Battery Temperature Control System for Nanofluids as Coolant for Electric Vehicle's 21700 Type Battery Cell Cooling Module: A Numerical Investigation

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ABSTRACT

Due to the high-power capacity, battery temperature management systems suitable for cooling batteries due to high temperatures have a significant impact on energy conservation, durability, life cycle, and efficiency. Therefore, selecting the appropriate cooling module for the electric vehicle (EV) module to maintain the appropriate temperature is required. This work introduces a computational analysis method to differentiate between temperature distribution and pressure reduction using nanofluids flowing through the narrow-corrugated mini channel of the EV battery cooling module. EV battery modules contain 444 lithium-ion cell batteries. The effects of temperature distribution and pressure reduction on the 18650 Battery Cell Battery Cooling Module containing TiO_2 nanofluid were confirmed by resulted data from the literature. To maximize the cooling effect of the battery module and to reduce the cost of the product Al_2O_3 nanofluid was used as a coolant. Distribution of temperature and pressure of the Battery Cooling Module Of 18650 Battery Cell with Al_2O_3 nanofluid was detected. It is found that the distribution of temperatures and pressures is exactly the same as the results from the literature. Therefore, the use of Al_2O_3 nanofluid to cool the battery is very economical. Further study was performed using 21700 battery cells in the same configuration as Al_2O_3 and the distribution of temperature and pressure was detected. Comparisons between these two types of battery module have been made. The current approach from this study could add a battery management system with an electric car with the right temperature.

Keywords: Electric vehicle battery, Temperature management system, Nanofluids

1. Introduction

Temperature management of Li-ion batteries is as important in safety issues as thermal runaway or overheating during operation. These issues can seriously affect battery performance and life expectancy. In addition, further research is needed on Li-ion battery transport systems where high-power consumption is short-lived. It has been shown that temperature affects longevity, performance, and battery safety. Heat leaks, electrolyte fires, and in some cases, explosions can occur when the battery temperature is too high. Many researchers had work on the battery temperature management system. Greco et al. [1] had conducted a theoretical and computational study of the heat management of lithium-ion battery batteries in electric vehicles using heat pipes. The aim of this work was to develop reliable and simple methods of analyzing the heat pipes used as a Phase Change Material solution, in order to direct the formation of Battery Thermal Management System. The more surface contact of the heat pipes allows for better cooling management compared to forced convection cooling. Therefore, heat pipes can be used to achieve efficient thermal management of a battery pack with enclosed surface areas. Sun et al. [2] has developed a cooling system for cooling lithium-ion battery packs. The purpose of this work was to predict the thermal performance of the battery pack by cooling it with the help of three different adjustments. This paper describes how to develop cooling strategies for air-cooled battery pack containing lithium-ion pouch cells used in hybrid electric vehicle (HEV). The analytical design of the test method Design of Experiments (DOE) using the Optimal Latin-hypercube process is developed by incorporating a DOE design model, a compatible battery pack model, and a configuration model. DOE analytical research was conducted to evaluate the effects of cooling techniques including cooling channel geometry, cooling duct, cooling plate, and corrugation on battery pack heat management and to suggest designing an air-cooled battery pack to increase its durability and its driving range. Rao et al. [3] introduced the thermal performance of a fluid-based control system based on a lithium-ion battery module with a different contact surface. This paper is devoted to investigating the thermal efficiency of a novel liquid cooling system designed for cylindrical lithium-ion pack by numerical simulation with structure of a different contact area intended to reduce temperature differences. Zhang et al. [4] investigated the promotion of Battery Pack temperatures and Liquid Flow temperatures designed for cooling. To keep the battery pack temperature in the correct range of electric vehicles (EV), the liquid heat exchange structure is designed to use aluminum flat tube bank. Flexible graphite is used to improve the heat transfer of the heat treatment of the battery, and its effect is tested and the correct cooling method. Huang et al. [5] conducted a study to evaluate the thermal performance of the heat pipe assisted phase change material of the battery temperature management system. This paper is dedicated to investigating the thermal performance of a cylindrical lithium battery module with three different configurations, namely a pure PCM, a PCM / HP-Air compliant heat pipe (PCM / HP-Air). heat pipe coupled with liquid assisted PCM (PCM/HP -Liquid), respectively. Chen et al. [6] investigated the cell spacing of the battery pack with the parallel air-cooling battery temperature control system. The purpose of this paper was to improve the cooling efficiency of a battery temperature control system by designing the distribution of spaces between battery cells. The Computational Fluid Dynamics (CFD) method was used to calculate the flow field and BTMS field temperature. S. Wiriyasart et al. [7] studied a thermal management system was with nanofluids module for cooling an electric vehicle's battery. The purpose of this work was to select the appropriate cooling method of EV battery module to maintain the required temperature range. This work introduces a computational analysis method to differentiate between temperature distribution and pressure reduction using nanofluids flowing through the narrow-corrugated channel of the EV battery cooling module. Y. Deng et al. [8] learned about the effects of different cooling and cooling techniques on the cooling performance of the lithium-ion battery system. This review summarizes recent research papers on the battery cooling system from three components, including cooling performance, separation of the cooling system and design of the battery pack. In terms of coolants, the properties and uses of various coolants such as water and oil, as well as various additives such as nanoparticles, are measured. With regard to the design of the battery pack, the series is introduced, parallel and series-parallel processing and the advantages and disadvantages of different configurations are analyzed.

