



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

by

**MUHAMMAD FAIZ HILMI BIN RANI
(1741412411)**

A thesis submitted in fulfillment of the requirements for the degree of
Doctor of Philosophy

**School of Mechatronic Engineering
UNIVERSITI MALAYSIA PERLIS**

2020

ACKNOWLEDGMENT

In the name of Allah, the Most Gracious, the Most Merciful.

Praise belongs to Allah who has bestowed upon me the strength and will to complete this thesis. Peace and blessings of Allah are due to His Messenger, the Prophet Muhammad (PBUH) and his family.

Upon completion of this thesis, I have acquired a lot of valuable knowledge, information and experience. I will embrace all these experiences, as this given opportunity does not come easily in life. It is impossible to achieve successful achievement in this research without nonstop support from all parties who contribute their kindness and professional skills to ensure this research able to accomplish its objectives as required. It is my pleasure to convey my gratitude to all of them who had helped me in my acknowledgement.

I would like to express my endless appreciation and indebtedness to my lead supervisor, Associate Professor Ir. Dr. Zuradzman bin Mohamad Razlan, my first co-supervisor, Associate Professor Ir. Ts. Dr. Shahrman bin Abu Bakar, and my second co-supervisor, Dr. Nur Saifullah bin Kamarrudin for providing continuous encouragements and advices during conducting this research. The guidance from all of them had helped me a lot in understanding the research and in solving unexpected problems throughout the research.

Finally, I would like to give an appreciation to Umi, Abah, my siblings, and friends for their helping, often-needed driving force and moral support when completing this study. This thesis was submitted for the Doctor of Philosophy (Mechanical Engineering) at Universiti Malaysia Perlis. This research was carried out based on the studies in the School of Mechatronic Engineering.

Muhammad Faiz Hilmi bin Rani

TABLE OF CONTENTS

	PAGE
DECLARATION OF THESIS	i
ACKNOWLEDGMENT	ii
TABLE OF CONTENTS	iii
LIST OF TABLES	viii
LIST OF FIGURES	xi
LIST OF ABBREVIATIONS	xvii
LIST OF SYMBOLS	xx
ABSTRAK	xxviii
ABSTRACT	xxx
CHAPTER 1 : INTRODUCTION	1
1.1 Research background	1
1.2 Problem statements	6
1.3 Research objectives	10
1.4 Research scopes	11
1.5 Thesis outline	13
CHAPTER 2 : LITERATURE REVIEW	15
2.1 Preface	15
2.2 Battery thermal management system (BTMS)	15
2.2.1 Forced air cooling	16
2.2.2 Thermal comfort	19
2.2.3 Suggested operating temperatures for lithium-based batteries (LIBs)	21

2.2.4	Humidity effects on lithium-based batteries (LIBs)	22
2.3	Introduction of lithium-ion polymer (LiPo) battery	23
2.3.1	Battery framework	23
2.3.2	Working principles	29
2.3.3	Vehicle electrification by LiPo battery	32
2.4	Thermal issues of Li-ion/LiPo battery	35
2.4.1	Capacity fade	36
2.4.2	Low temperature performance	38
2.4.3	Thermal runaway	40
2.4.4	Thermal maldistribution in battery pack	43
2.5	Battery performance estimation approaches	45
2.5.1	Ampere hour counting	46
2.5.2	Internal resistance measurement	47
2.5.3	Cycle number counting	47
2.5.4	Destructive methods	48
2.6	Gap in the existing knowledge	48
2.7	Summary	50
CHAPTER 3 : METHODOLOGY		51
3.1	Preface	51
3.2	Research flow	51
3.3	Cycling experiment (CLE)	53
3.3.1	Experimental setup	53
3.3.2	Theory of psychrometrics	61
3.3.2.1	Moist air	61
3.3.2.2	Humidity and enthalpy	63
3.3.2.3	Moist volume, density, specific heat, and dew point	65

3.3.2.4	Wet-bulb temperature and adiabatic saturation	67
3.3.2.5	Psychrometric charts	71
3.3.3	Testing conditions, case studies, and data collection	73
3.3.4	Cycling performance analysis	76
3.3.5	Determination of thermal comfort zone of LiPo battery	80
3.4	Infrared thermography experiment (ITE)	80
3.4.1	Experimental setup	80
3.4.2	Theory of thermography	83
3.4.2.1	Electromagnetic spectrum	84
3.4.2.2	Blackbody radiation	84
3.4.2.3	Thermographic measurement	85
3.4.3	Surface temperature distribution analysis	88
3.4.4	Maximum surface temperature and temperature rise evolution analysis	88
3.5	Hypothetical design of battery thermal management system	89
3.5.1	Theory of refrigeration	89
3.5.2	Heat load and required cooling capacity analysis	91
3.5.3	Battery compartment dimensions analysis	95
3.5.4	Mollier diagram	96
3.5.5	Compressor displacement volume and horsepower analysis	97
3.5.6	Heat exchanger volume analysis	98
3.5.7	Pressure regulation value analysis	101
3.5.8	Dehumidification value analysis	101
3.6	Measurement of uncertainty (MU) analysis	103
3.7	Summary	105

