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# Numerical Simulation on Heat Transfer Performance of a Liquid Cold Plate for Cooling of the Electric Vehicle Battery

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**ABSTRACT**

Around the world, there is a significant increase in the number of electric vehicles on the roads. Among the reasons are the aims to reduce the global dependency on oil as an energy source due to its political and economic dimensions especially for the non-oil producing countries by maximizing the use of electric vehicles. At the same time, it is also due to global concerns for the environmental aspect, especially global warming where transportation represents 30% of it. The battery is considered the main source of power for electric vehicles, but the battery tends to generate a significant amount of heat due to internal resistance during operation. The generated heat during the charging/discharging processes could lead to overheating in the battery which could end in battery failure. Therefore, dissipating the generated heat in the EV battery becomes essential through thermal management systems to ensure that the battery operates within a safe temperature range. Hence, the present study aims to introduce a new design of the liquid cooling system and also to investigate the effective parameter which affects its heat transfer performance. This paper is part of the overall study and describes the computational fluid dynamics by using ANSYS FLUENT software and numerical analysis to investigate the effect of the inlet/outlet arrangements on the heat transfer performance of a new LCP used for cooling the EV battery cell. There are three inlet/outlet arrangements: I-arrangement, Z-arrangement, and L-arrangement. The flow rate range of the present study is at the range of 0.4 – 1.6 l/min under 300 W heat flux. The L-arrangement has the best cooling performance compared to I-arrangement and Z-arrangement, where it achieves an average battery cell temperature which equals to 37.1 $^{o}$C along flow rates, while it is at 43.3 $^{o}$C and 38.0 $^{o}$C for I-arrangement and Z-arrangement, respectively. The temperature uniformity for both L-arrangement and Z-arrangement is almost similar, and they achieved good temperature uniformity at all flow rates, while I-arrangement failed to achieve good temperature uniformity at the lowest flow rates.

## 1. Introduction

The harmful effects of internal combustion engines, which produce more than 30% of the overall global warming emissions, have attracted worldwide attention, especially in the automotive industry.

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Electric vehicles (EVs) are thought to be an alternative solution towards achieving global sustainable development, because they could reduce the dependency on natural resources and could limit greenhouse gas emissions Many studies have been carried out in order to determine the effect of reducing fuel consumption and emission [1-3]. Ibrahim *et al.,* [3] study the effect of three main PHEV powertrains such as engine power, traction motor power and battery capacity on fuel consumption, electric consumption and carbon oxide emission is studied using AUTONOMIE. The overall simulation results show that the fuel consumption decreases as the motor power increases with the same battery capacity and engine power while the carbon oxide emission and fuel consumption increase following each other's.

Batteries are used as the power source of electric motors and supply sufficient energy for vehicles to move. Li-ion (Lithium-ion) batteries have become the most applicable energy storage system for EVs, due to their high energy density and high power. However, batteries of EVs are very sensitive to slight temperature changes. The high temperature encountered during battery operation will reduce the battery life, as it accelerates corrosion. The optimum operating temperature is slightly lower than 60 °C for Li-ion batteries [4-7]. Therefore, a battery thermal management system (BTMS) must be considered, as this will affect the performance and lifecycle of the batteries. The most promising thermal management system is liquid cooling, because it has the best cooling potential for EV batteries which gets the researcher's attention to improving it based on a wide number of increasing studies and developments in EV liquid cooling systems. Improving the hydraulic and thermal performance of the liquid cold plate which is part of the EV liquid cooling systems has not widely been explored in the fields of developing inlet design, outlets, and fins.

Japar *et al.,* [8] has studied the hydrothermal performance in the hydrodynamic entrance region of the rectangular microchannel heat sink. The hydrodynamic entrance region is one of the issues in a microchannel heat sink because it will affect hydrothermal performance in the conventional microchannel heat sink. His result showed that the thermal resistance in the hydrodynamic entrance region of microchannel heat sink is lower than in the developed region. However, pressure drop in the developing region is higher than developed region due to the highest wall shear stress in the entrance region. Ajeel *et al.,* [9] has studied the flow structure and heat transfer characteristics of the novel curved-corrugated channel. It involved numerical work using ZnO-water nanofluid and the presence of L-shaped baffles in order to determine the influences of corrugations, baffles manner arrangement, and geometric parameters. The results reveal that the formation of vortex flow and increased turbulence due to the effects of corrugations and baffles can improve heat transfer enhancement.

