CFD Simulation of Thermal Management System (Immersion Cooling) of Lithium Ion Batteries in EVs

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Abstract

The mobility future now belongs to the Electric Vehicles. Many nations and their government policies are supporting this mission. Along with the rapid growth of EVs in last few years, demand for quick charging, high efficiency and longer battery life as increased. To cater this, manufacturers have started generating high power batteries with quick charging and efficient cooling system for safety purposes. With faster charging-discharging cycles, there comes a challenge to maintain the efficiency with faster heat dissipation. One such way is immersion cooling, which has recently started to be practiced in EVs.

1. Introduction

With the increase in demand on the EVs, there's a more increasing need over improved performance of these electric vehicles. This can be the quick charging ability, increased power density of the batteries, faster charging-discharging cycles, etc. To cater to this a common solution lies with the Thermal Management System of the batteries, specifically the Lithium Ion batteries which are efficient till current date. In thermal management system, an efficient way of cooling of these Lithium Ion modules will be really helpful, to all the above up gradations expected. The different ways of cooling are as follows:

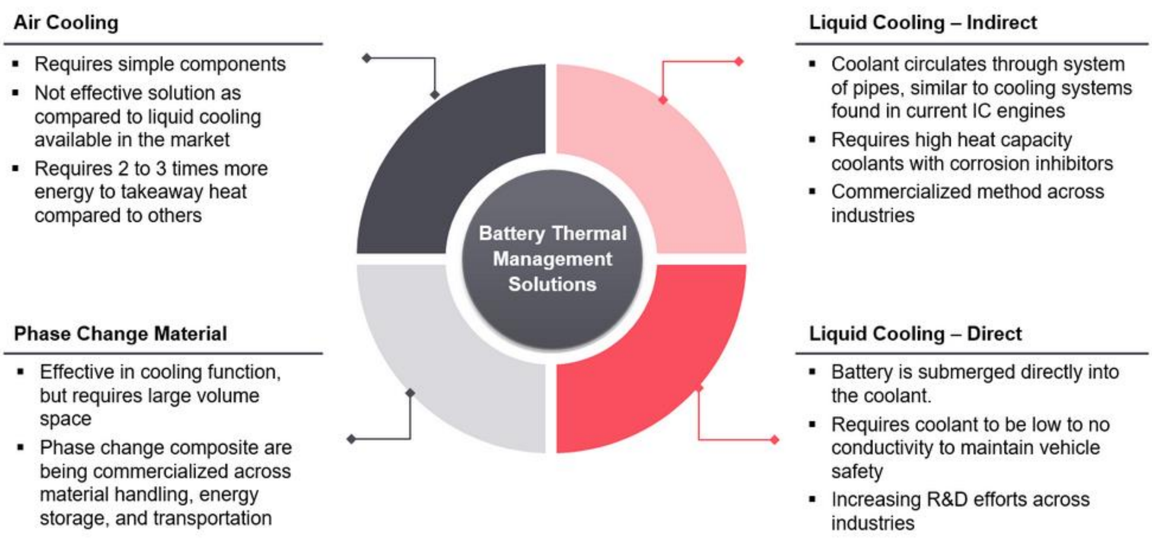


Figure 1: Different ways of Battery cooling [1]

However among all types of cooling methods, Direct Liquid Cooling (Immersion Cooling), serves as the most efficient way to drive away the heat. Here, the battery cells are immersed in a dielectric medium which is expected to drive away the heat along with providing electrical isolation. This method is also called as Single-phase Liquid Immersion Cooling (SLIC) [2]. The use of SLIC is quite common for cooling of super-computer GPUs, however using this technique in EVs is first of its kind, started by XING Mobility start-up [3]. Immersion cooling fluid absorbs the heat from the electric cells, which is then transferred to a heat transfer system using radiator or heat exchanger. Immersion cooling ensures highest thermal contact with efficient cooling.

