Thermal Analysis of a Sealed Battery Power System Enclosure for Underwater Operations

J. Chiew[1], C.S. Chin[2], J.B. Jia[*3] and W.D. Toh[4]
[1, 3 & 4]School of Engineering, Temasek Polytechnic, Singapore
[2]School of Marine Science and Technology (MaST), Newcastle University International Singapore
*Corresponding author: 21 Tampines Avenue 1 Singapore 529757, jiajunbo@tp.edu.sg

Abstract: This paper details the thermal study of a battery power system within a sealed enclosure via software modeling and simulation. The model has been developed as a tool to study the thermal effects of the battery system within the watertight enclosure in order to implement sufficient thermal management solutions to ensure the reliable and safe operation of the entire battery power system. The proposed method is based on thermal simulation using Computation Fluid Dynamics (CFD) program. The results determined from the simulations are compared with results based on an experiment. The error is deemed to be minor and acceptable.

Keywords: Thermal, Simulation, Conjugate Heat Transfer, Sealed Enclosure, Battery Power System.

1. Introduction

As technology advances, more unmanned underwater vehicles (UUV) are used to carry out specific subsurface underwater missions. These UUVs are powered by internally stored batteries within the hull of the UUV. However, for emergency usage, an emergency battery system is stored separate and external from the hull and faces the harsh working environment.

These battery systems used for emergency underwater applications faces several challenges. They are required to be pressure and corrosion resistant and yet, maintain a high level of reliability and power density ratio. The battery cells are encased within a completely sealed enclosure as protection from the hydrostatic pressure and moisture. Therefore, the battery system is not accessible to the crew if the system were to malfunction. Hence, they are required to be rugged and reliable for safe and efficient operations.

While the battery is discharging or charging within a sealed enclosure, it releases heat energy in terms of chemical reaction heat production and resistive losses [1]. The heat production by the battery is trapped in the enclosure due to lack of thermal management and free air cooling in typical battery systems [3]. This built up heat energy is extremely dangerous and detrimental to the health of the battery cells.

The battery used in the system is the $LiFePO_4$ (Lithium Iron Phosphate) battery. One of the most common causes of failure of the $LiFePO_4$ battery is high temperature. Battery failure by heat can be caused by charging/discharging at high current as well as built up thermal energy from its surroundings. Therefore, it is crucial to monitor the temperature of the batteries within the enclosure and ensure that it operates within the safety limits.

Failure to regulate and control the temperature in the casing could spell disaster for the entire system and jeopardize the mission of the UUV. Hence, thermal management is important due to the high energy content and risk of rapid temperature development in the high current range [4]. Thermal management also has a significant influence on the useful life of the components and ensures fault-free operations for extended periods of time [5].

Thermal simulation analysis in the early stages of the design can offer an inkling of the situation within the system and hence corrective actions can be carried out. Valuation of thermal performance of the battery system in actual deployment conditions may be hard to achieve due to lack of resources and logistics problems [3]. Any failures in the testing phase could also hinder any further advancement of the project. Hence, attention to safety of the system has to be taken into consideration during any sort of testing.

In this paper, the battery system will be modeled using Computer-Aided Design (CAD) software,

SOLIDWORKS, and the thermal heat transfer process to be simulated via Computational Fluid Dynamics (CFD) program, COMSOL Multiphysics, to determine the maximum temperature within the enclosure of the battery power system after a specified period of time. An experiment with the physical battery system will also be carried out to obtain the actual temperature readings. Verification of the simulated results is performed by comparing the simulated values with the actual values obtained in the experiment.

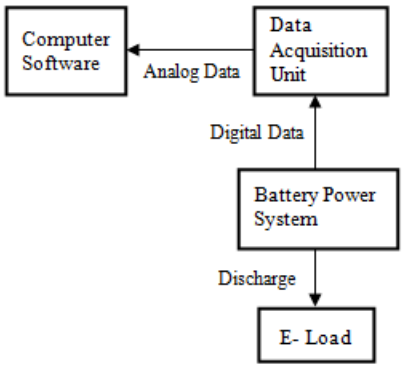

Figure 1: Proposed Experiment Sequence

The proposed method has a few advantages. Firstly, the usage of computational software reduces the cost of the project yet produces accurate results. Secondly, the results can be easily extracted from specific points and analysed with the tools available in the software. This reduces the time spent on data extraction and increased the overall project time efficiency. As a whole, the usage of computation simulation is an efficient and effective method of predicting the results in a thermal simulation.