For an electric vehicle, an effective BTMS is a liquid cooling plate (LCP), which is capable to remove heat from the battery through thin metal structures forming internal channels within the coolant [5]. Aldosry *et al.,* [10] has studied Heat transfer enhancement of liquid cooled copper plate with oblique fins for electric vehicles battery thermal management. He also studied the heat transfer enhancement of liquid cold plate systems with the oblique fin and different types of liquid coolants. The need for a liquid cold plate (LCP) to be used in EV batteries is now highly reliable in the distribution of the required temperature rather than only in standard cooling systems. The fins arrangement in the LCP would likewise impact the cooling efficiency of the EV battery. Mostly the LCP contains an inlet, outlet, and micro fins. The thermal and hydraulic performance of LCPs can be affected significantly by the inlet/outlet arrangements. Lu *et al.,* [11] stated that inlet/outlet arrangements have effects on the parallel-channel cold plate performance. The non-uniformity of temperature and velocity maldistribution is the core of studying these effects. They found that the best heat transfer performance is made by I-arrangement, due to the impingement configurations, while Z-arrangement made the worst heat transfer performance, because of misdistribution and dramatic flow recirculation.

Malazi *et al.,* [12] contradict with the results of Lu's study and claiming that I-arrangement and Z-arrangement do not have a big difference in the cooling performance. Chein *et al.,* [13] indicated that the V-arrangement heat sink had the best performance. The main aims of this study is to investigate the effect of three inlet/outlet arrangements (I-arrangement, Z-arrangement and L-arrangement) on the cooling of a new LCP that can further improve the Electric vehicle battery thermal management system.

## 2. Methodology

### *2.1 Test Section*

The test section consists of an LCP and two battery cells. The new LCP system is sandwiched by the two battery cells, as shown in Figure 1. The LCP is made of copper and represents the cooling system, while the heating plate source represent the lithium-ion batteries cells.