2. Problem Statement

The flow is assumed to be incompressible, laminar and unsteady. Initially a worse case check was done for turbulent model using PisoFoam for vertical configuration and was found that, there isn't a significant effect of vortex formation over the batteries. So the final simulation was defined for a fluid and heat transfer study using chtMultiregion Foam on both vertical and horizontal configuration of batteries. The geometry required for the simulation was coded in the blockMeshDict file without importing. Two types of dielectric Liquid coolants: Oils and fluorocarbons were be checked for the efficient temperature drop for the batteries. The number of batteries can be kept variable based on the time taken for simulation. Output from the simulation study will be the Velocity, Pressure and Temperature contours along with 2D plots of temperature variation (average,max) w.r.t time. (Enclosure: Simulation area)

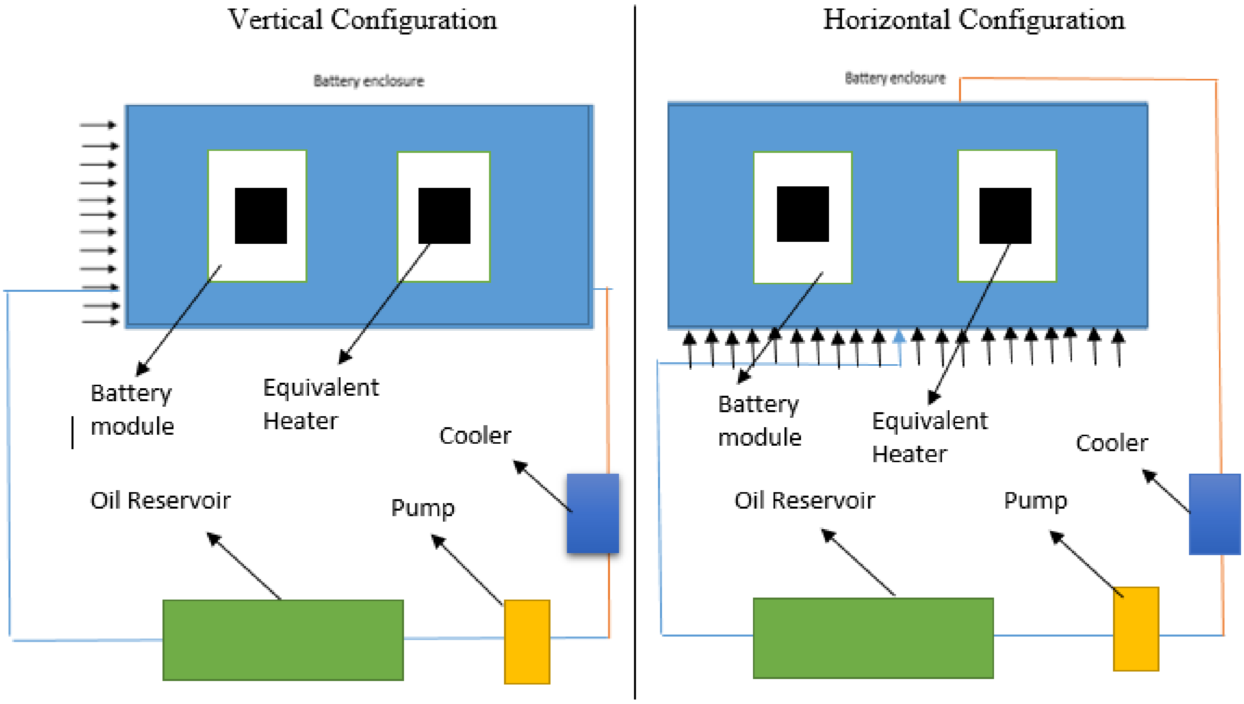


Figure 4: Block diagram of various configurations for immersion cooling

3. Governing Equations

The governing differential equations used for fluid flow are:

- Mass Conservation Equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_j}{\partial x_j} = 0$$

