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Performance of a silica-gel + water adsorption cooling system for use in small-scale tri-generation applications

R. de Boer

S.F. Smeding

R.J.H. Grisel

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Abstract

The SOCOOL project focuses on the development of a small-scale combined cold, heat and power (tri-generation) system, which utilises the engine waste heat for cold production. It is demonstrated at the CRF Eco-Canteen in Turin, Italy. The cooling machine is made of two separate sub-cooling systems, each of which is to produce 5 kW of cooling power. One of the cooling systems is driven by 'low-temperature' engine cooling water, the other by 'high-temperature' engine exhaust gases. Tri-generation systems that use heat-driven cooling, offer the possibility of saving 15-20% primary energy.

The low-temperature-driven sorption-cooling machine was designed and built at ECN, The Netherlands. Its performance was tested in our own laboratories, before shipment to Turin where it was integrated with the internal combustion engine.

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1. Introduction

Within the EU there is a growing demand for comfort cooling in the residential and commercial area. This leads to increased primary energy usage, CO_2 emissions and higher peak electricity demand [1]. The use of tri-generation systems for the combined production of heat, cold and power can contribute to the reduction of CO_2 emissions and thus help in meeting Kyoto targets, when 'waste' heat is used to produce the cooling. The SOCOOL project [2], funded under the EU Framework-5 Energy Programme, aims at the development of a small-scale tri-generation system, with emphasis on the use of engine waste heat for cold production.

Small-scale tri-generation concepts offer the possibility for energy savings in the range of 15-20% [1] for heating, cooling and power production, in comparison to conventional tri-generation technology based on compression cooling systems. In addition, sorption-cooling systems may use natural refrigerants that have zero ozone-depleting potential and zero global-warming impact.

Tri-generation is a well-known and proven technology for large-scale (>100kW electrical, 200kW thermal) applications. However, for small-scale applications (<50kW cooling) no heat driven cooling systems are available in the market.

The benefits for heat-driven cooling are, amongst others, a better utilization of thermal energy associated with power production and a reduction of the afternoon peak electrical power demand due to the use of electric chillers.

In the present study, the development and the performance of a solid-sorption cooling system driven by low-grade heat from the jacket cooling water of an internal combustion engine are presented. The performance targets for the cooling system are to reach a cooling power of 5 kW with a cooling power density >20 kW/m^3. This is to be achieved by applying advanced working pairs as well as an innovative heat exchanger design to obtain the required high rates of heat and mass transfer in the solid sorbent bed. This paper addresses the aspects of design, construction and laboratory testing of a small-scale low-temperature heat-driven solid-sorption cooling machine.

2. System development and test procedure

The sorption-cooling system works with a heat source of 80-90°C and cooling water of 20-35°C, producing cold at 6-10°C. Silica-gel + water was selected as the working pair for these operating temperatures. The selected silica-gel, designated as Sorbsil A, was kindly provided by Ineos Silicas from the UK.

The basic layout includes two sorbent reactors operating in counter phase in order to obtain continuous cold production, see Figure 2.1. Pneumatically-operated vacuum valves were installed to direct the water-vapour flows; from sorbent to condenser and from the evaporator to the sorbent again. The condenser and evaporator were both water-cooled plate-shell heat exchangers from Vahterus, Finland, designed for 5 kW thermal capacities. To maintain the necessary pressure difference between the condenser and evaporator, a U-tube was installed. A pump was used to continuously wet the evaporator surface area. A demister or separator was placed in the vapour line to prevent water droplets from entering the sorbent reactors.