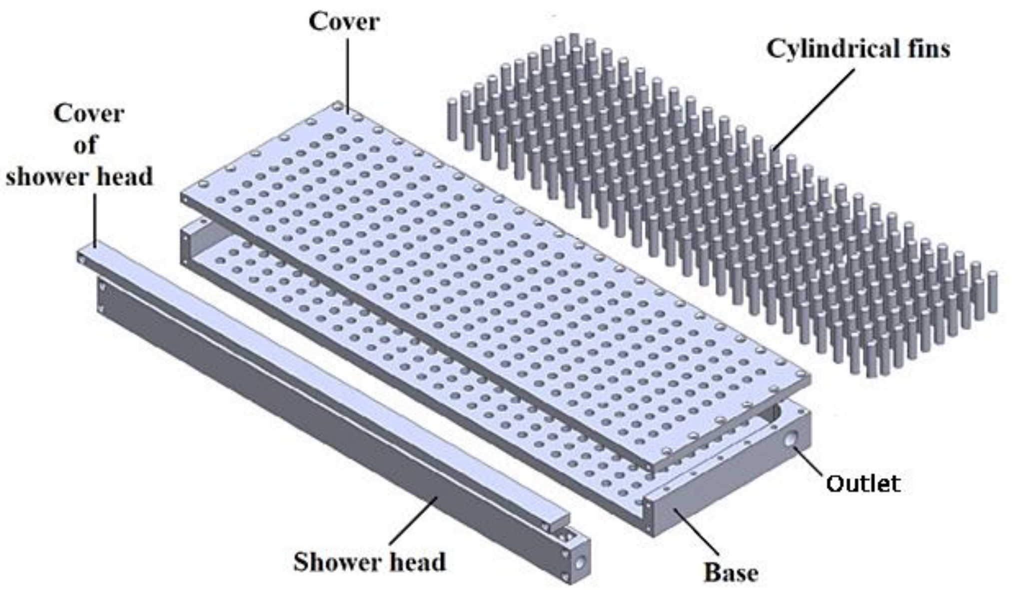
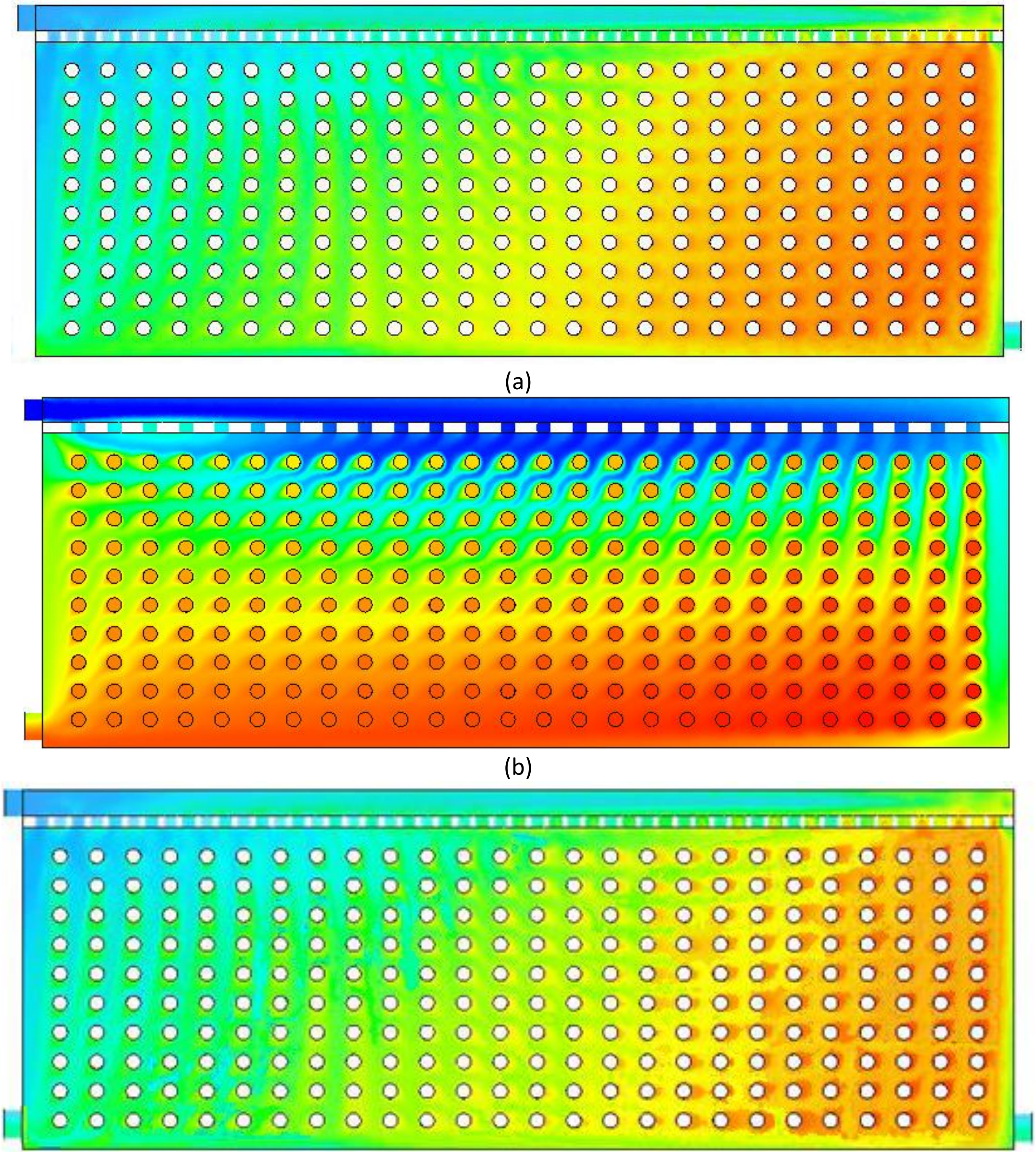



**Fig. 1.** Exploded view of the new LCP of the battery

The heat flux is the generated heat when the battery is under a charging/discharging process [14]. The shape of the battery cell is rectangular with 94 mm width and 282 mm length, and the thickness is 5 mm. The dimension of the base is 94 mm width, 282 mm length and 18 mm thickness. The dimension of the cover is a 94 mm width, 282 mm length and 5 mm thickness. The previous dimensions were taken under consideration of the most common dimensions for the rectangular EV lithium-ion battery.

The fixed components in this case study are the shower head, water and cylindrical fins. There are three inlet -outlet arrangements studied as follows: Z-arrangement (where the outlet position is on the opposite side of the inlet and directly to the direction of the storage tank), I-arrangement (where the outlet position is inline with the inlet) and L-arrangement (where there are outlets on both sides) as shown in Figure 2.



