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Modelling and experimental investigation of an adsorption chiller using low-temperature heat from cogeneration

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ABSTRACT

Adsorption technology enables construction of chillers that can be driven with a low temperature cogeneration, solar or waste heat source. As compared with absorption chillers, the adsorption devices have the unique advantages like the utilization of heat source characterized by lower temperature. The paper presents the thermodynamic model of a three-bed adsorption chiller of a cooling capacity equal to 90 kW. The chiller has been commissioned at Wrocław Technology Park and is instrumented in a way allowing a full identification of important thermodynamic and operational parameters like COP (coefficient of performance), switching time, temperatures and pressures of adsorption and desorption processes as well as water condensation. The chiller provides cooling power at two temperature levels of about 13 and 8 °C. Experimental results of a long-term chiller investigation are presented. The dependence of the chiller COP on the adsorption bed regeneration temperature in the range from 45 °C to 70 °C has been identified. It has been demonstrated that the chiller can be driven with a hot water of 65 °C, what is a typical cogeneration heating temperature in distributed systems. It allows the utilization of cogeneration heat in trigeneration mode, what is especially important for distributed heating systems in summer time.

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1. Introduction

Trigeneration is a system that allows for parallel electric energy, heat and chill production wherein the chill is a product of sorption technologies with the use of heat resulting from cogeneration. An effective trigeneration system should have the ability to convert heat of the lowest temperature to chill, for high cogeneration effectiveness. Available commercial sorption technologies (coolers that use a water solution of BrLi) allow for the use of heat with temperatures not lower than 85 °C. Those technologies can be integrated into cogenerative systems in the near neighbourhood of cogenerators but cannot be powered with heat provided by district heating during summer months, which has a mean temperature of about 65 °C.

Currently technologies that will allow the powering of cooling units with heat-sources of lower temperatures are being developed. The most promising research is being conducted in the field of sorption coolers working on the adsorbent-adsorbate: silica gel – water [2]. Recently many authors have investigated coolers based on silica gel – water. Szyc and Nowak [10] in 2014 investigated 4-bed chiller and achieved 0.52 COP (coefficient of performance). Wang, Lu and Xia [11] in 2013 achieved up to 0.56 COP for 90 °C heating water. Lu and Wang [11] achieved max 0.49 COP for 26 °C of cooling water and 79 °C heating water. Rahman [12] in 2013 modelled 3-bed adsorption chiller with COP reaching 0.6. This work is focused on a case of such a cooler: a Tri-bed twin-evaporator sorption cooler.

1.1. Tri-bed adsorption chiller

The described cooler consists of three absorbers. This is quite a non-standard configuration as as the most commonly applied coolers are twin- or quad-deposit coolers. An odd number of deposits is an innovative solution that allows for a more effective way to use the adsorptive abilities of the source during a single work cycle. The adsorption equilibrium is a function of temperature and pressure [1]. The temperature of the adsorption bed is increased during its regeneration and decreased during the rest of the work cycle. The bed absorptivity, the mass of water which 1 kg of silica-gel can adsorb, in such a case is related only to pressure and increases with its gain. The adsorption process conducted under high-pressure

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Nomenclature

A, B	polynomial coefficients
COP	coefficient of performance
COP_{teor}	theoretical COP value
C_w	specific heat of water
D_{S0}	pre-exponent constant in the kinetics equation
E_a	activation energy of surface diffusion
h_{vap}	heat of water vaporization
h_{des}	heat of water desorption from silica gel
K	kinetic coefficient
KA	heat transfer coefficient multiplied by heat exchanger area
$\dot{m}$	mass flow
$\dot{m}_{icewater}$	ice water mass flow
$\dot{m}_{heating\_water}$	heating water mass flow
Q	cooling capacity
q	quantity of adsorbate adsorbed in the mass of adsorbent, kg/kg
q^*	equilibrium quantity of adsorbate adsorbed in the mass of adsorbent, kg/kg
R_P	average radius of silica gel
T_{inlet}	inlet water temperature
T_{outlet}	outlet water temperature
$T_{icewater\_in}$	ice-water inlet temperature
$T_{icewater\_out}$	ice-water outlet temperature
$T_{inlet\_heating\_water}$	heating water inlet temperature
$T_{outlet\_heating\_water}$	heating water outlet temperature
τ_{cycle}	full cycle time

