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Development and testing of a rotating system for a continuous solid-sorption process

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Abstract

The use of solid-sorption heat pumps for heating and cooling purposes can be beneficial because of the potential to reduce primary energy consumption as well as to reduce direct and indirect greenhouse gas emissions. Because the basic type of operation of a solid-sorption heat pump is in batch mode, with repeated heating and cooling phases for the solid sorbent, a drawback of the technology is the fluctuation of the thermal powers consumed and delivered with time. Additional heat exchangers and/or intermediate fluids are also required to prevent the different thermal fluids for heating and cooling from becoming mixed. Another disadvantage is the use of multiple activated valves to direct the thermal fluids for heating and cooling to the sorbent heat exchangers. The efficiency of these systems is also limited because of the repeated heating and cooling of thermally inert masses, such as metal heat exchangers, that does not contribute to the heat pumping process. These drawbacks are barriers to a more widespread application of this environmentally benign technology.

This paper describes the design, construction, tests and results of an innovative system concept for solid-sorption heat pumps. In the new concept multiple sorbent reactors are positioned in a rotating carrousel arrangement, and by continuous rotation go repeatedly through the process phases of adsorption and desorption, to achieve a continuous cooling process with constant thermal power levels. A lab-scale test-rig based on this new design was constructed and its performance was determined. It is shown that with the new design a continuous operation of a solid-sorption heat pump can be obtained that has constant thermal power levels for heating and cooling. Further improvements of the performance still need to be achieved by reducing the thermal inertia of the individual batch reactors and improving the performance of the evaporator.

