International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 08 Issue: 10 | Oct 2021 www.irjet.net p-ISSN: 2395-0072

Prandtl Number and Other Parameters Affecting Battery Thermal Management System Performance

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Abstract - *This paper aims to study the significance of Prandtl Number and other parameters that affect the performance of Battery Thermal Management System (BTMS) for EV vehicles. BTP (Battery Thermal Plate) acts as a medium of rejecting heat from the batteries to coolant flowing within the system. BTP patterns are designed so that coolant covers the maximum area of the battery without major loss in momentum. These patterns were designed in two forms: linear channel flow distribution and random/zig-zag flow channel distribution. Here we studied how coolants with different Prandtl numbers flowing in various BTP patterns affect the heat transfer coefficients. For this study, BTMS was designed in NX, and its flow and thermal performance were analysed in SimFlow (OpenFoam) and ANSYS while post-processing in ParaView. Simulations in various BTPs showed that the coolant with lower Prandtl Number flowing in random/zig-zag flow pattern BTP gave the better heat transfer coefficient compared to other patterns. The future scope of the research will be inclined to compare heat transfer performances when random/zig-zag and linear channel flow distribution BTP patterns modules are placed together in series and parallel connections.*

Key Words: EV Battery, Battery Thermal management, Battery Thermal/Cooling Plates, Prandtl Number

1.INTRODUCTION

In recent years, the market of novel energy vehicles, including electric vehicles and hybrid electric vehicles, has taken a huge jump compared to the past decade. There has already been some incredible growth in the number of EVs worldwide, and it is just the starting. In 2019, the number of light electric vehicles reached up to 2264400 units worldwide, 9 % higher than for 2018 as stated by Vitra Global in Fig. 1. This is a clear deviation from the growth rates of the previous six years, which were between 46% and 69%. [1]

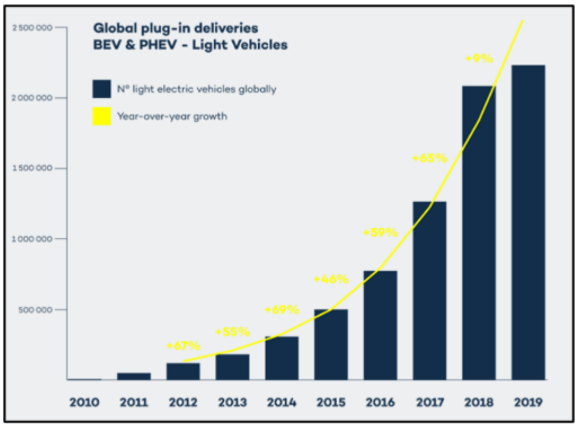

Fig -1: Growth is EV worldwide

1.1 Growth in EV vehicle world-wide

As technology evolves in the electrification of two-wheelers, three-wheelers, buses, and trucks; hence, the market grows for electric vehicles. According to the Global EV Outlook 2020, the sales of electric cars reached 2.1 million globally in 2019, surpassing 2018 as being presented in the Fig. 2. [2]

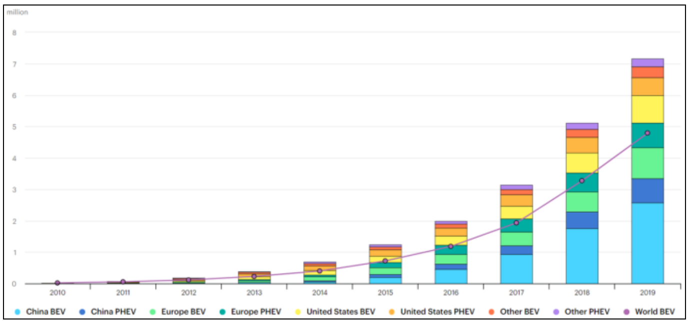

Fig -2: Global electric car stock, 2010-2019

Electric vehicles play a vital role in meeting the environmental goals of the Sustainable Development to improve local air quality and address climate change. In the current research, the way for the battery cooling is mainly liquid cooling. However, there are many cooling methods for battery, including air, liquid, heat pipe and phase change material. Compared with other battery cooling methods, liquid cooling is widely used due to its high efficiency, easy maintenance, and technical maturity [3].