Based on the literature review the required battery temperature management system (BTMS) is required to keep the battery temperature between the appropriate temperature range. According to literature review, the temperature generation of less than 10W/cell, the battery cell temperature should cool below 40 ° C and the temperature generated by 20W/cell should be cooled below 50 ° C [9]. In the use of a vehicle battery pack for heat pipe, air cooling, variable contact surface system, etc. is not the best way to maintain the temperature. However, very little research has been done on nanofluids as a coolant in the thermal management system of a battery. S. Wiriyasart et al. [7] uses nanofluid as a coolant and shows good heat management. However, the pressure drop increases, in addition to the nanoparticles used in the study by the more expensive TiO_2. To compensate for this problem a low-cost nanofluid will be used (water + Al_2O_3 instead of water + TiO_2). The battery pack model will be built in relation to the latest 21700 battery cell for further study.

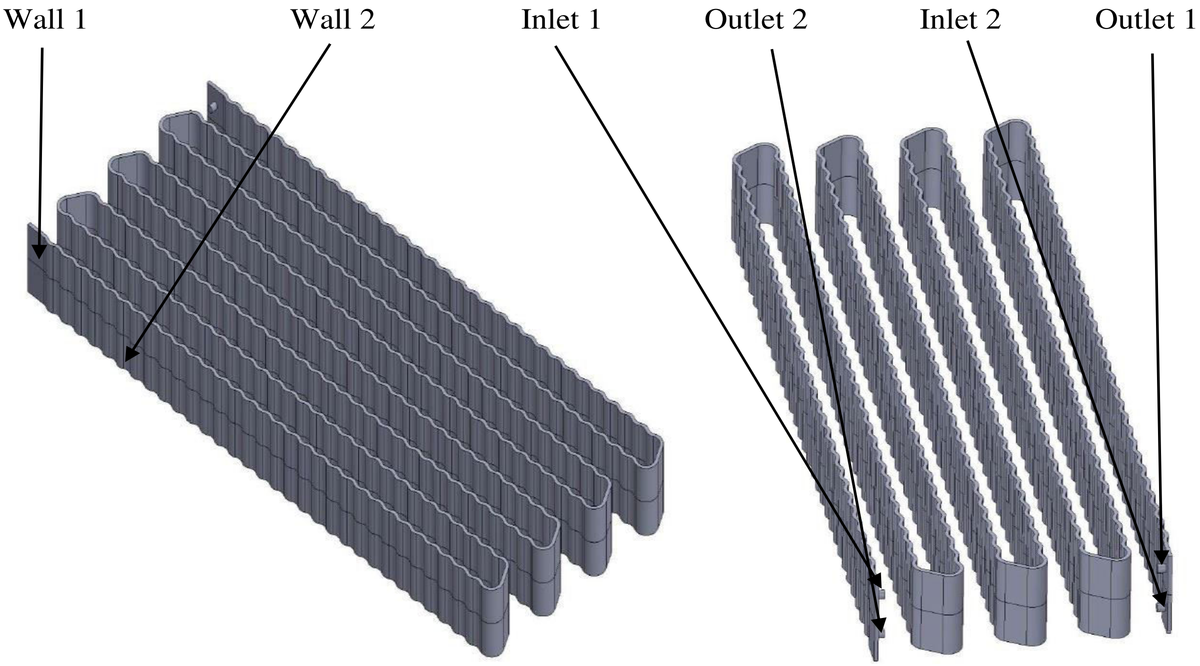

Fig. 1 Battery Cooling Module Of 18650/21700 Battery Cell

Table 1 Specification of Battery Cooling Module Of 18650/21700 Battery Cell [7]

Parameters of module	**18650's Values**	**21700's Values**
Number of cell electrical vehicle batteries	444	444
Distance of cell electrical vehicle batteries (mm)	1.5	1.5
Height of cell electrical vehicle batteries (mm)	65	70
Thickness of tube (mm)	3	3
Diameter of cell electrical vehicle batteries (mm)	18	21
Thickness of wall (mm)	0.5	0.5
Height of cooling flow channel (mm)	63	68
Diameter of inlet port (mm)	6	6

2. Mathematical modelling

The cooling module in the numerical analysis used in the current study are shown in Fig. 1, and its details are shown in Table 1. The different continuity, momentum, and energy equation are used for different stages, and the pressure is distributed by all stages. On the basis of assumptions, viscous dissipation and radiation neglected, the incompressible flow of nanofluids, homogeneous mixture of nanofluids with constant properties, a two-phase Multiphase Mixture model is used to analyze the problem. Following equations describe the flow of nanofluids fluid and the behavior of heat transfer flowing in the cooling module:

2.1 Geometry model and main governing equations

According to different physical phenomenon the governing equations of conservations of energy, mass momentum is used for mathematical modelling. These governing equations used are given below:

Continuity Equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u}{\partial x} + \frac{\partial \rho v}{\partial y} + \frac{\partial \rho w}{\partial z} = 0 \tag{1}$$

Conservation of momentum:

X-momentum equation:

$$u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} = -\frac{1}{\rho}\frac{\partial u}{\partial x} + \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) \tag{2}$$

Y-momentum equation:

$$u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} = -\frac{1}{\rho}\frac{\partial u}{\partial y} + \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) \tag{3}$$

Z-momentum equation:

$$u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} = -\frac{1}{\rho}\frac{\partial u}{\partial x} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) \tag{4}$$