Contents

List of figures

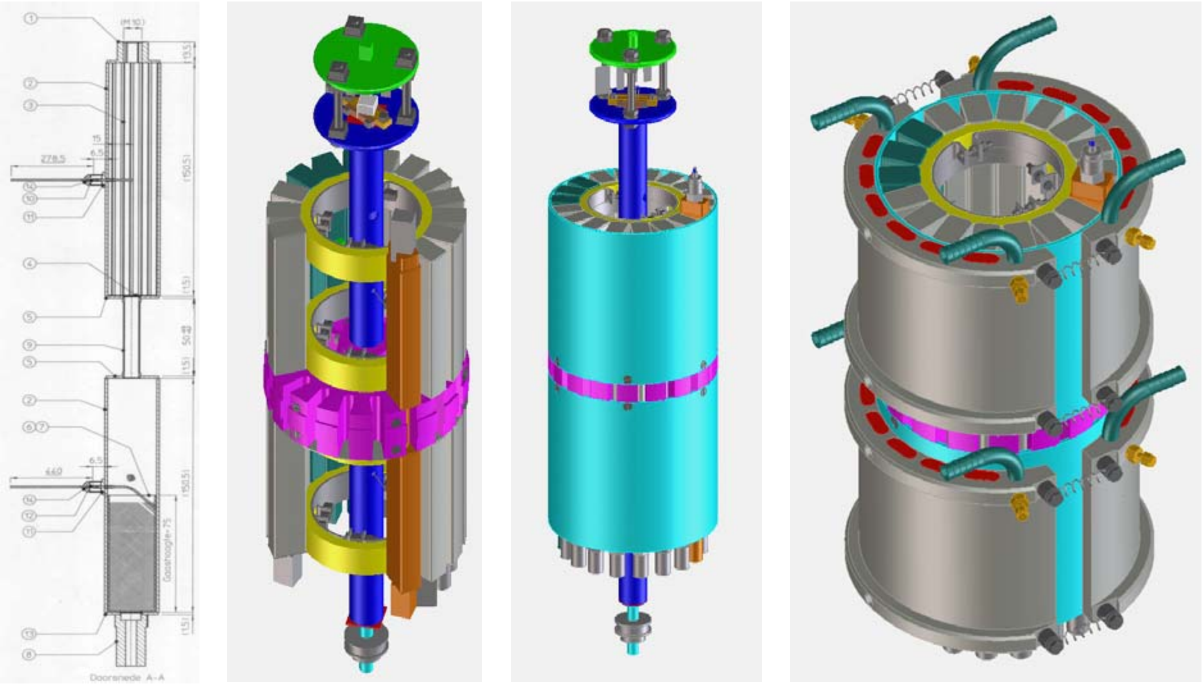
1. Introduction

Solid-sorption heat-pumping technology offers the possibility to re-use low-grade heat sources for heating and cooling purposes (Haije, 2002). With the re-use of low-grade waste heat significant primary energy savings as well as a reduction of greenhouse-gas emissions can be achieved. The basic type of operation of a solid-sorption heat pump is in batch mode, having repeated heating and cooling phases for the solid sorbent. The integration of a batch-operating solid-sorption heat pump in continuous processes has two major drawbacks. The thermal power that is consumed and delivered by the process fluctuates in time, and in switching a sorbent bed from the heating to the cooling phase, different thermal fluids for heating and cooling can get mixed. Additional heat exchangers and an intermediate heat-transferring system must be used to avoid mixing of different process streams. These drawbacks make the use of solid-sorption systems for re-use of waste heat less attractive.

In an effort to reduce these drawbacks of the environmentally friendly solid-sorption heat-pump technology a new system design was developed. This paper describes the design and construction of a lab-scale test-rig, and the tests and results of the new system. The new concept contains multiple sorbent reactors positioned in a rotating carrousel arrangement. By continuous rotation these sorbent reactors go repeatedly through the process phases of adsorption and desorption, to achieve a continuous cooling process with constant thermal power levels.

2. System development

To have a solid-sorption heat pump working in a continuous mode requires at least two sorbent beds to operate in counter-phase (De Boer, 2006), but then an external thermal buffering is often needed to smooth the fluctuations in thermal power of the solid-sorption process. Another approach to smooth these fluctuations is the use of multiple sorbent beds that are operating consecutively with a small phase shift. This approach generally leads to an increase of system complexity when sorbent beds are arranged in a stationary way. Many valves, complicated tubing and advanced control schemes are generally necessary. To avoid this complexity a rotating system of multiple sorbent beds can be considered. Many researchers have already explored the possibilities of such rotary solid-sorption systems (Critoph 2002, 2001, Chua et al., 2001, Llobet and Goetz, 1999). Almost all of the rotating concepts studied and patented use air as the heat-transfer medium. Only one patent was found that uses liquid as transfer medium (Duran, 1986). In the present concept the heat-transfer fluids can be either gaseous (air) or liquid.



A B C D

Figure 2.1 *Design drawings of the rotating system for a continuous solid sorption process. A: single sorption reactor element, B: open drawing of the carrousel of single reactor elements, C: complete carrousel within steel cylinders D: carrousel positioned between 4 stationary heat transfer elements*

The design of the test rig is shown in Figure 2.1. To study the performance of this system concept the well-known silica-gel + water (Trockenperlen-N) system was chosen as working pair. A single sorption reactor has an upper rectangular volume filled with about 40 g of dry silica-gel grains. The rectangular part is 15 cm in height, 2 cm width and 3 cm depth, and is made of stainless steel with 1.5 mm wall thickness. An aluminium honeycomb is inserted in the volume to enhance heat transfer in the silica-gel bed. The lower rectangular volume of equal dimensions is connected to the upper part by a thin-walled cylindrical tube of 5 cm length to avoid thermal losses between the upper and lower part. The lower part acts as a combined condenser and evaporator. The bottom section contains a metallic wick to enhance the evaporation. Each reactor element has a check valve mounted at the bottom in order to fill with water and to evacuate the assembly. Each reactor is a fully welded construction to avoid problems with maintaining the vacuum level inside. Eighteen sorption reactors are positioned together to form a carrousel with a diameter of 19 cm and height of 35 cm. Four of the sorption reactors are equipped with 2 thermocouples to monitor temperature changes inside the silica-gel bed and in the evaporator section while rotating. One has also a pressure transducer mounted at the top.

A metal cylinder of 180 mm internal diameter and 2.5 mm wall thickness is placed around the reactor elements. The outer walls of the reactor elements are slightly curved to obtain full surface contact with the cylinder wall, and spring elements are placed in the centre to press the reactors to the outside.

