The condenser and the absorber are water-cooled. Cold brine is used for the refrigeration circle of the evaporator.

3.2.2 Newly developed components

As a new development a fourth generator prototype was developed, constructed and built. Due to the smaller overall height of the second pilot plant, the lifting height of the bubble pump could be reduced. This led to a higher efficiency of the bubble pump and a noticeable reduction of the generator heating temperatures.

At present, the temperatures for the indirect heating system of the generator could be reduced to 130°C.

4. Measurement results and performance

4.1 Cooling capacity and COP of DACM No.1

A series of measurements from November 2000 to March 2002 were undertaken for the first pilot plant of the DACM at the generator heating inlet temperatures of 150°C and reached evaporator temperatures from 0°C to 25°C. The results show that COP values range from 0.1 to 0.2 and the cooling capacity of the pilot plant could reach 0.5 kW to 1.5 kW, but the operational stability was insufficient. In most experiments the evaporator capacity decreased with time. The measured heating capacities were in the range of 4.0 kW to 13.5 kW, depending on the mass flow rate and the heating temperature. In order to increase the cooling capacity and the COP, it was found that further optimisation of the internal fluid cycles and reduction of the heat losses were necessary.

Further investigations were also carried out with the indirect liquid heating system based on a simulated solar irradiation gradient for a vacuum tube collector field with a maximum irradiation of 900 W/m^2 and solar collector outlet temperatures (equal to the generator inlet temperatures) varied from 80°C to 170°C. In this case the solar collector outlet temperatures were calculated by the measured solar irradiation gradient over one sunny day and the efficiency of the measured 19.3 m^2 vacuum tube collector field at the University of Applied Sciences Stuttgart. Figure 4 shows the measured values of COP and cooling capacity of DACM No.1 for the operation period between 10:00 o'clock and 15:00 o'clock. The measurements were based on the solar irradiation gradient gave to heating capacities between 10.0 kW and 13.5 kW. The continuous cooling capacity obtained was 1.5 kW.

The operation experiences of the first pilot plant show that within the pure thermosyphon cyclic process of the pressure compensated auxiliary gas circuit, instabilities occurred, which led to fluctuation of the generated cooling capacity.

4.2 Cooling capacity and COP of DACM No.2

After a number of safety and pressure tests the cooling machine was tested in a first period from July 2003 to November 2003. The evaluated ammonia mass flow of the first measurements is in a range between 1 kg/h and 3 kg/h at 30% initial ammonia mass fraction of the whole ammonia/water fluid and a maximum cooling power of 800 W. The continuous cooling power is around 500 W with COPs between 0.1 to 0.2. The designed and required ammonia mass flow is approximately 5-8 kg/h for 2.5 kW cooling power. So in a first step the initial ammonia mass fraction was concentrated to 40%. The new results showed that the ammonia mass flow increased to 2-4 kg/h, but the cooling power is again in a range of 500 W.

The only effect that was observed is that the generator outlet temperature of the weak fluid decreased from 140°C to 120°C at the same external heating inlet temperature of 150°C by increasing of the degassing width. Due to insufficient heat exchange rates of 11% the plate heat exchanger of the second pilot plant was replaced by a coaxial heat exchanger in March 2004. By doing so the heat recovery factor could be increased to 78% and the temperature of the concentrated fluid entering the generator was lifted to 80°C-100°C and reached the design values.

After this change, the test runs and following data acquisition analysis showed a remarkably improved COP of 0.2 to 0.3 and continuous cooling performance of 1.5 kW for heating inlet temperatures between 135°C and 185°C (Figure 5).
A performance of 2 kW could be reached if the evaporator temperature was set up to relatively high values of 25°C.

After some more modifications of the second pilot plant and refilling it with 37% initial ammonia mass fraction a further period of measurements started in September 2004 until July 2005. The new results showed a further improved COP of 0.3 to 0.45 (Figure 6) and continuous cooling performance up 1.6 kW at evaporator outlet temperatures for air conditioning with static cooling surfaces between 22°C and 15°C. Among other things the heating inlet temperatures could be reduced down to 120°C. Figure 7 shows a 20-hour long-term measurement at a heating inlet temperature of 130°C, where an actual average COP of 0.43 was reached.

5. Conclusion and future work

Two solar driven diffusion-absorption cooling machines have been developed and built, to date. For the first pilot plant, low COP values from 0.1 to 0.2, a cooling capacity of 1.5 kW but an insufficient operating stability were achieved.

A second optimised pilot plant was built based on the experiences of the first, using partly standard components such as nickel soldered plate heat exchangers and a coaxial heat exchanger. For this much more compact pilot plant, the auxiliary gas circuit construction was reworked and a further generator was developed. The second pilot plant was put into operation in July 2003 and is running stably. COPs between 0.2 and 0.45 and cooling capacity ranging from 1.0 kW to 2.0 kW have been reached. Further development is required regarding cooling power and COP as well as weight and production cost reduction. With the second pilot plant promising steps regarding the above mentioned requirements have been made. For example it was possible by changing one of the five main components of the cooling machine to reduce weight of the unit about 20%, to double the performance and to reduce costs at the same time.

At present a third pilot plant with the dimensions 0.6 x 0.6 x 2.3 m is set up for 2.5 kW cooling power and moreover a 5 kW cooling machine is under development which should be set up by the middle of 2006.

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6. Nomenclature

COP	coefficient of performance	
Q_A	absorber cooling water capacity	(kW)
Q_C	condenser cooling water capacity	(kW)
Q_{Deph}	dephlegmator cooling water capacity	(kW)
Q_H	generator heating water capacity	(kW)
Q_O	evaporator chilled water capacity	(kW)

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