Conservation of energy

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} + \frac{\dot{q}}{k} = \frac{1}{\alpha}\left(u\frac{\partial T}{\partial x} + v\frac{\partial T}{\partial y} + w\frac{\partial T}{\partial z}\right) \tag{5}$$

The Correlations

The following correlations [10] [11] [12] [13] are used to determine the properties of nanofluids are labeled as follows:

$$\rho_{nf} = \varphi\rho_p + (1-\varphi)\rho_w \tag{6}$$

$$(C_p)_{nf} = \frac{\varphi(\rho C_p)_p + (1-\varphi)(\rho C_p)_w}{\rho_{nf}} \tag{7}$$

$$\mu_{nf} = (1 - 2.5\varphi)\mu_w \tag{8}$$

$$k_{nf} = \left[\frac{k_p + 2k_w - 2\varphi(k_w - k_p)}{k_p + 2k_w + \varphi(k_w - k_p)}\right] k_w \tag{9}$$

2.2 Boundary Conditions

Various boundary conditions are applied for carrying out numerical simulation of Battery Cooling Module Of 18650 Battery Cell and 21700 Battery Cell. The following boundary conditions are imposed for numerical simulation of, Battery Cooling Module. In this numerical simulation ambient pressure have been considered as 101.325 KPa, temperature is 25 °C

The boundary conditions of the simulation numerical analysis are as follows: -

1. Uniform velocity and uniform temperature at the inlet
2. Zero pressure condition at the outlet
3. Wall with constant heat flux
4. No slip condition for all directions on the wall

Table 2 Grid Independent Test

Module	Grids	Outlet Temperature(°C)	% Difference
18650 Battery Module	3,40,131	53.05	-
	4,46,290	52.89	0.3
	5,65,471	50.46	4.88
	6,68,000	50.27	5.24
	14,21,700	50.19	5.39
21700 Battery Module	3,51,766	69.14	-
	4,70,795	68.03	1.61
	6,42,121	67.51	2.36
	8,73,710	67.4	2.52
	10,33,900	66.99	3.11

Table 3 Properties of Battery (18650 vs. 21700) [14]

Properties	18650	21700
Diameter (mm)	18	21
Height (mm)	65	70
Capacity (mAh)	3400	4800
Nominal Voltage (V)	3.6	3.6
Weight (grams)	50	70
Volume (mm3)	660	970
Energy Density (Wh/kg)	244.8	247
Heat Generation (Wh)	12.24	17.28
Heat Flux (W/m^2)	3330	4700

2.3 Numerical simulation

ANSYS Fluent 19.0 is used for simulating the heat transfer phenomenon in Electric Vehicle Battery Cooling Module. The mating surface of two adjacent corrugated mini channels treated as a coupled wall in mesh interfaces of fluent setup. The surfaces of the mini corrugated channels treated as a constant wall heat flux. Various different steps are adopted to carry out the CFD simulation. As shown in Table 2, the grid independence test is done to check the performance of the heat transfer mechanism for three meshing qualities of Battery Cooling Module of 21700 Battery Cell, which having different numbers of meshing elements. The grid number of 6,42,121 ensure a satisfactory solution for Battery Cooling Module of 21700 Battery Cell and reduces computational time. And for the 18650 Battery Cell module 5,65,471 grid number utilized. The model includes energy model, realizable k-ε viscous model and mixture multiphase model were employed. In k-ε viscous model scalable wall function was used. Mixture model was employed to create accurate effect of nanofluid in order to get proper heat transfer effect over battery cooling module surface. SIMPLEC scheme was employed for solution method with second order upwind energy. Momentum employed in first order upwind to get accurate results. The simulation has been allowed to converge using 1000 iteration, to reach the convergence criteria of residual for energy 10^{-6}, for phase-two 10^{-9}, and for others 10^{-3} were considered.

3. Results and discussion

In order to obtain computational result accurate, the grid independent test for both cooling modules have been done as mentioned above. As shown in Table 3, the current study was performed at constant maximum generation of heat from a 12.24 W battery cell (18650 cylindrical type battery cell, 3.4A, 3.6V) and from 17.28 W battery cell (21700 cylindrical type battery cell, 4.8A, 3.6V). In the case of actual operation, the battery cell is subject to a critical operating condition. It means that the heat generated from the battery cell is less than the state of this study. A generation of heat of less than 10 W/cell, the battery cell temperature should cool below 40 °C and cool below 70 °C at a temperature of 20-40W/cell (Wang et al. [9]). The coolant fluid flows into the cooling module at the upper flow region and flows with the cooling module to cool the battery cells. Reducing the high temperature at the bottom at the downstream, another coolant stream flows into the cooling module below the other end, as shown in Fig. 4. It can be seen that the battery surface area is maintained at an average temperature (below 40 ° C at temperatures below 10W/cell, Wang et al. [9]). Table 4 shows the effect of cooling flow rate on the surface of battery temperature of different coolant modules. It can be seen in all simulations of the cooling module that the temperature of the battery is sensitive to the increase in the cooling flow rate.