The carrousel is placed in between four aluminium heat-transfer elements, connected together using metal springs to clamp them with good thermal contact around the carrousel. Lubricating oil is applied between the heat exchangers and the carrousel. The heat-transfer elements contain a serpentine inner structure to conduct a flow of heat-transfer medium, water in the present case. The heat exchangers are fixed at their location and the carrousel is rotated in between them. Heat transfer occurs by conduction from the outside to the inside of the system.

Of the upper two exchangers, one is connected with an external hot-water circuit, the other one with a cooling-water circuit. By rotation of the carrousel the silica-gel in the sorbent reactors is repeatedly heated and cooled again. Of the lower two heat exchangers, the one directly below the hot heat exchanger is connected with a cooling water circuit for condensation of water vapour inside the sorbent reactors. The other heat exchanger receives water from a water circuit to be chilled by evaporation inside the sorbent reactor.

The carrousel is rotating around its central axis, driven by an electric motor and its speed can be adjusted between 0.25 to 2 rotations per hour. The stationary heat exchangers have one rotary flow-measurement device and thermocouples at the inlet and the outlet to determine the thermal powers transferred. The heat exchangers receive water from thermostatic baths. The heat exchangers for the condenser section and for the sorbent cooling section are connected in series.

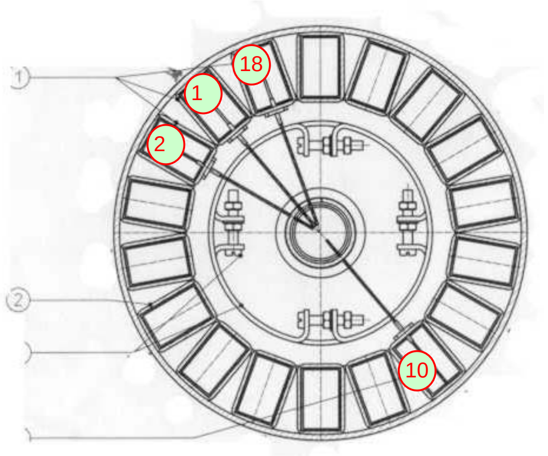


Figure 2.2 *Position of sorbent reactors equipped with thermocouples. Element 10 has also a pressure transducer*

