Applied Thermal Engineering 100 (2016) 744–752

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Optimizing performance of a three-bed adsorption chiller using new cycle time allocation and mass recovery

Bartosz Zajaczkowski *

Faculty of Mechanical and Power Engineering, Wroclaw University of Technology, Wyb. Wyspianskiego 27, 50-370 Wroclaw, Poland

HIGHLIGHTS

- A new cycle time allocation CTA for a three-bed silica-gel/water adsorption chiller is proposed.
- The new CTA allows for mass recovery phase that significantly increases capacity and performance.
- The improvement of performance is the largest for systems driven by 60–65 °C heat source.
- The optimal mass recovery time is approx. 10 s regardless of total cycle time or driving temperature.

ARTICLE INFO

Article history:
Received 20 November 2015
Accepted 14 February 2016
Available online 2 March 2016

Keywords:
Three-bed adsorption chiller
Cycle time allocation
Performance optimization
Mass recovery

ABSTRACT

In this paper a new cycle time allocation for a three-bed silica-gel/water adsorption chiller is proposed and analyzed analytically. In this operating cycle lengths of all the phases are adjusted in such a way that it becomes possible to introduce mass recovery process. The result is increased cooling capacity and overall system performance. This new cycle time allocation is especially suitable for three-bed chillers driven with 60–65 °C heat source, because within this hot water temperature range the improvement of performance is the largest.

The COP and SCP were calculated for a particular chiller described in the literature. Thanks to mass recovery the *COP* of analyzed chiller increased by 35% (from 0.268 to 0.362) at $T_{htf,in} = 65$ °C, and by 15% (from 0.350 to 0.405) at $T_{htf,in} = 85$ °C. Numerical optimization allowed to determine that at $T_{htf,in} = 85$ °C optimal mass recovery time is 8–12 s and the switching time is 27–35 s, while at $T_{htf,in} = 65$ °C optimal mass recovery time is 11–13 s and the switching time is 45–53 s.

The *COP* of chiller running new operating cycle and cooled with $T_{cool,in} = 30$ °C is comparable to the performance of chiller running conventional operating cycle and cooled with $T_{cool,in} = 25$ °C. The *SCP* at $T_{cool,in} = 30$ °C and new allocation is comparable to the *SCP* at $T_{cool,in} = 27.5$ °C and conventional operating cycle.

1. Introduction

Adsorption chillers are driven by heat. This feature makes them an attractive solution that helps reduce electric power demand during peaks caused by excessive use of air-conditioning and other refrigeration equipment.

The most important advantage of silica-gel/water adsorption systems is the ability to utilize 60–90°C heat sources. It is a feature that cannot be realized by most of absorption chillers. However, using fixed beds causes problems, such as periodic operation, low performance, elongated cycle times, over-sized heat exchangers (due to poor transfer rates in the bed), and significant temperature fluctuations in system components. Many researchers addressed these problems [1,2].

The cycle time and cycle time allocation are the most influential parameters influencing both cooling capacity and the COP [3,4]. The cooling capacity (and consequently the specific cooling power SCP) can be maximized at a certain cycle time, while the COP increases monotonically with cycle time.

Many studies have revealed performance characteristics and the optimum operating conditions of two-bed [3–6] and three-bed adsorption chillers [7,8]. Recently Glaznev and Aristov [9] proved that it is possible to improve system efficiency by shortening the regeneration time, because desorption process is 2–3 times faster than adsorption process. Sapienza et al. [10] experimentally analyzed the

* *E-mail address:* bartosz.zajaczkowski@pwr.edu.pl.

http://dx.doi.org/10.1016/j.applthermaleng.2016.02.066
1359-4311/

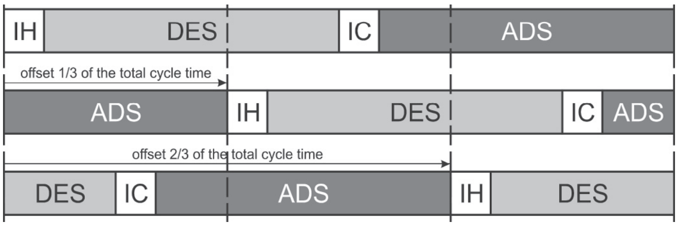

Fig. 1. Cycle time allocation for three-bed adsorption chiller proposed by Saha et al. [7].

influence of relative duration R of the isobaric adsorption and desorption steps on system performance. The authors showed that with large temperature difference between hot and cooling water, the optimal adsorption time might be 7 times longer than desorption time.

All recently developed cycle time allocations take advantage of this fact, including the new cycle time allocation that is proposed in this paper.

1.1. Three-bed cycle time allocations

There are two most fundamental three-bed cycle time allocations (CTA) that are described in literature.

The most basic three-bed cycle time allocation has been introduced by Saha et al. [7]. It consists of four distinct phases: adsorption (ADS), pre-heating (IH), desorption (DES), pre-cooling (IC). Lengths of adsorption and desorption phases are equal (see Fig. 1 for details). Each bed realizes identical operating cycle, but they are out-of-phase. The offset between operating cycles is approx. one third of the total cycle time.