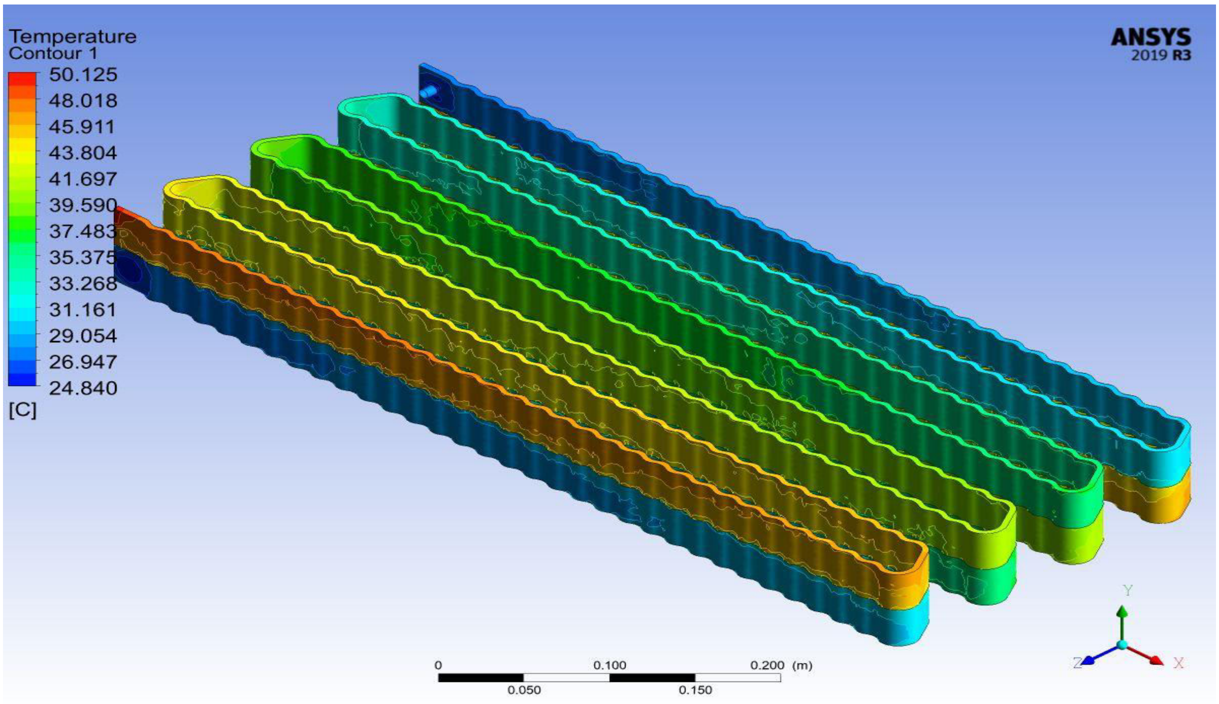

Fig. 2 Effect of 0.25% TiO_2 nanofluid concentration on temperature distribution 0.25% by volume (0.2m/s) (18650)

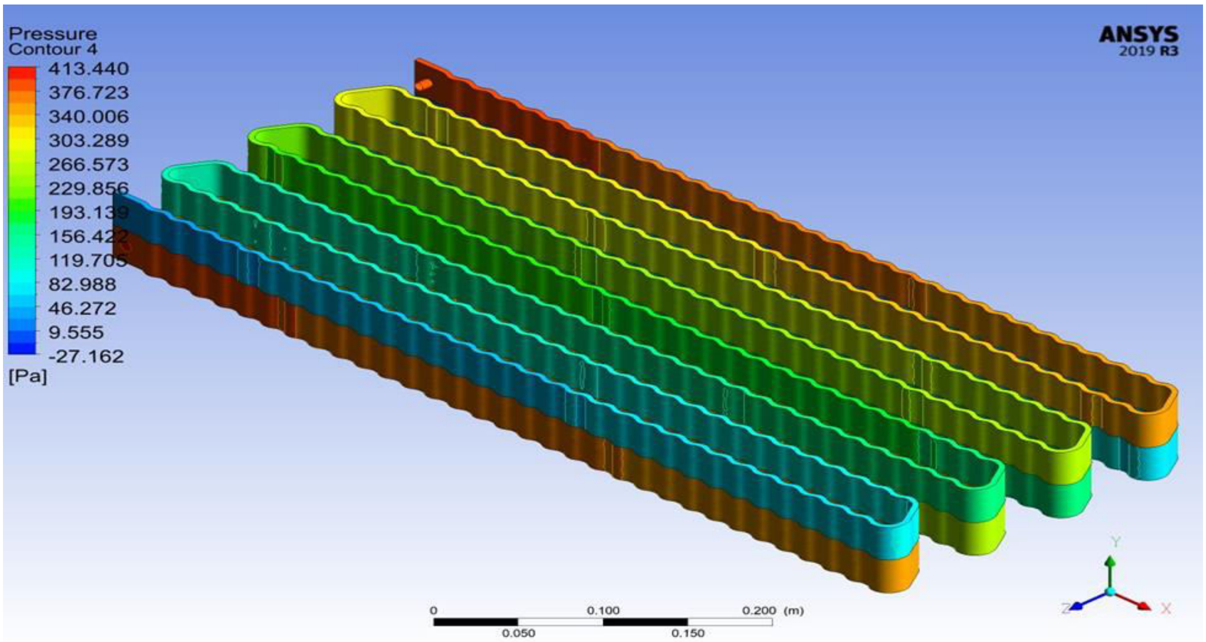

Fig. 3 Effect of 0.25% TiO_2 nanofluid concentration on pressure distribution 0.25% by volume (0.2m/s) (18650)

