THERMAL MANAGEMENT SYSTEM ENHANCEMENT BY CHARACTERIZATION BETWEEN PSYCHROMETRICS AND LITHIUM-ION POLYMER BATTERY LIFESPAN

by

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Muhammad Faiz Hilmi bin Rani

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LIST OF ABBREVIATIONS

1D	One-dimensional
3S1P	3 Cells Hooked in Series and in 1 Parallel Unit
AC	Air-conditioning
AC	Alternating Current
AES	Auger Electron Spectroscopy
AFM	Atomic Force Microscopy
Ah	Ampere Hour
aPMV	Adaptive Predicted Mean Vote
ASHRAE	American Society of Heating, Refrigerating, and Air-conditioning Engineers
BTMS	Battery Thermal Management System
C/?	Termination Settings
CC	Constant Current
CC-CV	Constant Current-Constant Voltage
CLE	Cycling Experiment
CV	Constant Voltage
CVolt	Cyclic Voltammetry
DC	Direct Current
DEC	Diethyl Carbonate
DOD	Depth of Discharge
EC	Ethylene Carbonate
EIS	Electrochemical Impedance Spectroscopy
EMC	Ethyl Methyl Carbonate
EV	Electric Vehicle
GPE	Gelled Polymer Electrolyte
HEV	Hybrid Electric Vehicle
HPPC	Hybrid Pulse Power Characterization
HVAC	Heating, Ventilation, and Air-conditioning
ICE	Internal Combustion Engine
IR	Infrared
ITE	Infrared Thermography Experiment
ISO	International Organization for Standardization
LCO	Lithium Cobalt Oxide
LFP	Lithium Iron Phosphate

Li^+	Lithium Ion
LIBs	Lithium-based Batteries
Li-ion	Lithium-ion
LiPo	Lithium-ion Polymer
LMP	Lithium Metal Polymer
LMTD	Log Mean Temperature Difference
LNO	Lithium Nickel Oxide
LTO	Lithium Titanate
MCMB	Mesocarbon Microbeads
MU	Measurement of Uncertainty
NCA	Lithium Nickel Cobalt Aluminium Oxide
NETD	Noise Equivalent Temperature Difference
Ni/Cd	Nickel Cadmium
Ni/MH	Nickel Metal Hydride
NiMH	Nickel Metal Hydride
NMC	Lithium Manganese Oxide
OCV	Open-circuit Voltage
P1	Point 1 in Psychrometric Chart
P2	Point 2 in Psychrometric Chart
P3	Point 3 in Psychrometric Chart
P4	Point 4 in Psychrometric Chart
P5	Point 5 in Psychrometric Chart
P6	Point 6 in Psychrometric Chart
P7	Point 7 in Psychrometric Chart
P8	Point 8 in Psychrometric Chart
P9	Point 9 in Psychrometric Chart
PAN	Polyacrylonitrile
PC	Propylene Carbonate
PEO	Polyethylene Oxide
PMMA	Polymethyl Methacrylate
PTC	Pressure, Temperature, Current
PVdF	Polyvinylidene Fluoride
RT	Room Temperature
SEI	Solid Electrolyte Interface

SEM	Scanning Electron Microscopy
SPE	Solid Polymer Electrolyte
STEM	Scanning Transmission Electron Microscopy
TC1	Thermocouple 1
TC2	Thermocouple 2
TC3	Thermocouple 3
TC4	Thermocouple 4
TC5	Thermocouple 5
TC6	Thermocouple 6
TC7	Thermocouple 7
TC8	Thermocouple 8
USABC	United States Advanced Battery Consortium
UV	Ultraviolet
VCC	Vapour Compression Cycle
XPS	X-ray Photoelectron Spectroscopy
XRD	X-ray Diffraction