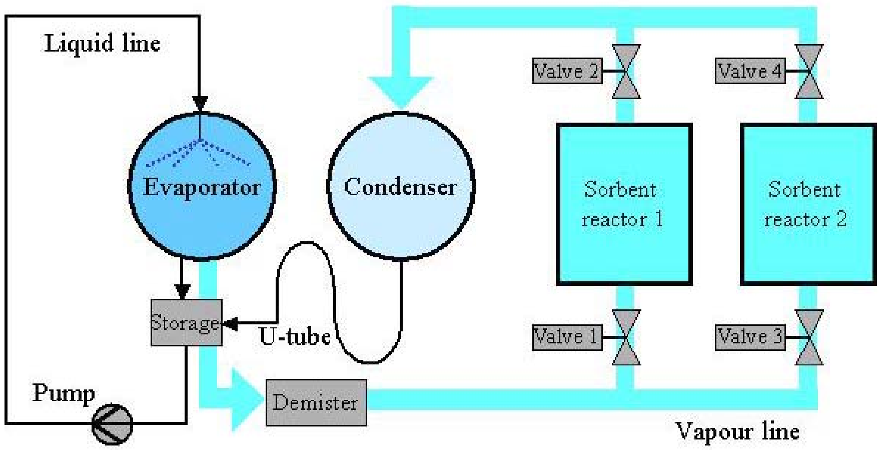


Figure 2.1 *Basic system layout of the sorption cooling system*

The key component of the solid-sorption cooling system is the sorbent heat exchanger. As a building block a 1.4 kg compact aluminium automotive plate-fin heat exchanger was selected (Figure 2.2), through which the heat-transfer medium is conducted in 3 passes. The inter-plate distance was 8 mm. Fins were stacked between the plates with a fin pitch of 3.5 mm. The specific surface area of the heat exchanger was estimated to be 950 m^2/m^3 including fin surface and 175 m^2/m^3 without. With outer dimensions of 200 x 265 x 65 mm, the total volume of the heat exchanger amounted to about 3.5 dm^3. The heat exchanger was filled in between the fins with about 1.5 kg of dry micro-porous silica-gel grains of 0.2-1.0 mm in diameter, resulting in a sorbent-to-metal mass ratio of slightly above unity. A wire mesh was wrapped around the heat exchanger to contain the silica-gel grains. Tests on the heat-transfer rate and cooling performance obtained with this specific type of heat exchanger were reported earlier [4]. Based on these results, supported also by system model calculations, the design of the sorption reactors was defined. Both sorption reactors consisted of six filled plate-fin heat exchangers stacked together in parallel flow mode (Figure 2.3).

Figure 2.2 *Plate fin heat exchanger to be used as sorbent reactor (left) and detail of a silica-gel filled part of the heat exchanger (right)*

A plate shell type heat exchanger was used as evaporator (Figure 2.3, middle). It comprised 100 corrugated plates with a total heat-exchange surface area of 3.1 m^2. The plate stack is positioned eccentrically towards the bottom to allow for a better distribution of the water, which enters from the top by two spray nozzles. The vapour generated on the exchange surface leaves the evaporator at the bottom. The water to be chilled flows through the plates.

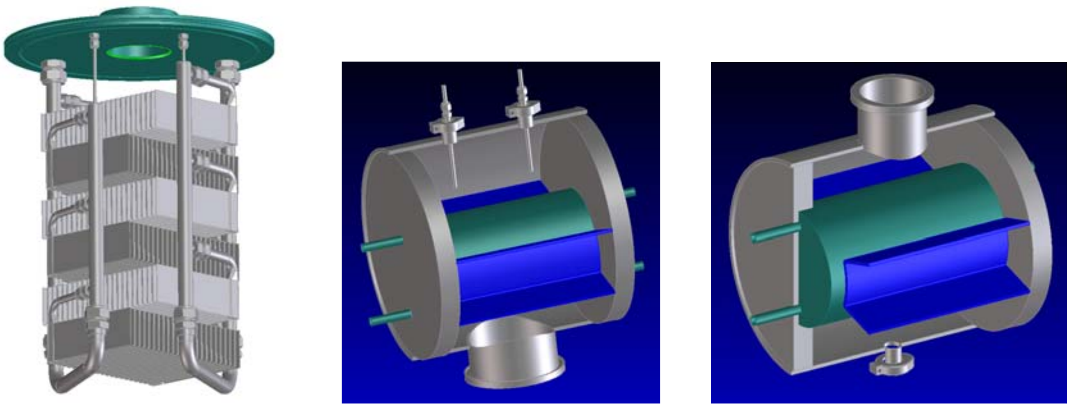


Figure 2.3 *Design drawings of the assembly of 6 plate-fin heat exchangers in the sorbent reactor (left), the plate-shell evaporator (middle) and the condenser (right). The green sections in the middle represent the plate area; the blue parts are support/separator plates*

The condenser was constructed similarly, except that the plate stack is positioned in the middle and the housing is slightly smaller. The water vapour enters from the top, condenses, and leaves at the bottom. The cooling-water flows through the plates. Both evaporator and condenser are made of fully-welded stainless steel.

The total volumes of the four vessels that contain the heat exchangers add up to 210 dm^3. The total volume of the active heat-exchanging components is 62 dm^3.