- Momentum Conservation Equation:

$$\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_{rj} u_i) + \rho \epsilon_{ijk} \omega_i u_j = -\frac{\partial p_{rgh}}{\partial x_i} - \frac{\partial \rho g_j x_j}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\tau_{ij} + \tau_{t_{ij}}\right)$$

- Energy Conservation Equation

$$\frac{\partial (\rho k)}{\partial t} + \frac{\partial}{\partial x_j}(\rho u_j k) = -\frac{\partial p u_j}{\partial x_i} - \rho g_j u_j + \frac{\partial}{\partial x_j}(\tau_{ij} u_i)$$

- Pressure Equation

$$\frac{\partial \rho}{\partial t} = \frac{\partial \rho^*}{\partial t} + \psi \frac{\partial p'_{rgh}}{\partial t}$$

For the solid regions in the geometry only energy equation has to be solved. The energy equation gives temporal change of enthalpy of the solid which is equal to the divergence of the heat conducted through the solid:

$$\frac{\partial(\rho h)}{\partial t} = \frac{\partial}{\partial x_j}\left(\alpha \frac{\partial h}{\partial x_j}\right)$$

.

h is the specific enthalpy, $\alpha = \kappa / c_p$ is the thermal diffusivity and ρ density

For the coupling between solid and fluid media,

At interface between solid s and fluid f the temperature T for both phases is same.

$$T_f = T_s$$

.

Furthermore the heat flux entering one region leaves and enters the second region.

$$Q_f = -Q_s$$

.

If we neglect radiation the above expression can be written as:

$$\kappa_f \frac{dT_f}{dn} = -\kappa_s \frac{dT_s}{dn}$$

.

n represents the direction normal to wall. κ_f and κ_s are thermal conductivity of the fluid and solid.

4. Simulation Procedure

4.1 Geometry and Mesh

Case 1: Flow as incompressible, turbulent and unsteady (without temperature effect)

Here six batteries in an enclosure were used to check the effect of vortex generation. The geometry however required region wise breakdown into various blocks, each having different mesh strategies.