LIST OF SYMBOLS

R-134a	1, 1, 1, 2-Tetrafluoroethane refrigerant
T_{source}	A blackbody source of temperature
ω	Absolute humidity
$\omega_{dry\ air}$	Absolute humidity at dry air
$\omega_{humid\ air}$	Absolute humidity at humid air
R_a	Actual internal resistance
P_{1-dry}	Air condition after dehumidifying process
P_{1-cool}	Air condition after sensible cooling process
T_∞	Ambient temperature
T_∞	Ambient temperature in environmental chamber
A_1	Area of LiPo battery at direction 1
A_2	Area of LiPo battery at direction 2
A_3	Area of LiPo battery at direction 3
T_{atm}	Atmosphere temperature
P_{atm}	Atmospheric pressure of the moist air
V_{air}	Available air volume
V_{air}	Available air volume in battery compartment
$\bar{x}$	Average of measuring system values
TI_{avg}	Average surface temperature (°C)
U_{obj}	Calculated camera output voltage for a blackbody of T_{obj}
CF	Capacity fade
CO_2	Carbon dioxide
V_{cell}	Cell voltage
ΔT	Change of air temperature
Δh	Change of enthalpy
CoO_2	Cobalt oxido
U_c	Combined standard uncertainty
V	Compressor displacement volume
N	Compressor motor revolution
$Q_{conduction}$	Conduction heat transfer
CL	Confidence level
C	Constant
$Q_{convection}$	Convection heat transfer
$R_{convection}$	Convection thermal resistance
F	Correction factor

k	Coverage factor
I	Current
μ	Degree of saturation
v_i	Degrees of freedom
$\Delta\omega$	Dehumidifying value
T_{dew}	Dew-point temperature
R-32	Difluoromethane
DC_f	Discharged capacity at final cycle
DC_i	Discharged capacity at initial cycle
T_{db}	Dry-bulb temperature
T	Dry-bulb temperature of air-vapour mixture
v_{eff}	Effective degrees of freedom
R_{eff}	Effective thermal resistance
e^-	Electrons
ε	Emittance
E	Energy
EE	Energy efficiency
EL	Energy loss
$E_{discharge}$	Energy released during discharging
$E_{CC\text{-}charge}$	Energy stored during CC charging
E_{charge}	Energy stored during charging
$E_{CV\text{-}charge}$	Energy stored during CV charging
h	Enthalpy
h_2	Enthalpy at outlet compressor
h_3	Enthalpy at outlet condenser
h_1	Enthalpy at outlet evaporator/at inlet compressor
h_4	Enthalpy at outlet regulation/expansion valve
Δh	Enthalpy difference
Δh	Enthalpy differential for efficient cooling
h_a	Enthalpy of dry air
h	Enthalpy of moist air
h_1	Enthalpy of moist air at the initial state
h_s^*	Enthalpy of saturated air at the end state
h_w^*	Enthalpy of water added at T_{wb}
h_v	Enthalpy of water vapour
e_{eqp}	Equipment error

ΣE	Error
$Q_{\text{evaporation}}$	Evaporation heat transfer
U	Expanded uncertainty
T_{f}	Film temperature
EE_f	Final energy efficiency
TI_{max}	Final maximum T_{s} by thermal imaging camera data
TC_{max}	Final maximum T_{s} by thermocouple data
R	Gas constant
R_a	Gas constant for dry air
C	Graphite
g	Gravitational acceleration of air
A	Heat equivalent of 1 horsepower
$\dot{Q}_L$	Heat extracted from the LiPo battery
Q	Heat generation rate
$\dot{Q}_{load}$	Heat load of LiPo battery
$\dot{Q}_H$	Heat rejected to the environment
Q_1	Heat transfer at point 1
Q_2	Heat transfer at point 2
Q_3	Heat transfer at point 3
Q_{battery}	Heat transfer from battery
$\text{L}_{compartment}$	Height of battery compartment
L	Height of LiPo battery
ω	Humidity ratio
ω_a	Humidity ratio of dry air
ω_1	Humidity ratio of moist air at the initial state
ω_s^*	Humidity ratio of saturated air the end state
ω_s	Humidity ratio of saturated moist air
ω	Humidity ratio of the moist air
ω_1	Humidity ratio of the moist air at interface of cotton wick
ω_1	Humidity ratio of the moist air based sling psychrometer
ω_s^*	Humidity ratio of the saturated film at surrounding air
$\text{P}_{1-humid}$	Initial air condition in battery compartment
EE_i	Initial energy efficiency
h_1	Initial enthalpy
ω_1	Initial humidity ratio
T_1	Initial temperature