1.1 Battery System data

The battery power system consists of 12 $LiFePO_4$ cells connected in series and is rated at 2 kWh. The battery system is electrically rechargeable and pressure tolerant with built-in vents to release pressure to avoid any hazards related to overcharging, discharging and use in general.

Table 1: Battery Power System Data

Battery Power System	
Dimensions	440 x 440 x 390 mm
Weight	36.5 kg
Energy	2 kWh
Voltage	40 V
Capacity	50 Ah
Discharge Current	50 A nominal
Charge Current	15 A nominal
Internal Resistance	1 mΩ
Operating Temperature	-20 ~ 50℃

These data were extracted from the product specification manual and it clearly states that, once the temperature of the cell surface is above 50℃, stop all charging and discharging activities.

1.2 Model of Battery Power System

The model of the battery power system, as shown in Figure 2, was designed in SOLIDWORKS and imported into COMSOL Multiphysics® Modeling Software for the thermal simulation.

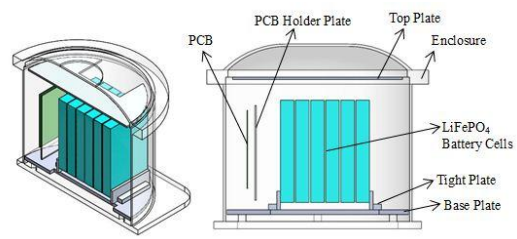

Figure 2: SOLIDWORKS Model (Left: Isometric View, Right: Front View)

Due to the symmetrical geometry of the model, the symmetry function in COMSOL was used to simulate the other half, hence, significantly reducing memory usage of the computer and the computational duration.

2. Theory

2.1 Heat Transfer Theory

The natural laws of physics govern that the driving energy in a system is incessant until a point of equilibrium is reached. If a temperature gradient is present, heat energy will be transferred from the hot medium to the cold medium.

Heat energy can be transferred by conduction, convection and radiation. Conduction is energy transferred between solid or stationary fluids via the movement of atoms and molecules. Convection describes the transfer of energy by the movement within a fluid. Radiation is energy transferred by electromagnetic waves, mainly in the infrared region.

In the case of our study of heat transfer in a sealed enclosure, with heat source being the batteries, heat transfer is mainly caused by natural convection and conduction. Hence, effects of heat transfer by radiation have been ignored.

2.2 Battery Thermal Theory

The Arrhenius laws dictate that the rate at which a chemical reactions proceeds, increases exponentially as temperature rises. This allows more power to be extracted from the battery at higher temperatures. The higher temperature also improves electron and ion mobility, reducing the cell's internal impedance, hence, increasing its capacity.

At high temperatures, at the upper end of the scale, irreversible chemical reactions and/or loss of electrolyte could occur and cause permanent damage or complete failure of the battery. This emphasizes the importance of operating the battery under its operational limits so that charge capacity and cycle life can be optimized.

The risks of batteries operating at high temperatures are as follows:

- Active chemicals expand and causing the cell to swell
- Chemical reactions speed up which leads to thermal runaway
- Pressure built up within cell walls due to production of gases
- Cell may rupture and explode

2.3 Thermal Runaway

When the battery is subjected to excessive currents, the possibility of thermal runaway increases, hence, resulting in catastrophic destruction. This occurs when the rate of heat generation within the battery has exceeded its limitations.

Causes of thermal runaway are,

- Initially, the electrical heating heats up the battery, the resistance decreases with temperature. This will result in a higher current and increases the temperature until runaway conditions is reached.
- During charging/discharging, current induces an exothermic chemical reaction.
- Excessive ambient temperature built up.

3. Governing Equations

There are several equations that describe the characteristics of the system and its activities during the discharging process. The battery is producing heat energy and the heat energy is being transferred to the components within the system via conduction and convection during the stipulated period of time.

