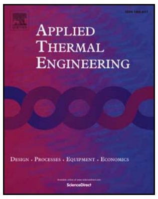
Applied Thermal Engineering 136 (2018) 16–27

Contents lists available at ScienceDirect

Applied Thermal Engineering

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



Research Paper

Investigation on an integrated thermal management system with battery cooling and motor waste heat recovery for electric vehicle

Zhen Tian[a,*], Wei Gan[a], Xuelai Zhang[a], Bo Gu[b], Lin Yang[c]

[a] Institute of Thermal Engineering, Shanghai Maritime University, 201306 Shanghai, China
[b] Institute of Refrigeration and Cryogenics, Shanghai Jiaotong University, Shanghai 200240, China
[c] School of Mechanical Engineering, Shanghai Jiaotong University, Shanghai 200240, China

HIGHLIGHTS

- EVTMS for cabin thermal comfort, battery cooling and motor cooling was proposed.
- Experiments for EVTMS performance were carried out in environmental chamber.
- Hybrid simulation method was adopted to investigate dynamic characteristics.
- PCCR varied between 26.3–32.1% and SOC was reduced 10.6% with battery cooling.
- EV driving range was increased 31.71% with motor waste heat recovery.

ARTICLE INFO

Keywords:
Electric vehicle
Thermal management system
Hybrid simulation method
PCCR
PWHR
Driving range

ABSTRACT

In the present study, an integrated electric vehicle thermal management system (EVTMS) for cabin thermal comfort, battery cooling and motor waste heat recovery was proposed. The effects of parameters such as compressor speed, environmental temperature and waste heat load on EVTMS cooling and heating performance were investigated. The results demonstrated that the percentage of cooling capacity reduction (*PCCR*) was in the range of 26.30–32.10% and the percentage of waste heat recovery (*PWHR*) was in the range of 18.73–45.17%. In addition, EVTMS model was developed and validated with experimental data, which predicted energy consumption, system capacity and COP with MRE in the range of 0.68–21.05%. Hybrid simulation method was carried out to study the effect of EVTMS on vehicle's driving range. Meanwhile, dynamic characteristics of battery temperature, motor temperature and battery State of Charge (SOC) were investigated. The results showed that SOC was reduced up to 10.60% with battery cooling and heating COP was increased up to 25.55% with motor waste heat recovery. Compared to PTC heaters, vehicle's driving range with EVTMS was improved 31.71%.

1. Introduction

Transport industry is facing serious resource and environmental problems because of high fuel consumption and gaseous pollutant [1–3]. Electric Vehicle (EV) is considered as a potential replacement for conventional internal combustion engine automobile to reduce the pressure of environmental protection [4,5]. EV energy management issue is critical because of electric storage limitation, especially for auxiliary subsystems, such as air conditioning system, battery cooling system and motor cooling system.

Heating ventilation air conditioning system is important to guarantee driver and passenger's thermal comfort. Internal combustion engine automobiles utilize the waste heat from engine exhaust gas for cabin heating. Different from that, EV requires independent heating equipment since there is no exhaust gas for heating. Positive temperature coefficient (PTC) electric heater was initially employed to supply heat for cabin. However, experimental results of Lee demonstrated that the EV driving range can be reduced up to 50% with PTC electric heater due to its low heating efficiency [6].

Afterwards, air source heat Pump (HP) system is considered as alternatively option to meet heating in winter and cooling in summer. However, the air source cannot supply sufficient heat under severe cold conditions. Suzuki [8] pointed out that there was ice formation on external heat exchanger surface when the ambient temperature was below −10 °C, which led to the sharply declination of heating performance of air source HP. Solutions for this problem have been proposed,

---

* Corresponding author.
E-mail address: tianzhen20036@sjtu.edu.cn (Z. Tian).

https://doi.org/10.1016/j.applthermaleng.2018.02.093
Received 15 December 2017; Received in revised form 28 January 2018; Accepted 26 February 2018
1359-4311/