(a)

(b)

(c)

**Fig. 2.** The surface temperature of the battery cell for different inlet-outlet arrangements, (a) Z-arrangement, (b) I-arrangement and (c) L-arrangement

### *2.2 Numerical Study: Governing Equations and Data Reduction*

Number of following assumptions are taken under consideration to study the heat transfer performance of the LCP

i. Fluid flow is in steady state, laminar, incompressible, single phase and three dimensional.
ii. Independent properties of water in pressure and temperature.
iii. The material properties in lithium battery cell were uniformly distributed. Because of the multi-layer structure and manufacturing process of lithium battery cells, only the thermal conductivity was anisotropic.
iv. Thermal radiation and convection can be neglected inside the lithium battery cells.
v. The specific heat capacity and thermal conductivity of materials in the lithium battery cells were constant and independent of the temperature.

vi. When the battery cells were charged and discharged, the current and heat generation were considered uniformly distributed.

Computational fluid dynamics (CFD) software package with the finite volume calculations solves the Navier-Stokes and the continuity equations along with the associated assumptions and boundary conditions. Therefore, the following list contains the equations governing the energy equation, momentum equation and continuity equation for the present study:

Equation of continuity

$$\frac{\partial \rho_n}{\partial t} + \nabla.(\rho_w \overrightarrow{v}) = 0 \tag{1}$$

Equation of conserving momentum

$$\frac{\partial}{\partial t}(\rho_w \vec{v}) + \nabla.(\rho_w \vec{v}\vec{v}) = -\nabla P + \nabla.\left[\mu_w\left(\nabla\vec{v} + \nabla\overrightarrow{v^T}\right)\right] + \rho_w \beta_w (T - T_w) g \tag{2}$$

Energy equation of water

$$\frac{\partial}{\partial t}\left(\rho_w c_{pw} T_w\right) + \nabla.\left(\rho_w c_{pw} \vec{v} T_w\right) = \nabla.(k_w \nabla T_w) \tag{3}$$

Energy equation of LCP

$$\frac{\partial}{\partial t}\left(\rho_c c_{pc} T_c\right) = \nabla.(k_c \nabla T_c) \tag{4}$$

The definition of the Reynolds number in the simulation is as following

$$\mathrm{Re} = \frac{\rho_w \mathrm{v} \mathrm{D_h}}{\mu_w} \tag{5}$$

where $\rho_f$ is the density, v is average velocity, $\mu_f$ is viscosity of water and $D_h$ is the hydraulic diameter. The average working fluid ($T_f$) and average surface temperature ($T_s$) are obtained as following in the numerical simulation

$$T_s = \frac{1}{n}\sum_{X,Y,Z}^{n} T_s(X,Y,Z) \tag{5}$$

$$T_f = \frac{T_i + T_o}{2} \tag{6}$$

where $T_i$ is the inlet water temperature and $T_o$ is the outlet water temperature. The average convection heat transfer coefficient (h) is numerically calculated by the following equation

$$h = \frac{Q}{A(T_s - T_w)} \tag{7}$$

$$D_h = \frac{4A}{P} \tag{8}$$

where Q is the heat flux, A is the heated surface area and $P$ is the wetted perimeter of the cross-section. The absorbed energy by water ($Q_f$) is defined by the following:

$$Q_f = \dot{m}.c_p.(T_o - T_i) \tag{9}$$

where $\dot{m}$ is the mass rate of water and $c_p$ is the specific heat.

*2.2 Numerical Study: Boundary Conditions and Assumptions*

In this study, the momentum and pressure equations have second order upwind discretization. The double precision pressure-based solver is selected with a standard simple algorithm as its pressure-velocity coupling method. The working fluid is water. Copper is the material of LCP, which has a thermal conductivity of 387.6 W/mK [15]. A uniform inlet velocity of water with inlet temperature equals 25 °C. A gauge pressure of 0 Pa is set for the outlet pressure. A heat flux of 300 W is applied by the battery cells on the surfaces of the LCP, this value of heat load is similar to real generated heat load by the lithium-ion battery cells [16].

*2.3 Numerical Study: Grid Independence Test*

As shown in Figure 3, a mesh plays important role in keeping the consistency between the tiny dimensions in the flow domain, and the surrounding fins area is the most important. A tetrahedral mesh scheme is used for the flow domain, while horizontal mesh is used for the LCP layers. Ensuring that ANSYS FLUENT software obtains the grid independent solution is through performing an extensive mesh testing. Different grid sizes of 5 mm, 4 mm, 3 mm and 2 mm are chosen for the grid independent test, while their % error is between 3-7%. A grid size of 2 mm ensures a grid independent solution.