The equations from COMSOL provide solutions for conjugate heat transfer. They solve the fundamental differential equations governing the laws of conservation, namely, mass, momentum and energy.

2.1 Joule Heating Effect

Batteries give off heat during their charging/ discharging cycles via electrical heating (Joule heating effect) and thermochemical heating effect. Due to the complex thermochemistry of the lithium cells and the unstable thermic reaction, its effect has been ignored in this paper.

The more significant heating effect, the Joule heating effect, often referred to as resistive loss, occurs when there is a current flow through a resistive element. In the case of the battery, heat is dissipated through the resistive properties of the battery cell, i.e. battery internal resistance.

The Joule heating effect, Q_{Joule} is described as:

$$Q_{Joule} = I^2 Ri \qquad (1)$$

Where, I is the current (A) and Ri is the internal resistance of the battery (Ω).

However, it is extremely difficult to define the exact battery resistance due to its dynamic nature of the polarized reaction. Hence the heat generation is always changing during the process of charging and discharging [1].

2.2 Heat Transfer

The time dependent heat transfer equation is as follows:

$$\rho C_P \frac{\partial T}{\partial t} + \rho C_P \boldsymbol{u} \cdot \nabla T = \nabla \cdot (k \nabla T) + Q \qquad (2)$$

Where, ρ is the density (kg/m^3), C_P is the heat capacity at constant pressure (J/kgK), T is the temperature (K), $\boldsymbol{u}$ is the velocity field (m/s), k is the thermal conductivity (W/mK) and Q is the heat source (W/m^3).

2.4 Fluid Flow

In COMSOL, the Navier-Stokes equations govern the motion of fluids. In the case of a compressible Newtonian fluid, the equation is as shown.

$$\rho\left(\frac{\partial \boldsymbol{u}}{\partial t} + \boldsymbol{u} \cdot \nabla \boldsymbol{u}\right) = -\nabla p + \nabla \cdot \left(\mu(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T) - \frac{2}{3}\mu(\nabla \cdot \boldsymbol{u})\boldsymbol{I}\right) + \boldsymbol{F} \qquad (3)$$

Where, $\boldsymbol{u}$ is the fluid velocity field (m/s), p is the fluid pressure (Pa), ρ is the fluid density (kg/m^3), μ is the fluid dynamic viscosity (Pa.s) and $\boldsymbol{F}$ is the volume force field (N/m^3).

Each term of the equation represents and corresponds to the inertia forces, pressure forces, viscous forces and the external forces applied to the fluid.

The Navier-Stokes equations represent the conservation of momentum while the continuity equation represents the conservation of mass. These equations are always solved together. The continuity equation is as follows:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{u}) = 0 \qquad (4)$$

Where, $\boldsymbol{u}$ is the fluid velocity field (m/s) and ρ is the fluid density (kg/m^3).

3. Simulation Setup

The thermal analysis of the battery power system has been spilt into two parts, simulation and experiment. The simulation setup is as follows.

The CAD model from SOLIDWORKS was imported into COMSOL Multiphysics simulation software, where the meshing and thermal simulation was carried out.

The CAD model as shown in Figure 3 has been simplified to reduce overall memory usage and hence, reducing the computational time.

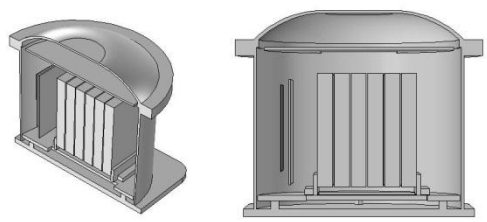

Figure 3: COMSOL Model

3.1 Boundary Conditions

The main boundary conditions for the study are as follows:

- Physics used is the conjugate heat transfer package
- Time dependent
- Simulation time of 10800 seconds, with step size of 60 seconds.
- Initial temperature of 295 K (22℃)
- Initial pressure of 1 bar
- Heat source set at 9.375 W
- In order to simulate the effects of gravity, and hence natural convection, the volume force in y-axis had been changed to "-nitf1.rho*g_const".

The material properties used in the simulation is shown in Table 2.

