International Journal of Heat and Mass Transfer 117 (2018) 80–94

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heat transfer characteristics of the integrated heating system for cabin and battery of an electric vehicle under cold weather conditions

Jae-Hyeong Seo [a], Mahesh Suresh Patil [a], Chong-Pyo Cho [b], Moo-Yeon Lee [a,*]

[a] School of Mechanical Engineering, Dong-A University, 37 Nakdong-Daero 550, Saha-gu, Busan, Republic of Korea
[b] Korea Institute of Energy Research, 152 Gajeong-ro, Yuseong-gu, Daejeon 34129, Republic of Korea

ARTICLE INFO

Article history:
Received 8 July 2017
Received in revised form 2 October 2017
Accepted 2 October 2017

Keywords:
Battery thermal management
Cabin air heater
Electric vehicle
Heat transfer
Heating system

ABSTRACT

The objective of this study is numerically to investigate the heat transfer characteristics of the integrated heating system considering the temperature of cabin and battery of an electric vehicle under the cold weather conditions. The integrated heating system consists of a burner to combust fuel, an integrated heat exchanger for CHE (coolant heat exchanger) and AHE (air heat exchanger). The heat transfer characteristics like the overall heat exchanger effectiveness, the heat transfer rate, the temperature distribution and the fluid flow characteristics like the pressure drop, velocity distribution of the investigated integrated heating system were considered and analyzed by varying the inlet mass flow rates and the inlet temperatures of the cold air and water, respectively. The average Nusselt numbers for the cold air side and the water side were increased 28.4% and 9.5%, respectively, with the increase of the cold air side Reynolds numbers from 15,677 to 72,664 and the water side Reynolds numbers from 4330 to 11,912. The numerical results showed good agreement within ±9.0% of the existed data and thus confirmed that the present model was valid. In addition, the proposed integrated heating system could be used as the thermal management of the cabin and the battery system of the electric vehicle under the cold weather conditions.

1. Introduction

Environmental degradation caused by excessive use of fossil fuels has resulted in the sharp growth of worldwide interest in the development of the eco-friendly transportation. The transportation field is one of the high-consuming industry of the primary energy, as it represents 30–35% of the total primary energy needs for most of the industrialized countries [1]. In 2007, the dependency on oil as fuel was observed to be as high as 95% for private transport, and it accounted for almost 50% of total oil consumption [2]. Therefore, it would obviously become increasingly difficult for the transportation industry to comply with stringent emission standards for solving an international environmental issue. These changes in the industry have resulted in shift of interest of the automotive companies to the green vehicles, such as hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV) and fully pure electric vehicle (EV), as a promising option for transport in the future. Due to the continuous revision of international rules and regulations for fossil fuel usage and environmental concerns to reduce the carbon footprint, many automotive industries have developed battery-operated electric vehicles to assist or replace ICE. As a result, much research on EVs (electric vehicles) been conducted in the automotive industry and related academia to develop high-performance EVs. Though internal combustion engine (ICE) operated vehicles are the most popular, they have an inferior efficiency of only around 40% [3]. Despite the higher efficiency, no emission of the polluting substances and a near zero carbon footprint of EVs driven by batteries, EVs are still struggling to solve the issues such as safety, vehicle range, cost and reduced battery performances at extreme temperatures [4,5]. Especially, the vehicle range of EVs is the most important reason for the slow market penetration of EVs. Although the vehicle range can be increased by increasing the battery capacity of EVs, the weight, volume and cost of the vehicle could be increased.

EVs have the limited availability of charging infrastructure in comparison with ICE vehicles, which have a long vehicle range with easily available fuel refill systems [6]. Moreover, air-conditioning (AC) system for cooling and heating the EVs cabin to improve the passenger's thermal comfort consume a considerable amount of battery power of EVs, thereby, sharply reducing the vehicle range of EVs. A significant amount of research on increasing the vehicle range in cold and hot conditions has focused

* Corresponding author.
E-mail address: mylee@dau.ac.kr (M.-Y. Lee).

