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Experimental study on the effects of the operation conditions on the performance of a chemisorption air conditioner powered by low grade heat

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HIGHLIGHTS

- ▶ We studied a chemisorption air conditioner driven by low temperature heat.
- ▶ The machine was driven by heat with temperatures between 55 and 75 °C.
- ▶ The machine produced cooling effect with temperatures between 5 and 13 °C.
- ▶ We assessed the working conditions that maximize the cooling power and the COP.

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ABSTRACT

A chemisorption air conditioner with NaBr/expanded graphite composite sorbent and NH_3 as refrigerant was designed and constructed to be powered by low temperature heat. The effect of independent variables (chilled water inlet temperature, heat source temperature and cycle time) on the coefficient of performance (COP) and cooling power of the machine was investigated with a 2^k factorial design experimental set-up. This set-up was extended according to a central composite design to identify the coefficients of a 2° order polynomial equation that related the performance of the system and the independent variables. This equation was used to create response surfaces that enabled the identification of the operation conditions that maximized the machine performance. The experimental results indicated that the machine had a cooling power between 1.27 and 3.16 kW and a COP ranging from 0.28 to 0.48, depending on the operation conditions. The response surface analysis showed that when the heat sink was 25 ± 1 °C the maximization of the cooling power occurred at a driving heat source of at least 71 °C, in cycles not longer than 21 min. Contrarily, the maximization of the COP occurred at cycle time above 77 min, and heat source of around 56 °C. For simultaneous maximization of both the COP and the cooling power, the heat source should be 56 °C, and the cycle time between 20 and 25 min.

1. Introduction

Concerns about greenhouse gas emissions, global warming and climate change led to development of environmental regulations which are now changing how energy is obtained and utilized around the world. The 1987 Montreal Protocol [1]and the Kyoto Protocol [2] put restrictions on the production and use of ozone depletion substances such as chlorofluorocarbons (CFCs') and hydrochloroflourocarbons (HFCs'), and limits the emission of greenhouse gases, respectively. Air conditioning and refrigeration industry is one of those hardest affected by the protocols. The use of refrigerants of CFCs' and HFCs' type in the vapor compression refrigeration systems, not only contribute to the ozone layer depletion and greenhouse gas emissions, but also the electricity consumed by the systems during operation contribute to the depletion of fossil fuels. As consequence, refrigeration experts are required to devise ways of mitigating the above mentioned negative effects. Some of the ways that have been proposed include proper containment, recycling, recovery of the refrigerants, and also the qualification and use of alternative technologies to the vapor compression systems [3].

Solid–gas sorption can be considered a promising alternative refrigeration technology due to its potential for energy conservation and ecological protection. Sorption machines are driven by heat and may need only very little electricity; hence, unlike the conventional mechanical compression systems, the former

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Nomenclature

CCD	central composite design
COP	coefficient of performance (–)
Cp	specific heat (kJ kg^{-1} K^{-1})
DM	percentage increase of the dependent variable above its minimum value at a fixed operation condition (%)
f_g	mass fraction of expanded graphite in the composite sorbent (–)
$\dot{m}$	mass flow rate of the heat transfer fluid
m	mass (kg)
MW_s	molecular weight of anhydrous salt (kg mol^{-1})
P_C	Cooling power (kW)
Q	heat load (kJ)
R_{Cp}	heat capacity ratio (–)
R_m	mass ratio (–)
Rs	dependent variable
t_C	cycle time (min)
$T_{Ds,In}$	inlet heat transfer fluid temperature in the reactor during the regeneration period (°C)
$T_{Eq,}$	equilibrium temperature (K)
$T_{Ev,In}$	inlet heat transfer fluid temperature in the evaporator (°C)
$T_{Sink,In}$	inlet heat transfer fluid temperature in the condenser and in the reactor during the adsorption period (°C)
V_{net}	volume of composite adsorbent between fins, (m^3)

Subscripts

Ads	reactor case covers (shell) and fin tubes
CS	carbon steel
Ds	regeneration period
EG	expanded graphite
Ev	evaporator
fin	fins
g	graphite
In	heat transfer fluid inlet
Min	minimum
Max	maximum
Out	heat transfer fluid outlet
s	NaBr
W	water