CHAPTER 4 :	RESULTS & DISCUSSION	106
4.1	Preface	106
4.2	Cycling performance of LiPo battery	106
4.2.1	Discharge characteristics	108
4.2.2	Charge characteristics	117
4.2.3	Energy efficiency	126
4.2.4	Overall internal resistance	131
4.2.5	Thermal comfort zone of LiPo battery	135
4.2.6	Experimental uncertainty	135
4.3	Infrared thermography of LiPo battery	142
4.3.1	Surface temperature distribution	142
4.3.2	Maximum surface temperature	157
4.3.3	Temperature rise evolution	167
4.3.4	Experimental uncertainty	171
4.4	Proposed hypothetical design of forced air cooling	182
4.4.1	Heat load and required cooling capacity	183
4.4.2	Battery compartment dimensions	186
4.4.3	Compressor displacement volume and necessary horsepower	188
4.4.4	Heat exchanger volume	189
4.4.5	Pressure regulation value	192
4.4.6	Dehumidification value	192
4.5	Summary	196
CHAPTER 5 :	CONCLUSION	197
5.1	Preface	197
5.2	Conclusion	197
5.3	Recommendations for future work	200
5.4	Summary	200

REFERENCES	201
APPENDIX A PROPERTIES OF AIR AT 1 ATM PRESSURE	216
APPENDIX B PROPERTIES OF SATURATED REFRIGERANT-134A	217
LIST OF PUBLICATIONS	218

©This item is protected by original copyright

LIST OF TABLES

	PAGE
Table 1.1: Comparison of thermal comfort factors between human beings and LiPo battery.	5
Table 1.2: Method used for controlling psychrometry conditions in capacity fade studies of Li-ion batteries.	8
Table 2.1: Suggested operating temperature range of LIBs.	21
Table 2.2: Characteristics of LIBs based on anode and cathode materials.	24
Table 2.3: Comparison of Li-ion and LiPo batteries.	34
Table 2.4: General reactions and internal battery temperature ranges during thermal runaway of LIBs batteries.	42
Table 3.1: Properties of tested LiPo battery pack.	56
Table 3.2: Battery workstation settings.	57
Table 3.3: Psychrometry conditions set in the environmental chamber.	73
Table 3.4: Case studies based on psychrometry conditions.	75
Table 4.1: Summary of case studies based on psychrometric properties.	107
Table 4.2: Capacity fade of LiPo battery cycled in different psychrometry conditions.	109
Table 4.3: Percentage of discharging time reduction of LiPo battery cycled in different psychrometry conditions.	114
Table 4.4: Percentage of charging time increment of LiPo battery cycled in different psychrometry conditions.	123

Table 4.5: Variation in energy for LiPo battery cycled in different psychrometry conditions.	127
Table 4.6: Percentage in energy loss for LiPo battery in different psychrometry conditions.	129
Table 4.7: Percentage of overall internal resistance increment of LiPo battery cycled in different psychrometry conditions.	133
Table 4.8: Uncertainties of final capacity fade of LiPo battery.	137
Table 4.9: Uncertainties of final discharging time decrement of LiPo battery.	138
Table 4.10: Uncertainties of final charging time increment of LiPo battery.	139
Table 4.11: Uncertainties of final energy efficiency decrement of LiPo battery.	140
Table 4.12: Uncertainties of final overall internal resistance increment of LiPo battery.	141
Table 4.13: Summary of average surface temperature of LiPo battery at various surface views during charging mode.	154
Table 4.14: Summary of average surface temperature of LiPo battery at various surface views during discharging mode.	155
Table 4.15: Summary of maximum surface temperature of LiPo battery during charging mode.	164
Table 4.16: Summary of maximum surface temperature of LiPo battery during discharging mode.	165
Table 4.17: Final location of maximum surface temperature of LiPo battery based on surface views at various charging rates.	166
Table 4.18: Final location of maximum surface temperature of LiPo battery based on surface views at various discharging rates.	166

