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Design and experimental analysis of an efficient HVAC (heating, ventilation, air-conditioning) system on an electric bus with dynamic on-road wireless charging

In-Soo Suh [a, *], Minyoung Lee [a], Jedok Kim [a], Sang Taek Oh [c], Jong-Phil Won [b]

[a] *Graduate School for Green Transportation, KAIST, Daejeon, Republic of Korea*
[b] *Korea Automotive Technology Institute, Cheonan, Republic of Korea*
[c] *Seoul Industry Engineering Co., Gyunggi-Do, Republic of Korea*

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ABSTRACT

The design, control and experimental verification of an HVAC (heating, ventilation, air-conditioning) system to achieve high operational efficiency for an electric bus equipped with a dynamic wireless charging capability are described in this paper. Target power capacities of the HVAC system have been set as 28 kW of cooling and 26 kW of heating with a 600 V in-vehicle environment with COPs (coefficient of performance) of more than 1.6 for cooling and 2.6 for heating, which are required for customer's comfort. For an efficient HVAC system design, an integrated air-conditioning with a heat pump system is proposed and analyzed to meet the objectives of the HVAC system, incorporating the waste heat recovery from the drive motor, its driver, and other wireless charging electric modules. In addition, a control algorithm for operational energy management, considering the real-time power consumption and the wirelessly delivered power, is also proposed and verified to secure an actual operational energy consumption target. Through the component- and vehicle-level of the experimental performance verification, combined with energy demand dynamic model, the proposed HVAC system is verified experimentally to meet target power capacities and efficiency measures for cooling and heating, which are important to electric buses, especially with dynamic wireless charging capability.

1. Introduction

In recent years, there have been increased interest and demand for EVs (electric vehicles) as a green transportation technology. Due to the limited specific energy and power of on-board batteries, reducing energy consumption in EVs is very important for massive introduction to the market in regard to longer driving range and reduced total operating cost of ownership. During the vehicle operation, the energy consumption due to the operation of HVAC (heating, ventilation, air-conditioning) system has been proved to be a significant part of the in total energy consumption, especially for purely electric or hybrid or fuel-cell electric bus applications [1–3].

For a passenger EV, the energy consumption due to heating and cooling system can reduce the overall driving range by 40%–60% under typical standard driving testing conditions [4,5]. Thus, there is a strong interest in electric vehicles' climate control systems, such as heating and cooling inside the cabin. Electric vehicles including hybrid and full electric vehicles have the wasted heat to warm up the passenger cabin and the climate control system has a very significant effect on the energy consumption and driving range per charge. In the case of very high ambient temperatures and high solar radiation, almost half of the stored energy might be used for cooling the passenger cabin and the battery, where the driving range can be reduced significantly for pure EVs. Under such conditions, the HVAC is the second-largest on-board consumer of electrical energy [6,7]. An HVAC system in current automotive applications means the heating and AC (air-conditioning) system in addition to the ventilation. An AC system usually adopts a vapor compression refrigeration circuit using R134a as a working fluid to obtain thermal comfort in the passenger cabin during summer. A

* Corresponding author. Tel.: +82 10 9125 5964 (mobile); fax: +82 42 350 1251.
E-mail address: insoo.suh@kaist.ac.kr (I.-S. Suh).

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Nomenclature

c_a	specific heat capacity of air
COP	coefficient of performance
DTM	overall thermal inertia of inside cabin other than air
E	consumed electrical energy
F_d	vehicle driving resistance force
F_{rol}	rolling resistance force from ground and tire interaction
F_{air}	air resistance force
F_{acc}	accelerating resistance force
F_g	hill-climbing force
$\Delta h_{c,i}$	refrigerant enthalpy change of compressor for cooling
$\Delta h_{e,i}$	refrigerant enthalpy change of evaporator for cooling
$\Delta h_{e,o}$	air enthalpy change of evaporator for cooling
$\dot{m}_a$	mass flow rate of air
$\dot{m}_r$	mass flow rate of refrigerant
P_a	available instantaneous power in a vehicle
P_{ESS}	power drawn from an on-board energy storage system
P_{WPT}	power delivered wirelessly to a vehicle
P_r	required power to drive a vehicle
$\dot{Q}_{AC}$	heat transfer rate by air-conditioning
$\dot{Q}_{ambient}$	heat transfer rate delivered from ambient
$\dot{Q}_{cabin}$	heat transfer rate inside a vehicle cabin
$\dot{Q}_e$	heat transfer rate of evaporator for cooling
$\dot{Q}_{total}$	total heat transfer rate inside a vehicle cabin
t_c	time required reaching the target temperature
T_{cabin}, T_{target}	temperature of cabin and target to cooling or heating
ΔT_i	temperature decrease due to cooling or increase due to heating
V	vehicle velocity
$\dot{W}$	work by compressor during cooling

