Waste heat driven silica gel/water adsorption cooling in trigeneration

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ABSTRACT

A low-grade waste heat driven solid/vapour adsorption chiller has been successfully designed and tested. A simple model was developed to aid the design and predict the performances. The system comprised two identical sorption reactors operating out of phase in order to ensure continuous cold production. One sorption reactor consisted of six commercially available automotive plate/fin heat exchangers in which silica gel grains were accommodated between the fins. The system was tested as to the power delivered at 12 °C and the power density. The average cooling power was 3.6 kW. This is only 72% of the design value and can be largely attributed to the lower heat transfer fluid flow rate through the sorbent reactor. The thermal efficiency, COP, was 0.62 and the power density was 17 kW/m³ for the system as a whole. Higher power densities are possible. At present, the adsorption chiller is integrated in a prototype trigeneration system, which is tested at CRF's Eco-building in Turin.

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1. Introduction

The EU Member States are facing a growing demand for comfort cooling in the residential and commercial area. Nowadays, electric vapour compression heat pumps are the most commonly used machinery in comfort cooling or refrigeration [1]. During energy consumption for cooling duty, greenhouse gases are released into the atmosphere. Moreover, common refrigerants in compression chillers, i.e. CFC's, HCFC's, and HFC's, are notorious contributors to global warming; some of them have an ozone depleting effect as well. During production, servicing, and recycling part of these substance will end up in the environment. In the future, cooling demand, and hence energy consumption for climate control and refrigeration, will continue to grow. This intrinsically leads to a faster depletion of known fossil fuel reserves, more CO_2 emissions and a higher peak electricity demand [2].

Alternatives for vapour compression cooling are already in put into use or are under development. Promising technologies include heat driven liquid absorption refrigeration [3–5] and solid sorption heat pumps [5–8]. These types of cooling machines bring about a lower primary energy usage and lower CO_2 emissions per unit cold produced. The present sorption systems, however, are only suitable for large-scale industrial applications (>100 kW). Research on heat driven solid sorption cooling technology concentrates on the development of cooling machines for smaller applications, such as for example comfort cooling and refrigeration in the build environment [9] and mobile air conditioning. Solid sorption heat pumps do not need any CFC, HCFC or HFC refrigerant; most of them

make use of natural refrigerants. Examples of solid sorbent vapour combinations are silica gel/water [10–13], SWS/water [13–15], zeolite/water [16], and NH_3/carbon [17–19]. This technology does not have moving parts, is therefore silent, and does not require much servicing.

Solid sorption technology can be deployed either stand-alone or integrated in a trigeneration system [2]. Such a system offers the possibility of saving 15–20% primary energy for cooling, heating, and power demands, by utilisation of the waste heat of a CHP system for the production of cold by means of solid sorption cooling technology.

In the present paper, the work on modelling, design, and testing of small-scale adsorption chiller prototype in our laboratories are described. The main scientific objective was the realisation of a 5 kW adsorption chiller with a power density of about 20–30 kW/m³, where 10 kW/m³ is state-of-the-art [20]. To achieve these targets new concepts for integration of a heat exchanger and solid sorbent material are required to achieve sufficient overall heat transfer. A simple model was developed to aid the design of the adsorption chiller test facility. After laboratory testing the adsorption chiller prototype was integrated in an experimental combined heat and power module trigeneration setup at CRF, Italy. Note that throughout this study all the temperatures mentioned are those of the external heat transfer fluids, unless mentioned otherwise.

2. Model development

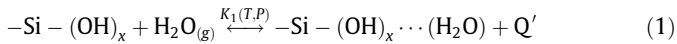### 2.1. Description of the thermodynamic cycle

Sorption cooling systems operate via a reversible sorption reaction between a solid sorbent and a vapour. This is an equilibrium reaction. The 'counter reaction' can be the alternating evaporation

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Nomenclature

A	heat-exchanging surface area (m^2)
COP	coefficient of performance, thermal efficiency
Cp	heat capacity at constant pressure (J/mol K)
ΔH	latent heat of ad-/desorption (J/mol)
$\dot{m}$	mass flow rate
m_{sorb}	sorbent mass (kg)
p	pressure (bar)
P	power transferred (W)
Q, q	heat quantity (J)
R	universal gas constant (8.3145 J/mol K)
Re	Reynolds number
ΔS	entropy change upon ad-/desorption (J/mol K)
SCP	specific cooling power (W/kg dry sorbent)
SWS	selective water sorbent
t_{cycle}	duration of the thermodynamic cycle (s)
T	absolute temperature (K)

U	overall heat transfer coefficient (W/m^2 K)
UA	overall heat transfer (W/K)
W	water content in adsorbent (w-%)

