DESIGN AND ANALYSIS OF HEAT EXCHANGER FOR BATTERY THERMAL MANAGEMENT SYSTEM

[1]Hanamant Yaragudri,[2]Mohan Narayana K,[3]Ravikumar M
[1]Assistant Professor, [2] M. Tech Scholar, [3] Assistant Professor
[1 2 3] Department of Mechanical Engineering, New Horizon College of Engineering, Bangalore, India-560103

Abstract: In the recent years electric vehicles (EV) developed quickly and have become popular due to their zero emission and high tank-to-wheels efficiency. However, some factors limit the development of the electric vehicles, especially performance, cost, lifetime and safety of the battery. Therefore, the management of batteries is necessary in order to reach the maximum performance when operating at various conditions. The battery thermal management system (BTMS) plays a vital role in the control of the battery thermal behaviour. The BTMS technologies are: air cooling system, liquid cooling system, and direct refrigerant cooling system, phase change material (PCM) cooling system.Battery thermal management system (BTMS) is critical to dissipate the heat generated by the battery pack and guarantee the safety of the electric vehicles. In this paper study is made on different cooling system and water cooled heat exchanger is designed to remove the heat generated by Electrical Battery using LMTD method. Heat exchanger is modelled using CAD software Solid Edge ST4, temperature distribution analysed using Ansys Fluent.

IndexTerms - **BTMS, Heat Exchanger, Li-on Battery, LMTD Method, Solid Edge, Ansys Fluent.**

I. INTRODUCTION

Lithium-ion batteries are the key factor in the development of energy storage station and electric vehicles, due to its lower self-discharge rate, higher power density and efficiency, longer life and the absence of memory impact. Nonetheless, critical temperature gradients can be developed inside the pack of battery because of internal resistance and generation of heat resulting from the electrochemical reactions inside the individual batteries. Battery pack performance has major effect on the performance of an electric powered vehicle. Thermal energy is generated due to the chemical reaction inside battery during charging and discharging processes. Temperature of inside lithium ion battery increases if thermal energy generated is not removed. In such case, the temperature of the battery rises continuously and shortens the service life of the battery. Diverse cell-to-cell inner resistance and voltage are because of the temperature varieties inside the battery pack which can corrupt the pack execution and shortening batteries life cycle. It is broadly recognized that operating temperature of lithium ion battery is in the range of 20^{0}C–40 °C.

II. DIFFERENT BATTERY COOLING SYTEMS

A battery cooling system generally consist of battery pack, a fan/pump, a heat exchanger and coolant pipes as shown in Figure 1[5].

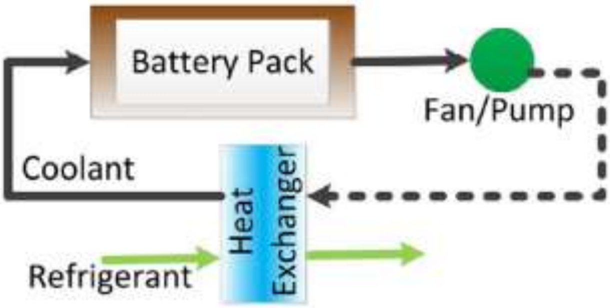

Figure 1: General schematic of battery pack cooling loop.

Different cooling systems for Li-ion battery are studied [6]. The different cooling configurations are

- Configuration of air cooling.
- Configuration of fin cooling.
- Configuration of indirect liquid cooling.

- Configuration of direct liquid cooling.

From the literature study it is found that,

- Fin cooling adds the most extra weight when all cooling methods have the same volume.
- Air cooling consumes the most parasitic power.
- Indirect liquid cooling has the highest maximum temperature difference point because of the longest coolant channel.
- Using the low mass flow rates of indirect liquid cooling to control the temperature rise and temperature difference within a battery should be avoided.

An indirect liquid cooling is the better option for Li-ion battery. It consists of a heat exchanger which removes the heat from liquid and transfers to atmosphere. Heat exchanger must remove the required amount of heat to maintain safe temperature inside the battery pack.