heating system is to provide hot air to the passenger cabin during winter. While these functions were usually implemented as separate circuits in conventional ICE (internal-combustion engine) driven vehicles, an integrated air-conditioning and heat pump system has been proposed recently to improve overall operational efficiency for ICE or EVs [8].

The HP (heat pump) concept is employed by reversing the direction of the refrigerant flow in the AC system and by combining the heat from the waste heat recovery either from the ICE or electric components of EVs. Heat pump systems offer economical alternatives of recovering heat from various sources for use in industrial, commercial, and residential applications. Recent advances in heat pump systems have focused on advanced cycle designs of both heat- and work-actuated systems, improved cycle components and exploiting a wider range of applications [8]. The waste heat recovery by means of the Rankin Cycle is a promising approach for achieving significant improvement in energy efficiency for ICE driven vehicles [9,10]. The recovered heat is examined for cabin cooling for an absorption cooling cycle through energy and exergy analyses in hybrid electric vehicles, and the mechanical exergy loss rates are analyzed on heat exchangers using waste heat recovery [11,12]. Various research efforts have been performed recently with a strong emphasis on the energy efficiency in especially electric automotive applications [6,7,11–18].

In this paper, the target vehicle is a pure electric bus, driven by a 240 kW-rated AC induction motor with a high-voltage power of 580–680 V DC, supplied by a Li-polymer on-board battery system, with an additional power source of 80 kW wirelessly from the on-road powered track when the bus is driving on the power supply track, as summarized in Table 1. While ICE –driven buses have typical HVAC systems, an electric bus requires a fully electric one with a similar capacity to typical electric buses in the market to respond to customers' demands [1]. In addition, the operating efficiency of the electrical energy supplied from the limited capacity of the on-board battery's energy should be emphasized in the design and control of the system.

Table 1
Specification of target bus.

Item	Specification	Unit	Value
Bus	Seats		45
Pick-up device	Capacity	[kW]	80
Super capacitor	Max voltage	[V]	720
	Continued current	[A]	150
Battery	Type		Li-polymer
	Nominal voltage	[V]	620
	Rated capacity	[A]	40
	Energy	[kWh]	25
	Max. charge	[A]	120
	Max. discharge	[A]	320
Motor	Type		Induction motor
	Motoring power	[kW]	240
	Efficiency	[%]	93

On-road dynamic wireless charged electric vehicles are being developed and demonstrated very actively in recent research [19–30]. The application feature of WPT (wireless power transfer) will be described and discussed in this paper. In this research, we consider WPT as an additional power source and as additional vehicle electrical components during electric bus operation. The target electric bus and the related concept of the wireless power transfer system that is used for this paper's research are shown in Fig. 1, and the concept of wireless power transfer is described in Fig. 2. The wireless power transfer system for an electric bus, applied to this research, is largely composed of the Power Supply System, and the Vehicle's Power Pick-Up System, coupled with an induced magnetic field between the primary and secondary coils, with the mutual inductance of M, as in Fig. 2. The electric power is delivered from the grid to PWM (pulse-width modulation) power supply to the driving motor or an on-board ESS (energy storage system) system through the proper compensating circuitry operation between the primary and secondary coils. The magnetic field couplings or inductive power transfer with compensating circuit tunings are well documented in the literature [30–32].

This paper is organized as follows: in Section 2, the objectives of HVAC system research are defined as quantitative goals of required capacity and efficiency, the system architecture and modeling approach are described in Section 3, the experimental and simulation results are summarized and discussed in Section 4, and Section 5 concludes the paper.

2. Research objectives of the HVAC system

For typical ICE buses, the maximum power capacities are in the range of 25 kW (about 85,300 Btu/hr) for cooling and 50 kW (about 170,000 Btu/hr) for heating, respectively. For electric buses, the required thermal comfort from the customer domain would remain

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