Table 4 Simulation results of battery cooling module of 18650 battery cell with TiO_2

Velocity (m/s)	0.25% TiO_2		0.5% TiO_2	
	Avg. Surface Temp. (°C)	Pressure Drop (Pa)	Avg. Surface Temp. (°C)	Pressure Drop (Pa)
0.2	37.72	434.21	37.66	436.93
0.3	33.88	915.61	33.82	921.59
0.4	31.91	1563.68	31.86	1574.18

Table 4 shows the effect of nanofluid concentrations at high temperatures on the surface of the battery. In the numerical process, concentrations of nanofluids of 0.25%, 0.50% by volume are designed for the battery cooling module. Titanium Dioxide (TiO_2) nanoparticles were used in the analysis as nanoparticle suspension in base fluid. It has a significant effect on the physical properties (high thermal conductivity) of nanofluids and has an effect on the Brownian movement of nanoparticles in base fluid. Therefore, nanofluids provide heat transfer capabilities beyond those liquids. It means that the high temperature of the battery surface using nanofluids as a coolant gives less of that water as a coolant, as shown in Table 4. Because of the large surface area and molecular collisions, the distribution of momentum and energy tends to increase with

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the concentration of nanofluids. Therefore, high concentration of nanofluids leads to an increase in cooling power with a slight decrease in total pressure throughout the cooling module. Table 4 shows the variation in pressure reduction in the cooling module of the two different coolant models. It can be seen that the pressure drop across the cooling module is sensitive to the increase in the cooling flow rate with the cooling module.

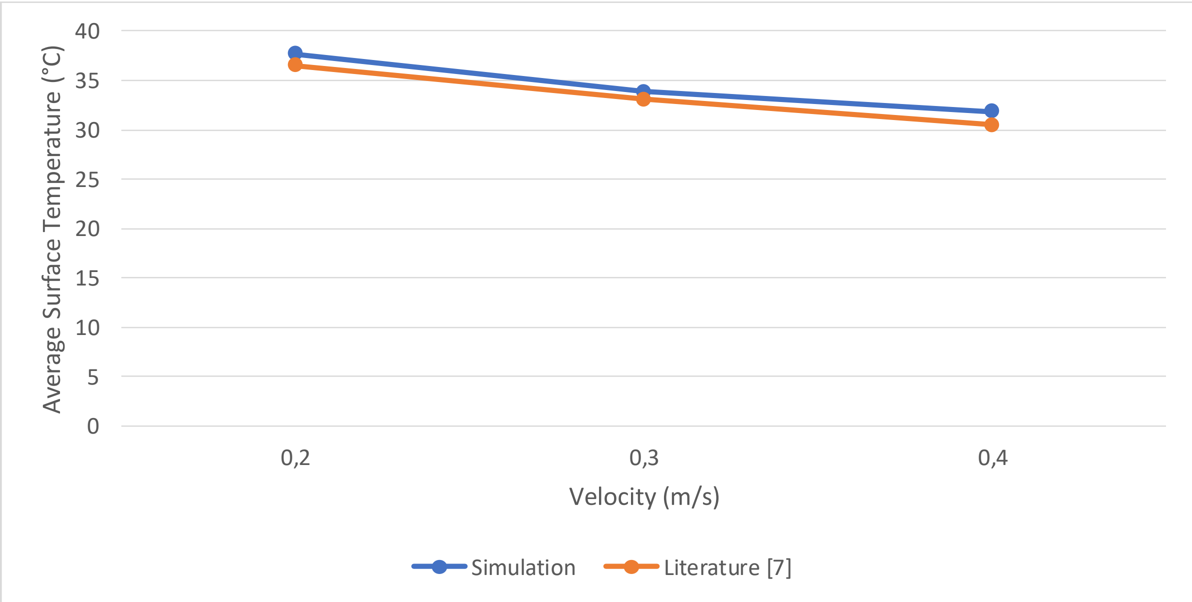

Fig. 4 Effect of coolant velocity on outlet temperature

Fig. 4 and Fig. 5 showed the resulted values of temperature distribution and pressure drop from simulation were compared with the literature values [7] from literature survey respectively. The temperatures plot and pressure drop plot for both numerical and literature values are showed same trend of variation. The temperature and pressure drop values of simulated results were higher than the literature results, because of assumption made in meshing.

Table 5 shows the comparison between battery cooling module of 18650 battery cell using TiO_2 nanofluid vs Al_2O_3 nanofluid. Change in nanoparticles has a significant effect on the thermal physical properties (high thermal conductivity) of nanofluids and the effect on the Brownian motion of nanoparticles in the base fluid. Therefore, Al_2O_3 nanofluids gives the heat transfer capacity higher than that TiO_2 nanofluid due to high thermal conductivity of Al_2O_3 relative to TiO_2. The results from both nanofluids were quite identical, but using Al_2O_3 nanofluids is highly cost effective, because it is approximately 40% less expensive than TiO_2.