III. DESIGN OF HEAT EXCHANGER

3.1 Calculation for Heat exchanger coil length

Assumptions:

- Velocity of air is equal to average speed to the vehicle, which is 50 km/hr.
- Velocity of water in the heat exchanger is 0.0091 kg/s.
- Material used for heat exchanger is Aluminium 6061.
- Al tube of outside diameter 10 mm and inside diameter 7.6 mm is used.

Heat Generation Calculation:
Heat generation of 20 AH Li-ion Battery at various temperature and discharge rate are given Table 1 [8].

Table 1: Rate of heat generation of Li-ion battery.

Temp. [° C]	Discharge rate				
	0.25C	0.5C	1C	2C	3C
-10	0 to 2.09	0 to 5.29	0 to 10.82	0 to 24.71	-
0	-0.33 to 2.05	0 to 5.20	0 to 10.21	0 to 19.52	0 to 29.93
10	-0.24 to 1.43	0 to 4.37	0 to 8.87	0 to 16.72	0 to 24.79
20	-0.44 to 0.87	0 to 3.32	0 to 4.92	0 to 13.78	0 to 4.92
30	-0.46 to 0.85	-0.33 to 1.86	0 to 4.56	0 to 10.39	0 to 16.48
40	-0.43 to 0.71	-0.44 to 1.62	0 to 3.70	0 to 7.88	0 to 14.21

Here, C= Discharge rate.

Maximum heat generation at 30 °C is taken.
Rate of discharge - 3C discharge/recharge.
Heat generation for 20AH battery at 30 °C with rate of discharge 3C = 16.48 W
Heat generation for 280AH battery = 280/20 X 16.48
= 230.72 W

Design of Heat Exchanger(Crossed flow heat exchanger-both fluids unmixed) by LMTD Method

Temperature of hot Fluid (water) = Thermostat set temperature
$T1 = 40\ ^{\circ}C$
Velocity of water = 0.2 m/s
Volume Flow rate = Velocity X area

Volume Flow rate = 0.2 X (π X D2)/4
$= 0.2 \times (\pi \times (7.6 \times 10^{-3})^2)/4$
$= 9.07 \times 10^{-6}\ m^3/s$
Mass flow rate = Volume flow rate X Density
$= 9.07 \times 10^{-6} \times 1000$
= 0.0091 Kg/s
From Energy balance equation,

$$Q = mCp\Delta T \qquad (3.1)$$

$$230.72 = 0.0091 \times 4178 \times (40-T2)$$

Output temperature of water T2 = 33.93 ºC
To calculate output air temperature
Velocity of air = average speed of vehicle.
= 50 Km/hr
= 13.8 m/s
Mass flow rate = (velocity X area) X desnsity
= (13.8 X 0.125) X 1.165
= 2.01 Kg/s
Heat lost by water = Heat gained by air
230.72 = mCpΔT
230.72 = 2.01 X 1005 X (t2-28)
Output air temperature, t2 = 28.11 ºC

To find LMTD,

Q = FUA (LMTD) (3.2)
LMTD= ((T1-t2)-(T2-t1))/(ln((T1-t2)/(T2-t1)))
LMTD = ((40-28.11)-(33.93-28))/(ln((40-28.11)/(33.93-28)))
= 8.57 ºC

To calculate heat transfer coefficient U,

Internal flow: For water flows inside the heat exchanger
Kinematic viscosity of water ν = 0.657 X 10^{-6} m^2/s
Velocity of water V= 0.2 m/s

Reynolds Number Re = (V d)/ν
= (0.2 X 7.6 X 10-3)/ (0.657 x 10-6)
= 2313.55
Re > 2300 turbulent flow,
Nu = 0.023 $Re^{0.8}$ Pr^n
= 0.023 X 2313.55 0.8 X 4.340.3
= 17.5549
Nu =hd/k
17.5549 = (h X 0.0076)/ (597.8 X 10-3)
h_i= 1380.83 W/m^2k