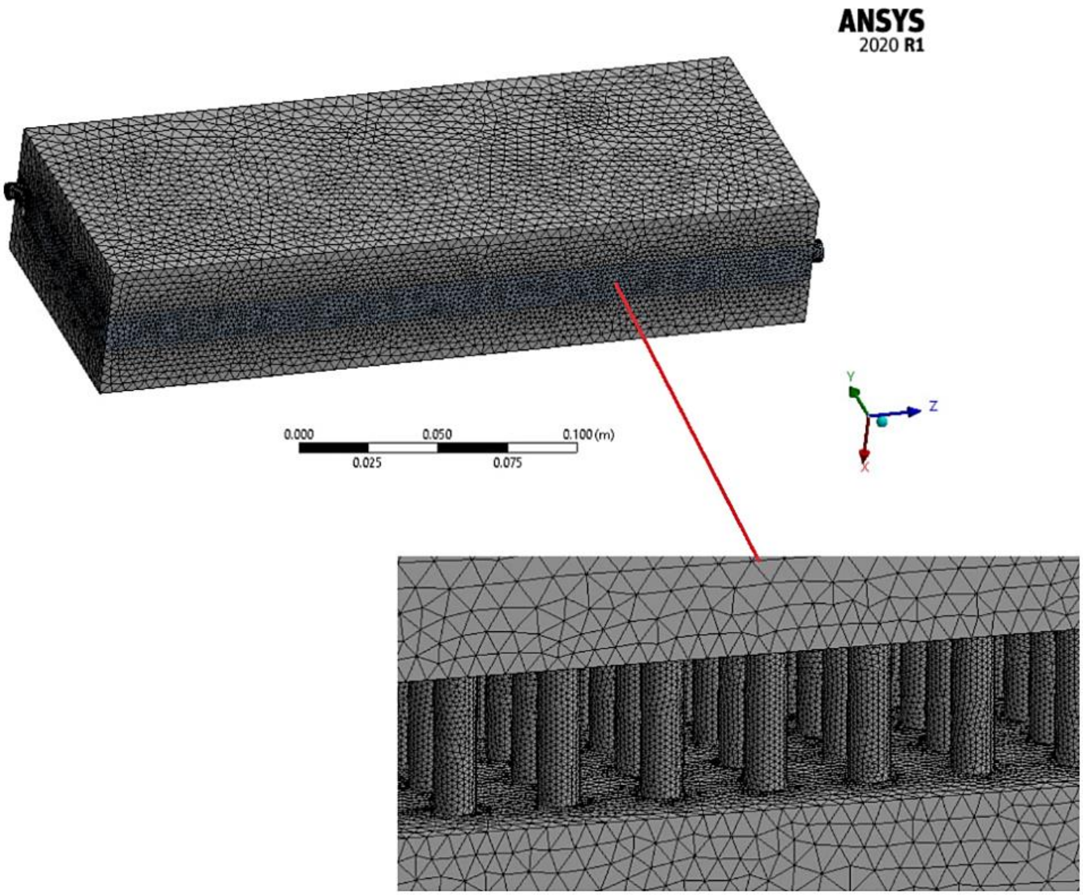



**Fig. 3.** Mesh scheme and computational domain for the simulation

## 3. Results and Discussion

### *3.1 Validation of the Numerical Simulation*

This study compared the results of the present numerical model with the experimental results of Om *et al.,* [17] to guarantee the accuracy of the model assumptions used in the simulation. The present study and Om's study are liquid cold plates for cooling the EV lithium-ion battery cells, also the applied heat flux for all studies is 300 W. Om's study has two inlets and two outlets (I-arrangement). As shown in Figure 4, all arrangements of the present LCP system showed lower average surface temperature than Om's system at all flow rates. The surface temperature decreases as the flow rates of the coolant increases for both studies, also the surface temperatures of the present study have reasonable values range compared to Om's study and other EV LCP systems [17-19].