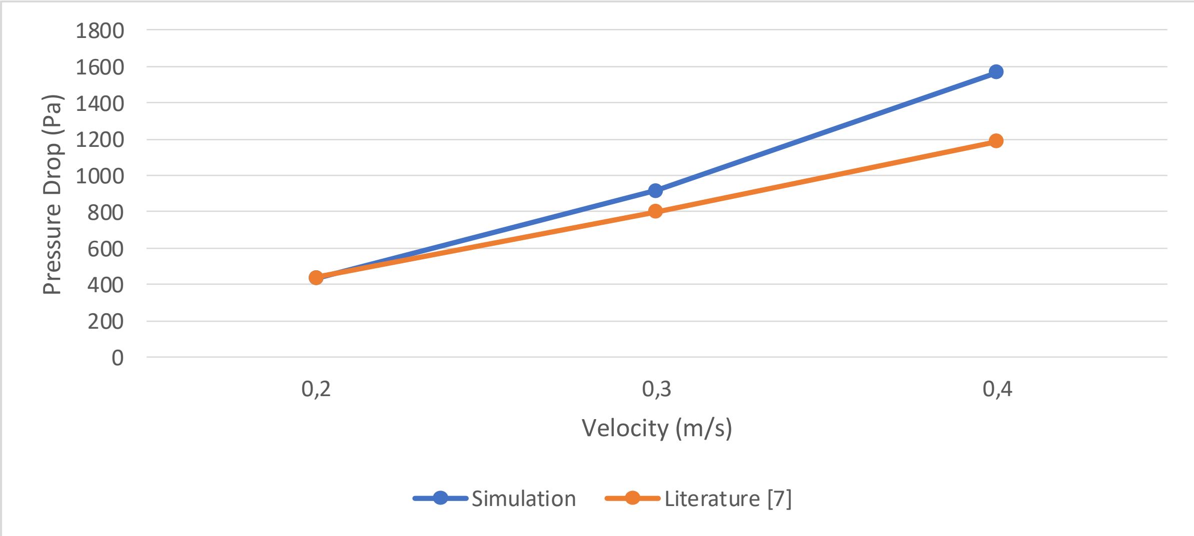

Fig. 5 Variation of pressure drop of coolant

Table 5 Simulation results of battery cooling module of 18650 battery cell using TiO_2 nanofluid vs Al_2O_3 nanofluid

Velocity (m/s)	TiO_2		Al_2O_3	
	Avg. Surface Temp. (°C)	Pressure Drop (Pa)	Avg. Surface Temp. (°C)	Pressure Drop (Pa)
0.2	37.69	435.57	37.48	435.2
0.3	33.85	918.6	33.68	917.79
0.4	31.88	1568.93	31.72	1567.51

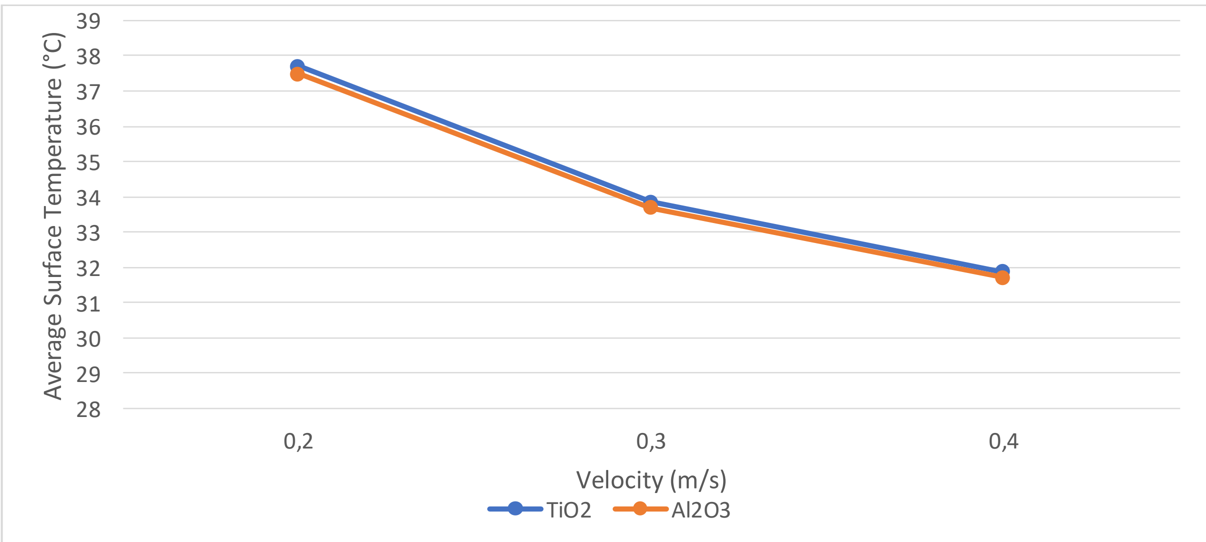

Fig. 6 Effect of coolant velocity on outlet temperature

Fig. 6 and Fig. 7 showed simulated temperature distribution and pressure drop over battery cooling module respectively. The temperatures plot and pressure drop plot for both TiO_2 nanofluid and Al_2O_3 nanofluid are showed same trend of variation. The simulation values of Al_2O_3 nanofluid were slightly lesser than the values of TiO_2 nanofluid as shown in Table 5, due to high thermal conductivity of Al_2O_3 relative to TiO_2.