Greek symbols

α	star points
a_i	coefficients of the polynomial regression
ΔH_r	reaction enthalpy (kJ mol^{-1})
ΔS_r	reaction entropy (J mol^{-1} K^{-1})
ΔT_{Eq}	temperature equilibrium drop (°C, K)
ϕ	porosity of the composite adsorbent (–)
$\bar{v}_s$	molar volume of salt (m^3 mol^{-1})
ρ	density or apparent density (kg m^{-3})

machines can utilize a variety of heat sources such as solar, biomass, and waste heat from engines and industrial processes. Moreover, sorption systems use natural working fluids such as water, methanol and ammonia, with zero ozone depletion potential (ODP) which meets the requirements of Montreal Protocol. These refrigerants also have zero global warming potential (GWP) and fulfill the Kyoto Protocol. A wider application of sorption systems can therefore lead to a reduction of greenhouse gases emissions resulting from thermal electric power generation. A comprehensive review on the feasibilities of solid sorption systems can be obtained from literature [4,5].

Sorption air conditioners which can operate at temperatures as low as 55 °C [6], but most commonly in the range between 65 and 95 °C [4,7–10], can effectively use a variety of energy sources such as solar energy or low temperature waste heat. Since such low temperature heat sources are widely available, low temperature driven systems have potential for wider application. Various researches have been carried out on potential low temperature driven working pairs for adsorption systems. Most of the sorbents studied were adapted for solar powered refrigeration and air conditioning, and include physical adsorption working pairs such as activated carbon–methanol [11,12], activated carbon–acetonitrile [13], activated carbon fibre (ACF)–methanol [14], and silica gel–water [15], among others. These working pairs have divariant equilibrium, and the amount of adsorbed refrigerant is a function of both temperature and pressure.

Machines that use chemical sorbents such as metal chlorides [16–19] and metal hydrides [20] have been also studied. Ammonia is often employed as the refrigerant in the former machines, whereas hydrogen is used as the refrigerant in the latter ones. The chemisorption process is monovariant, regardless of the refrigerant or the sorbent employed.

Li et al. [21] showed that a chemisorption system operating under double stage cycle could produce cooling effect below −30 °C with temperatures around 100 °C, depending on the working pairs chosen. However, the authors noted that this approach had the drawback of reducing the COP because heat had to be supplied during two desorption periods to achieve a single useful cooling effect production.

Considering only single stage machines, the main advantages of the use of chemisorptions working pairs instead of the physical sorption pairs are the larger sorption capacity and cooling power density normally obtained with the former pairs, which can enable the construction of simpler, smaller, and cheaper systems. Furthermore, machines using ammonia as the refrigerant are not sensitive to small leaks as compared to those using methanol or water. Kiplagat et al. [18] showed that the specific cooling capacity of a consolidated composite of LiCl and expanded graphite was 1.8–6.7 times the value obtained when activated carbon was the adsorbent. Their work focused on evaporation temperatures suitable for ice making, and the regeneration of the adsorbent occurred with low grade heat between 70 and 80 °C.

Moreover, some studies [22,23] indicated the feasibility of using NaBr composite sorbent to achieve high COP and cooling power density in single stage cycle operating under evaporation conditions suitable for air conditioning and driven by low temperature heat sources. In the study carried out by Oliveira et al. [23], bench-scale prototypes with NaBr-expanded graphite composite sorbent produced 219 kJ kg^{-1} of cooling at 5 °C and 510 kJ kg^{-1} at 15 °C, when the heat source temperature was 65 °C and the heat sink temperature was 30 °C. For the same heat source and heat sink temperatures mentioned above, the system achieved a cooling power density in the range of 75–79 kW m^{-3} with a COP between 0.43 and 0.46, when cooling occurred at 15 °C.

Hence, in the present work we studied the performance of a small scale (between 1 and 3 kW) air conditioner chiller using NaBr-expanded graphite composite sorbent.

The system was designed, constructed, and its performance was tested under different operation conditions, according to a 2^k factorial design and to a central composite design (CCD) [24–26].

The 2^k factorial design was used to identify the quantitative effect of independent variables (inlet heat transfer fluid temperature in the evaporator, inlet heat transfer fluid temperature in the reactor during the regeneration period and cycle time) on the COP and