Applied Thermal Engineering 115 (2017) 726–735

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Investigation on an improved heat pump AC system with the view of return air utilization and anti-fogging for electric vehicles

Guiying Zhang [a,b,c], Huiming Zou [a,b,*], Fei Qin [a,b,c], Qingfeng Xue [d], Changqing Tian [a,b]

[a] Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China
[b] Beijing Key Laboratory of Thermal Science and Technology, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China
[c] University of Chinese Academy of Sciences, Beijing, China
[d] China FAW Group Corporation R&D Center, Changchun, China

HIGHLIGHTS

- An improved EV AC system using return air with continuous anti-fogging was presented.
- Thermal model of electric vehicle on maximum return-air-using was established.
- Energy-saving potential of air source heat pump & auxiliary PTC was predicted.

ARTICLE INFO

Article history:
Received 23 August 2016
Revised 26 December 2016
Accepted 31 December 2016
Available online 03 January 2017

Keywords:
Heat pump
Return air
Electric vehicle
Air-conditioning

ABSTRACT

Utilizing the return air and fresh air properly is a promising approach to meet the demand for anti-foggy and energy-saving at the same time in electric vehicle (EV). In this paper, a concept of applying a continuous anti-fogging air curtain for front windshield glass to realize the maximum-return-air utilization in winter is presented. Accordingly, heating demand model of EV is built up by taking account of the return air ratio (RAR). The research results indicate that the heating demand can be reduced by 46.4–62.1% compared to the all-fresh-air condition when the ambient temperature is −5 °C to −20 °C. And, air source heat pump (ASHP) system performance under different RARs is tested experimentally in −20 °C ambient temperature to predict the energy-saving potentials. The coefficient of performance (COP) of ASHP decreases with the increasing of RARs. Heating capacity of ASHP presents little difference at different RARs. Equivalent COP (ECOP) is used to evaluate the EV heating, ventilation and air conditioning (HVAC) system comprehensive performance. The highest ECOP is 1.57 when the RAR is 0.46, which is 12.1% higher than that of all-fresh-air condition. Accordingly, the maximum energy saving is 40.6%. Moreover, COP change rate of ASHP with compressor speed is used to get optimal compressor speed.

1. Introduction

Electric vehicle (EV) is a potential low-emissions-vehicle replacement for traditional internal combustion engine to release the pressure of environment protection and energy shortage [1,2]. Heating ventilation air conditioning (HVAC) system is an important part of vehicle to insure safe driving by defogging and deicing, and maintain passengers comfortable by controlling air temperature, relative humidity and air velocity.

Different from traditional heating system using waste heat of internal combustion engine [3], EVs need the independent heating equipment driven by battery unit in winter [4,5]. Pure electric heating, such as positive temperature coefficient (PTC) electric heater, has been employed to warm the cabin. However, this kind of heating equipment consumes much energy due to its low heating efficiency [6]. The experimental results of Lee showed that AC system full load had a significant influence on the total driving range of EV. The reduction percentage was up to 50.0% for heating [7]. Air source heat pump (ASHP) is the alternatively choice to meet heating in winter and cooling in summer using R134a or CO_2 as

Abbreviations: ASHP, air source heat pump; COP, coefficient of performance; COPCR, COP change rate with compressor speed; CIP, compressor input power; ECOP, equivalent coefficient of performance; EV, electric vehicle; HVAC, heating, ventilation and air conditioning; PTC, positive temperature coefficient; RAR, return air ratio.

* Corresponding author at: Key Laboratory of Cryogenics, Technical Institute of Physics and Chemistry, Chinese Academy of Sciences, Beijing, China.

E-mail address: zouhuiming@mail.ipc.ac.cn (H. Zou).

http://dx.doi.org/10.1016/j.applthermaleng.2016.12.143
1359-4311/

Nomenclature

q	heat dissipation capacity of each part/heat generation from the human body /heating demand (kW)
Q	air supply volume rate/heating capacity of heat pump ($m^3 \cdot h^{-1}$/kW)
T	temperature (°C)
RH	relative humidity
v	driving speed (km h^{-1})
w	compressor power (kW)
α	convective heat transfer coefficient (W m^{-2} K^{-1})
λ	heat conductivity coefficient (W·m^{-1}·K^{-1})
ω	humidity ratio of the air (g kg^{-1})/moisture gain from the people in cabin (g h^{-1})
ρ	density (kg m^{-3})
φ	relative humidity of the supply air