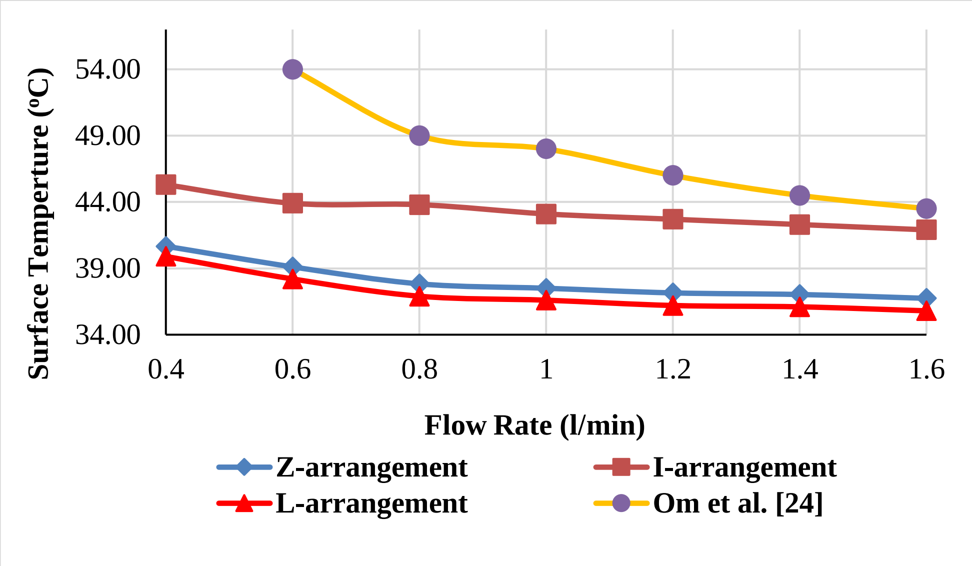



**Fig. 4.** A comparison between the results of published experimental study and present numerical study

### *3.2 Velocity Profile and Fluid Distribution*

An important factor that influences the heat transfer enhancement is the fluid mixing inside the liquid cold plate. Better flow mixing inside the LCP could initialize and disrupt boundary layer development near the solid surface in the LCP. This phenomenon increases advection within the fluid and subsequently improves heat transfer significantly. It is beneficial to carry out the flow field mechanism into account for the heat transfer performance in the LCP.

One of the most used methods to increase the fluid mixing inside the LCP to get better cooling performance is increasing the flow rate, but this option could have penalties such as increasing in the pressure drop or/and bad fluid flow mechanism. For I-arrangement, the latitudinal vortex concentrates in some areas are more than other areas inside the LCP as shown in Figure 5. The vortex concentration in particular areas inside the LCP more than others makes the fluid mixing inside the LCP affected and unbalance. This leads to lower fluid heat absorption, and the impact is seen clearly on the surface temperature of the battery cell as previously shown in Figure 2(b). It also has strong impact on the temperature uniformity of the battery cells which should not exceed 5 ºC.

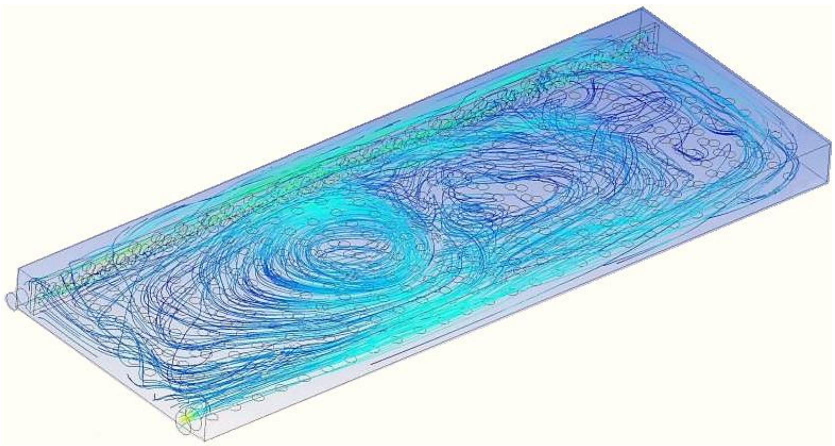


**Fig. 5.** Flow profile of the LCP using I-arrangement at 1.6 l/min

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### *3.3 Surface Temperature of Battery Cells*

The surface temperature of the battery cells gives clear indication on how much the cooling performance is effective. From Figure 6, there is clear difference in the surface temperature between I-arrangement and both Z and L arrangements, where the average difference between I-arrangement and Z-arrangement along flow rates is 13.9%, while it is 16.7% with L-arrangement. The difference between Z-arrangement and L-arrangement is only 2.4%.

