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Optimal cycle selection in carbon-ammonia adsorption cycles

S.J. Metcalf*, R.E. Critoph, Z. Tamainot-Telto

School of Engineering, University of Warwick, Gibbet Hill Road, Coventry CV4 7AL, UK

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ABSTRACT

Computational modelling of multiple-bed and thermal wave adsorption cycles is carried out in order to determine which method of heat recovery gives the superior trade off between coefficient of performance (COP) and power density (the power output per unit mass or volume of machine). The modelling is performed for the activated carbon-ammonia pair with a high power density plate heat exchanger type generator. It is discovered that multiple-bed cycles give a superior trade-off between COP and power density and are therefore recommended over thermal wave cycles. The principal application is considered to be a gas fired heat pump and it is found that the technology compares favourably with competing systems.

Choix du cycle optimal parmi des cycles à adsorption au charbon actif / ammoniac

Mots clés : Adsorption ; Pompe à chaleur ; Ammoniac ; Charbon actif ; Modélisation

1. Introduction

The most basic implementation of an adsorption cycle refrigeration device is illustrated in Fig. 1 and consists of two linked vessels. The left-hand vessel is termed the generator and contains a solid adsorbent and refrigerant. The right-hand vessel is termed the receiver which acts as a condenser and evaporator and contains only refrigerant. Initially the system is at low pressure, the adsorbent is near ambient temperature and contains a high concentration of adsorbed refrigerant and the receiver contains refrigerant gas (a). The generator is heated, driving out refrigerant and raising the system pressure. The increased pressure causes the refrigerant to condense in the receiver, rejecting heat (b). Finally, the generator is cooled back to ambient temperature, readsorbing the refrigerant and reducing the pressure. The reduced pressure causes the liquid refrigerant in the receiver to boil, producing the refrigeration effect. The system is then back to its initial state at (c) and the cycle is complete. The cooling is discontinuous and occurs for only approximately half of the cycle. However, continuous cooling can be provided by operating two or more generators out of phase.

There are two main development challenges for adsorption cycles which have prevented them from being commercially

* *Corresponding author*. Tel.: +44 2476 151442; fax: +44 2476 418922.
E-mail address: s.j.metcalf@warwick.ac.uk (S.J. Metcalf).

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Nomenclature

A	Heat transfer area (m^2)
c	Specific heat ($J\ kg^{-1}\ K^{-1}$)
C	Slope of the saturated liquid line for ammonia on a Clapeyron diagram
h	Enthalpy ($J\ kg^{-1}$)
H	Heat of adsorption ($J\ kg^{-1}$)
k	Thermal conductivity ($W\ m^{-1}\ K^{-1}$)
K	Constant in the modified Dubinin–Astakhov equation
LHS	Left-hand side
$\dot{m}$	Mass flow rate ($kg\ s^{-1}$)
M	Mass (kg)
Nu	Nusselt number
n	Constant in the modified Dubinin–Astakhov equation
p	Pressure (Pa)
$\dot{Q}$	Power (W)
RHS	Right-hand side
SCP	Specific cooling power ($W\ kg^{-1}$)
SHP	Specific heating power ($W\ kg^{-1}$)
t	Thickness (m) or time (s)
T	Temperature (K)
U	Heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
x	Concentration of adsorbed ammonia ($kg\ kg^{-1}$)

Greek symbols

μ	Dynamic viscosity ($N\ s\ m^{-2}$)
ν	Specific volume ($m^3\ kg^{-1}$)
ρ	Density ($kg\ m^{-3}$)

Subscripts

0	Limiting value
a	Adsorbate
ads	Adsorption
amm	Ammonia
c	Carbon
cond	Condensing
f	Fluid
g	Gas
in	Inlet
LM	Log-mean
out	Outlet
sat	Saturation
sup	Superheated
w	Wall

viable. Firstly, the power density (the power output per unit mass or volume of machine) is low due to the low thermal conductivity of adsorbent materials, which results in large machines with a high capital cost. Mass transfer resistances may lower power density further, particularly with sub-atmospheric refrigerants.

Secondly, the COP of the basic adsorption cycle is low; a carbon-ammonia air conditioner typically has a COP of 0.3. This can be improved using heat recovery or regeneration in which the heat required for desorption of generators undergoing heating may be partially provided by generators undergoing cooling. However, this further lowers the power density and a trade-off must be made between the two. Regenerative cycles mainly fall into two categories: thermal wave cycles and multiple-bed cycles.

Thermal wave cycles were first proposed by Tchernev (1987) and Shelton (1986) and are reported in Tchernev (1989) and Shelton et al. (1989). They offer a simple method of carrying out effective heat recovery to achieve higher COP. Shelton et al. (1989) predicted zeolite-ammonia heat pump COPs of 1.625 and 1.87 with driving temperatures of 212 °C and 316 °C, respectively. Miles and Shelton (1996) and Miles et al. (1993) experimentally tested carbon-ammonia machines with heating COPs between 1.59 and 1.75 with driving temperatures between 230 and 250 °C. Amar et al. (1996) predicted a cooling COP of around 1 for zeolite-water and carbon-ammonia systems for driving temperatures between 220 and 270 °C. Pons et al. (1996) carried out experimental testing of a zeolite-water system and achieved cooling COPs between 0.6 and 0.9.

Critoph (1996a, 1999a) proposed a variation of the thermal wave cycle termed the convective thermal wave cycle in which the refrigerant gas is used as the bed heat transfer fluid. Cooling COPs of around 1 were predicted for 200 °C driving temperature.

Multiple-bed cycle performance was investigated by Meunier (1985) for the zeolite-water pair. Heating COPs of 1.42, 1.67, 1.988, and 2.337 were predicted for 1, 2, 4 and 6 bed systems, respectively.

This paper carries out computational modelling of thermal wave and multiple-bed heat recovery methods in order to determine which provides the optimal trade-off between COP and power density.

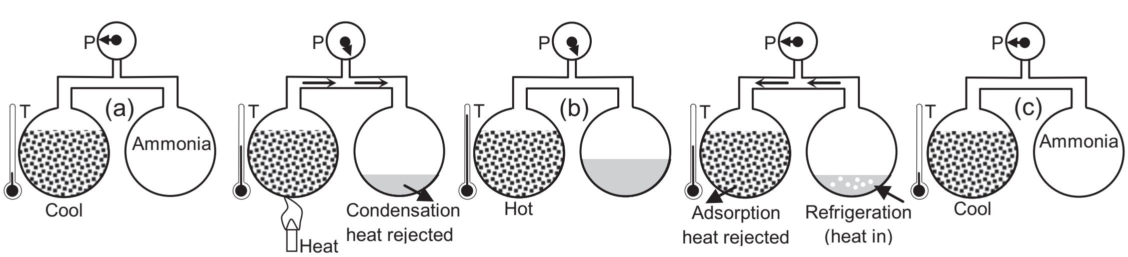

Fig. 1 – Simple adsorption cycle device.