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Performance of a modified zeolite 13X-water adsorptive cooling module powered by exhaust waste heat

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ABSTRACT

A modified adsorption cooling module with a working pair of 13X zeolite-water used for engineering truck air-conditioning driven by engine waste heat is presented in this paper. The cooling powers at different evaporating temperatures for the module were first tested, and the cycle operating characteristics of the module at different cooling powers were then analyzed and discussed. The performance of the cooling module is found to have a strong coupling with exterior ambient parameters such as the heat source temperature (T_{hs}), ambient temperature (T_a), air velocity (v) and air relative humidity (φ). Experiments were carried out systematically and analyzed in detail to study the effects of the ambient parameters on the module performance. Our results indicate that the demonstrated cooling module has a good performance, and the minimum evaporating temperatures corresponding to the cooling powers of 2.0 W and 10.5 W are 0.7 °C and 16.2 °C, respectively, under the conditions of T_{hs} at 325 °C, T_a at 18 °C, φ at 70%, and natural convection. Based on the presented module, a preliminary multiple module adsorption air conditioning system for engineering truck driver's cab was also proposed in this work.

1. Introduction

As a consequence of the Kyoto Protocol and its predecessor, the Montreal Protocol, environmental consideration will play an important role in the choice of a refrigeration or heat pump system [1]. Effective energy utilization is also required for prevention of global warming and decrease in the use of fossil fuels. Heat driven sorption heat pump/refrigeration systems have drawn considerable attention due to their lower environmental impact and large energy saving potential as the systems using neither ozone depleting gases nor the fossil fuel or electricity as driving source [2–5]. Zeolite-water heat pump system was originally proposed by D. I. Tchernev [6] for effective use of low temperature heat sources such as the solar heat and waste heat.

Waste heat adsorption cooling is a clean process which does not contribute at all to global warming. At present, car air conditioning systems using HFCs as refrigerants have very high HFC leakage rates (20–40% per year) [1,7,8]; moreover their annual operation time is very short. Waste heat adsorption cooling is, therefore, highly competitive from the global warming point of view even with low COP. As a good example, adsorption systems could be applied in automotive air conditioning systems in which heat recovered from the exhaust gas could be re-used as the powering source. Some studies [9–18] have been carried out in this direction, but to date no commercial product exists, which is mainly due to the need for light and compact units. This brings a great challenge for adsorptive cooling to be realized and widely applied, and technological breakthroughs are still required.

Zhu et al. [19] designed a waste-heat-powered adsorption cooling module with 400 g of zeolite and 120 g of water as the adsorbent-adsorbate pair to produce chilled water for fish preservation in a fishing boat. The adsorption cooling module was different from the conventional adsorption systems, because, as an independent and integrated micromation adsorption refrigeration unit, it had a very simple structure which was comprised of a generator/adsorber and an incorporated condenser/evaporator. No moving parts or controlling valves were included. It is noteworthy that we could easily assemble such an adsorption cooling system with different cooling power by utilizing different quantity of modules. Since that, similar adsorption modules with different adsorbent-adsorbate pairs such as silica gel and water [20], zeolite-active carbon compound and water [21], activated carbon PX21 and NH_3 [22], active carbon and ammonia [23,24], and domestic type of charcoal and methanol [25,26] were successively studied and reported in theoretical modeling and/or experimentally.

Despite the above efforts, heretofore no module is successfully applied in automotive air conditioning. In the present study,

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Nomenclature

COP	coefficient of performance
c_p	specific heat [kJ kg^{-1} K^{-1}]
m	mass [kg]
P	electric heating power [W]
p	pressure [Pa]
Q	quantity of heat [kJ]
q_{des}	desorption heat [kJ kg^{-1}]
q_{fg}	evaporation latent heat of refrigerant [kJ kg^{-1}]
R	resistance [Ω]
SCP	specific cooling power [W kg^{-1}]
T	temperature [°C]
t	time [min]
T_{a1}	final adsorption temperature in adsorber [K]
T_{a2}	initial adsorption temperature in adsorber [K]
T_{g1}	initial desorption temperature in adsorber [K]
T_{g2}	final desorption temperature in adsorber [K]
t_{ad}	adsorption refrigerating time [min]
V	voltage [V]
v	air velocity [m/s]
x	adsorption quantity [kg kg^{-1}]
x_a	adsorbed capacities at the end of adsorption [kg kg^{-1}]
x_b	adsorbed capacities at the end of desorption [kg kg^{-1}]