Table 4.19: Uncertainties of final maximum surface temperature of LiPo battery at various charging rates.	173
Table 4.20: Uncertainties of final maximum surface temperature of LiPo battery at various discharging rates.	173
Table 4.21: Uncertainties of final maximum surface temperature of LiPo battery at various charging rates (comparison of $T_{I_{max}}$ and $T_{C_{max}}$ data).	180
Table 4.22: Uncertainties of final maximum surface temperature of LiPo battery at various discharging rates (comparison of $T_{I_{max}}$ and $T_{C_{max}}$ data).	181
Table 4.23: Summary of heat load and required cooling capacity analysis.	185
Table 4.24: Summary of battery compartment dimensions analysis.	187
Table 4.25: Summary of compressor displacement volume and horsepower analysis.	188
Table 4.26: Summary of heat exchanger volume analysis.	191
Table 4.27: Summary of pressure regulation value analysis.	192
Table 4.28: Summary of dehumidification value analysis.	194

LIST OF FIGURES

	PAGE
Figure 1.1: Heat exchange between the human body and its environment.	3
Figure 1.2: Heat exchange between the LiPo battery and its environment.	3
Figure 1.3: Thermal comfort factors for human beings.	4
Figure 1.4: Batteries series based on energy density and specific density.	6
Figure 2.1: Classification of battery cooling strategies.	16
Figure 2.2: Battery cooling system by forced air cooling.	17
Figure 2.3: The acceptable zone of the cotton textile workshop.	20
Figure 2.4: OCV drops at different humidity conditions.	22
Figure 2.5: Basic lithium-based battery structure.	23
Figure 2.6: LIB cell configurations: (a) cylindrical; (b) prismatic; and (c) pouch.	28
Figure 2.7: Movement of lithium ions during (a) initial and (b) final charging mode.	29
Figure 2.8: Movement of lithium ions during (a) initial and (b) final discharging mode.	30
Figure 2.9: Lithium ions storage in the battery during (a) charging and (b) discharging modes.	31
Figure 2.10: Key components of electric vehicle.	33
Figure 2.11: Discharge capacity of Sony 18650 cells cycled at different temperatures based on cycle number.	37
Figure 2.12: Cycling performance for pouch cells at 25 °C and 60 °C.	37

Figure 2.13: Classification of battery SOH estimation methods by experimental approach.	46
Figure 3.1: Research flowchart.	52
Figure 3.2: Schematic diagram of CLE.	53
Figure 3.3: Test bench for LiPo battery cycling experiments.	54
Figure 3.4: Method in storing the tested LiPo battery inside the environmental chamber.	54
Figure 3.5: Wild Scorpion LiPo battery pack.	55
Figure 3.6: Revolectrix Cellpro PowerLab 8 (v2).	56
Figure 3.7: Binder KBF 115 (E5.2) environmental chamber.	58
Figure 3.8: Temperature-Humidity diagram for KBF version.	58
Figure 3.9: Applent AT4808 Handheld Multi-channel Temperature Meter.	59
Figure 3.10: SHT31 digital humidity and temperature sensor.	59
Figure 3.11: Location of thermocouples attached on the surface of LiPo battery.	60
Figure 3.12: Location of thermocouples inside the environmental chamber.	60
Figure 3.13: A sling psychrometer.	69
Figure 3.14: ASHRAE psychrometric chart.	72
Figure 3.15: Graphical representation of psychrometry conditions using ASHRAE Psychrometric Chart No.1.	74
Figure 3.16: Test bench for infrared thermography experiments.	81
Figure 3.17: FLIR E6 thermal imaging camera.	82
Figure 3.18: Overall setup of infrared thermography experiments.	83

Figure 3.19: The electromagnetic spectrum based on wavelength regions.	84
Figure 3.20: Blackbody cavity.	85
Figure 3.21: General thermographic measurement situation.	86
Figure 3.22: Transfer of heat.	89
Figure 3.23: Refrigerating unit.	90
Figure 3.24: Graphical representation of air-conditioning processes as a psychrometric chart.	91
Figure 3.25: Battery thermal model.	92
Figure 3.26: Refrigeration cycle in Mollier diagram.	96
Figure 3.27: Schematic of cross-flow heat exchanger.	99
Figure 3.28: Design of air-conditioning processes.	102
Figure 3.29: Sources of uncertainty—PESMECO fishbone diagram.	104
Figure 4.1: Discharge capacity of LiPo battery in different psychrometry conditions as a function of number of cycles.	108
Figure 4.2: Discharge curves of LiPo battery cycled in different psychrometry conditions and various number of cycles: (a) P1, (b) P2, (c) P3, (d) P4, (e) P5, (f) P6, (g) P7, (h) P8, and (i) P9.	113
Figure 4.3: Charge curves of LiPo battery cycled in different psychrometry conditions and various number of cycles: (a) P1, (b) P2, (c) P3, (d) P4, (e) P5, (f) P6, (g) P7, (h) P8, and (i) P9.	120
Figure 4.4: Variation in (a) constant current (CC) charging time and (b) constant voltage (CV) charging time with number of cycles for LiPo battery in different psychrometry conditions.	122
Figure 4.5: Overall internal resistance with various number of cycles for LiPo battery cycled under different psychrometry conditions.	132