1.2 Requirement of effective cooling system

Batteries work on the principle of a voltage differential. Due to increase in temperatures, the electrons inside become excited and decrease the difference in voltage between the two sides of the battery. As batteries are manufactured to work between certain temperature limits, they will stop working if there is no adequate cooling system to keep them within the working range. Cooling systems are designed to keep the battery pack in the temperature range between 20-40 ^{0}C, as well as keep the temperature difference within the battery pack to a minimum (no more than 5^{0}C) [4].

1.3 Design of effective cooling system

As utilization of electric vehicles got increased, the high demand for longer battery life and higher power output parallelly increased. Towards achieving this, the battery thermal management systems will need to transfer heat away from the battery pack at higher rates as they are charged and discharged. For the study, Battery cooling module was designed in UGNX software, where Fig. 3 demonstrates the coolant flow channel in BTP. There is a step-by-step process of designing an effective battery cooling module.

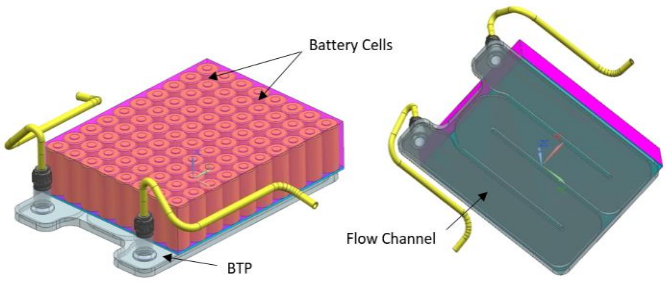

Fig -3: Coolant Flow Channels in BTP (Battery Thermal Plate)

STEP 1: Selection of BTP (Battery Thermal Plate) size. BTP are flat plates on which battery modules are mounted. A battery module will either be sitting on a BTP, or a BTP will be placed between every two battery modules. The more BTP covers the area of the battery; the better will be the heat transfer coefficient.

STEP 2: Designing of proper channel for optimum heat transfer. A fluid always follows the least resistant path. More the obstacles, more will be resistance to the flow. If there is more resistance, there will be more pressure drop, and hence load on the Coolant Pump will increase, leading to more power consumption. Liquid cooling is the most efficient and widely used method for cooling battery packs.

STEP 3: Selection of coolant. The Coolant used in the system has a significant impact on the heat transfer of BTP. If coolant with proper properties is not selected, the temperature homogeneity per module will not be met. Temperature homogeneity is the temperature difference that is to be maintained within each module to have controlled cooling.

Prandtl Number is an important factor that is to be considered for effective cooling. The Prandtl number is the ratio of molecular diffusivity of momentum to the molecular diffusivity of heat. It assesses the relation between momentum transport and thermal transport capacity of the fluid. [5]

$$Pr = \frac{momentum\ diffusion\ rate}{thermal\ \ diffusion\ rate} = \frac{\mu Cp}{k}$$

Eq. 1: Prandtl Number equation

The Prandtl number is an example of a dimensionless number and also an intrinsic property of a fluid. Fluids with small Prandtl numbers are liquids flowing freely with high thermal conductivity and therefore a good choice for heat-conducting liquids. With increase in viscosity, the momentum diffusion rate dominates over the heat diffusion rate, making a liquid a bad choice for heat conduction.[5]

2. DESIGN AND SIMULATION

It's important to keep the battery under controlled temperature otherwise, it will have a negative impact on its performance, lifetime and safety of the batteries hence a BTMS (Battery Thermal Management System) is required. The main function of a BTMS is to keep the batteries in the most favorable temperature range. In BTMS, BTP has a vital role in keeping the battery at optimum temperature. Its performance affects the performance of the battery as well as the part surrounding it. [6] Fig. 4 shows the nomenclature of BTMS designed in UGNX software.

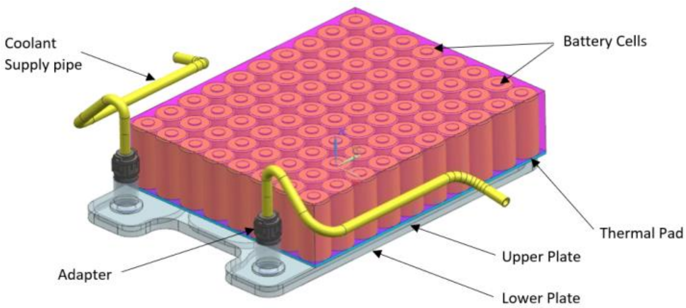

Fig -4: BTMS (Battery Thermal Management System) Nomenclature

A BTMS consists of a few basic elements such as Battery Cell, Thermal Pad, Upper Plate, Lower Plate, Adapter and Coolant Supply pipes. [7]

Battery Cell/Module/ Pack: Battery cells are the source of heat. Hybrid and electric vehicles have a high voltage battery pack, where they consist of individual modules and cells organized in series and parallel connection. A cell is the smallest encased form a battery can take.