External flow: For air flowing outside the heat exchanger
Kinematic viscosity of air ν = 16 X 10-6 m^2/s
Prandtl Number Pr = 0.701
Thermal conductivity k = 0.02675 W/mk
Velocity of air = 13.8 m/s

Reynolds No Re = (V d)/ν
= (13.8 X 10 X 10-3)/ (16 x 10-6)
= 8625
Nusselt Number Nu = C Re^m $Pr^{0.333}$
= 0.193 X 8625 0.618 X 0.701 0.333
= 46.4
Nu =hd/k
46.4 = (h X 0.01)/ (0.02675)
h_o= 124.12 W/m^2k

U = 1/ (1/h_o+r_o/k ln[r_o/r_i]+r_o/$r_i h_i$)
U = 1/ (1/124.12+ (0.005)/204.2 ln[0.005/0.0038]+5/(3.8 X 1380.83))
= 113.8 W/m^2k

Correction Factor F
P = (t2-t1)/(T1-t1)
= (28.11-28)/(40-28)
= 0.0092

R = (T1-T2)/(t2-t1)

= (40-33.93)/(28.11-28)
= 55.18
For the above P and R value
F = 0.9

From Equation (3.2), Q = FUA (LMTD)
230.72 = 0.9 X 113.8 X A X 8.57
A = 0.2365 m2

A = πdL
0.2365 = π X .01 X L
L = 7.53 m

Coil length required for Heat Exchanger = 7.53 m

3.2 Creation of Geometric Model

Heat exchanger is modeled for the length of 7.53 m using Solid Edge.

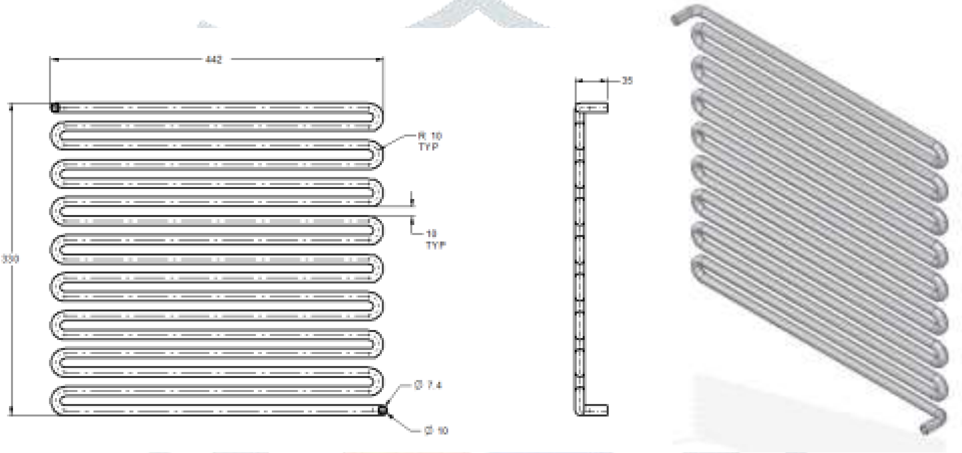

Figure 2: CAD model of heat exchanger.

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3.3 Creation of Finite Element Model

CAD model is imported in ANSYS 14.5 to carry out further pre-processing and meshing is done. Meshing details are provided in table 2.

Table 2: Mesh information.

Type of Element Used	Quadrilateral	
Domain	**Nodes**	**Elements**
coil 2	246432	144930
water_1	274456	220500
All Domains	520888	365430

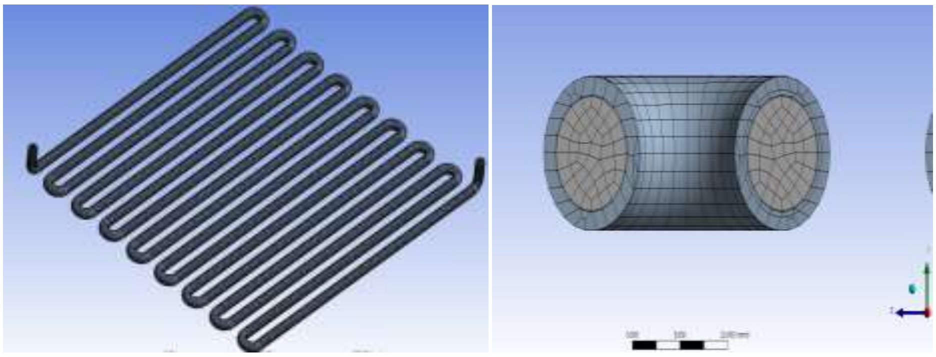


Figure 3: Meshed Model.