Table 2: Material Properties

Material	Phase	Thermal Conductivity, k [W/mK]	Heat Capacity, C_p [J/kgK]	Density, ρ [kg/m^3]
Acrylic	Solid	0.18	1470	1190
Air	Liquid	Defined by piecewise functions, dependent on temperature		
Aluminum	Solid	238	900	2700
FR4 (Circuit Board)	Solid	0.3	1369	1900
$LiFePO_4$ (Battery)	Solid	1.58	1217	1950

3.2 Assumptions

A few assumptions were used in this study to reduce the complexity and complications of the simulations, hence cutting down computation time. These assumptions are as listed:

- Non-essential structural components are removed and not considered in the simulation
- Each battery cell is treated as a homogenous model
- Heat generation from the battery cells via electrochemical reactions is not considered.
- Heat generation from the wiring and circuit boards are not considered.

4. Experiment Setup

The results extracted from the experiment are used to verify and affirm the accuracy of the thermal simulation done in the COMSOL Multiphysics software. The physical model of the battery power system is as shown in Figure 4.

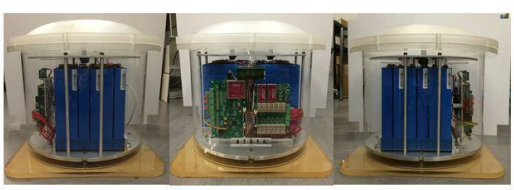

Figure 4: Physical Model of Battery Power System

The experimental setup of the battery power system consist of the battery power system, thermocouples, data acquisition unit, electrical load and the computer software for data analysis. The experiment sequence is shown in Figure 5.

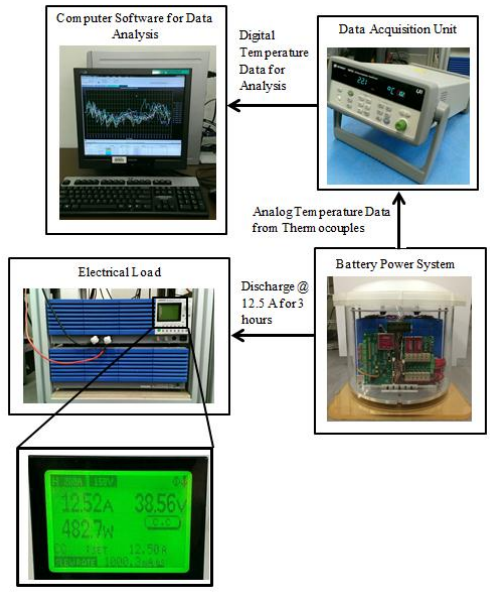

Figure 5: Data Flow for Experiment

The batteries are discharged at 12.5 A into an electrical load for 3 hours (10800 seconds). Thermocouples are attached at strategic locations to measure and transmit thermal data to the data acquisition unit, which converts the analog data to digital data for further analysis and processing in the computer software. The locations of the thermocouples are displayed in Table 3 and Figure 6.

Table 3: Name and Location of Data Points

Thermocouple Measuring Points	
N.O.	Location
1	PCB
2	PCB Holder Plate
3	Battery Cell 1
4	Top of Battery Stack
5	Battery Cell 6
6	Between the Battery Stacks
7	Between Battery Stack and Enclosure
8	Top Plate
9	Cover
10	Air Temperature Inside the Enclosure

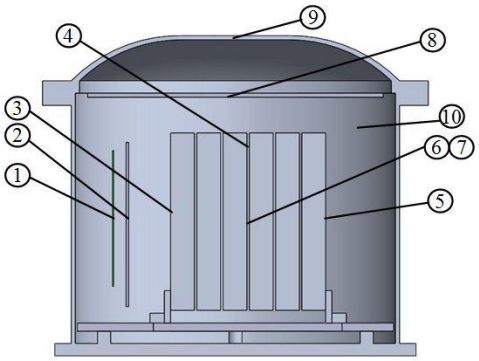

Figure 6: Data Points on Model

These temperature data points are located at their corresponding locations to measure the temperature of the crucial components such as the printed circuit board, battery cells and ambient air temperature.