Thermal Pad: Thermal pads and thermal compounds are used to fill air gaps caused by imperfectly flat or smooth surfaces in thermal contact.

Upper and Lower plates: BTPs are divided between two plates, where the upper plate is flat and smooth as the battery is placed over it by means of a thermal pad. The lower plate has cooling channels.

Coolant Supply pipe: They are responsible for bringing the coolant in and taking the coolanst out of the system.

Adapter: The adapter joins the coolant supply pipe with the BTP Upper plate such that there is no leakage in the system.

2.1 Design and Consideration of BTP patterns

As discussed earlier, designing BTP is a step-by-step process. From selecting the correct pattern of BTP to the selection of coolant flowing within BTP, it's required to understand the effect to every parameter affecting the system individually. In this study, a battery module generates 200 W of energy, and an optimum BTMS is required to maintain its temperature. The below Fig. 5 highlights the entry and exit regions of coolant flowing in circuit.

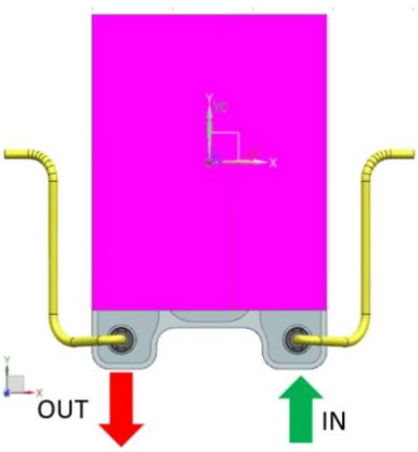

Fig -5: Coolant In-Out location

To simplify software computation, battery cells are represented by solid cuboid (as represented in Fig. 6) and is maintained at 200W. To simplify the CFD simulation, the electrochemical reactions were not considered in the simulation.

Fig -6: Representation of Battery module as Cuboid for simulation

A BTP is designed in a way that it doesn't offer resistance to the motion of fluid and distributes fluid in the maximum area of BTP. If the fluid flowing has good momentum, then heat transfer will be more. In this study, six different patterns of BTP with a constant channel depth of 5mm were studied. These patterns were divided into two categories. [8]

1. Pattern A_ Linear Distribution: In these patterns, fluid flows in a linear path with turns. Further in linear flow distribution, there are three types of patterns divided based on channel width. Below Fig. 7 shows the three different modes of Pattern A.

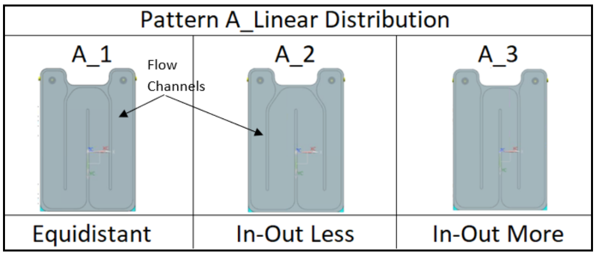

Fig -7: Pattern A_ Linear Distribution BTP patterns

2. Pattern B_ Zig-Zag /Random Distribution: In these patterns, fluid flows in a zig-zag path with turns by means of ribs. The significance of this pattern is to create turbulence within the flow to increase heat transfer. Further in zig-zag flow distribution, there are three types of patterns divided based on channel width. Below Fig. 8 shows the three different modes of Pattern B.

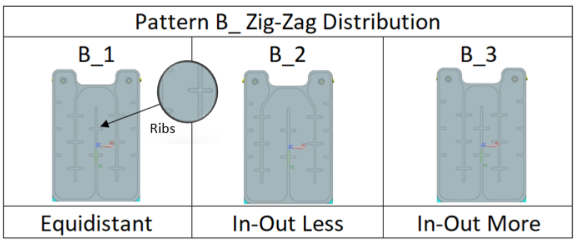

Fig -8: Pattern B_ Zig-Zag Distribution BTP patterns

In Equidistant pattern, all the fluid flow channels are equidistant from each other. In the In-Out Less pattern, the channel width of Inlet and Outlet is less compared to the central channels. In the In-Out More pattern, the channel width of Inlet and Outlet is more compared to the central channels.

