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Research Paper

Investigation on thermal performance and pressure loss of the fluid cold-plate used in thermal management system of the battery pack

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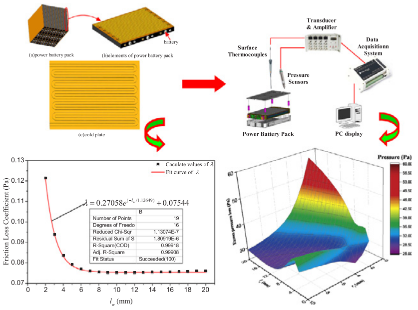
HIGHLIGHTS

- An improved serpentine-channel cold plate is designed to cool the power battery.
- Pressure loss model and the thermal resistance model are developed.
- Thermal performance as well as pressure loss of the serpentine-channel cold plate is obtained.
- Optimum structure of serpentine-channel cold plate is obtained.
- Methodology can quickly design the optimal serpentine-channel cold plate structure.

GRAPHICAL ABSTRACT



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ABSTRACT

For poor high-temperature performance of power battery utilized in electric vehicles, a battery thermal management system (BTMS) functioned as reducing battery's temperature is indispensable. This work designs a serpentine-channel cold plate as cooling unit of fluid BTMS, and a parameterized U-tube representing a part of serpentine-channel in cold plate is created. A thermal resistance model, as well as an objection function f_1 based on it, is developed to characterize thermal performance of cold plate. This study using theories of friction loss and excess loss defines a pressure loss model of cold plate based on the parameterized U-tube. After a series of simulations performed on different U-tube with varying structural parameters, combining with pressure loss model, objective function of pressure loss f_2 is obtained. By calculating f_1 and f_2, the laws of thermal performance with pressure loss and the optimum structure of the serpentine-channel cold plate can be obtained. This work provides a simple way to design the structure of the fluid cold-plate BTMS with optimum thermal performance and minimum pressure loss.

1. Introduction

With the growing energy crisis and environmental crisis [1–3], modern internal combustion-engine vehicles [4,5] can't meet the demand of increasingly stringent environmental requirements [6,7]. Under such circumstances, new energy vehicles ushered in the great development [8–10]. New energy vehicles in general refer to the vehicles which use unconventional energy (oil), including hydrogen

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Nomenclature

Decision variables

Aa	area of serpentine-channel's bottom wall in form 1 (m^2)
Ab	area of serpentine-channel's bottom wall in form 2 (m^2)
Ai	area of a part of serpentine-channel (m^2)
b	thickness of aluminium sheets and serpentine-channel (mm)
c_p	specific heat of fluid ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)
d_h	hydraulic diameter of pipe (mm)
h_c	height of serpentine-channel (mm)
h_p	height of rectangular channel (mm)
h_{wall}	height of pipe's side wall (mm)
k_{Al}	conductivity coefficient of aluminium ($W{\cdot}m^{-1}{\cdot}K^{-1}$)
k_f	thermal conductivity of fluid ($W{\cdot}m^{-1}{\cdot}K^{-1}$)
l_b	average length of bent pipe (mm)
$l_{h\text{-plate}}$	height of the aluminium sheets (mm)
l_{io}	length of inlet or outlet straight pipe (mm)
l_p	length of pipe (mm)
l_s	length of straight pipe (mm)
$l_{t\text{-plate}}$	thickness of the aluminium sheets (mm)
l_w	width of channel (mm)
$l_{w\text{-plate}}$	width of the aluminium sheets (mm)
r_i	inner radius of channel's bend (mm)
r_o	outer radius of channel's bend (mm)
q_m	mass flow rate of fluid ($kg{\cdot}s^{-1}$)
Q_{fluid}	the heat flow rate of fluid (W)
Q_{gen}	the battery heat rate (W)
Q_{plate}	the heat flow rate of cold plate (W)
Q_{total}	the total heat flow rate of thermal management system (W)
u	velocity of fluid at x direction ($m{\cdot}s^{-1}$)
v	velocity of fluid at y direction ($m{\cdot}s^{-1}$)
w	velocity of fluid at z direction ($m{\cdot}s^{-1}$)
α_m	mean convective heat transfer coefficient of liquid water ($W{\cdot}m^{-2}{\cdot}K^{-1}$)
μ	dynamic viscosity of fluid (Pa·s)
ρ	density of the fluid ($kg{\cdot}m^{-3}$)