5. Results and Discussion

5.1 Thermal Simulation Results

The objective of performing the thermal simulation is to determine the maximum temperature and define its location.

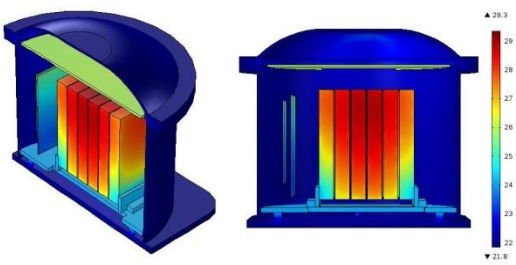

Figure 7: COMSOL Thermal Simulation Results

As seen in Figure 7, the maximum temperature achieved is 29.3℃, which compiles with the requirement of being under 50℃. As expected, due to natural convection within the enclosure, the upper region is generally higher temperature than that in lower region.

5.2 Experiment Results

The experiment was carried out to verify and determine the accuracy of the thermal simulation performed in COMSOL Multiphysics. Figure 8 displays the results obtained from the experiment in a graphical format.

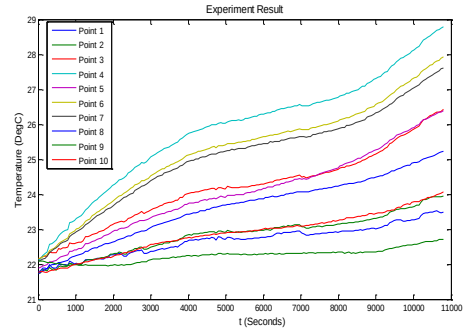

Figure 8: Experiment Results

As seen in Figure 8, the maximum temperature achieved in the experiment is 28.8℃ which comply with the requirement of being under 50℃.

However, from 4000s to 8000s, it has been observed that there is a dip in temperature. This can be explained by a negative entropic heat contribution, which is a characteristic of a lithium type battery [4].

5.3 Comparison of Results

The results obtained in the thermal simulation have been compared with the experiment results in order to validate the accuracy of the simulation results. It is observed that the simulated results closely match that of the experiment results.

Table 4: Simulation vs. Experiment Results (Maximum Temperature)

Data Points	Simulation (℃)	Experiment (℃)	Error (℃)	Error (%)
1	24.2	23.5	0.7	3.0
2	24.2	23.9	0.3	1.3
3	27.1	26.4	0.7	2.7
4	29.3	28.8	0.5	1.7
5	27.1	26.4	0.7	2.7
6	28.0	27.9	0.1	0.4
7	28.3	27.6	0.7	2.5
8	25.9	25.2	0.7	2.8
9	22.5	22.7	0.2	0.9
10	25.1	24.1	1.0	4.1

Table 5: Error Table

Mean Error (%)	2.21
Standard Error of the Mean (%)	0.35
Root Mean Squared Error (%)	2.45

Maximum temperature data was extracted from the simulation and experiment at 10800 seconds for each point. As seen in Table 5, the results from the simulation and experiment produced a marginal and acceptable error value.

As predicted in the simulation, the maximum temperature achieved would be at the top of the battery stacks in the middle of the battery stacks, cell 3 and 4. The results are shown in Table 6 and Figure 9.

Table 6: Maximum Temperature Obtained

Method	**Max Temperature**
Simulation (℃)	29.3
Experiment (℃)	28.8
Error (%)	0.5

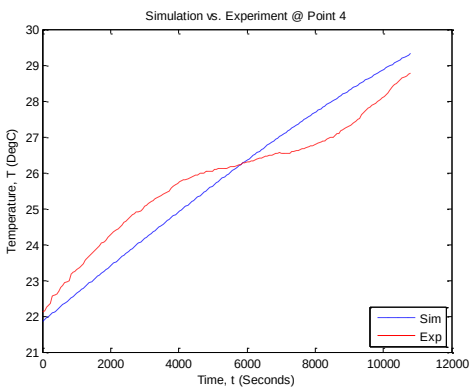

Figure 9: Simulation vs. Experiment Result at Point 4

Point 4 is the top of the battery stack, between cell 3 and 4. The maximum temperature achieved is 29.3℃ in the simulation and 28.8℃ in the experiment. Thus, the results produced and error of 0.5℃ which correlates to an error of 1.7%.