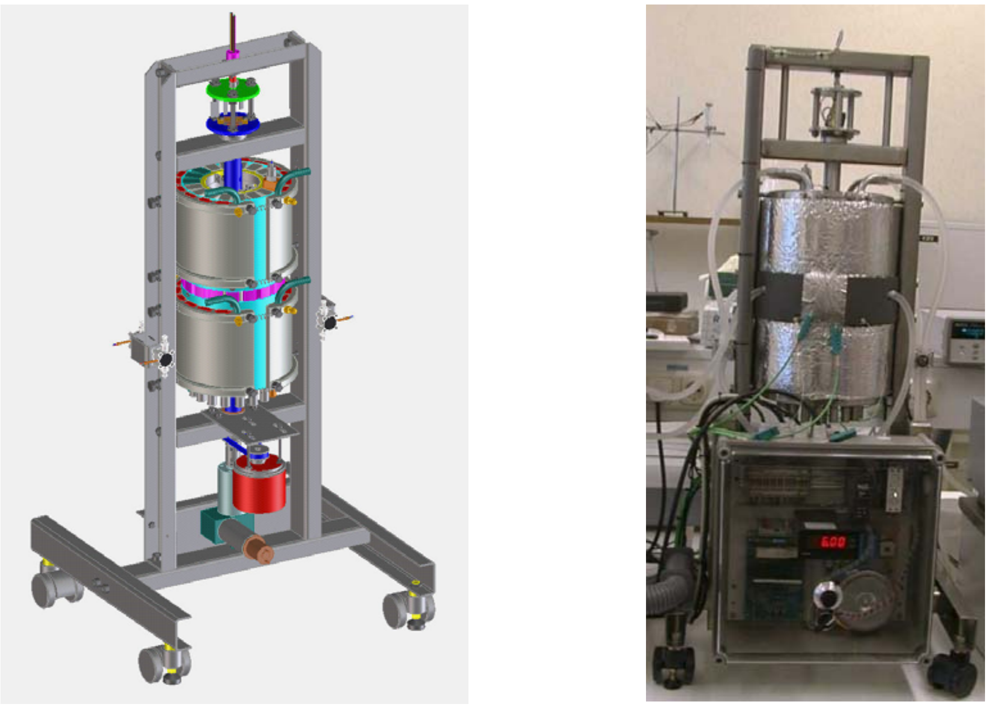


Figure 2.3 *Design drawing and picture of the complete test-rig*

3. Tests and Results

Measurements were performed to determine the influence of the operating temperatures, the rotational speed and the flow of heat-transfer medium on the overall performance of the rotating system. As standard conditions the input temperatures were set at 80/20/15°C (heating/cooling/chilling) with a speed of 1 rotation per hour for the carrousel. The flow through the heat exchangers was set at 2 $dm^3.min^{-1}$ for the heating of silica-gel, 1 $dm^3.min^{-1}$ for the condenser and the cooling of the silica-gel and 0.5 $dm^3.min^{-1}$ for the evaporator.

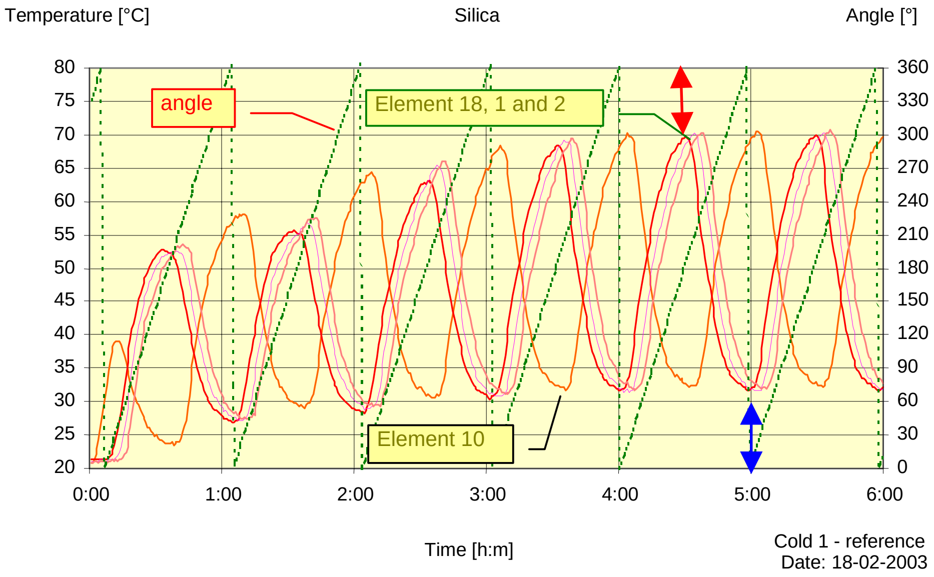


Figure 3.1 *Temperature change of the silica-gel sections in the sorbent reactors during the first 6 rotations after start-up. The blue and red arrows indicate temperature difference with the applied external temperatures*