Fluent Parameters are,

Type of Solver used: Transient /Pressure based
Model:Realizable k-epsilon with Enhanced wall treatment
Material used: Aluminium 6061
Coil/Solid: Aluminum
Coolant/Fluid: Water

Table 3: Thermal properties**.**

Material	**Thermal Conductivity W/m K**	**Density kg/m^3**	**Specific Heat kJ/kg k**
Aluminium-6061	204.2	2.71×10^3	1.256
Water	0.6286	992.2	4.03
Air	2.624×10^{-2}	1.177	1.0049

Table 4: Boundary conditions.

Domain	**Boundary condition**	
Coil	**Boundary – contact region trg**	
	Type	Interface
	Boundary - wall coil	
	Type	Wall
Water	**Boundary – contact region src**	
	Type	Interface
	Boundary – inlet	
	Type	Velocity-Inlet
	Boundary – outlet	
	Type	Pressure-Outlet

IV. RESULTS AND DISCUSSION

4.1 Temperature distribution

Temperature distribution for different velocities in designed heat exchanger is shown in figure 4, figure 5, figure 6 and figure 7. Graph 1 shows the temperature variation along the coil length of heat exchanger.

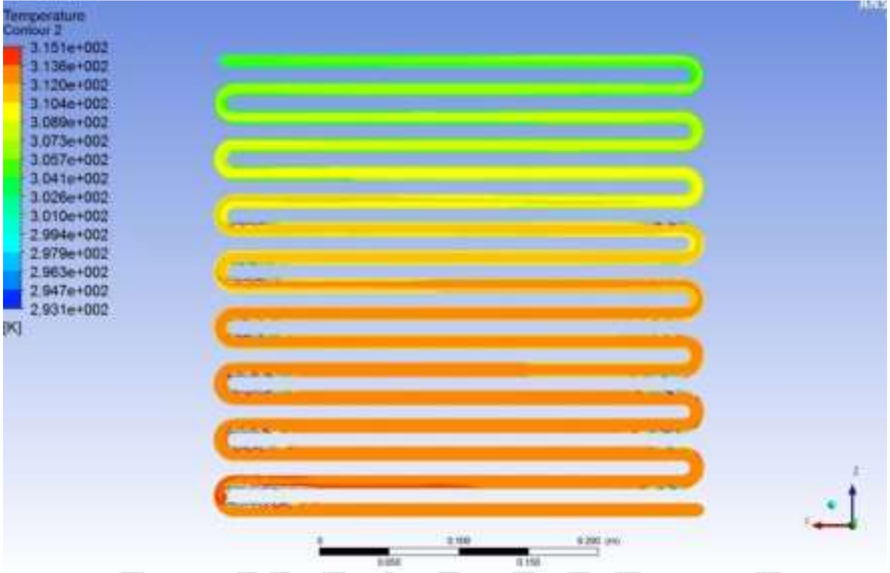


Figure 4: Temperature distribution contour for 0.15 m/s flow velocity.