https://doi.org/10.1016/j.ijheatmasstransfer.2017.10.007
0017-9310/

Nomenclature

AC	air conditioning
AHE	air heat exchanger
ASHP	air source heat pump
CAD	computer aided drawing
CHE	coolant heat exchanger
COP	coefficient of performance
EHR	exhaust heat recovery
MW	molecular weight
PTC	positive thermal coefficient
P	static (thermodynamic) pressure (Pa)
$\dot{Q}$	heat transfer rate (W)
$\dot{m}$	mass flow rate
Δ	change in quantity
T	temperature (°C, K)
ρ	density (kg/m^3)
T	static (thermodynamic) temperature
U	average velocity (m/s)
F	weight function for blending
D	characteristic length
δ	identity matrix or Kronecker delta function
h	enthalpy
S_M	momentum source
S_E	energy source
Δp	pressure drop (Pa)
τ	stress tensor
μ	dynamic viscosity
μ_t	turbulent viscosity
h_c	average heat transfer coefficient W/(m^2 K)
λ	thermal conductivity (W/mK)
k	Turbulence kinetic energy per unit mass
ω	angular velocity
σ	Prandtl number
ε	effectiveness
C_p	specific heat capacity (J/(kg K))
α_i	coefficient in BSL RS model
β_i	coefficient in BSL RS model
Nu	Nusselt number
x, y, z	Cartesian coordinates
$\otimes$	dyadic operator
∇	gradient operator

Subscripts

in	inlet
out	outlet
h	hot gas
c	cold air
w	water

on reducing the power used for cooling and heating the cabin of EVs. Lee et al. [7] conducted experimental studies to investigate the effect of full-load AC on driving characteristics and found that the driving range was reduced by up to 16.7% and 50% for cooling and heating, respectively. For ICE operated vehicles in general, the exhaust heat is collected by an EHR (exhaust heat recovery) system since burning fuel produces a quite large amount of exhaust heat. Hatami et al. [8] conducted a numerical study of the EHR of ICE operated vehicles and reported that the heat is recovered in the range from 0.6 kW to 5.9 kW, depending on the engine speed. This value could be as large as 18 kW for high-capacity vehicles (around 90hp) like the 13B Toyato [9]. Currently, PTC (positive thermal coefficient) heater is widely used as auxiliary heating in ICE vehicle and EVs. The important issue with PTC heating technology is high cost with high power (>2 kW) along with higher energy consumption. It is reported that the PTC heater could lead up to 24% of loss in driving range of fully charged EVs [10]. Ayartürk et al. [11] observed that, depending on COP, 5.5 kW of electric power is consumed to heat a cabin space when a PTC system is used. Assuming an EV battery capacity of 28 kWh and average power consumption of 20 kW while cruising at a constant velocity of 100 km/h, an EV could have a maximum range of 140 km. If an additional 5 kW of power is consumed to heat the cabin, then the vehicle range decreases to 112 km, a sharp decrease in range of 20%. This indicates that efficiently heating the cabin space of EVs could have a substantial influence in preventing a decrease in the vehicle driving range. ASHP (air source heat pump) is another option for cabin heating in EVs. An electric heater system based on PTC could be installed at a low cost, but under operation draws a significant amount of battery power since it is electric conversion-based system, resulting in a dramatic reduction in vehicle range. Many researchers have also investigated the performance of a heat pump system for vehicular thermal management [12,13]. In case of PTC heater, the ratio of heat output to electric input is less than 1.0, whereas, coefficient of performance (COP) for a heat pump is larger than 1.0, indicating a heat pump system as a reasonable method to enhance the thermal comfort in EVs. In EVs, when the PTC heating element is employed for heating cabin air, all power is drawn from the battery power source. Many early developed EVs like Mitsubishi i-MiEV [14,15] and Nissan LEAF [16] used this type of heating system. The heat pump system provides sufficient amount of heat to an incoming air stream under mild weather conditions, nevertheless its heating capacity drops under more severe conditions when the outside temperature is lower [17]. Qi reviewed state-of-the-art advances in air conditioning and heat pump system in electric vehicles. Although, heat pump systems are efficient, there are few challenges in air conditioning heat pump systems [18]. A heat pump uses atmospheric heat, which makes it highly efficient as they provide more thermal energy than the input energy [19]. There are many studies related to the performance and feasibility of heat pump system in electric vehicles. Kim et al. found that although CO_2 heat pump increased heating capacity by 35–54% and COP increased by 16–22% for evaporator front arrangement, cooling capacity decreased by 40–60% and COP decreased by 43–65% for the same arrangement [20]. Kim et al. suggested that heat pump system with heater core could enhance the performance of the heating system [21]. Cho et al. explored the heating performance of the coolant source heat pump for an electric bus, which could use exhaust heat from its electric devices [22]. Lee et al. investigated performance of stack-coolant source heat pump using R744 for fuel cell electric vehicles and found that heating capacity of 5.0 kW was attained [23]. Lee et al. investigated the performance of mobile heat pump for the large passenger electric vehicle and found that cooling and heating is sufficient under ambient temperatures [24]. The above studies have been conducted at ambient or lower temperatures, which points out that the heat pump is effective for cooling as well as heating. However, many researchers found that although a heat pump heater system is more efficient than PTC heating element, heat pump performance reduced severely during extreme cold condition [17,25,26,27]. Relatively lower COP under very cold conditions with a very thick frost layer formation on the exterior heat