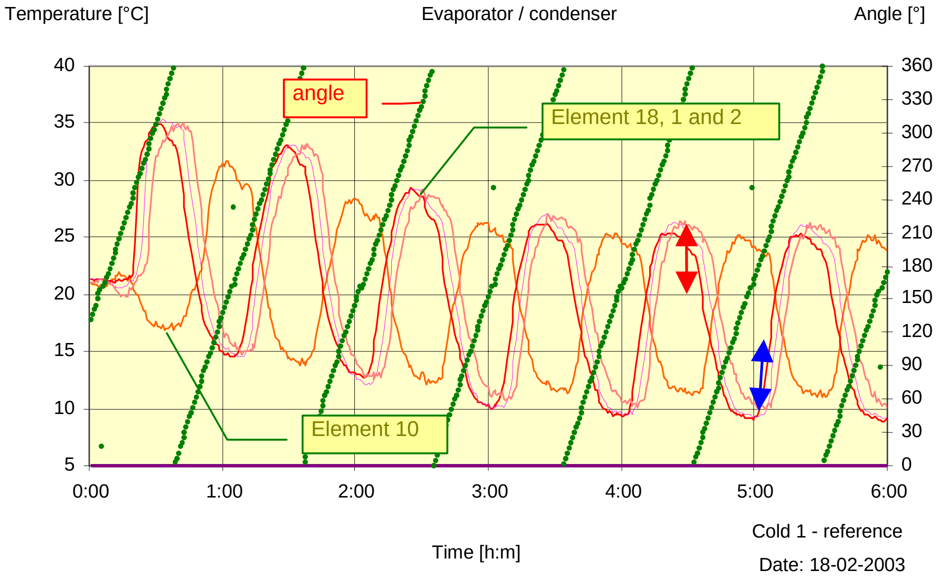


Figure 3.2 *Temperature change of the evaporator/condenser section in the sorbent reactors during the first 6 rotations after start-up. Blue and red arrows indicate temperature difference with the applied external temperatures*

In Figure 3.3 the thermal powers are shown for the four heat exchangers that surround the carrousel, as well as the COP derived from the ratio of cold output and heat input. From this it can be seen that at 4 h after start-up the thermal powers of the system become constant, and the system operates as a real continuous cooling system. Figure 3.4 shows the variations of cooling power and COP with different operating temperatures and rotating speed.

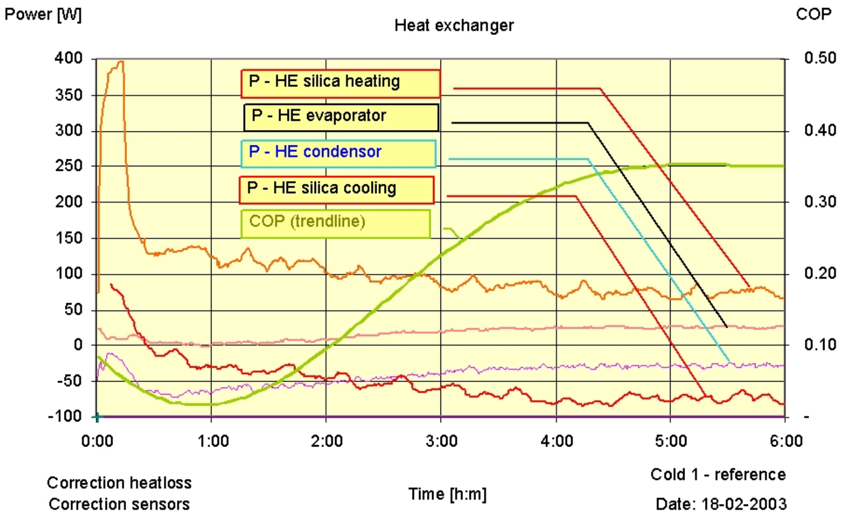


Figure 3.3 *Trends in thermal powers of the four heat exchangers and COP of the rotary sorption cooling system during 6 hours op operation at standard conditions*

