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Study on a waste heat-driven adsorption cooling cum desalination cycle

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ABSTRACT

This article presents the performance analysis of a waste heat-driven adsorption cycle. With the implementation of adsorption–desorption phenomena, the cycle simultaneously produces cooling energy and high-grade potable water. A mathematical model is developed using isotherm characteristics of the adsorbent/adsorbate pair (silica gel and water), energy and mass balances for the each component of the cycle. The cycle is analyzed using key performance parameters namely (i) specific cooling power (SCP), (ii) specific daily water production (SDWP), (iii) the coefficient of performance (COP) and (iv) the overall conversion ratio (OCR). The numerical results of the adsorption cycle are validated using experimental data. The parametric analysis using different hot and chilled water temperatures are reported. At 85 °C hot water inlet temperature, the cycle generates 3.6 m^3 of potable water and 23 Rton of cooling at the produced chilled water temperature of 10 °C.

Etude sur un cycle de refroidissement à adsorption utilisé également pour le dessalement, entraîné à l'aide de la récupération de chaleur

Mots clés : Adsorption ; Refroidissement ; Dessalement ; Chaleur Rejetée ; Récupération

1. Introduction

Significant contribution by anthropogenic emission of greenhouse gases over the past 200 years from the burning of fossil fuels has been affecting the Earth's climate. According to the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) data, the Earth's average surface temperature has increased by about 1.2–1.4 °F in the last 100 years (U.S. EPA 2010). This temperature rise causes global warming increasing the melting rate of sea ice. The National Ice and Snow Data Center (NISDC) reports that the Arctic sea ice has

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Nomenclature

Symbols

A	total area (m^2)
c_p	specific heat capacity ($J\ kg^{-1}\ K^{-1}$)
COP	coefficient of performance
D_{so}	kinetic constant for the silica gel water system ($m^2\ s^{-1}$)
E	characteristic energy ($kJ\ mol^{-1}$)
E_a	activation energy ($kJ\ kg^{-1}$)
h_f	sensible heat ($J\ kg^{-1}$)
h_{fg}	latent heat of vaporization or condensation ($J\ kg^{-1}$)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
M	mass (kg)
n	D–A constant (–)
OCR	overall conversion ratio (–)
P	pressure (Pa)
PR	performance ratio (–)
q	fraction of vapor adsorbed by the adsorbent ($kg\ kg^{-1}$)
q_0	maximum adsorbed amount ($kg\ kg^{-1}$)
q^*	equilibrium uptake ($kg\ kg^{-1}$)
Q	power (W)
Q_{st}	isosteric heat of adsorption ($J\ kg^{-1}$)
R	gas constant ($J\ kg^{-1}\ mol^{-1}$)
R_p	particle radius (mm)
SCP	specific cooling power (Rton $tonne^{-1}$)
SDWP	specific daily water production ($m^3\ tonne^{-1}\ day^{-1}$)
t	time (s)
T	temperature (°C)
τ	number of cycles per day (–)
U	overall heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
υ	specific volume ($m^3\ kg^{-1}$)

Subscripts

abe	adsorbate
chilled	chilled water
cond	condenser
cw	cooling water
cycle	one cycle with one bed undergoing complete adsorption and desorption
d	distillate
evap	evaporator
feed	feed water
HX	heat exchanger
hw	hot water
Mads	master adsorber
Mdes	master desorber
in	inlet
out	outlet
S	sea water, salinity ($g\ kg^{-1}$)
Sads	slave adsorber
Sdes	slave desorber
sg	silica gel
switching	switching period

declined dramatically over the past thirty years. If the ocean surface receives a layer of fresh water from the melting ice, thermohaline circulation that contributes to a proper temperature balance across the earth can be disrupted (NISDC, 2010). Thus, it is crucial to reduce the burning amount of hydrocarbon and to develop thermodynamic cycle that can re-utilize or convert waste heat to useful effects, without additional hydrocarbon burning. The savings in extra emission is critical to slow down global warming.

Potable water is a necessity for living of human and industrial processes. The accessible fresh water on Earth is less than 1% of all the available water since 97% of the available water is in the sea and 65% of the fresh water is locked in the ice-caps and under the ground (Frenkel, 2004). Moreover, water consumption doubles every 20 years which is about two times the population growth rate (Frenkel, 2004). According to the 2nd UN World Water Development Report, more than one billion people lack access to safe drinking water, and 40 percent lack access to basic sanitation (Saha et al., 2009).

On the other hand, it is likely that cooling demand will increase proportionally with the increase in individual income. For instance, the cooling demand in metropolitan Mumbai has increased in the last decade and now it is about 24% of that for the entire United States (Saha et al., 2009). The additional burning of fossil fuels to meet Global potable water and cooling demands would contribute to further environmental problems. Therefore, current situation calls for the development of innovative thermodynamic cycles that can produce cooling power and potable water simultaneously using waste heat or renewable energy sources.

Ng et al. (2009) have reported low temperature waste heat-driven cooling cum desalination cycles which employ adsorption process. This article discusses the performance of a multi-bed adsorption cooling cum desalination cycle where the heat recovery strategy is applied which not only significantly improves the potable water production rate but also cooling power.

2. Description of the multi-bed adsorption cooling cum desalination cycle

The adsorption (AD) cycle utilizes the physisorption process between the adsorbent and adsorbate to produce cooling power from the evaporation of the saline water in the evaporator, and potable water at the condenser. These useful effects are achieved by the amalgamation of "adsorption-triggered-evaporation" and "desorption-resulted-condensation" processes driven by a low temperature hot water that can be extracted from industrial waste heat or solar energy (Ng et al., 2006a,b; Saha et al., 2006; Thu et al., 2009; El-Sharkawy et al., 2007, Chakraborty et al., 2008a,b). When the unsaturated silica gel is exposed to the de-aerated saline water in the evaporator, the uptake of water vapor is quickened by the high affinity of the water molecules to the pores of the adsorbent which are of the order of 2–6 nm. Such