2.2 Coolant flowing in the channels

Heat transfer fluid selection for a cooling system involves consideration of performance, maintenance factors and compatibility. Water has very good heat transfer properties, making it somewhat of a standard for other coolant fluids.[9] Water as a coolant flowing in a recirculating system is also prone to biological fouling. The resultant slime can restrain heat transfer between the wetted surfaces and fluid. Glycol as an additive agent is commonly used as a control against biological growth. For our study, coolant properties were taken from Laird Thermal Systems catalogue shown below in Table 1.

Fluid	Thermal Conductivity (W/m.K)	Specific Heat (J/Kg.K)	Viscosity (cP)	Density (Kg.m3)
Water	0.58	4181	1	1000
50-50 Water/ Ethylene Glycol	0.402	3283	2.51	1082
50-50 Water/ Propylene Glycol	0.357	3559	5.2	1041

Table -1: Comparison of the different coolants and their properties

Many different thermophysical properties are used to assess a fluid's thermal performance, including thermal conductivity, specific heat, density, and viscosity. The main goal of maximizing these properties is to improve heat transfer between the fluid and the heat exchange surfaces it is in contact with. Prandtl number is an imperative quantity that assesses the relation between momentum transport and thermal transport capacity of a fluid.

Here we will study the performance of BTMS when different fluids having different Prandtl numbers are flowing in the BTP channels. The simulation will be carried out with 50-50 Water/Ethylene Glycol and 50-50 Water/Propylene Glycol.

Prandtl Number: 50-50 Water/Ethylene Glycol= 19.61 (Calculated using Eq.1)
Prandtl Number: 50-50 Water/Propylene Glycol = 51.83 (Calculated using Eq.1)

2.3 Pump for coolant circulation

The coolant flow needs to be driven by the applicable device. A pump will be installed along the coolant flowing loop. The pump used here is a general brushless DC pump with a working voltage range of 5 to 12 V. Flow rate can be up to 4-10 litres per minute (L/min). Coolant enters the BTMS setup at 25^{0}C (298K). [4]

2.4 BTMS simulation setup and material properties

For heat transfer and flow simulation, software requires physical as well as thermal properties of the fluid and solid components surrounding it. The overall length of zone in which battery lies is 200mmX250mm as shown in below Fig. 9.

1. Battery (heat source)

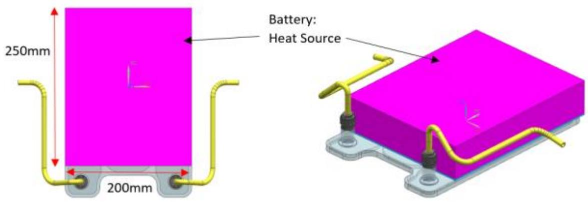

Fig -9: Battery (Heat Source)

Battery heat source will be taken as Aluminum 6000 Series [10]. Since battery casing is made of the same material, it's highly conductive so that the maximum amount of heat could be passed to BTP and further be taken out from the system through coolant flowing through it. The properties of Al 6000 Series are stated below in Table 2.

Thermal Conductivity	k(W/m.K)	218
Specific Heat	Cp(J/kg.K)	895
Density	ρ(g/cm3)	2.7

Table -2: Battery: Al 6000 Series Properties

2. Thermal Pad/Thermal Interface material

Fig -10: Thermal Pad/Thermal Interface material

Gap fillers (also commonly referred to as thermal pads) are a specific type of Thermal Interface material ideal for conforming to rough, curved, uneven or dynamic surfaces.[11] This provides a thermally conductive pathway to exhaust excess heat and keep components within operating specifications, even if the component surfaces present challenges. The thermal pad is intended to maintain maximum surface area contact between the battery and the heat sink, minimizing potential thermal impedance and providing the shortest pathway to conduct the heat away. The picture shown above in Fig. 10 is of thermal interface material manufactured by Henkel. Helkel is a leading thermal interface material manufacturer and the properties of thermal pad for this study stated in the below Table 3 are taken from the same.

