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Performance improvement of a dehumidifying heat pump using an additional waste heat source in electric vehicles with low occupancy

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ABSTRACT

A DHP (dehumidifying heat pump) has been proposed to save energy consumption in electric vehicles during the dehumidifying and heating operation. Since the mean occupancy rate in a vehicle is less than two people, it is required to optimize the performance of the DHP at low occupancy for an effective operation. The objective of this study is to investigate the performance improvement of a DHP by using the additional waste heat source in electric vehicles with low occupancy. The experiments on the DHP were conducted by varying operating modes, according to various numbers of passengers. Even though the air source DHP in an AL (alternating) mode showed 7.6% lower heating capacity on average, compared to that in the DH (dehumidifying and heating) mode, the COP improvement of the air source DHP in the AL mode against the DH mode was approximately 31% for one passenger. In addition, the dual source DHP in the AL mode showed 15.8% higher heating capacity and 5.2% higher COP on average, compared to the air source DHP in the AL mode.

1. Introduction

In cold weather, appropriate heating should be provided in the cabin of a vehicle to allow thermal comfort for passengers. A heat pump has been adopted in electric vehicles to provide heating effectively as a replacement of PTC (positive temperature coefficient) heaters [1–4]. Under fogging conditions on the windshield inside of the car, a dehumidifying and heating operation can be used for demisting and heating in the cabin, especially in cold and rainy weather conditions. The dehumidifying and heating operation is effective for demisting in cold and rainy weather conditions because the heating only mode cannot defog the windshield quickly. In electric vehicles, an air-conditioning unit and an electric heater have been used for demisting and heating in the cabin, respectively [5]. To replace the conventional dehumidifying and heating system in electric vehicles, a heat pump for heating the cabin can be modified to a DHP (dehumidifying heat pump) by adding an indoor condenser. It should be noted that the heating only mode with the heat pump is impossible to defog the windows effectively even though it shows much better COP than the DHP.

In a simple DHP, as shown in Fig. 1, the indoor air is cooled and dehumidified in the indoor evaporator, and then it is heated in the indoor condenser. The DHP may be more effective in the recirculated air mode than in the outdoor air mode due to higher humidity ratio with the breath of passengers and higher air temperature at the evaporator inlet in the recirculated air mode. The DHP showed higher specific moisture extraction rate and COP than the conventional dehumidifying and heating system in electric vehicles [6]. In the vehicles used in Western Europe, the mean occupancy rate remains fairly constant at approximately 1.5 persons per car [7] and the required MER (moisture extraction rate) is dependent on the number of passengers [8]. Since the DHP shows lower heating performance with the decrease in the MER due to lower heat absorption in the evaporator, the DHP may not satisfy the target heating capacity at low occupancy. In order to satisfy the target heating capacity and improve the efficiency, the DHP in electric vehicles can use the waste heat source from electric devices and batteries. The use of an additional heat source in the DHP leads to the decrease in the MER and the increase in the heating capacity due to the increases in the suction pressure and mass flow rate. Besides, the coolant loop for the waste heat recovery is capable of being acted as a heat storage system.

Most studies on a DHP using an air source in electric vehicles

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Nomenclature

AC	air-conditioning
AL	alternating mode of DH and HO operations
COP	coefficient of performance
c_p	specific heat (kJ kg^{-1} k^{-1})
CSR	compressor speed ratio (%)
db	dry bulb
DH	dehumidifying and heating
DHP	dehumidifying heat pump
EEV	electronic expansion valve
H	humidity
h	enthalpy (kJ kg^{-1})
HO	heating only
HR	humidity ratio (kgv kga^{-1})
IDCON	condenser in the indoor side
IDEEV	EEV at the indoor heat exchanger inlet
IDEVA	evaporator in the indoor side
MER	moisture extraction rate (kg h^{-1})
N_{psg}	number of passengers
ODEEV	EEV at the outdoor heat exchanger inlet
ODHX	outdoor heat exchanger
P	pressure (kPa)
PTC	positive temperature coefficient
Q	volumetric flow rate (m^3 h^{-1})
q	heat transfer rate (kW)
T	temperature (°C)
v	specific volume (m^3 kg^{-1})
W	power consumption (kW)
WHEEV	EEV at the waste heat exchanger inlet
WHX	waste heat exchanger
wb	wet bulb

