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Heating performance enhancement of a CO_2 heat pump system recovering stack exhaust thermal energy in fuel cell vehicles

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Abstract

A CO_2 heat pump system using recovered heat from the stack coolant was provided for use in fuel cell vehicles, where the high temperature heat source like in internal combustion engine vehicles is not available. The refrigerant loop consists of an electric drive compressor, a cabin heater, an outdoor evaporator, an internal heat exchanger, an expansion valve and an accumulator. The performance characteristics of the heat pump system were investigated and analyzed by experiments. The results of heating experiments were discussed for the purpose of the development and efficiency improvement of a CO_2 heat pump system, when recovering stack exhaust heat in fuel cell vehicles. A heater core using stack coolant was placed upstream of a cabin heater to preheat incoming air to the cabin heater. The performance of the heat pump system with heater core was compared with that of the conventional heating system with heater core and that of the heat pump system without heater core, and the heat pump system with heater core showed the best performance of the selected heating systems. Furthermore, the coolant to air heat pump system with heater core showed a significantly better performance than the air to air heat pump system with heater core.

Keywords: Heat pump; Automobile; Fuel cell; CO_2; R744; Transcritical cycle; Enhancement; Heat transfer; Performance

Amélioration de la performance en terme de chauffage d’un système à pompe à chaleur au CO_2 avec récupération de l’énergie thermique des systèmes d’échappement des véhicules à pile à combustible

Mots clés : Pompe à chaleur ; Automobile ; Pile à combustible ; CO_2 ; R744 ; Cycle transcritique ; Amélioration ; Transfert de chaleur ; Performance

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Nomenclature

COP	coefficient of performance
C_p	specific heat (kJ kg^{-1} K^{-1})
D	depth (mm)
DSH	degree of superheat (°C)
H	height (mm)
L	length (m)
$\dot{m}$	mass flow rate (kg h^{-1})
P	pressure (MPa)
ΔP	differential pressure (kPa)
$\dot{Q}$	heat capacity (kW)
RH	relative humidity (%)
T	temperature (°C)
W	width (mm)
$\dot{W}$	compressor power (kW)

Greek

ϕ	diameter (mm)

Subscripts

a	air
c	coolant
ch	cabin heater
ci	coolant inlet
comp	compressor
dis	discharge
hc	heater core
i	inlet
ind	indoor
o	outlet
out	outdoor
r	refrigerant
suc	suction

1. Introduction

During the last several decades, environmental problem such as global warming effect due to greenhouse gas accumulation in the lower atmosphere has been growing with increasing speed. R134a as a conventional refrigerant used in an automotive air conditioning system is one of main refrigerants that influence global warming. In the automotive air conditioning system, the efforts to protect the environment have been mainly focused on using carbon dioxide as an alternative refrigerant. The global warming potential (GWP) of CO_2 refrigerant which is one of the promising R134a alternatives is much lower than that of R134a. Compared to conventional refrigerants, the most remarkable property of CO_2 is the low critical temperature of 31.1 °C and the high critical pressure of 7.38 MPa. The size and weight of the CO_2 automotive air conditioning system can be reduced, because CO_2 operates at high pressure with increased volumetric refrigeration capacity. Some of the recent studies on the CO_2 automotive air conditioning system have investigated that the CO_2 system could provide the performance level of the conventional system using R134a as a refrigerant [1–3].

Finding an alternative solution to fossil fuels is inevitable in our automobile industry, which leads to the next generation of automobiles. Among the many options that are being researched a lot of investment has been put into the fuel cell vehicles. The use of fuel cells as driving source is a potential replacement for the internal combustion engine vehicles, because hydrogen fuel is clean and efficient energy. On the other hand, the heat rejected from the fuel cell stack is not sufficient to heat the cabin in cold climates. The limited amount of heat recovery is mainly due to the finite sized heater core whose size is chosen as the same as in the conventional internal combustion engine vehicles. The recovered heat with the heater core is a small amount due to the limited size and the reduced temperature difference between the stack coolant temperature and the ambient temperature compared with that in the conventional vehicles. So for supplementary heating in the cabin, the CO_2 heat pump system can be used as a promising heating system. In addition, the CO_2 system can be properly used for supplementary heating by achieving high capacity due to rather a high heat releasing temperature even at low ambient temperature.

As one of supplementary heating devices, a positive temperature coefficient (PTC) heater system transfers heat directly to the cabin with electric energy. Due to its direct heating effect the PTC heater system has a spontaneous response and comfortable air supply temperature is achieved right after a cold start-up. However, commercial 1.6 kW PTC heater system falls short of obtaining sufficient heating capacity and comfortable cabin temperature. In case of a fuel fired heater system, it is the only system among the considered supplementary heating systems that can be operated when the engine is turned off, because engine coolant is heated by a furnace. The fuel fired heater system has been used widely until now due to sufficient heating capacity for high-priced internal combustion engine vehicles. On the other hand, a heat pump system has been developed in response to an increasing need for supplementary heating and a growing environmental concern. The heating capacity of heat pump system exceeds that of the PTC heater system and it significantly reduces emissions compared with the fuel fired heater system [4]. Hammer and Wertenbach [5] showed the test data for an Audi A4 car with 1.6 L gasoline engine, comparing a CO_2 heat pump system without heater core and a conventional heating system with heater core. The