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Novel absorption refrigeration system with a hollow fiber membrane-based generator

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ABSTRACT

Vapor absorption refrigeration systems using the LiBr–water pair can be an alternative to existing automobile air-conditioning systems. To this purpose, the new system must be compact enough to fit into automobiles, and robust against sloping roads and unexpected vibrations while driving. The system uses a micro-porous hydrophobic hollow fiber membrane-based generator (HFM-G) instead of the conventional generator in the absorption cycle. HFM-G extracts water vapor from the LiBr solution that is mechanically constrained by a hydrophobic membrane. This paper presents the results of a parametric steady-state simulation investigating how the HFM-G affects the proposed absorption cooling cycle. We first describe the mechanism of the HFM-G, and the system performance of the proposed cycle under various operating conditions is examined. Simulation results show that the proposed system can achieve a cooling capacity and COP of approximately 2.88 kW and 0.63, respectively, by incorporating the solution recirculation process.

Nouveau système frigorifique à absorption avec un générateur à base de membrane en fibre creuse

Mots clés : Conditionneur d'air d'automobile ; Désorbeur ; Membrane en fibre creuse hydrophobe ; Générateur ; Système frigorifique à absorption à simple effet ; Distillation membranaire sous vide

1. Introduction

Vapor absorption refrigeration systems (VARs) have several advantages over vapor compression refrigeration systems (VCRs): the use of an eco-friendly refrigerant and its low energy consumption. In addition, in the absorption cycle, the solution is pressurized by means of a solution pump in a heat-operated generator to which waste heat is supplied; while, in the compression cycle in VCRs, a compressor is used for pressurizing

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Nomenclature

a	circulation ratio
c_p	specific heat [J kg^{-1} K^{-1}]
d	hydraulic diameter [*m*]
D	mass diffusivity of solute [m^2 s^{-1}]
Δx	length [*m*]
ΔH_v	latent heat of vaporization [J kg^{-1}]
EA	the number of membrane
h	convective heat transfer coefficient [W m^{-2} K^{-1}]
J_v	mass flux through membrane [kg m^{-2} s^{-1}]
k	thermal conductivity [W m^{-1} K^{-1}]
B_m	membrane distillation coefficient [kg m^{-2} s^{-1} Pa^{-1}]
l	*length* [m]
M	molecular weight [kg mol^{-1}]
$\dot{m}$	mass flow rate [kg s^{-1}]
P	pressure [Pa]
Q	heat transfer rate [W]
r	radius [m]
R	gas constant [m^3 Pa K^{-1} mol^{-1}]
Re	Reynolds number
T	temperature [K]
Pr	Prandtl number
v	velocity
W_c	circumference of hollow fiber membrane [m]
x	concentration [%]

Greek symbols

α	convective mass transfer coefficient [m s^{-1}]
Φ	membrane porosity [%]
τ	membrane tortuosity
δ	membrane thickness [m]
μ	dynamic viscosity [kg m^{-1} s^{-1}]
ρ	density [kg m^{-3}]
ε	effectiveness of heat exchanger
β	recirculation ratio

Subscript

abs	absorber
ass	assumed value
b	bulk
cal	calculated value
cool	cooling water
cond	condenser
evap	evaporator
f	feed
gen	generator
HE	heat exchanger
in	inlet
inter	intermediate
LiBr	lithium bromide solution
m	membrane
out	outlet
p	partial pressure of vapor
pore	membrane pore
ref	refrigerant
s	surface
SHE	solution heat exchanger
strong	strong solution
weak	weak solution

the solution. Thus, the performance of the generator plays a significant role in the cooling performance and the coefficient of performance (COP) of VARs. In general, automobile manufacturers use VCRs owing to their small size and high performance-to-volume ratio. However, they have two major disadvantages: (1) the energy requirement for compressor operation and (2) the use of hydrocarbon derivatives causing environmental problems (Farrington and Rugh, 2000). CO_2 emission from the transportation sector accounts for 18.6% of the total emission in Japan, and it is estimated that the existing air-conditioning units used in automobiles contribute to 7% of fuel consumption (or emission of 8 million ton CO_2) (Ministry of Land, 2016). On the other hand, VARs use water and lithium bromide (LiBr) solution as a refrigerant and an absorbent, respectively. Further, by adopting an environmental refrigerant and using the low-grade heat energy of the exhaust gas from the car engine, the aforementioned drawbacks of VCRs can be eliminated. Thus, there is increasing interest in the use of VARs in automobiles although the system needs to be sufficiently scaled and its weight needs to be reduced while maintaining its high performance. In the conventional generator in VARs, the free surface of aqueous solution exists in the region where the evaporation occurs, making the system performance unstable when a vehicle drives on hills, or undergoes unexpected vibrations (Koehler et al., 1997).

Several researchers have introduced VARs to the automobile industry. Koehler et al. (1997) designed a prototype of VARs powered by exhaust gas for a truck. They estimated the available heat in the exhaust gas, and considered it as an energy source for VARs. They found large variations in the available heat depending on the driving conditions: uphill, flat, and downhill road sections. The system performance becomes degraded especially on the slope. Therefore, it is hard to obtain the optimal design of the generator. The COP of this prototype was approximately 0.27, which is quite lower than that of the conventional VARs; however, their simulation results showed that the COP is expected to be doubled by the optimization of the system. Horuz (1999) conducted an experimental investigation mainly to observe the effect of engine output power on the flow rate, temperature of the exhaust gas, and the cooling capacity. They considered several obstacles to the application of VARs in the road transport vehicles: the facts that an auxiliary energy source is necessary when the vehicle is stationary or is stuck in a very slow moving traffic, that the effect of increased back pressure on engine performance has to be considered, and that the scale of the VARs has to be significantly reduced to suit the vehicles. Talom and Beyene (2009) presented a mathematical model and conducted an experimental study on 10.55 kW VARs operated using the exhaust gas from a 2.8 L V6 internal combustion engine (Talom and Beyene, 2009). The experiments were mainly conducted to evaluate the system performance. The variations in chilled water temperature (CWT; i.e., evaporation temperature) at various rotational speeds (revolutions per minute, RPM) of the engine were