Figure 4.6: Final capacity fade of LiPo battery with uncertainty.	137
Figure 4.7: Final discharging time decrement with uncertainty.	138
Figure 4.8: Final charging time increment with uncertainty.	139
Figure 4.9: Final energy efficiency decrement with uncertainty.	140
Figure 4.10: Final overall internal resistance increment with uncertainty.	141
Figure 4.11: Surface temperature evolution of LiPo battery at various views and charging rates: (a) 2.0 A, (b) 4.0 A, (c) 6.0 A, (d) 8.0 A, and (e) 10.0 A.	147
Figure 4.12: Surface temperature evolution of LiPo battery at various views and discharging rates: (a) 2.0 A, (b) 4.0 A, (c) 6.0 A, (d) 8.0 A, and (e) 10.0 A.	152
Figure 4.13: Maximum surface temperature plot of LiPo battery at charging rate of 2.0 A.	159
Figure 4.14: Maximum surface temperature plot of LiPo battery at charging rate of 4.0 A.	159
Figure 4.15: Maximum surface temperature plot of LiPo battery at charging rate of 6.0 A.	160
Figure 4.16: Maximum surface temperature plot of LiPo battery at charging rate of 8.0 A.	160
Figure 4.17: Maximum surface temperature plot of LiPo battery at charging rate of 10.0 A.	161
Figure 4.18: Maximum surface temperature plot of LiPo battery at discharging rate of 2.0 A.	161
Figure 4.19: Maximum surface temperature plot of LiPo battery at discharging rate of 4.0 A.	162

Figure 4.20: Maximum surface temperature plot of LiPo battery at discharging rate of 6.0 A.	162
Figure 4.21: Maximum surface temperature plot of LiPo battery at discharging rate of 8.0 A.	163
Figure 4.22: Maximum surface temperature plot of LiPo battery at discharging rate of 10.0 A.	163
Figure 4.23: Temperature rise evolution based on average maximum surface temperature of LiPo battery at different current rates.	168
Figure 4.24: Final maximum surface temperature of LiPo battery during charging mode with uncertainty based on thermal imaging camera data.	172
Figure 4.25: Final maximum surface temperature of LiPo battery during discharging mode with uncertainty based on thermal imaging camera data.	172
Figure 4.26: Comparison of final maximum surface temperature of LiPo battery with uncertainty at various charging rates: (a) 2.0 A, (b) 4.0 A, (c) 6.0 A, (d) 8.0 A, and (e) 10.0 A.	177
Figure 4.27: Comparison of final maximum surface temperature of LiPo battery at various discharging rates: (a) 2.0 A, (b) 4.0 A, (c) 6.0 A, (d) 8.0 A, and (e) 10.0 A.	179
Figure 4.28: Proposed hypothetical design of forced air cooling in Mollier diagram.	182
Figure 4.29: Thermal resistance of LiPo battery.	184
Figure 4.30: LiPo battery dimensions.	184
Figure 4.31: Design of battery compartment.	187
Figure 4.32: Schematic of cross-flow heat exchanger with inlet and outlet temperatures.	189

Figure 4.33: Correction factor chart for single-pass cross-flow with both fluids unmixed.	190
Figure 4.34: Design of desiccant-based air-conditioning.	193
Figure 4.35: Illustration of proposed hypothetical design of forced air cooling.	195

©This item is protected by original copyright

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

©This item is protected by original copyright

LIST OF SYMBOLS

R-134a	1, 1, 1, 2-Tetrafluoroethane refrigerant
T_{source}	A blackbody source of temperature
ω	Absolute humidity
$\omega_{\text{dry air}}$	Absolute humidity at dry air
$\omega_{\text{humid air}}$	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
T_{avg}	Average surface temperature ($^{\circ}\text{C}$)
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
$Q_{\text{conduction}}$	Conduction heat transfer
CL	Confidence level
C	Constant
$Q_{\text{convection}}$	Convection heat transfer
$R_{\text{convection}}$	Convection thermal resistance
F	Correction factor

k	Coverage factor
I	Current
μ	Degree of saturation
ν_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
ν_{eff}	Effective degrees of freedom
R_{eff}	Effective thermal resistance
e^-	Electrons
ε	Emittance
E	Energy
EE	Energy efficiency
EL	Energy loss
$E_{\text{discharge}}$	Energy released during discharging
$E_{\text{CC-charge}}$	Energy stored during CC charging
E_{charge}	Energy stored during charging
$E_{\text{CV-charge}}$	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
$L_{\text{compartment}}$	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
$P_1 - \text{humid}$	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
$R_{internal1}$	Internal resistance for cell 1
$R_{internal2}$	Internal resistance for cell 2
$R_{internal3}$	Internal resistance for cell 3
ν	Kinematic viscosity of air
ν	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