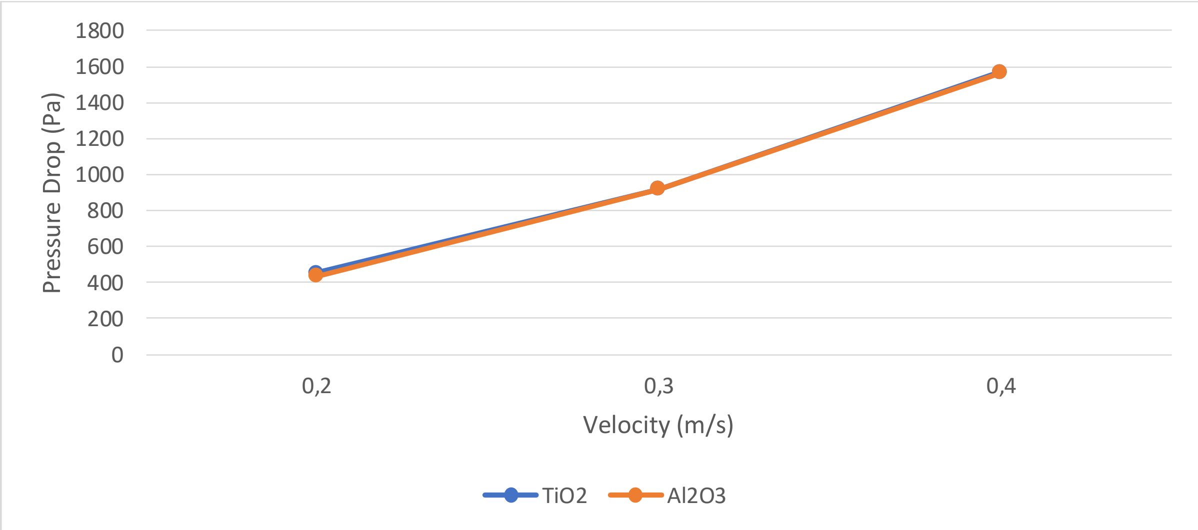

Fig. 7 Variation of pressure drop of coolant

Table 6 Simulation results of battery cooling module of 18650 battery cell vs 21700 battery cell using Al_2O_3 nanofluid

Velocity (m/s)	21700		18650	
	Avg. Surface Temp. (°C)	Pressure Drop (Pa)	Avg. Surface Temp. (°C)	Pressure Drop (Pa)
0.2	46.48	356.63	37.48	435.2
0.3	40.02	755.32	33.68	917.79
0.4	36.68	1293.87	31.72	1567.51

Table 6 shows the simulation results and comparison between battery cooling module of 18650 battery cell vs 21700 battery cell using Al_2O_3 nanofluid. Increasing cell dimensions approximately by 10% results in approximately 1.4* the volume and energy storage as well as increases heat generation in battery, which results in high surface temperature compare to 18650 battery cell. It can be seen that the battery surface is maintained the average temperature in the appropriate range (below 50 ℃ for the generated heat less than 20W/cell, Wang et al. [9]).

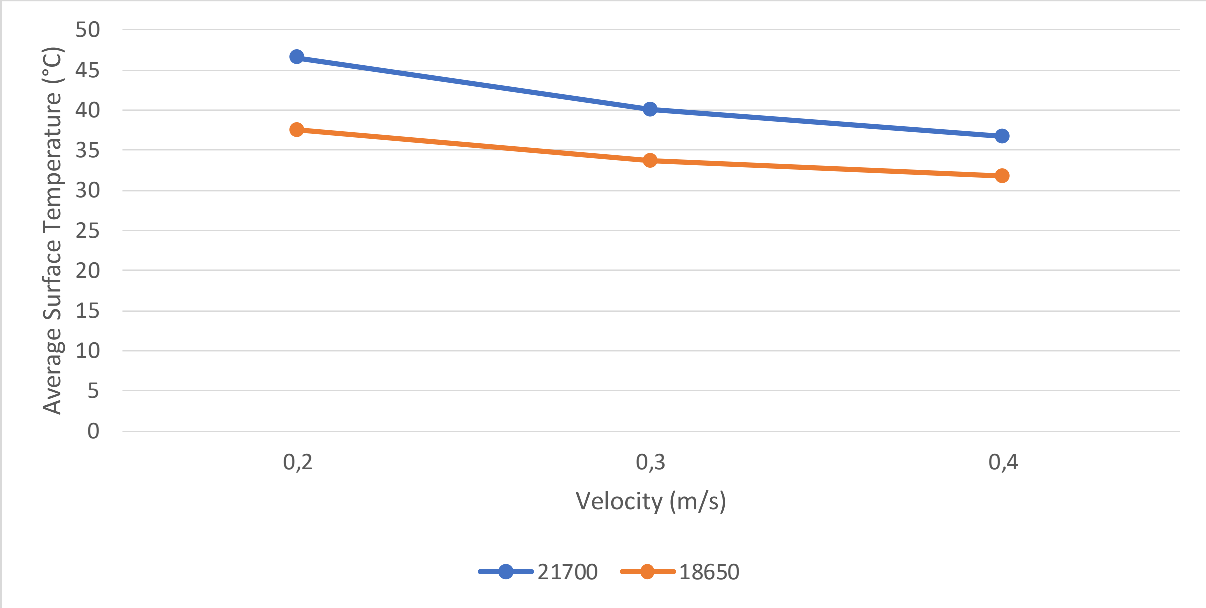

Fig. 8 Effect of coolant velocity on outlet temperature

Fig. 8 and Fig. 9 showed simulated temperature distribution and pressure drop over battery cooling module respectively. The temperatures plots and pressure drop plot for both 18650 battery cell vs 21700 battery cell are showed same trend of variation. The temperature values and pressure drop values of 18650 battery cell module were slightly lesser than the values of 21700 battery cell module as shown in Table 6.

