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COP trends for ideal thermal wave adsorption cooling cycles with enhancements

Onur Taylan [a], *Derek K. Baker* [a,*], *Bilgin Kaftanoğlu* [b]

[a] *Department of Mechanical Engineering, Middle East Technical University, 06531 Ankara, Turkey*
[b] *Department of Manufacturing Engineering, Atilim University, 06836 Incek, Ankara, Turkey*

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ABSTRACT

Models are presented for ideal thermal wave adsorption cooling cycles without mass recovery, with adiabatic mass recovery and with isothermal mass recovery. Coefficient of performance (COP) values obtained from simulations are compared with the results of a reversible cycle and previously developed models for a simple cycle and heat recovery cycle with two spatially isothermal beds (2SIB). The effects of maximum and minimum bed temperatures, bed's dead mass, and condensation and evaporation temperatures on COP were investigated. The thermal wave cycle has significantly higher COP's than the simple and 2SIB cycles. For the conditions investigated, adding mass recovery to the thermal wave cycle does not affect its COP significantly. The COP of the thermal wave cycle increases with increasing maximum bed and evaporation temperatures and decreasing minimum bed and condensation temperatures. Unlike for the simple and 2SIB cycles, variations in the bed's dead mass have minimal impact on COP.

Cycles de refroidissement améliorés idéaux aux ondes thermiques à adsorption : tendances des COP

Mots-clés : Système à adsorption ; Modélisation ; Simulation ; Onde-chaleur ; Transfert de masse

1. Introduction

Air-conditioning loads are rapidly increasing in Turkey, especially on the Mediterranean coast due to a large and expanding tourism industry with many luxury hotels. The common use of electrically-driven vapor-compression air conditioning units in these hotels is driving an increase in electricity consumption, especially during the summer. As described by Naukkarinen (2009), it is crucial to decrease the electricity consumed at these sites for cooling.

One effective way to decrease electrically-driven cooling loads is to replace conventional electrically-driven air-conditioning systems with environmentally benign, thermal-powered cooling systems, such as adsorption cooling systems, that are driven with a low-grade energy source like solar energy or waste heat. Many excellent reviews of adsorption cooling

* *Corresponding author*. Tel.: +90 312 210 5217; fax: +90 312 210 2536.
E-mail address: dbaker@metu.edu.tr (D.K. Baker).
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Nomenclature

c	Specific heat of incompressible substance (kJ kg^{-1} K^{-1})
c_p	Ideal gas specific heat at constant pressure (kJ kg^{-1} K^{-1})
h	Enthalpy (kJ kg^{-1})
Δh_{ads}	Heat of adsorption (kJ kg^{-1})
m	Mass (kg)
P	Pressure (kPa)
q	Heat transfer per unit mass of adsorbent (kJ kg^{-1})
R	Ratio of bed's design to inherent heat capacities (–)
T	Temperature (°C)
T_{hot}	Maximum bed temperature (°C)
T_o	Minimum bed temperature (°C)
ΔT_{excess}	Excess bed temperature ($T_o - T_{cond}$) (°C)
u	Internal energy (kJ kg^{-1})
X	Adsorption load (kg$_{ref}$/kg$_{ads}$)
y	Thermal wave position (–)

Subscripts

ads	Adsorbent
b	Back region of the bed
bed	Adsorbent bed
clr	Cooler
cond	Condenser/condensation
e	Exit
evap	Evaporator/evaporation
f	Front region of the bed
htr	Heater
i	Inlet
l	Liquid refrigerant
ref	Adsorbed refrigerant
rev	Reversible
s	Unspecified/unknown
shell	Adsorbent bed's shell
v	Refrigerant vapor
w	Thermal wave

Greek symbol

ε	Convergence criterion

Abbreviations

2SIB	heat recovery cycle with two spatially isothermal beds
AMR	adiabatic mass recovery
COP	coefficient of performance
HTF	heat transfer fluid
IMR	isothermal mass recovery
NMR	no mass recovery
TW	thermal wave

technologies exist (e.g., Dieng and Wang, 2001; Lambert and Jones, 2005; Demir et al., 2008). The work presented herein is part of an ongoing research program on adsorption cooling cycles at the Middle East Technical University (METU). This program includes experimental determination of the adsorption load of water on a natural zeolite native to Turkey and numerical comparison with other adsorption working pairs (Solmuş et al., 2010). Additionally, a prototype solar assisted adsorption cooling system using natural zeolite-water adsorbent-refrigerant pair was developed and tested at METU. Within the same research program, these experiments were supported with a number of numerical analyses of adsorption cooling cycles (Baker and Kaftanoğlu, 2007a, 2008; Baker, 2008) and solar driven adsorption cycles (Baker and Kaftanoğlu, 2007b; Taylan et al., 2009).

Although adsorption systems can help to decrease electricity consumption, they often have low coefficient of performances (COP's). COP has been shown to be sensitive to the bed's ratio of design to inherent heat capacities, where the inherent heat capacity is due to the choice of adsorbent-refrigerant pair and the design heat capacity is due to the structural design of the bed (Wang, 2001; Baker and Kaftanoğlu, 2008). Several enhanced cycles have been explored to increase COP including a forced convection adsorption cycle by Critoph (1998), adsorption cycles with heat and mass recovery by Wang (2001) and Akahira et al. (2004), a periodic reversal convective thermal wave cycle by Lai (2000), a three-bed cascading system with two different adsorption pairs by Liu and Leong (2006), and a three-stage adsorption cycle by Khan et al. (2008). Additionally, thermal regeneration in a multi-bed adsorption system was investigated by Chua et al. (2001), a transient theoretical model was developed for a two-bed heat recovery adsorption cycle by Chua et al. (2004) and another model was developed for heat recovery adsorption cycles using lumped parameters by Wang and Chua (2007a). Shelton et al. (1990) also proposed and patented a thermal wave adsorption cycle, which is the main focus of this study.

To appreciate the elegance of the thermal wave cycle for heat recovery, consider the heat from an external source required for a bed with only sensible loads (no sorption occurs and therefore there is no change in loading or latent loads) and constant specific heat capacities to undergo a cycle from T_o to T_{hot} to T_o. For a simple cycle (no heat or mass recovery), a heat transfer from an external source Q_{simple} is required to heat the bed from T_o to T_{hot}. Now consider a two-bed system with one bed initially at T_o (cold bed) and the second at T_{hot} (hot bed). The cold bed can be heated to $(T_o + T_{hot})/2$ by bringing it into thermal communication with the hot bed, and only $Q_{simple}/2$ is required from an external source to complete the heating to T_{hot}. A first approximation for the transient behavior of this heat recovery process is to assume that the beds are spatially isothermal, which is referred to herein as the two spatially isothermal beds (2SIB) cycle. Now consider the same initially cold and hot beds connected thermally by a heat transfer fluid (HTF) flowing in a loop. The flowing HTF causes the cold bed to be heated by a *thermal wave* passing through the bed. Ideally the HTF and bed are perfectly isothermal perpendicular to the HTF flow direction and perfectly adiabatic (i.e., no heat transfer) parallel to the HTF flow direction (infinite temperature gradients possible). As the thermal wave passes through the cold bed, ideally the bed is uniformly at T_{hot} behind the wave and at T_o in front of the wave. In the limit, as the width of the thermal wave goes to zero (a square wave), the thermal wave is able to heat the entire cold bed to T_{hot} and cool the