Thermal Conductivity	k(W/m.K)	1.8
Specific Heat	C(J/kg.K)	1000
Density	ρ(g/cm3)	2.7

Table -3: Thermal Pad/ Thermal Interface material properties

3. BTP (Battery Thermal Plates)

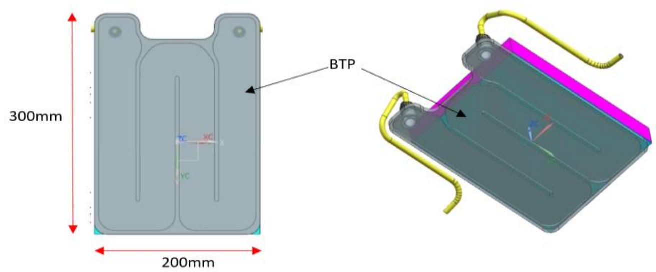

Fig -11: BTP (Battery Thermal Plates)

The material used in BTP (Fig. 11) must have high thermal conductivity to reject the maximum amount of heat into the coolant. Hence, BTP material will be taken as Aluminum 6000 Series. Aluminum 6000 Series is widely accepted to manufacture BTPs and its properties are mentioned below in Table 4. [12-13]

Thermal Conductivity	k(W/m.K)	218
Specific Heat	Cp(J/kg.K)	895
Density	ρ(g/cm3)	2.7

Table -4: BTP (Battery Thermal Plates): Al 6000 Series Properties

3. RESULT AND DISCUSSION

The simulation was done in SimFlow (Open Foam), ANSYS Fluent and postprocessing in ParaView. As engineers, we optimize the shape of a product and its properties to enhance its performance. In this study, we will study the effect of such parameters on the performance of BTMS individually and at the system level.

3.1 Pressure drop of fluid flowing in BTP

Pressure drop is the difference in total pressure between two points of a fluid. A pressure drop occurs when frictional forces, act on a fluid as it flows through the tube (caused by the resistance to flow). Thermal and physical properties of fluid along with mechanical properties (shape) of components around which fluid is flowing affect pressure drop.

In this study, BTP were divided among two types of designs, one with linear division and the other with the zig-zag distribution. Among these, two BTPs were further divided based on channel width (equidistant, In-Out Less & In-Out more). Pressure drops in all the patterns were studied and compared with each other. [12-13]

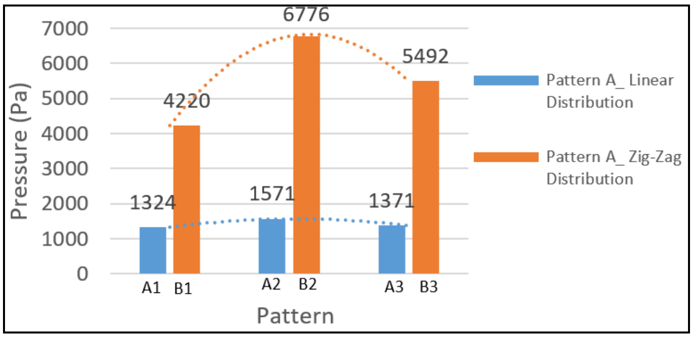

Fig -12: Pressure Drop: Bar Chart of all BTP Patterns

The above bar chart in Fig. 12 shows the pressure drop comparison among all the BTPs (A1, A2, A3, B1, B2, B3). When we offer resistance in the path of flow, pressure drop increases and the same trend can be observed in pressure drop for six BTP patterns. The pressure drop in the zig-zag pattern is 68% more compared to the linear pattern. Pressure drop has a direct relation with the power consumption of the coolant supply pump. The greater the pressure drop more will be power consumption by the pump.[14]

In both the types of patterns (zig-zag & linear), BTP having equal channel width has the least pressure drop. Channel that has Inlet and Outlet channel width less has the maximum pressure drop. In these patterns, when fluid enters BTP, it faces huge resistance as the area available to flow is less. In other patterns, the inlet channel area is more comparatively, and hence pressure drop is less. [15]