Subscripts

evap	evaporator
htf	heat transfer fluid
H	concerning high temperature source, i.e. hot water circuit or waste heat
L	concerning low temperature source, i.e. chilled-water circuit
M	concerning middle temperature source, i.e. cooling-water circuit
in	associated with what is going into the system
out	associated with what is coming out of the system
sorb	sorbent

and condensation of refrigerant. The physical processes in a silica gel/water system can be represented as follows:

$$-\mathrm{Si} - (\mathrm{OH})_x + \mathrm{H_2O}_{(g)} \overset{K_1(T,P)}{\longleftrightarrow} -\mathrm{Si} - (\mathrm{OH})_x \cdots (\mathrm{H_2O}) + Q' \tag{1}$$

$$\mathrm{H_2O}_{(g)} \overset{K_1(T,P)}{\longleftrightarrow} \mathrm{H_2O}_{(l)} + Q'' \tag{2}$$

The equilibria are dictated by the thermodynamics of the system and depend on local temperature and pressure. Adsorption of water by the silica gel and condensation of water are exothermal processes and generate heat. In a sorption cooling system, this heat is useless and is disposed of. Desorption and evaporation are endothermic, so heat is required to drive the equilibria in this direction. Desorption can be waste heat driven and is part of the regeneration phase. Heat required for evaporation is withdrawn from the environment, so causing the refrigeration effect. The extent of the refrigeration effect is determined by the amount of water circulating between evaporator and sorbent, and thus on the differential water loading of the silica gel, per unit time. The differential water loading of the silica gel depends on the intrinsic interaction of the refrigerant with the sorbent, the temperature, and pressure. When temperature and pressure inside the silica gel bed are known, the water loading in the sorbent (W) can be calculated:

$$\begin{aligned} \ln(p/p^0) &= \frac{\Delta S}{R} - \frac{\Delta H}{RT} \\ &= (a_0 + a_1 \cdot W + a_2 \cdot W^2 + a_3 \cdot W^3) \\ &\quad + \frac{(b_0 + b_1 \cdot W + b_2 \cdot W^2 + b_3 \cdot W^3)}{T} \end{aligned} \tag{3}$$

The parameters a_n and b_n are characteristics of the sorbent refrigerant interaction and describe a set of isosteres, i.e. lines of constant refrigerant concentration, as a function of temperature, pressure, and refrigerant concentration (Fig. 1).

In the ideal situation, in equilibrium the pressure inside the sorbent bed equals the pressure in either the evaporator or the condenser, and the sorbent bed has homogeneously adopted the temperature of the adjacent heat exchanger and heat transfer fluid. If it were possible in the sorbent reactors to alternately reach the cooling-water temperature (T_M) and the heating-water temperature (T_H) and corresponding evaporator, respectively condenser pressure, the thermodynamic cycle the silica gel/water system is subjected to can be represented by the dotted trapezium in Fig. 1. In horizontal direction (L_{eq}) the trapezium crosses several isosteres, therefore the thermodynamic cycle predicts water flow

from and to the silica gel. The more isosteres are crossed, the higher is the equilibrium differential water loading and, accordingly, the higher is the heat effect of that cycle:

$$q = m_{sorb} \int_{W_x}^{W_y} \Delta H(W) \cdot dW \tag{4}$$

being

$$\Delta H = -(b_0 + b_1 \cdot W + b_2 \cdot W^2 + b_3 \cdot W^3) \cdot R \tag{5}$$

and W_x, W_y the isosteres with maximum and minimum water content of the cycle.

Note that the system cannot be in equilibrium, whereas a pressure difference is required to obtain the necessary refrigerant vapour flow between the different components and a temperature difference is required to enable heat transfer.

Now, during evaporation heat is withdrawn from the refrigerant buffer and thus the temperature inside the evaporator will decrease. On the other hand, due to the heat of condensation the temperature inside the condenser will increase. The temperature effects mainly depend on the rate of evaporation/condensation and the thermal mass of the evaporator/condenser. Because of these temperature effects, the pressure inside the evaporator and condenser will change with respect to the 'isothermal equilibrium'. The pressure limits in the sorbent bed will change accordingly. In Fig. 1 this is represented by a vertical shift of the equilibrium pressure in the evaporator to P'_{evap} and in the condenser to P'_{cond}. Accordingly, the two equilibrium corner points of the trapezium at T_L and T_H are shifted to the positions denoted with an '×'. In the case there is a non-zero pressure drop in the sorbent bed, the vertical shift of these points is larger and will be located below and above the pressures inside the evaporator and condenser, respectively. In reality, there will also be resistance to heat transfer between the heat transfer fluid and heat exchanger and between the heat exchanger and sorbent bed. This results in a temperature difference between the sorbent bed and the heat transfer fluid. Moreover, due to a low intrinsic heat conductivity of the silica gel, the temperature in the sorbent bed will not be homogeneous and the average bed temperature will differ from that of silica gel near the heat exchanger. Both temperature effects are represented in Fig. 1 by a horizontal shift of the positions marked '×' to the positions indicated by black dots. The now originating trapezium crosses less isosteres: due to temperature effects in the evaporator, condenser and sorbent bed and due to the resistance to heat transfer, the real differential water loading (L_{real}) is reduced with