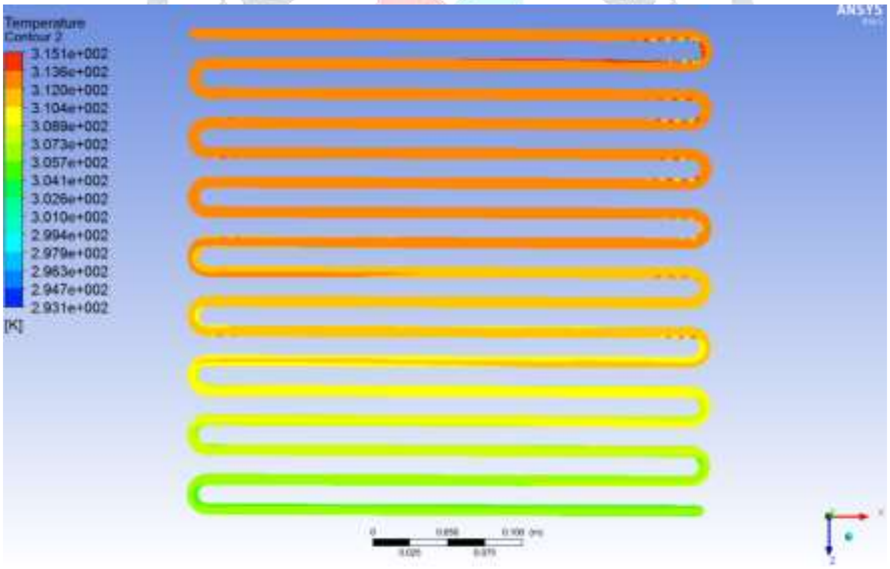


Figure 5: Temperature distribution contour for 0.2 m/s flow velocity.

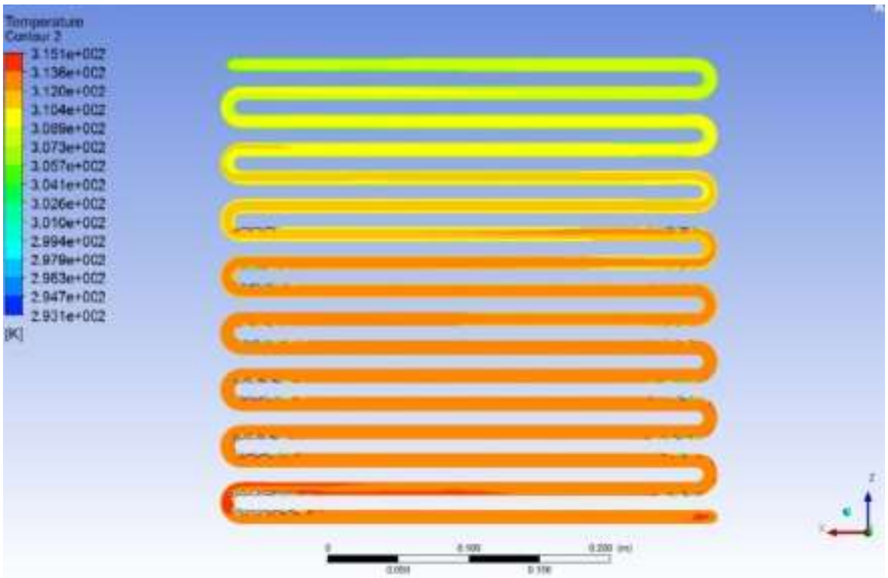


Figure 6: Temperature distribution contour for 0.25 m/s flow velocity.