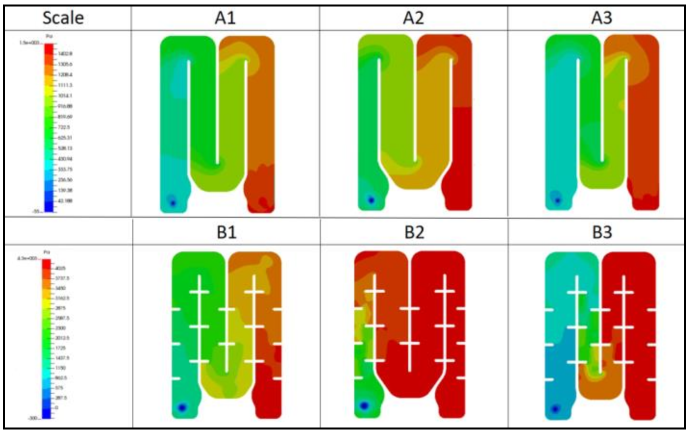

Fig -13: Pressure contours of BTP Patterns

After simulation, pressure contours were taken at the center of BTP fluid volume as shown in above Fig. 13. As stated in last paragraph, the same can be observed through pressure contours. Pressure at the inlet is maximum for pattern 2 (A2 and B2) as the area is less at the entrance and as it approaches exit, pressure reduces.

3.2 Flow across BTP channels

The main purpose of fluid flowing in BTP is to take the heat from the battery out of the system. Heat transfer by fluid will be more if it has high momentum throughout the BTP. High momentum will increase the heat transfer coefficient. Heat transfer can be achieved by increasing the flow rate or by designing the BTP pattern in a way that it creates turbulence within the flow [16-17], as turbulence increases heat transfer. One of the most usual ways is by creating dimples in the BTP. Heat transfer has an adverse effect if the flow is stagnant in a region.

As heat transfer is proportional to the momentum of fluid, every model is studied based on the range of momentum throughout the BTP volume. They are divided into four ranges: no flow region, less flow region, medium flow region and high flow region. The high flow region and medium flow region will be the major contributors to heat transfer, whereas no-flow region will have the least heat transfer.

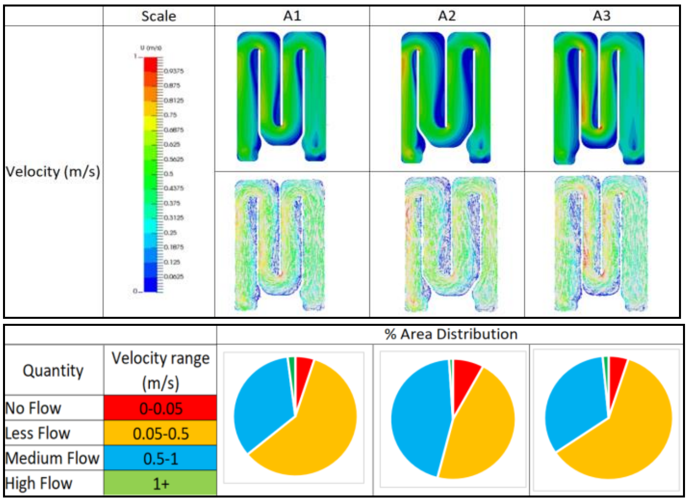

Fig -14: Pattern A_ Linear Distribution: Velocity contour and % distribution

The above result in Fig. 14 showcases the velocity contour and % area distribution for the Linear Distribution pattern. It is observed that there is very less amount of high flow (above 1 m/s) in the above three BTP patterns. A2 pattern has maximum medium-range flow followed by A1 and then A3. For the Linear Distribution pattern, medium-range velocity will be a major contributor to heat transfer. All the patterns have less no-flow regions. Although momentum is less in these patterns, velocity is well distributed throughout the BTP.

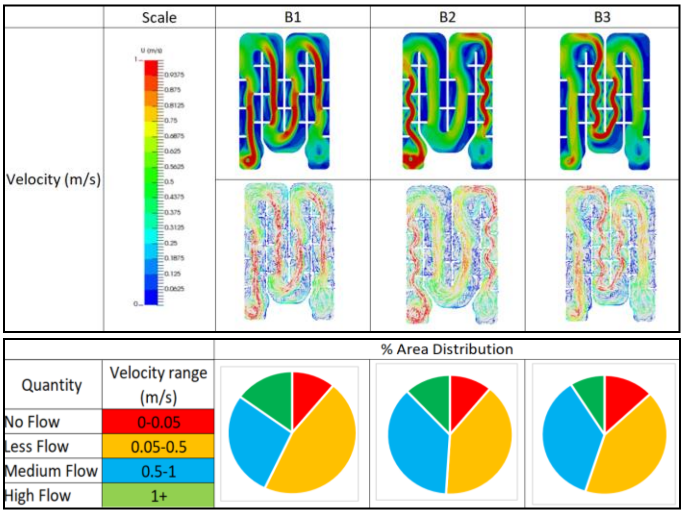

Fig -15: Pattern B_ Zig-Zag Distribution: Velocity contour and % distribution

The above result shown in Fig. 15 showcases the velocity contour and % area distribution for the Zig-zag Distribution pattern. The main purpose of the zig-zag pattern was to increase momentum in the flow, and the same can be observed here. On an average, there is 80% increment in high flow area compared to the Linear Distribution patterns. Although there is an increment in the high-flow region, there is a slight increase in the no-flow region too.