The remaining result comparisons at the other points are displayed in Appendix A: Graphical Representation of Thermal Results.

6. Conclusions

The results obtained from the simulation demonstrate that the maximum temperature obtained during the discharge cycle of the battery is lower than the safe working temperature of 50℃. This proves that the battery power system is capable of operating for 3 hours continuously without exceeding the temperature limit.

The experiment results are relatively close to the simulations results. Hence, the simulation model using COMSOL can be used in subsequent thermal simulations from heat generating components such as the modules on the circuit board and the upcoming addition of a battery charger and DC-DC converter in the battery power system.

For future works, a possible method of thermal management could be implemented to the battery power system in the form of a phase change material heat sink as well as a temperature feedback control system to reduce battery power consumption when it hits a certain temperature and allow them to cool down before discharging again.

7. References

[1] Jiangong, Zhu et al. 'Preliminary Study of a Distributed Thermal Model for a LFP Battery in COMSOL Inc. Multiphysics (MP) Software'. *IEEE*, **5.13**, 256 – 260 (2013)

[2] Madarapu, Anjaiah. 'Thermal Design And Analysis Of Electronic Enclosure Of Ground Radar'. *IOSR-JMCE* **4.5**: 41-46. (2012).

[3] Muthuraj, M, and N Parameswaran. 'Thermal Analysis of Sealed Enclosure for Over the Ocean Application'. *19th IEEE SEMI-THERM Symposium*, **1.02**, 134 – 137 (2003)

[4] Rad, Mojtaba Shadman et al. 'Thermal Modeling of Cylindrical $LiFePO_4$ Batteries'. *Journal of Modern Physics*, **4.7**, 1-7 (2013)

[5] Toma, Daniel Mihai et al. 'Study on Heat Dissipation and Cooling Optimization of the Junction Box of OBSEA Seafloor Observatory'. *IEEE/ASME Transactions on Mechatronics* **20.3**, 1301-1309 (2015)