All the thermal components were assembled together in a test-rig, see Figure 2.4. External heating, cooling and chilled water circuits were connected to mimic operating temperatures and flow rates of the tri-generator system. The sorption reactor and condenser were connected in parallel with respect to the cooling water, in order to achieve the lowest possible temperatures for both components.

Figure 2.4 *Design drawing of the test-rig (left) and a photograph of the test-rig in the laboratory (right)*

A PLC system controlled the operation of the vacuum valves as well as the valves in the heating and cooling-water circuits. The test-rig was equipped with flow, temperature and pressure measurement devices to measure thermal powers transferred to every heat-exchanging component of the cooling system and to monitor proper operation of each component. A test program was executed to characterize the cooling power and COP of the cooling system under varying operating temperatures.

3. Results

The first experiments were dedicated to the identification of the optimum cycle time of the sorption reactors (Figure 3.1). During these 'scanning' experiments a good compromise between the chilling power and the COP was found at a cycle time of 15 minutes. One thermal cycle consisted of 7 minutes of heating followed by a 30–second interval, then 7 minutes of cooling, and again a 30-second interval before repeating the whole cycle. At the start of the intervals only the heat-transfer fluid flows at the inlet of both reactors were switched; at the end of the intervals, also the flows at the exit were switched. In this way, the hot water, still present in the heat-exchanger stack at the beginning of the interval, is prevented from entering the cooling-water circuit directly and, similarly, the relatively cold cooling water is prevented from entering the hot-water circuit. Yet after 30 seconds, when the temperature of the streams emerging from both heat-exchanger stacks were allowed to level somewhat, connections to the ‘proper’ circuits were made. With this procedure, less heat is short-circuited during switching, and therefore the COP of the system is increased.

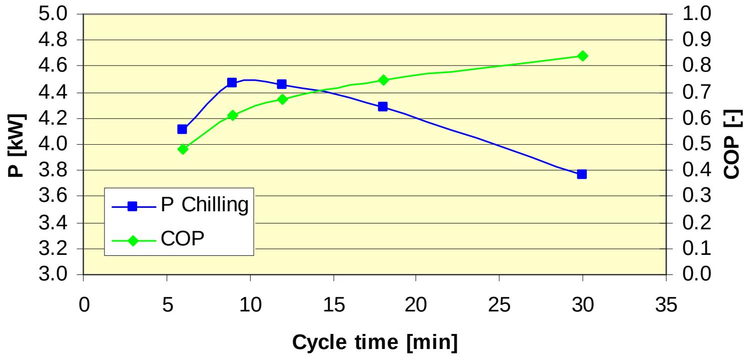


Figure 3.1 *Chilling power and COP as a function of cycle time at inlet temperatures: $T_{heating}$ 85°C, $T_{cooling}$ 25°C, $T_{chilling}$ 15°C*

The standard operating conditions as well as the temperature ranges used to test the performance of the cooling system are summarized in Table 3.1. The design flow rates through the sorbent reactors for heating and cooling were 1.4 m^3/h. The actual flow rates obtained were, due to restrictions in the tube layout, only 70% of the design value.

Table 3.1 *Applied operating conditions and results for the test-rig*

Water circuit	Flow rate [m^3/h]	Standard inlet temperature [°C]	Temperature ranges for testing [°C]	Average thermal power [kW]
heating reactor	0.97	87	73-91	5.6
cooling reactor	0.91	25	21-43	6.6
cooling condenser	0.83	25	21-43	4.0
chilling evaporator	0.66	12	6-25	3.6

The thermal power profiles of the sorbent reactors, the condenser and the evaporator during a 15-minute cycle are shown below in Figure 3.2.