The three arrangements have big surface temperature difference at flow rate range between 0.4 - 0.6 l/min. The impressive result is that L-arrangement at flow rate 1.6 l/min achieves surface temperature almost equals to 35 °C, which is considered within the optimal operating temperature range for Li-ion battery cell [20]. Figure 6 shows that all the arrangements are able to generate lower surface temperature as the flow rate increases.

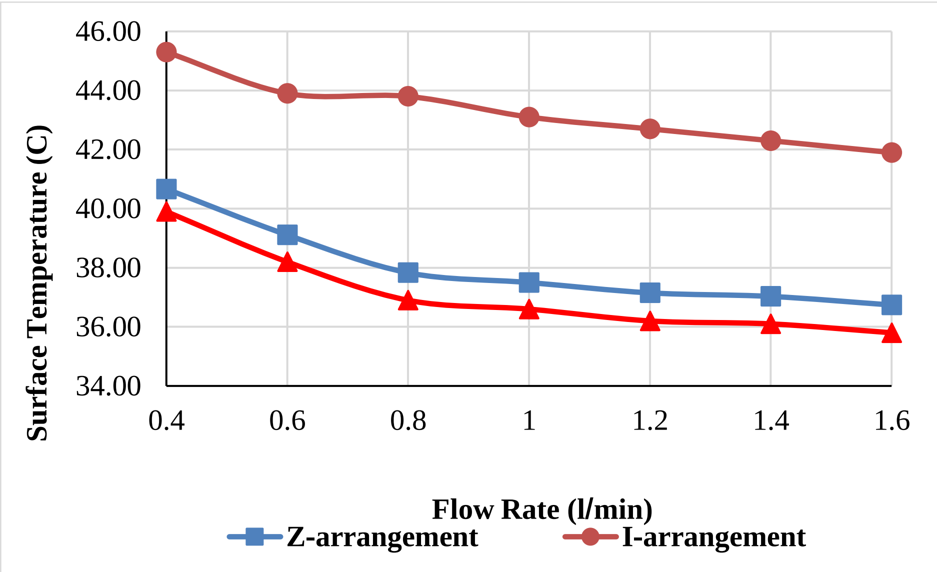


**Fig. 6.** Surface temperature of different inlet/outlet arrangements

### *3.4 Heat Transfer Performance*

It is important to know the ratio of the convective heat transfer to the conductive heat transfer which is known as Nusselt number. Nusselt number gives indication about the cooling capacity of the system and how much it fits the amount of heat which comes from the source, so a larger value of the Nusselt number implies enhanced heat transfer by convection [21].

From Figure 7, L-arrangement from has the highest Nusselt number at flow rates 0.4 – 1.6 l/min, where the difference in the Nusselt number between L-arrangement and Z-arrangement is averagely 4.19% along flow rates, while the difference with I-arrangement is 46.7%. The bad performance of I-arrangement in Nusselt number is caused by the unbalance vortex inside the LCP which made the convection heat transfer lower than the heat absorption from the battery cells. The Nusselt number of the three inlet/outlet arrangement increases with flow rate increasing. This is due to the thermal boundary layer thickness decreases with increased fluid velocity. As the inlet velocity increases, the effect of buoyancy becomes limited and various inlet/outlet arrangements present different cooling value.