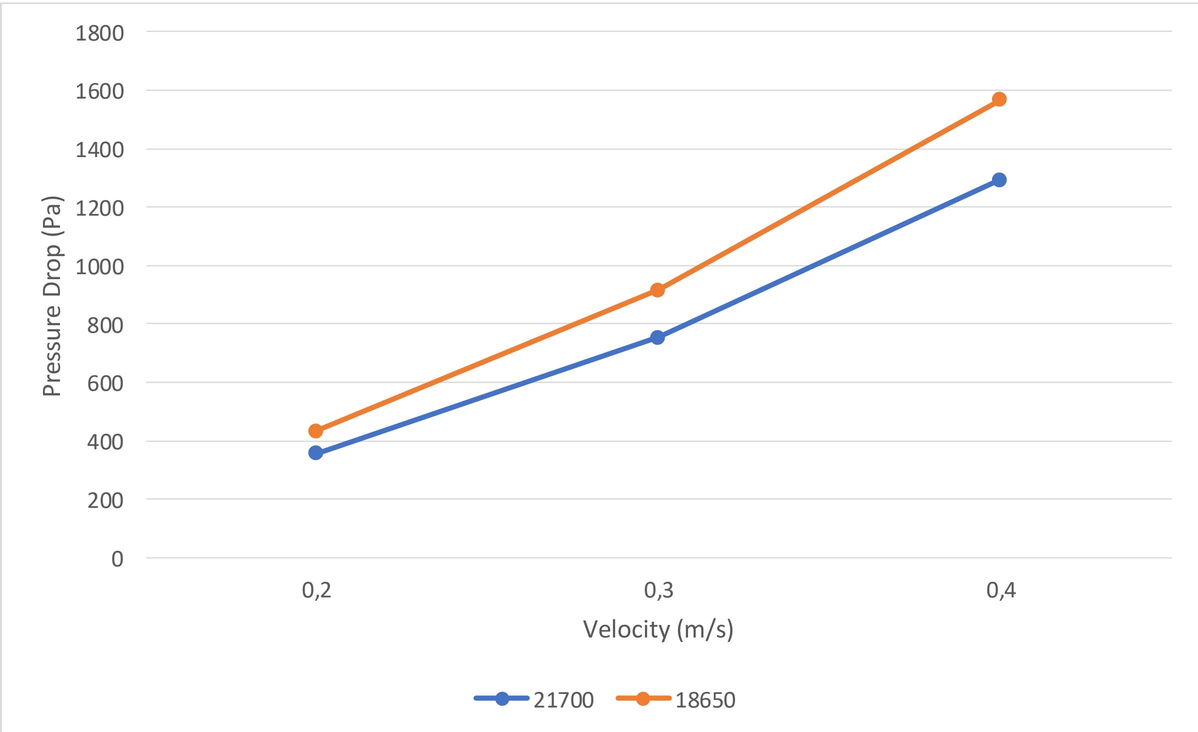

Fig. 9 Variation of pressure drop of coolant

4. Conclusion

The maximum capacity of the battery pack is required to improve the modern heat transfer to distribute that heat evenly is dissipate in the battery pack to maintain its performance, reliability, safety, durability, and life cycle. Due to the limited space and cooling capacity of the cooling system installed in the electric vehicle, good cooling performance is developed. Numerical results of nanofluids flowing through a small corrugated channel of electric vehicle battery cooling modules have been presented. The results of the entry and cooling flow of various liquids and nanofluid mass flow rates were presented. The following conclusions can be drawn from the numerical results:

- The capacity of heat dissipation is enhanced firstly at the upstream and then weakened along the downstream, so by providing second counter flow channel increases cooling capacity.
- The movement of nanoparticles suspending in the base fluid has a significant effect on the cooling capacity of coolant, which results in lower maximum battery temperature for higher nanofluids concentration.
- Use of Al_2O_3 nanofluid instead of TiO_2 nanofluid slightly lowers the battery surface temperature and saves the project cost up to 40%.
- It is feasible to use same battery module configuration to 21700 battery cell. It can be seen that the battery surface is maintained the average temperature in the appropriate range (below 50 °C for the generated heat less than 20W/cell).
- The proposed model of 21700 battery cell with Al_2O_3 nanofluid from this study can be able to optimize the battery thermal management system for an electric vehicle battery cooling module.

Nomenclature

Letters

Cp	specific heat, [kJ/kg °K]
Cd	drag coefficient
dp	nano-particle diameter, [m]
Fcd	particle-particle interaction force, [Pa/m]
Fd	drag force, [Pa/m]

FVm	virtual mass force, [Pa/m]
hv	volumetric heat transfer coefficient, [W/m^2 °K]
hp	liquid-particle heat transfer coef., [W/m^2 °K]
k	thermal conductivity, [W/m °K]
p	pressure, [Pa]
Pr	Prandtl number
Re	Reynolds number
T	temperature, [°K]
V	velocity, [m/s]

Greek symbols

β	friction coefficient, [kg/m^3 s]
ρ	density, [kg/m^3]
φ	nanofluids concentration, [%]
μ	fluid dynamic viscosity, [kg/m s]
ω	defined in Eq. (18)
Γ	defined in Eq. (17)

Subscripts

b	bulk
cd	drag coefficient
d	drag force
l	liquid
nf	nanofluids
p	particle
Vm	virtual mass
w	water

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