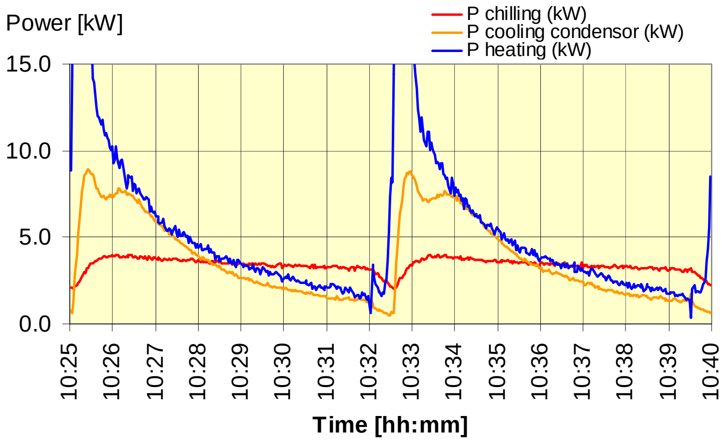
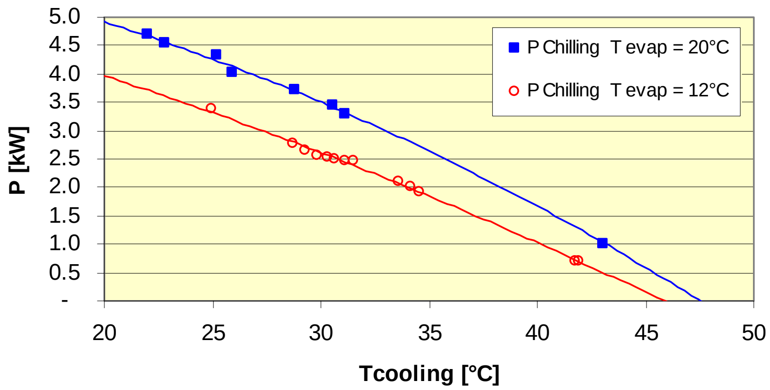


Figure 3.2 *Thermal power for heating the sorbent reactor, cooling of the condenser and chilling of the evaporator during the 15-minute cycle under standard conditions*

It can be seen that the chilling power of the evaporator remained fairly stable in the range of 4-3 kW over the cycle except for a 1-minute dip directly after switching (the temperature of) the heat-transfer medium through the sorbent reactors. The thermal powers for heating and condensation fluctuated much more.

The thermal power transferred by the evaporator (P chilling) as a function of the cooling-water inlet temperatures is shown in the left-hand side of Figure 3.3. At standard conditions the average chilling power was 3.6 kW. This corresponds to 200 W of chilling power per kg dry silica-gel. Considering the volume of the heat exchangers in the system alone, a volumetric thermal power density of 58 kW/m^3 is calculated. However, the power density only remains 17 kW/m^3 for the system as a whole.

The chilling power decreased almost linearly with increasing cooling-water temperature (Figure 3.3). The targeted 5 kW of chilling power was reached only under favourable operating temperatures, i.e. 20°C chilled-water inlet and 20°C cooling-water inlet. On the right-hand side of Figure 3.3 the change of cooling power and COP as a function of the heat-source inlet temperature is shown. The performance in terms of chilling power and COP changes only slightly over the range 70 - 90°C of driving temperature.



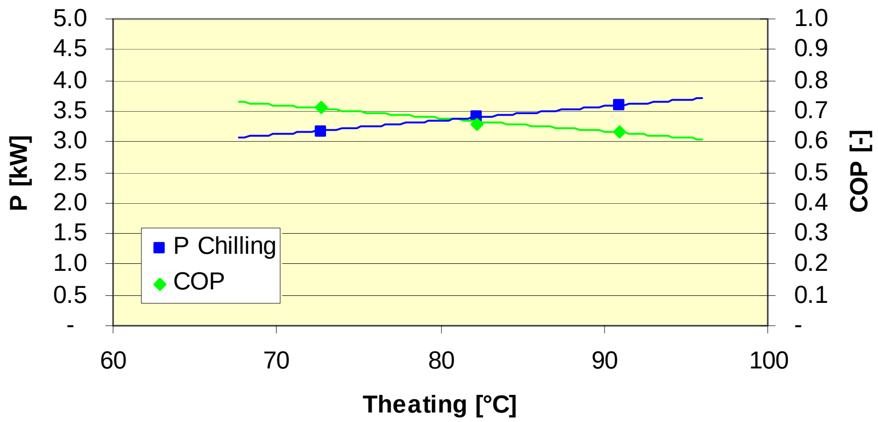


Figure 3.3 *Cooling power as a function of the cooling water inlet temperature at different chilled water (T evap) temperatures (first). Cooling power and average COP at different heat source inlet temperature (second)*