$T_{c,\ in}$	Inlet temperature of cold fluid
T_1	Inlet temperature of cold fluid (refrigerant)
$T_{h,\ in}$	Inlet temperature of hot fluid
t_1	Inlet temperature of hot fluid (air)
D_i	Internal diameter of copper tube
$D_{i,\ evap}$	Internal diameter of copper tubes at evaporator
Q_{internal}	Internal heat transfer
$R_{\mathrm{internal1}}$	Internal resistance for cell 1
$R_{\mathrm{internal2}}$	Internal resistance for cell 2
$R_{\mathrm{internal3}}$	Internal resistance for cell 3
v	Kinematic viscosity of air
v	Kinematic viscosity of air of T_{f}
h'_{fg}	Latent heat of vaporization at T_{wb}
$l_{compartment}$	Length of battery compartment
l	Length of LiPo battery
Le	Lewis number
T_s	LiPo battery's surface temperature
$LiCoO_2$	Lithium cobalt oxide
$LiPF_6$	Lithium hexafluorophosphate
Li^+	Lithium ions
$LiFePO_4$	Lithium iron phosphate
$LiMn_2O_4$	Lithium manganese oxide
$LiNiO_{0.85}Co_{0.10}Al_{0.05}O_2$	Lithium nickel cobalt aluminium oxide
$Li(NI_{0.33}Mn_{0.33}Co_{0.33})O_2$	Lithium nickel manganese cobalt oxide
$LiNiO_2$	Lithium nickel oxide
$Li_4Ti_5O_{12}$	Lithium titanate
ΔT_{lm}	Log mean temperature difference
$\dot{m}_c$	Mass flowrate of cold fluid
$\dot{m}_h$	Mass flowrate of hot fluid (air)
$\dot{m}$	Mass flowrate of refrigerant
m_a	Mass of dry air
m_v	Mass of water vapour
Q_{max}	Maximum available capacity
T_{max}	Maximum temperature
ΔT_{max}	Maximum temperature difference
h_{cond}	Mean conductive heat transfer coefficient

h_d	Mean convective mass transfer coefficient
T_{rad}	Mean radiant temperature
h_{rad}	Mean radiative heat transfer coefficient
U_{total}	Measured camera output voltage for the actual case
MV	Measured value
η_m	Mechanical efficiency
$Q_{mechanical}$	Mechanical heat transfer
S	Method bias
CV	Method coefficient of variation
U	Method uncertainty
$\dot{V}$	Minimum volumetric flowrate of air
ρ	Moist density
v	Moist volume
x_{atm}	Mole fraction of atmospheric air
x_a	Mole fraction of dry air
x_v	Mole fraction of water vapour
x_{vs}	Mole fraction of water vapour in saturated air
$h_{c.\ air}$	Natural convection heat transfer coefficient of air
N	Necessary horsepower of compressor
$W_{net,\ in}$	Net work input to the cooling system
$Q_{nominal}$	Nominal capacity
$n_{tube,\ evap}$	Number of copper tubes at evaporator
n_a	Number of moles of dry air
n	Number of moles of the gas
n_v	Number of moles of water vapour
n_{vs}	Number of moles of water vapour in saturated air
Nu	Nusselt number
D_{obj}	Object distance
ε_{obj}	Object emittance
T_{obj}	Object temperature
U	Open circuit voltage
$T_{c,\ out}$	Outlet temperature of cold fluid
T_2	Outlet temperature of cold fluid (refrigerant)
$T_{h,\ out}$	Outlet temperature of hot fluid
t_2	Outlet temperature of hot fluid (air)
U_i	Overall heat transfer coefficient