Velocity vectors show that the zig-zag pattern is increasing momentum but also creating vortexes in the flow. These vortices lead to momentum reduction, and hence there is a slight increase in no flow area.

3.3 Heat Transfer

Heat Transfer simulation was carried out with material properties stated in Section 2. The simulation was carried out for all six BTMS modules (A1, A1, A3, B1, B2, B3) for two conditions: one where the coolant was 50-50 Water/Ethylene Glycol having Prandtl Number 19.61 and the other where the coolant was 50-50 Water/Propylene Glycol having Prandtl Number 51.83 as stated in Section 2.2.

A simulation was carried out when fluid flowing at a rate of 4 L/min entered the system at 25^{0}C to cool a battery at 200W. The simulation provided fluid's outlet temperature as output. The overall heat transfer of the system was calculated by the formula,

$$Q=hA\Delta T_{s\text{-}f}$$

Eq. 2. Convective heat transfer equation

where:

h: heat transfer coefficient, W/(m2•K)
A: surface area where the heat transfer takes place, m2
Ts: temperature of the solid surface, K
Tf: temperature of the surrounding fluid, K

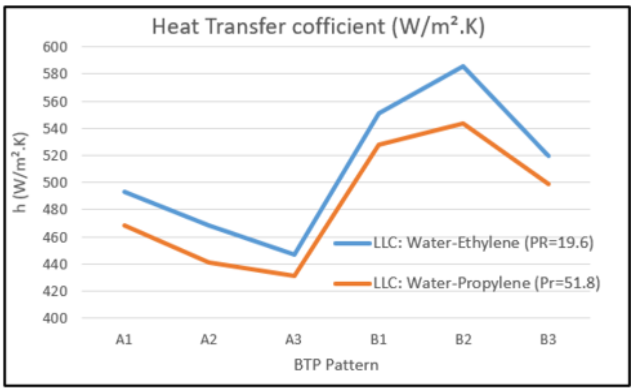

Fig -16: Heat transfer coefficient for every individual pattern

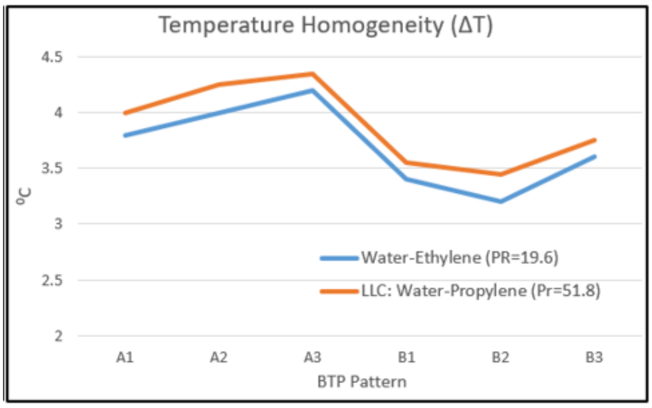

Fig -17: Homogeneity for every individual pattern

Solver provides simulation output as h (W/(m2•K)) by evaluating heat flux (W/m2) and solid-fluid interface temperature (K). Fig. 16 shows the simulation result for al the BTP patterns when simulated at different Prandtl Number. It was observed that the system with coolant as Ethylene Glycol (Prandtl Number 19.61) had more heat transfer coefficient compared to Propylene Glycol (Prandtl Number 51.83). It is quite evident from the output that to improve the heat transfer coefficient of a system, the fluid must have a low Prandtl Number. Temperature Homogeneity is also maintained under 5^{0}C.

BTMS setup with pattern B2 gave maximum heat transfer coefficient followed by B1 and then B3. It was observed that in pattern B2 momentum of fluid was highest compared to all these patterns.