Subscripts

a	ambient air
b	adsorber metal
c	condensation
e	evaporation
h	heating
hs	heating source
ref	refrigeration
w	water
z	zeolite

Greek symbols

Ψ	dimensionless factor
φ	air relative humidity [%]

a modified adsorption cooling module with zeolite 13X and water as adsorbent-adsorbate pair was presented for application in engineering truck adsorption air conditioning driven by exhaust gas waste heat. The performance of the cooling module was experimentally investigated in detail. The variations of the evaporating temperatures at different cooling powers were analyzed and the effects of parameters such as the heat source temperature, ambient temperature, air velocity and air relative humidity on the cooling performance of the module were discussed. Moreover, a preliminary multiple module adsorption air conditioning system for engineering truck driver's cab by utilizing the presented cooling modules was proposed and described in this article.

The objective of the present article is to obtain the detailed performance and working characteristics of the proposed adsorption cooling module, to provide a reference basis for optimization design of engineering truck adsorption air conditioning with these modules and to encourage its further applications in other industrial fields.

2. Cycle description

2.1. Modified adsorption cooling module

The prototype of the adsorption cooling module modified with zeolite13X-water as the adsorption working pair, 16 mm in diameter and 1020 mm in length is shown in Fig. 1. Zeolite13X-water was chosen as the working pair in our work, since 13X zeolite is suitable for using a high temperature heat source (above 150 °C), and also the high temperature heat of the exhaust gas from the diesel engine can be utilized directly (its temperature is up to 400 °C and the available temperature is up to 200–300 °C). And also, compared to other adsorbents such as silica-gel, activated carbon, $CaCl_2$, and 4A zeolite, 13X zeolite has a larger pore size and higher specific surface area, and can be arranged in a perfect adsorbent-adsorbate pair with water, a natural refrigerant with a high heat of vaporization. 13X zeolite–water pair has a property of level adsorption isotherms [27], that is, the quantity of water adsorbed by zeolite 13X is strongly dependent on temperature and only weakly dependent on vapor pressure, which makes 13X zeolite have a satisfactory refrigeration ability.

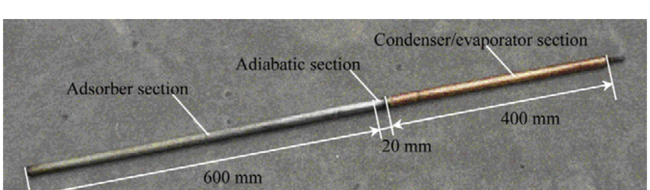

Fig. 1. Prototype of the adsorption cooling module.

The module is comprised of three sections, i.e., a stainless steel tube of 600 mm in length as the generator/adsorber at one end; a copper tube of 400 mm in length as the combined evaporator/condenser at the other end; and an adiabatic section (20 mm in length) in the middle which is used to prevent heat transfer between the adsorber and the condenser/evaporator. The copper was used for the evaporator/condenser due to its excellent heat transfer property, however the stainless steel was used in the adsorber as it has better anti-corrosion ability than the copper especially under the circumstance of high temperature exhaust gas of more than 200 °C. The insulating material between the adsorber and the condenser/evaporator was ceramic, which was bonded to the wall at one end of the stainless tube. To fix zeolite in the adsorber (the average diameter of zeolite particles used in our work is 1.2 mm), stainless steel wire gauze rolled into a hollow cylinder shape was used and installed concentrically in the stainless steel tube by using a pair of metal rings at the two ends of the stainless tube, and then zeolite 13X was compactly filled in the enclosed space between the wire gauze and stainless tube wall (which is about 3 mm thick layer, and the weight of filled zeolite per one module is about 45 g). Here the wire gauze together with the metal rings plays a role in stopping zeolite from moving around. Also, the existence of wire gauze is convenient for the mass transfer of vapor molecules. The stainless tube end with ceramic was connected to the copper tube of the condenser/evaporator by brazing. The charged quantity of water in the module is about 10.5 g. Heat may be transferred to or from the adsorber and condenser/evaporator with the surroundings by passing air or any other fluid across them. Refrigerant is either evacuated to the condenser or transferred from the evaporator through the empty central bypass of the adsorber.