Nomenclature

a_i, b_i	coefficients
A	flow area (m^2)
c_p	specific heat capacity (kJ kg^{-1} K^{-1})
C_D	flow coefficient
E_{cons}	energy consumption (W)
f	derived parameter
h	enthalpy (kJ kg^{-1})
L_{dri}	driving distance (km)
m	mass flow rate (kg s^{-1})
N_{comp}	compressor speed (rpm)
k	thermal conductivity (W m^{-1} K^{-1})
p	pressure (kPa)
Q	capacity (W)
t	temperature (°C)
$t_{a,o}$	outlet air temperature
t_c	condensing temperature (°C)
t_e	evaporating temperature (°C)
U	overall heat transfer coefficient (W m^{-2} K^{-1})
v	velocity (km h^{-1})
W	power consumption (W)

Greek letters

α	heat transfer coefficient (W m^{-2} K^{-1})
ρ	density (kg m^{-3})
δ	thickness (m)
δf	parameter uncertainty
ξ	heat exchange efficiency
τ	time (s)
Yi	independent variable
$\Psi_{ele,100}$	electricity of 100 km (kWh)

Subscripts

aux	auxiliary
bat	battery
c	coolant
cab	cabin
cdu	conduction
cold	cold side
comp	compressor
cond	condensing
cool	cooling
cov	convection
ele	electricity
env	environment
evap	evaporating
ex	external
fan	fan
heat	heating
hot	hot side
in	inlet
leak	leakage
mot	motor
out	outlet
occ	occupants
pow	power system
r	refrigerant
rad	radiation
rat	rated
res	residual
spec	specific
sub	sub cooling
sup	super heat
sys	system
veh	vehicle
w	wall
wst	waste

Acronyms

AC	Air Conditioning
ADVISOR	ADvanced VehIcle SimulatOR
AHU	Air Handling Unit
BC	Battery Cooling
COP	Coefficient Of Performance
EV	Electric Vehicle
EVTMS	Electric Vehicle Thermal Management System
EXV	EXpansion Valve
HP	Heat Pump
HEx	Heat Exchanger
MC	Motor Cooling
MCPF	Mini Channel Parallel Flow
MRE	Mean Relative Error
SOC	State Of Charge
SV	Solenoid Valve
PCCR	Percentage of Cooling Capacity Reduction
PWHR	Percentage of Waste Heat Recovery
PTC	Positive Temperature Coefficient
UDDS	Urban Dynamometer Driving Schedule

such as utilizing return air to replace all fresh air [7], decreasing humidity of evaporator inlet air [8], using refrigerant injection to increase mass flow rate [9–11], and creating hybrid power-driven system [12]. All methods afore mentioned essentially concentrate on increasing evaporating temperature and refrigerant mass flow rate. From this point of view, searching for a low-cost and stable heat source to prevent HP performance recession is imperative.

Battery and motor are essential for EV to achieve high power and high energy, which are very sensitive to temperature. Thermal runaway caused by waste heat accumulation of battery and motor can lead to capacity degradation and vehicle range reduction, which has been thoroughly demonstrated in the literature [13–16]. In addition, thermal runaway in stressful conditions can decrease component life span, and create the risk of fire and explosion. Therefore, waste heat generated from battery pack and motor electronics should be removed in time to guarantee EV's life cycle, efficiency and safe operation [17–20]. Both passive and active strategies have been proposed for battery and motor thermal management, which can be classified into five categories based on medium, namely, (1) air, (2) liquid, (3) phase change materials, (4) heat pipe and (5) combination of (1)–(4) [21]. Compared to the other four methods, liquid cooling is commonly used for battery and motor applications because of high efficiency and easy maintenance [22,23]. However, cooling behaviors for battery and motor greatly limit EV's driving range [24–27].

In order to make use of limited electricity in EV, some researchers have proposed electric vehicle thermal management system (EVTMS), which is expected to achieve cabin thermal comfort, battery cooling and motor cooling [28,29]. However, very limited examples can be found in the literature for EVTMS design and performance analysis.

Zou et al. [30] proposed an EVTMS with HP circuit and battery cooling circuit. Energy consumption for cooling mode and heating mode was studied with the variation of battery discharge rate.