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Research Paper

Ram air compensation analysis of fuel cell vehicle cooling system under driving modes

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HIGHLIGHTS

- A FCVs model including a ram air compensation mode is designed.
- A controls strategy of a cooling system dependents on ram air compensation.
- A FCVs model is carried out to assess the cooling performance under driving modes.
- A control strategy should be strictly evaluated to reduce parasitic power in a FCVs.

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ABSTRACT

The cooling system is one of the major factors used to ensure the performance of the fuel cell vehicle system. In general, the cooling system is composed of a radiator, a reservoir, a water pump, a bypass valve, and a radiator fan. The ram air that enters the vehicle frontal area is also critically important while the vehicle is operating. In this study, cooling system responses considering ram air compensation were investigated to evaluate the control strategy, and control gain was addressed to optimize the control strategy. A dynamic vehicle model was integrated with the fuel cell system model.

Three driving cycles were applied to investigate the responses of the cooling system under driving conditions. Three driving conditions considering ram air compensation were investigated to evaluate the cooling system operating trajectory. When the ram air compensation is considered, the cooling system operating trajectory and parasitic power can be accurately predicted. The control adjustment also needs to optimize the parasitic power. As a consequence, the trajectory of system pressure line 1 was found to be more effective for energy saving.

1. Introduction

The growing number of vehicles in use around the world is causing a number of problems, including global warming, abnormal weather, and the rapid depletion of fossil fuels [1–5]. To resolve these problems, renewable energy sources are being heavily investigated by energy researchers. Among other renewable energy sources, the fuel cell is one of the attractive options because it offers higher efficiency than other energy alternatives [6–9]. For example, fuel cells called Proton Exchange Membrane Fuel Cells (PEMFC) are used in automotive applications because they provide fast start-up, high power density, low operating temperature, and silent operation [10–15]. These PEMFCs, however, have a thermal management problem that reduces the performance of the components of the fuel cell in the vehicle. These problems, such as uniform control of the stack temperature, the stack temperature, and cooling system strategies, need to be solved. To address these issues, in a previous study we designed control strategies for a cooling system to optimize the parasitic power [16]. The previous study also focused on the cooling system to evaluate three cases of control strategies under a step load profile. It was found that if the ram air entering a moving frontal area, such as the radiator grill of a vehicle, is not considered, it is impossible to accurately evaluate the cooling system characteristics. The operation of the water pump and the radiator fan is important to reject the generation heat of the stack in the fuel cell vehicle, and the parasitic power of both the water pump and the fan is inevitably generated in this process. In general, it is important to reduce the parasitic power for improvement of the vehicle performance, because the parasitic power is about more than 10% of the net power [44]. Especially, in the case of the centrifugal fluid machine's such as compressor, pump, and fan, the operating is operated with P-Q system curve as shown in Fig. 1, and the power consumption of centrifugal fluid machine depends on the operating strategy. For instance,

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Nomenclature

A	active area [cm^2]
B	volume [m^3]
C_p	specific heat capacity [$J\,K\,kg^{-1}$]
D	diameter [m]
E	electric potential [V]
F	force [N]
f	friction factor [–]
G	mass flow velocity [$m^2\,s\,kg^{-1}$]
H	height [m]
HWFET	the highway fuel economy test [–]
h	heat transfer coefficient [$W\,K\,m^{-2}$]
j	current density [$A\,cm^{-2}$]
j_c	Colburn factor [–]
L	length [m]
M	vehicle mass [kg]
m	mass flow rate [$kg\,s^{-1}$]
n	number of cell [–]
P	pitch [m]
p	pressure [kPa]
pr	Prandtl number [$m^2\,s\,kg^{-1}$]
Δp	pressure difference [kPa]
q	heat transfer [W]
R	resistance [$\Omega\,cm^2$]
Re	Reynolds number [$m^2\,s\,kg^{-1}$]
T	temperature [K]
TMS	thermal management system [–]
t	thickness [m]
U	overall heat transfer coefficient [$W\,K\,m^{-2}$]
UDDS	urban dynamometer driving schedule [–]
V	volume [m^3]
v	vehicle speed [m/s]
w	work [W]
y	rolling resistance coefficient [–]

Subscripts and superscripts

ac	actual
act	activity
aero	aerodynamics
air	air side
amb	ambient condition
cha	channel side
cl	cell
Con	concentration
cond	conduction
cons	condenser
conv	convection
cool	coolant side
core	core side
el	electric
f	fin side
fc	fuel cell
fr	frontal area
gas	gas side
grill	grill
H_2	hydrogen
H_2O	water
in	inlet
L	limiting current
l	louver side
min	minimum
mem	membrane
Nern	Nernst voltage
N_2	nitrogen
ohm	ohmic
out	outlet
O_2	oxygen
rad	radiator
ram	ram
reac	reaction
res	resistance
roll	rolling
s	stack
slop	slope
t	tube side
trc	tractive
veh	vehicle

Greek

ψ	activation loss tuning factor [–]
θ	angle [deg]
ρ	density [$kg\,m^{-3}$]
η	efficiency [–]

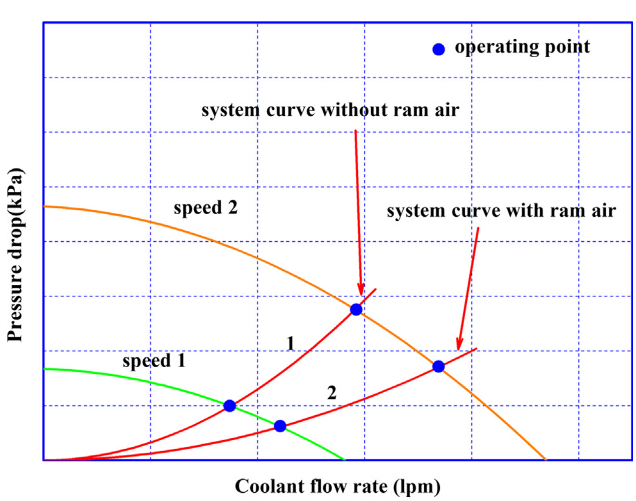

Fig. 1. The operating strategy of the system curve with ram air.

if the ram air is not considered, system curve is operated as 1, but if the ram air is considered, system curve is operated as 2. System curve affects the parasitic power. This is because the ram air affects the performance of the fuel cell vehicle power. As described above, since the system curve is closely related to the parasitic loss of the cooling system, it is important to design a precise pressure difference value. Also, because the pressure difference is compensated by the ram air, the ram air compensation needs to be considered when designing an accurate control algorithm, and when assessing the cooling system of a fuel cell. Therefore, it is necessary to design the ram air and evaluate the operating strategy of the cooling system according to the ram air.

In recent years, many papers have been published about fuel cell cooling system.

As mentioned above, the performance of the fuel cell cooling system in automotive applications under driving conditions is very important to maintaining the performance of the fuel cell vehicle. Nonetheless, most studies have only focused on controlling the fuel cell temperature and analyzing the cooling system. Most have focused on methods of analyzing the thermal characteristics and investigating the cooling management.