would be optimal in terms of the beds absorptivity usage but pressure is strictly correlated to the water boiling temperature. Inside the evaporator the intensively boiling water under a lowered pressure receives heat from the ice-water flowing through pipes generating cooling power. The temperature of ice-water which can be achieved by using the cooler is correlated with the pressure inside the evaporator and lower temperatures of ice-water can be achieved by using low pressure throughout the adsorption process. In coolers with a twin-evaporator construction a compromise between effectiveness and chill generation temperature is gained. Chill power is generated in two evaporators on two temperature levels. Such a solution allows for cooling capacity under low temperature in one of the evaporators and cooling capacity using a slightly higher temperature (with a difference in temperatures of 4–8 °C) under higher pressure providing higher effectivity in bed usage. It is currently the most effective way to receive chilled water from sorption coolers. A one can imagine coolers with more steps of cooling effect generation. It would allow for the chiller to work closer to its equilibrium conditions, however the investment in more complex equipment and additional ice-water reception networks would be disproportionately higher than profits from increased efficiency

2. Working principle

Chillers contain three main elements: a condenser, adsorption beds and evaporators. Beds are able to be heated or cooled accordingly to the flow of heating or cooling water through their heat exchangers. Beds are equipped with steam connections containing valves to evaporators and to the condenser. The scheme is shown in Fig. 1. Water in evaporators boils under 500–1200 Pa, which is close to the saturation pressure of about 5 °C (low pressure evaporator) or 12 °C (high pressure evaporator). Such a low pressure is achieved by adsorption of steam on the adsorbent storage in the chillers beds. Rising bed temperature reduces the beds absorptivity. It is possible to regenerate the bed by desorbing some amount of water in 3500–6000 Pa, by heating the bed. Desorbed steam is liquefied in the condenser.

A full bed cycle consists of 3 stages. The chiller is equipped with 3 beds in order to ensure the continued production of the cooling power. Operational cycles of individual beds are shifted towards each other in time and can be divided into three stages as shown in Table 1. The periods of individual stages are the same and equal to 1/3 of the full cycle. The duration of a single operational stage (known as a bed switching time), is a crucial parameter

There are 3 main stages in the working cycle of a chiller. Two of them are divided into two under stages because of the time required to cool down or heat up the bed. The first step is cooling down the bed that just regenerated (Fig. 2 P1 ->P2). When the pressure in the bed is lower than the pressure in LP evaporator, the steam connection is opened between them and the adsorption process is started (Fig. 2 P2 ->P3). After some time an adsorption effectivity is lowered. In that time the steam connection between the bed and the LP evaporator is closed and the connection to a high pressure evaporator is opened (Fig. 2 P3 ->P4). The pressure rise causes the adsorption rate to increase. When the amount of adsorbate on adsorbent approaches the equilibrium state and effectivity of adsorption process is insufficient, steam connection to the evaporator is closed and the bed is switched from cooling to heating (Fig. 2 P4 ->P5). When the beds pressure is equal to or higher than the condenser's pressure, the steam connection to that element is opened, and bed is being regenerated (Fig. 2 P5 ->P1). That stage closes the whole sequence. During the chillers work bed stages are shifted, so that the cooling effect is continuous. The working sequence and valve openings are shown in Table 1 [3,4].

3. Modelling adsorption chiller

The adsorption chiller model is one – dimensional model based on differential equations. The model does not consider losses and can be treated as an ideal chillers reference model. Model results can be used to optimise real chillers and to evaluate device efficiency.

Model was based on an adsorption equilibrium, law of conservation of mass and the kinetic of an adsorption process [5]. The following assumptions were made:

- Pressure and temperature are equal in the whole bed,
- The process is adiabatic, heat is transferred only by heat exchangers,
- No friction in steam flow,
- No water droplets stripping by water vapour flow.

Linear Driving Force model was used to count adsorption kinetic equation. (1) [9].

$$\frac{dq}{dt} = K(T_{sg})(q^* - q) \tag{1}$$

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