8. Appendix

Appendix A: Graphical Representation of Thermal Results

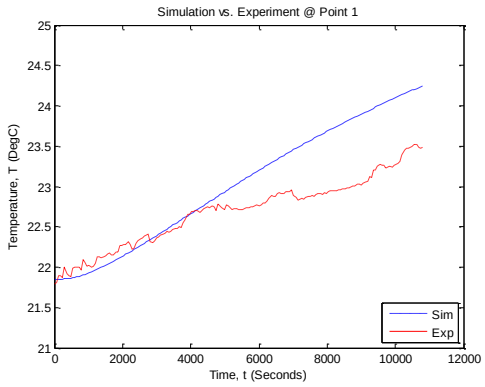

Figure 10: Simulation vs. Experiment Result at Point 1

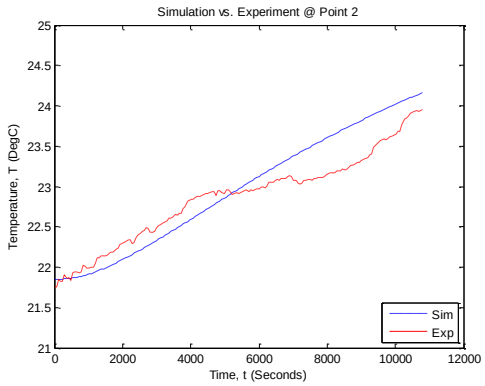

Figure 11: Simulation vs. Experiment Result at Point 2

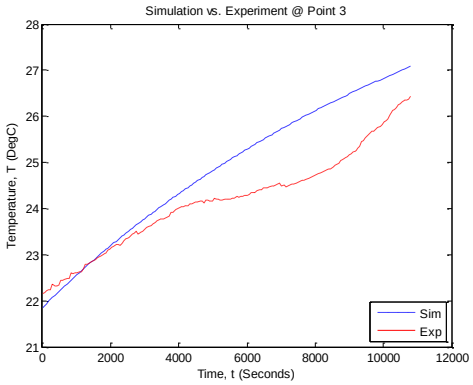

Figure 12: Simulation vs. Experiment Result at Point 3

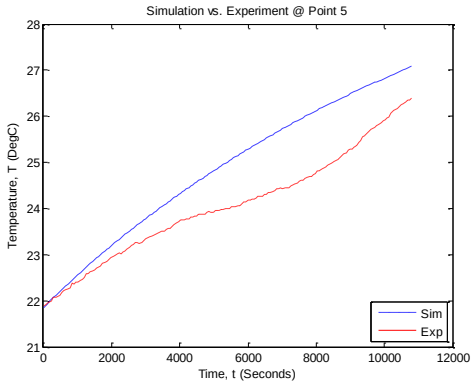

Figure 13: Simulation vs. Experiment Result at Point 5

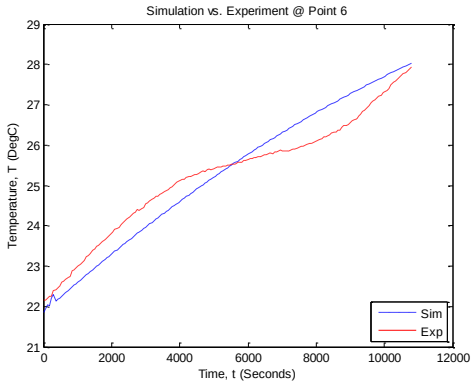

Figure 14: Simulation vs. Experiment Result at Point 6

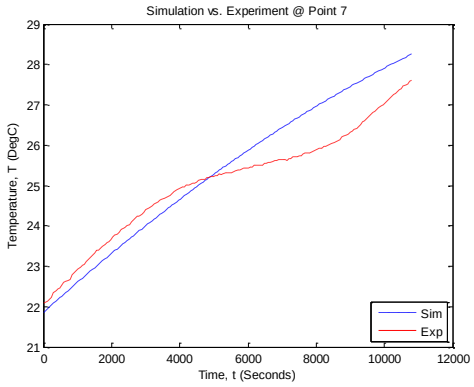

Figure 15: Simulation vs. Experiment Result at Point 7

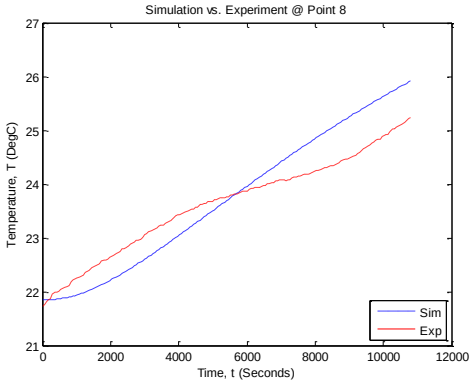

Figure 16: Simulation vs. Experiment Result at Point 8

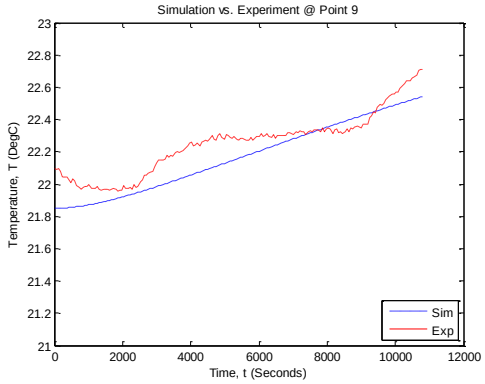

Figure 17: Simulation vs. Experiment Result at Point 9

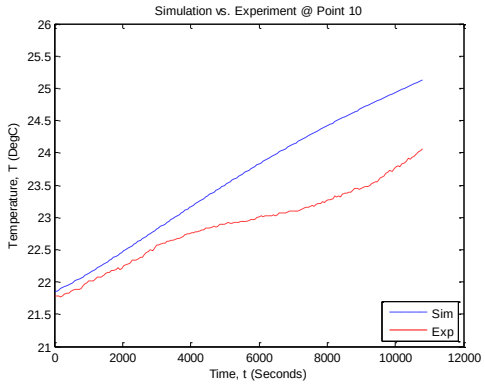

Figure 18: Simulation vs. Experiment Result at Point 10