Subscripts

a	air
as	air source
c	coolant
cond	condenser
ds	dual source (air source and waste heat source)
h	heating
in	inlet
out	outlet
whs	waste heat source
whx	waste heat exchanger

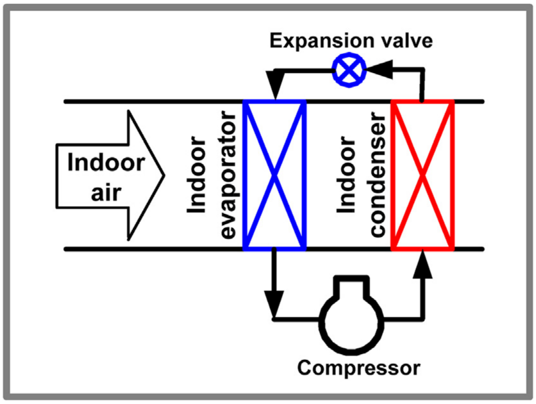

Fig. 1. Schematic diagram of a DHP.

have focused on the feasibility and the performance comparison with the conventional systems. Suzuki et al. [9] tested the performance of a DHP for electric vehicles in several dehumidifying modes by controlling EEV (electronic expansion valve). Tamura et al. [10] suggested the use of a CO_2 heat pump for dehumidifying and heating the vehicle compartment. The performance of the CO_2 heat pump was superior to that of the conventional R134a system, because of the waste heat recovery in the CO_2 heat pump from the dehumidification process. Ahn et al. [6] suggested a dual-evaporator heat pump using the air source for dehumidifying and heating in electric vehicles. The dual-evaporator heat pump system showed superior performance to the conventional air-conditioning system in the dehumidifying and heating operation. In addition, while air source heat pumps have been studied for residential applications [11–15], waste source heat pumps using the recovered heat from batteries and electric devices have been studied for electric vehicles. Kim et al. [1,2] investigated a CO_2 heat pump that used the recovered heat from the stack coolant in fuel cell vehicles, which resulted in higher performance compared to the conventional heating system. Lee et al. [3] investigated the performance of a CO_2 heat pump that used the stack coolant as the heat source for fuel cell electric vehicles under cold weather conditions. They showed that the heating capacity and COP of the stack coolant source heat pump using CO_2 were sufficient to cover the heating load of the fuel cell vehicle under cold weather conditions. Ahn et al. [4] investigated the feasibility of a dual source heat pump using both air and waste heat in electric vehicles. They showed that the heating performance of the dual source heat pump was higher than those of single source heat pumps. Cho et al. [16] investigated the performance of an R134a heat pump that used the waste heat from electric devices in an electric bus. They suggested that the heat pump was applicable as a cabin heating device.

A DHP using a waste heat source has not been investigated in open literature. Besides, even though the mean occupancy rate strongly affects the energy consumption in the DHP, its effect on the performance of the DHP in electric vehicles has not been considered. The energy saving control of the DHP using a waste heat source according to the occupancy rate in electric vehicles is a novel concept. The objective of this study is to investigate the improvement in the heating performance of the DHP at low occupancy in electric vehicles. In this study, the DHP using the waste heat source was proposed to improve the COP of the DHP at low occupancy while satisfying the target heating capacity in electric vehicles. The AL (alternating) mode of the DH (dehumidifying and heating) and HO (heating only) operations was applied to the DHP using the air source only and the dual heat source of air and waste heat. The performance of the DHP in the AL mode using the air source (AL_{as} mode) was measured by varying dehumidifying time for required MERs, depending on the number of passengers. The performance of the DHP in the AL_{as} mode was compared with that in the DH mode using the air source (DH_{as} mode). In addition, the performance of the DHP in the AL mode, using both the air and the waste heat sources (AL_{ds} mode), was measured by varying waste heat amount for required MERs. The performance of the DHP in the AL_{ds} mode was also compared with those in the DH_{as} and AL_{as} modes.