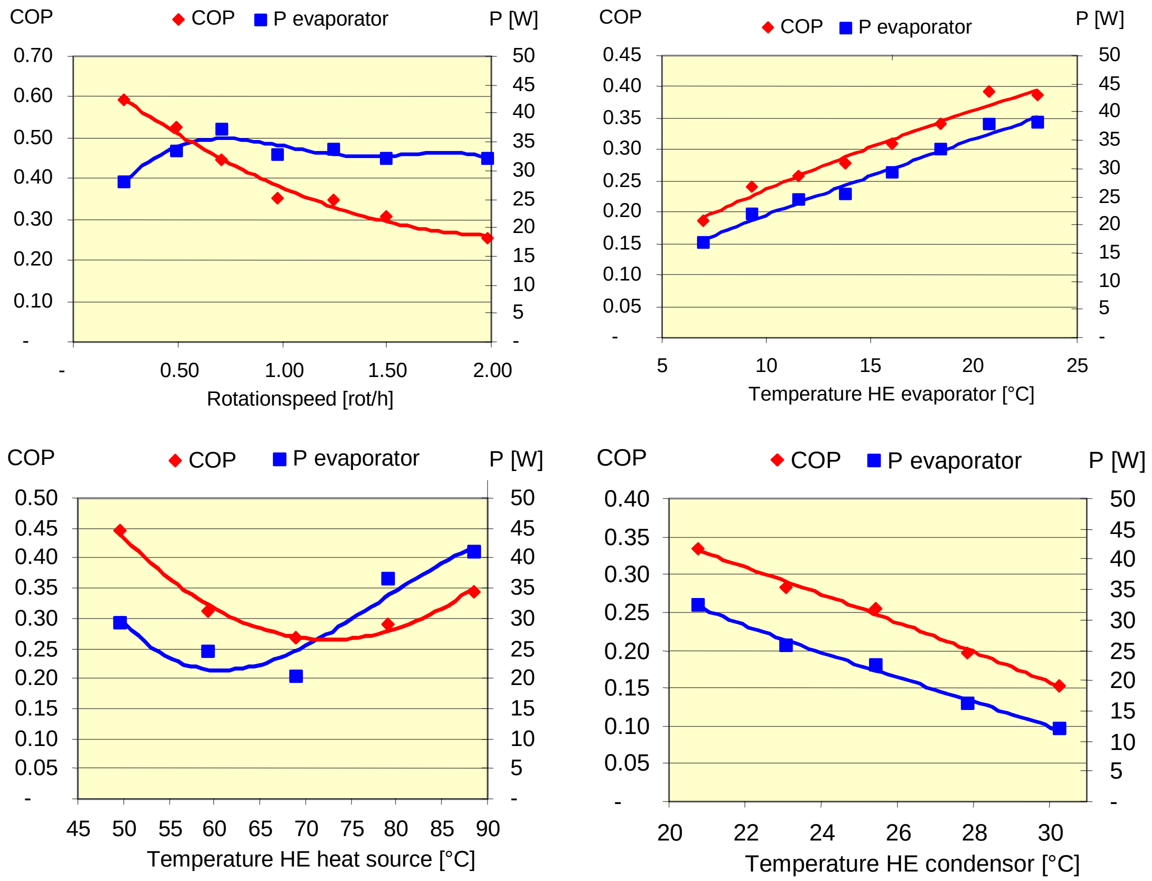


Figure 3.4 *Variation of COP and cooling power output with rotational speed and operating temperatures of evaporator, heat source and heat sink*

4. Conclusions and Discussion

With this test-rig the technical feasibility of the new rotating concept for solid-sorption cooling technology has been demonstrated. The system uses low-grade heat to produce cooling in a continuous mode. With the test rig a nominal cooling power of 25 W and a COP_{cold} of 0.35 was obtained. A maximum COP of 0.6 was obtained when the rotation was set at 0.25 rotations per hour. The thermal power levels are really stabilized and constant in time after 4 complete rotations from start-up. This provides a real advantage with respect to system integration of this system concept for solid-sorption technology in comparison to conventional solid-sorption systems. The same concept could also be applied for a heat-pump mode of operation or for a heat-transformer operation, where a second solid sorbent could replace the evaporator/ condenser sections.

During the testing period of about 8 weeks not a single mechanical problem was encountered with the operation of the system. Also the performance of the reactor elements remained stable during the testing period, indicating that there was no build up of non-condensable gases inside the elements. This shows that this rotating system is a feasible concept from the mechanical point of view.

However, from the thermal point of view many improvements are still required to obtain a system that could compete with commercially available cooling technology. These improvements relate primarily to heat transfer and reduction of the thermally inert masses in the system. Other improvements are possible through a reduction of internal and external heat losses, the application of internal heat recovery between hot and cold sorbent reactors, and the use of separated evaporator and condenser sections.

Improvements of the new system concept are required to increase its overall performance. Further development should focus on improved thermal performance of a single batch reactor, both for the silica-gel section and for the evaporator and condenser section, a decrease of the internal and external heat losses of the system, a decrease of the thermally inert mass and an increase of the rate of heat transfer to the carrousel.

5. Nomenclature

COP: coefficient of performance
LPM: litre per minute

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