Subscripts

a	air
a, fv	air flow velocity
a, dp	dew point of the supply air
am	ambient
asv	air supply volume
c	cabin
dp	dew point
ds	driving speed
f	fresh air condition
Hd	heating demand of AC system
hdc	heat dissipation capacity
hb	human body
masv	maximum air supply volume
mg	moisture gain from the people in cabin
n	compressor speed
r	return air condition
r, a	return air
s, a	supply air
sm	safety margin
TEC	total energy consumption
wis	windshield

refrigerant [8–13]. These researches indicate that ASHP can utilize less energy to make better performance and drivability. But according to the existing research results, heating performance of ASHP declines when the ambient temperature is lower than −10 °C. Suzuki [8] pointed out that there was an ice formation on the heat exchanger surface when the ambient temperature was below −10 °C, which led to the sharply declination of heating performance of ASHP. Ideal defrost start time [14], waste heat utilization [15,16], and refrigerant injection heat pump [17–19] were used to improve the heating performance in the low ambient temperature. Improving the heating performance of HP system is one approach to decrease the energy consumption of AC system of EV. Utilizing return air maximally would be another solution in decreasing the heating demand of EV.

In winter, for the demand of anti-fogging, all-fresh-air mode is used in most of conditions. The heating load from fresh air takes up most of the energy consumption of EV in winter. Therefore, using return air rationally in HVAC system is a potential energy-saving method for EV. Return air utilization mainly has two methods: indirect use and direct use. Indirect use is realized by recovering exhaust heat of return air to preheat fresh air [20,21]. This method will not bring about fogging problem, but its energy utilization efficiency is lower and needs heat recovery exchanger which makes the HVAC system more complex. Direct use is mixing the fresh air and return air before heated. This method has higher energy utilization efficiency and makes few changes in the regular system. Nonetheless, it is necessary to figure out a proper return air ratio (RAR) to avoid front windshield fogging. In general, thermal model of EV is a practical tool to determine the RAR based on no-fogging of front windshield. However, the current thermal models [22,23] are mainly focused on summer condition and all-fresh-air condition. Moreover, when the return air is used, the inlet air temperature of condenser will be raised and the ASHP system performance will be affected. However, there are few relative researches on this orientation.

In this work, a continuous anti-fogging air curtain is taken as a concept on EV for anti-fogging of the front windshield so that the return air can be utilized as much as possible. Meanwhile, the thermal model of EV is built up considering the fogging condition, ambient environment, and driving speed. Moreover, ASHP performance under different RARs is investigated experimentally in low ambient temperature as −20 °C. Combined with the thermal load calculation and the ASHP performance testing, the energy-saving potential of return air utilization for ASHP & auxiliary PTC heater is analyzed.

2. An improved AC system for EV

2.1. System description

Fig. 1a shows the traditional AC system using ASHP & auxiliary PTC electric heater for EV. Supply air is heated by the ASHP system firstly. The lack of heating capacity is made up by PTC heater in low ambient temperature. There are two operation modes, namely all-fresh-air and all-return-air. It is pretty easy to cause fogging problem for all-return air in winter and deterioration of air quality in long period application. All-fresh-air mode is usually used in winter. Anti-fogging air curtain is used selectively. Fig. 1b shows the improved AC system for EV which features the return air using maximally and properly. An adjustable opening degree three-way air valve is used to adjust the ratios of fresh air and return air. Continuous anti-fogging air curtain is adopted for the purpose of return air maximum utilization.

Maximum-return-air utilization decreases heating capacity of the supply air. At the same time, continuous anti-fogging air curtain strengthens the heat dissipation of front windshield which is affected by ambient temperature and driving speed. Therefore, thermal model of EV also needs to be established to estimate the energy saving performance of this novel AC system.

2.2. Thermal model establishment and calculation process

Fogging problem is taken account into the thermal model. The heat transfer model of front windshield depends on the parameters of the air curtain. The relationship between the inner surface temperature of front windshield and supply air dew point temperature is shown in Fig. 2. When the inner surface temperature of front windshield is lower than the dew point temperature of the supply air, the moist air dewing brings about the fogging problem. In this thermal model, safety margin (ΔT_{sm}) of 5 °C is taken to avoid