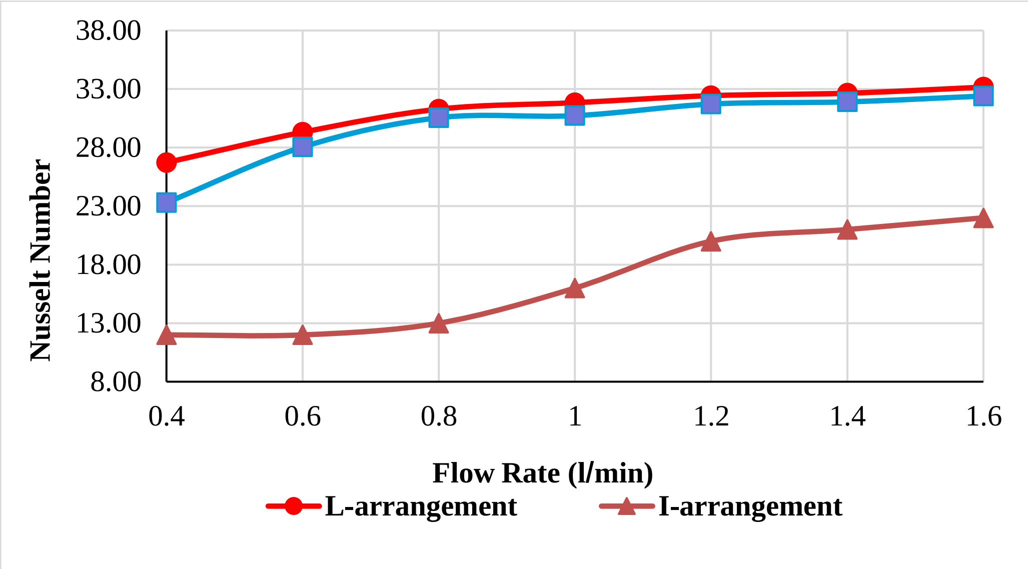


**Fig. 7.** The Nusselt number of different inlet/outlet arrangements

### *3.5 Temperature Uniformity*

There is a parameter that should be taken into consideration in order to show the performance of the battery cooling system which is the maximum temperature difference in the surface battery cell which are also called as the battery temperature uniformity as shown in Figure 8. Any cooling performance is not acceptable if the surface temperature difference is more than 5 °C [22-25]. Bad temperature uniformity causes different charging/discharging in the battery cells, resulting in an electrical imbalance in the cells, thereby reducing the performance of the battery cell [26].

From Figure 8, almost no difference between the Z-arrangement and L-arrangement, while a sufficient difference between them and I-arrangement averagely equals to 69.3% along flow rates. I-arrangement has unacceptable maximum temperature difference from 0.4 – 0.8 l/min, where their values is over than 5 °C.

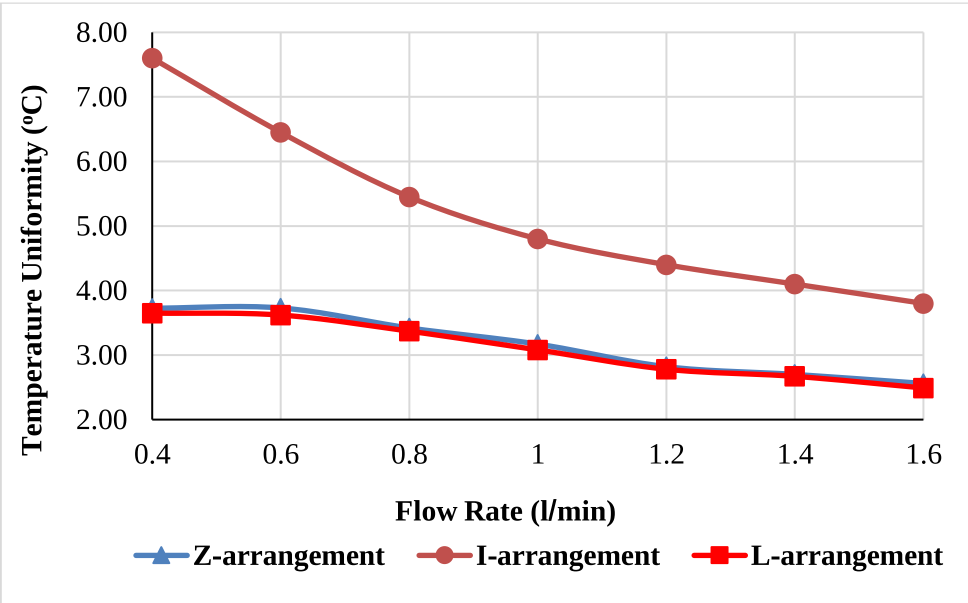


**Fig. 8.** The temperature uniformity for different inlet/outlet arrangements

## 4. Conclusions

In conclusion, the L-arrangement at flow rate 1.6 l/min achieved surface temperature almost equals to 35 $^{o}$C, which is considered within the optimal operating temperature range for Li-ion battery cell. The I-arrangement has latitudinal vortex concentrated in one area inside LCP which negatively affect on the surface temperature of the battery cell and the temperature uniformity. The results also shows that the L-arrangement has the lowest surface temperature, while I-arrangement has the lowest performance with big difference compared to the other inlet/outlet arrangements. Increasing the flow rate keeps decreasing the surface temperature in all inlet-outlet arrangements. The L-arrangement and Z-arrangement has the same temperature uniformity performance, while I-arrangement failed to achieve good temperature from 0.4 l/min to 0.8 l/min.

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