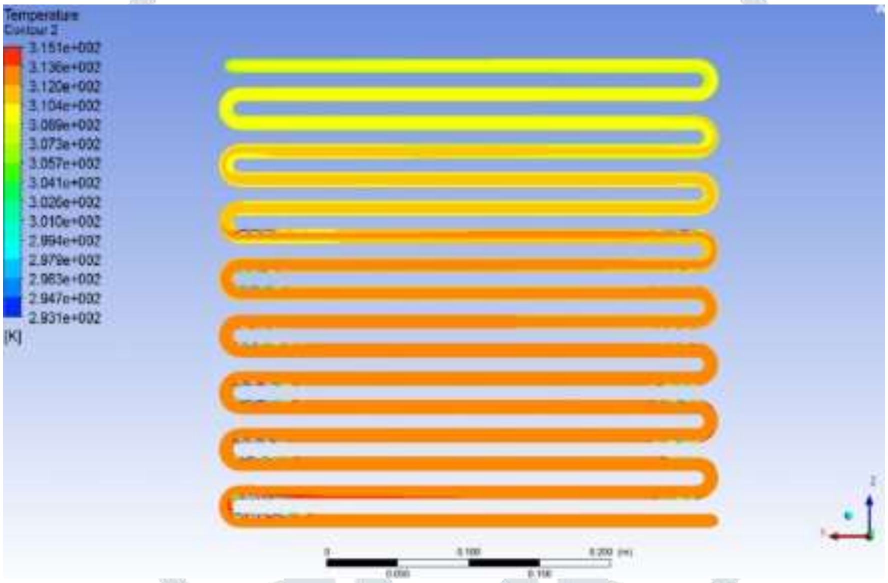
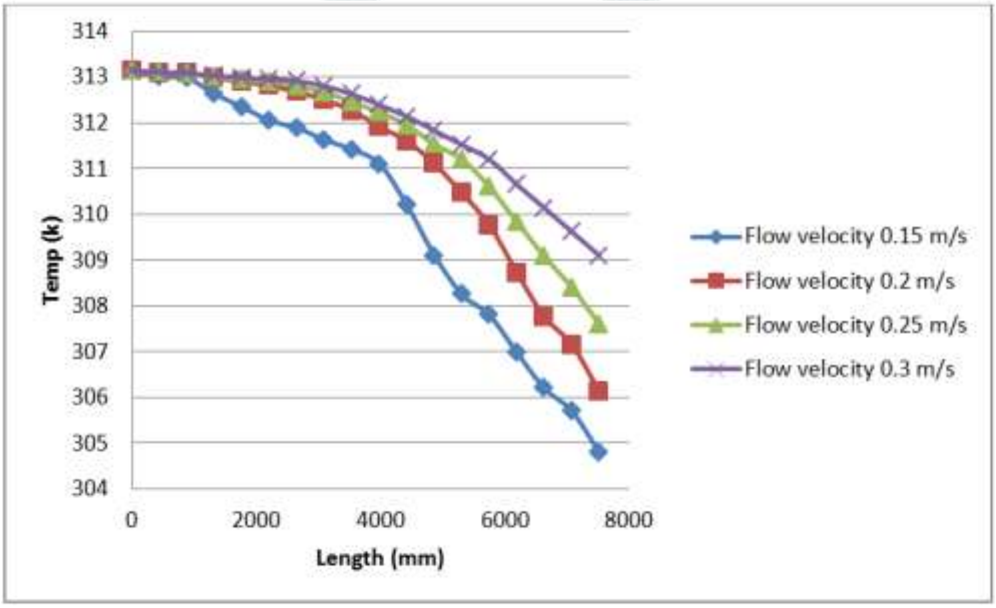


Figure 7: Temperature distribution contour for 0.3 m/s flow velocity.



Graph 1: Temperature v/s coil length.

It is found that as the flow rate decreases temperature reduction in the designed heat exchanger increases. This is because of more time availability for convection between water and atmospheric air.

4.2 Cooling rate

Cooling rate for different flow velocities are tabulated in table 5 is shown below,

Table 5: Cooling rate.

Flow velocity (m/s)	Water outlet temperature (ºC)	Cooling rate (ºC/s)
0.15	31.8	0.166
0.2	33	0.194
0.25	34.6	0.179
0.3	36.1	0.155

For the flow velocity of 0.2 m/s cooling rate is found to be high in the designed heat exchanger as compared to other flow velocities.

V. CONCLUSION

A well-designed thermal management system is required to regulate EV and HEV battery pack temperatures evenly, keeping them within the desired operating range. Indirect liquid cooling configuration has more effective cooling method for Li-ion battery. Heat exchanger is one of the main part of BTMS system. Designed heat exchanger is able to remove the heat generated by Li-ion battery. Procedure used for designing the heat exchanger is correct, which is evaluated using ansys fluent. Result obtained from manual calculation and ansys fluent are correlating each other. It is suggested to use 0.2 m/s flow velocity since it gives optimum result. Temperature of water is reduced by 7 ºC in 0.2 m/s flow velocity and this cooled water is circulated back to battery pack to remove heat.

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