Indices

p_b	total excess pressure loss of bent pipe (Pa)
p_f	total friction pressure loss (Pa)
p_{fu}	friction loss of U-tube (Pa)
p_{fb}	friction pressure loss of bent pipe (Pa)
p_{fio}	friction pressure loss of inlet or outlet straight pipe (Pa)
p_{fs}	friction pressure loss of straight pipe (Pa)
p_{total}	total pressure loss (Pa)
p_{utube}	total pressure of U-tube (Pa)
R_a	thermal resistance of form 1 ($K{\cdot}W^{-1}$)
R_b	thermal resistance of form 2 ($K{\cdot}W^{-1}$)
R_{i}	thermal resistance of a part of cold plate ($K{\cdot}W^{-1}$)
R_{fluid}	thermal resistance of enthalpy change ($K{\cdot}W^{-1}$)
$R_{\mathrm{half\text{-}plate}}$	structure thermal resistance of single cold plate ($K{\cdot}W^{-1}$)
R_{plate}	structure thermal resistance of cold plate ($K{\cdot}W^{-1}$)
R_{total}	total thermal resistance of cold plate ($K{\cdot}W^{-1}$)
$T_{\mathrm{avg\text{-}fluid}}$	average temperature of fluid
$T_{\mathrm{avg\text{-}plate}}$	average temperature of aluminium sheet surface
T_{fluid}	difference of $T_{out\text{-}avg}$ and $T_{in\text{-}avg}$
$T_{\mathrm{in\text{-}avg}}$	average temperature of inlet (K)
$T_{\mathrm{out\text{-}avg}}$	average temperature of outlet (K)
T_{plate}	difference between $T_{avg\text{-}plate}$ and $T_{avg\text{-}fluid}$
λ	friction loss coefficient
ζ	excess loss coefficient

Set

C_b	l_w/r_i

Set

C_b	l_w/r_i

Acronyms

ATL	Amperex technology limited
BEV	battery electric vehicles
BTMS	battery thermal management system
CFD	computational fluid dynamics
PCM	phase change material

energy [11], electrical energy, solar energy [12,13], alternative energy and so on, as a driving source, or use conventional fuel vehicles with new driver unit like hybrid power unit [14]. Among these kinds of new energy vehicles, Battery Electric Vehicles (BEV) have got the great progress because of the merits such as high energy utilization, zero release [15]. The performance of the electric vehicles are constrained by the capability and the life of batteries, and one of the key factor to these two performance criterias is the temperature of battery [16–19]: at low temperature conditions, the battery discharge capacity decays very fast as the temperature decreases [20,21], making mileage reduced, and when temperature is higher than normal temperature, the elevated temperature will bring about the shorter battery life [22–24]. Liu et al. [22] had shown that when lithium battery work at 53 °C, after 100 charge-discharge cycles, the capacity of battery decreased to 88% retention. Guo et al. [23] compared capacity characteristics of 18,650 lithium battery under 30 °C and 50 °C. It is concluded that the capacity of battery working on the 50 °C decays faster. Yuksel et al. [24] researched the influence of operational environment on battery life. The results indicated that using air BTMS to cooling battery can increase battery life by a factor of 1.5–6. The temperature of the battery will also affect the safety performance of electric vehicles [25]. The generation and accumulation of heat will lead to the high battery temperature, especially in high charge/discharge rate. If the heat can't be excluded promptly, there might be thermal runaway in battery pack, even explosion [26].

In order to control battery's temperature in a certain range, battery thermal management system (BTMS) [27–29] must be used in EV battery pack. There are two mainstream ways of battery thermal management: air cooling [30,31] and liquid cooling. With further research, some new cooling modes have been tried to use in battery pack such as heat pipes [32,33], thermoelectric refrigeration, PCM (phase change material) cooling [34–36].

Air cooling is divided into natural convection cooling and forced convection cooling. At present, the mainstream of air cooling method is forced convection cooling [37–39] which use fans or air pumps to promote air flow, absorbing the heat of battery. Yang et al. [37] investigated the effects of cell arrangement including longitudinal or transverse spacing and aligned or the staggered arrays on the performance of forced-air cooling system. The correlation between cell's temperature or temperature consistency and cell interval for both aligned and staggered cell arrangements was obtained. Their research has some guidance significance towards cell arrangement of air-cooling battery pack. Lu et al. [38] researched the temperature uniformity and the remission of hotspots of a compact EV battery pack with forced air