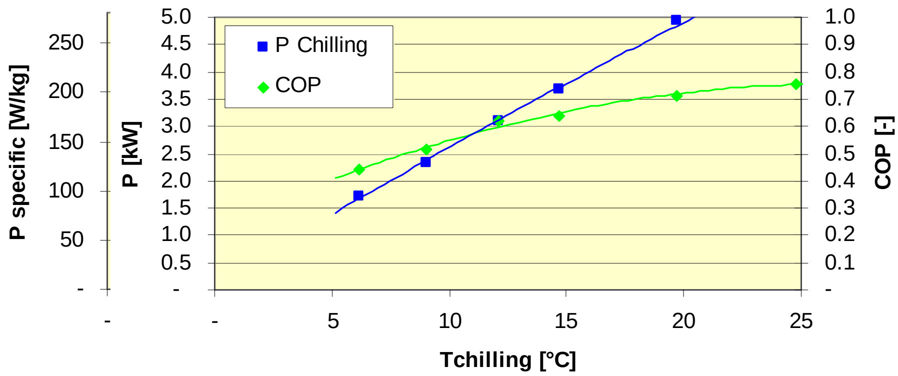


Figure 3.4 *(Specific) average chilling power and average COP as a function of the chilled water inlet temperature*

Figure 3.4 shows the measured average chilling power and COP with varying chilled-water inlet temperatures. The chilling power increases almost linearly with increasing chilled-water inlet temperature from 5-20°C.

4. Discussion and Conclusions

The solid-sorption cooling system developed for small-scale tri-generation applications can meet the desired thermal performance in terms of chilling power (5 kW) as well as the required power density (>20 kW/m^3). At this stage, however, the targeted performance is only reached under favourable temperature conditions. A further increase in chilling power is expected when the flow rates through the sorbent reactors during heating and cooling are increased to their original design values. The actual values of just below 1 m^3/h were only at 70% of the design flow rates of 1.4 m^3/h. The overall heat-transfer rate in the sorbent reactors is therefore reduced with respect to its design value, resulting in a reduced overall system performance. The future tests at the ECO-Canteen will be performed with the higher flow rates.

Taken into account that the laboratory system was spaciously built, there remains ample room to improve the power density of future systems, viz. by placing more heat-exchanging components in a single vacuum containment, and/or by using a containment that more tightly envelops the heat exchangers.

The inlet temperature of the chilled-water circuit was found to have a large influence on the system's performance; a lower chilled-water temperature led to less chilling power. The temperature of the heat source in the range of 70-90°C has little influence on the system's performance.
The performance of the evaporator was limited because of poor wetting of the surface area. The wetting was imperfect due to a badly functioning pump in the internal water circuit. Improved active wetting of the evaporator heat-exchange surface area is expected to increase the overall system performance.

The thermal powers transferred to the sorbent reactors during the heating and cooling phases fluctuate very strongly. This fluctuation of thermal power is an aspect of solid-sorption cooling systems that has to be considered carefully when integrating such a cooling system with a heat source, such as an internal combustion engine that may not be capable of coping with these strong thermal power fluctuations. Integrating a thermal-storage unit in between the engine and the cooling system, or installation of an improved control system, is expected to solve this problem.

Heat recovery is performed in an interval of about 30 seconds between the switching of the reactor inlet valves and switching of the outlet valves of the water circuits. This avoids mixing of hot water from one reactor with the cooling-water circuit and cooling water from the other reactor with the hot-water circuit, until the temperature of both flows are somewhat levelled. The thermal energy contained in this water would otherwise be completely destroyed, resulting in a significantly lower COP. Test results obtained without the use of this switching interval indicated a more than 30% decrease of efficiency, with a COP of about 0.4.

The cooling system is now installed at the Eco-canteen demonstration site at project partner CRF and is connected to the co-generator unit. The first tests have been performed, indicating proper operation of the cooling system combined with the co-generator. Further testing is foreseen during the summer period of 2006.

References

[1] Chwieduk, D., W. Pomierny, R.E. Critoph, G. Restuccia, A. Freni, R. de Boer, S.F. Smeding & C. Malvicino (2004): *Tri-generation in the tertiary sector: Market potential in some European countries, Technical solutions and Demonstration project*. Proceedings of the VIII World Renewable Energy Conf., Denver, USA.

[2] http://socool.ippt.gov.pl/home.php

[3] Boer, R. de, D. Chwieduk, R.E. Critoph, C. Malvicino & G. Restuccia (2004): *SOCOOL - Solid Sorption System for Cooling in Tri-generation.* Proceedings of the 3rd Int. Heat Powered Cycles Conference Larnaca, Cyprus.

[4] Boer, R. de, S.F. Smeding & R.J.H. Grisel (2005): *Development and testing of a sorbent filled heat exchanger for use in compact solid sorption cooling system*. Proceedings of the Int. Sorption Heat Pump Conference, Denver, USA 2005.