Another cycle time allocation has been recommended by Aristov et al. [11]. In proposed three-bed allocation the length of a single adsorption phase (ADS) is equal to the sum of pre-heating (IH), desorption (DES) and pre-cooling (IC) phases. However, there is one additional adsorption phase in the cycle, i.e. total adsorption time is doubled (see Fig. 2). As a result, at any given time, two out of three adsorbers remain connected to the evaporator and produce cooling, which improves stability of the cooling output. This concept is similar to the proposition of Miyazaki et al. [5] for two-bed adsorption chiller, in which the authors suggested that adsorption phase (ADS) should take half of the cycle time. As a consequence the length of adsorption phase is equal to the length of three complimentary phases (pre-heating, desorption, and pre-cooling), and one of adsorbers is also always connected to the evaporator.

Many authors addressed the problem of cycle time optimization in three-bed adsorption systems.

Saha et al. [7] analytically investigated the performance of a three-bed silica gel–water adsorption chiller using lumped parameter model and conventional cycle time allocation (Fig. 1). The authors analyzed variations of the cooling capacity and the *COP* by changing inlet temperatures of heat transfer fluids and lengths of adsorption/desorption phases. They also studied the influence of driving source temperature on the efficiency of waste heat recovery. The authors observed that three-bed systems show the continuation of cooling energy production and chilled water outlet temperature profile is smoothened in comparison with that of two-bed cycle. In another paper, Saha et al. [12] investigated the influence of other parameters on performance, including thermal conductance of all the heat exchangers.

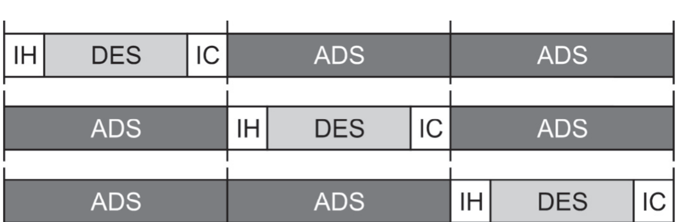

Fig. 2. Cycle time allocation for three-bed adsorption chiller proposed by Aristov et al. [11].

Zajaczkowski [13] conducted cycle time optimization for a three-bed adsorption chiller looking for optimal desorption/adsorption time ratio f that maximizes system performance. The analysis shows that in a three-bed setup for switching time 30 s and adsorption time 300 s, $f \approx 0.6$ yields the biggest improvement in both cooling capacity and the *COP*.

The literature reports two other complex three-bed cycle time allocations that were introduced by Khan et al. [14] and Uyun et al. [15]. These cycles were developed for a three-bed chiller which works on completely different principle, i.e. by combining a single-stage cycle and a mass recovery cycle into one. Therefore, the beds realize two cycles with different refrigerant release mechanisms. These cycles have been evaluated and optimized by Rahman et al. [8,16] with the Particle Swarm Optimization (PSO) method.

1.2. Mass recovery

The mass recovery operation improves performance of adsorption chiller [17]. Mass recovery occurs between cold adsorber at low pressure and hot desorber at high pressure. Two beds are directly connected at the beginning of pre-heating/pre-cooling, which allows two pressures to reach equilibrium in both vessels. Pressure equalization process is best shown on a Dühring diagram, as shown in Fig. 3. The connecting valve is opened for a short period of time (usually between 10 and 20 s). Math recovery causes further desorption in hot bed, making the silica gel dryer. As a result the total cycle mass of the refrigerant is increased, so is the refrigeration effect and the *COP*.

Points 1 and 3 are states at the end of a cyclic steady state of the adsorber and the desorber correspondingly. They correspond to their respective isosteres (q_{max} and q_{min}). When mass recovery phase is initiated (adsorber and desorber are connected), the pressure inside hot bed drops rapidly from point 3 to point 3′ and more vapor is further desorbed (reaching new minimum q'_{min}). The released vapor flows across the adsorber where it experiences an increase in vapor-uptake (point 1′ and new maximum uptake q'_{max}).

In order to take advantage of mass recovery process, cycle time allocation has to be designed in such a way that at desired cycle time direct connection between hot bed and cold bed is established. One of these beds has to be at the beginning of pre-heating phase, while the other has to be at the beginning of pre-cooling phase. Due to symmetry of operation this is usually very simple to arrange in a two-bed setup, but more complicated in a three-bed setup.

In this paper, a new cycle time allocation for a three-bed adsorption system is proposed. In this operating cycle the order and lengths of phases are chosen to allow for mass recovery process.

2. System description

Schematic diagram of a three-bed adsorption chiller that allows for direct connection between adsorbent beds (i.e. mass recovery) is presented in Fig. 4. The device is powered by low temperature driving heat source 65–85 °C. For this reason silica gel–water pair has been selected as the most suitable in desired temperature range [18].