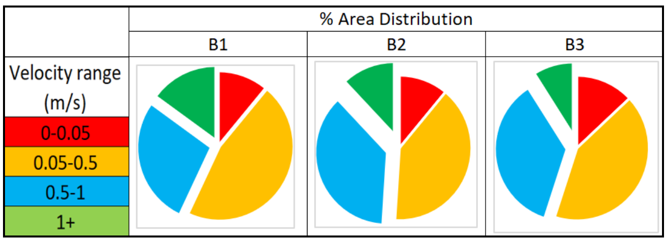

Fig -18: Pattern B_ Zig-Zag Distribution: % distribution for high velocity region

Fig. 17 highlights the % velocity distribution for the patterns having maximum heat transfer (B1, B2 & B3). It was observed that in these BTP patterns % area distribution was maximum for medium flow and high flow (blue and green) compared to other regions and hence are the major contributor to heat transfer coefficient.

$$Re = \frac{\rho v D}{\mu}$$

Eq. 3. Reynold's Number

Increase in momentum leads to an increase in heat transfer coefficient. Reynold's Number is the parameter that describes the momentum of fluid. B2 pattern with Water/Ethylene Glycol having Prandtl Number 19.61 has maximum heat transfer coefficient. To understand the effect of Reynold's Number of BTMS, B2 pattern will be simulated with different flow rates (4Lpm, 5Lpm, 6Lpm and 7Lpm). The hydraulic diameter of the fluid inlet duct is 15mm. Reynolds Number in Table 5 at different flow rates were calculated through Eq. 3 and Water/Ethylene Glycol properties in Table 1.

Flow Rate (L/min)	4	5	6	7
Reynolds No	2440.6	3050.7	3660.9	4271.1

Table -5: Reynolds Number at different flow rates

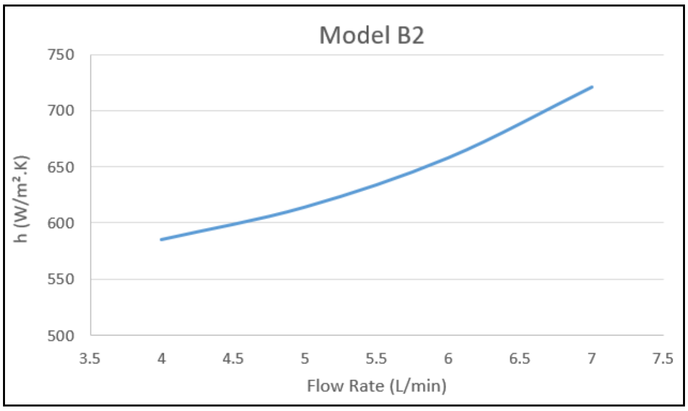

Fig -19: Heat transfer coefficient at different flow rates

The above result in Fig. 18 shows that the heat transfer coefficient increases with an increase in Reynolds Number. Out of all the BTP patterns, the pattern with less entrance width has a maximum heat transfer coefficient. This is because less area increases velocity leading to an increase in Reynold's Number accompanied by fluid with a low Prandtl number.

4. CONCLUSION

This study illustrates the BTMS (battery thermal management systems) performance comparison on various parameters. One of the main contributions of this work is to present a thorough comparison of BTMS performance when coolants with different Prandtl number flow within BTPs (battery thermal plates). This study also shows a brief performance comparison, when different BTP patterns are used in a system and how every individual BTP affects the performance of BTMS. Further, this study shows a detailed view of how different BTPs and coolants affect the momentum and pressure that ultimately affect the heat transfer coefficient. Simulation provides a very clear idea about the application of fluid. To design a BTMS system with a high heat transfer coefficient, coolant flowing within the circuit must have a low Prandtl number.

Overall, to develop a BTMS system with a high heat transfer coefficient, coolant must have a low Prandtl Number, BTP must have high momentum and optimum pressure drop. Out of six different setups, BTMS with B1 BTP will be the most optimum pattern. B2 pattern has the highest heat transfer coefficient among all, but it also has the highest pressure drop and will increase energy utilization. B1 pattern has the least pressure drop among Pattern B_ Zig-Zag Distribution and has the second-highest heat transfer coefficient hence the most suitable.

ACKNOWLEDGEMENT

I am extremely grateful to my guide, Mr. Rajamani A. (Project Lead; CFD team; L&T Technology Services Ltd., India), for his invaluable advice, continuous support, and patience during my research work. His immense knowledge and plentiful experience have encouraged me in all the time of my professional research work

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