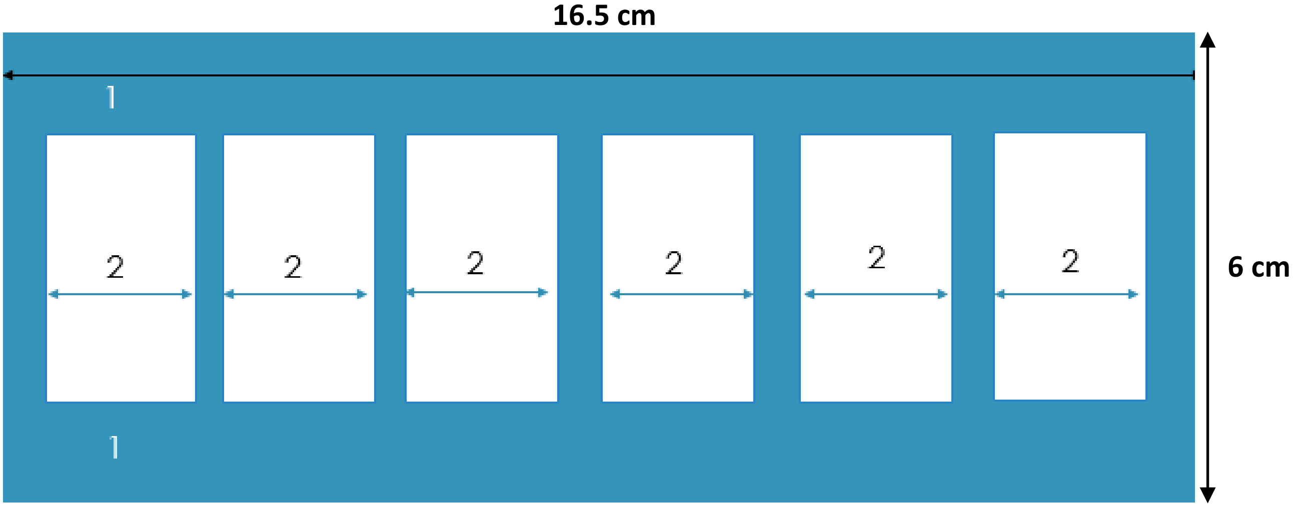


Figure 5: Geometry for turbulence model

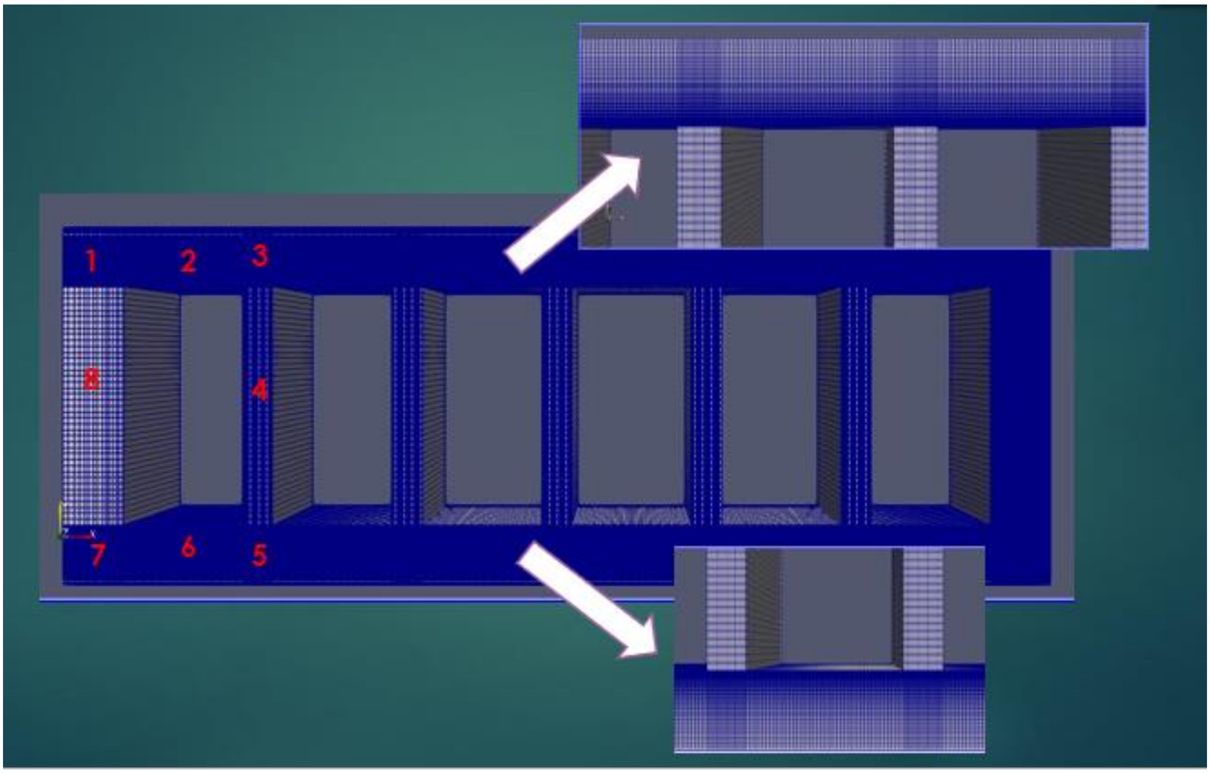


Figure 6: Mesh strategy for different blocks

The various simpleGrading strategies applied for 8 different regions as highlighted above are simpleGrading (0.1 0.2 1), (1 0.2 1), (10 0.2 1), (0.1 1 1), (1 1 1), (10 1 1), (0.1 5 1) and (10 5

1). The cell formations in these regions respectively were (14 40 1), (20 40 1), (80 40 1), (64 40 1), (14 20 1), (80 20 1) and (64 20 1).

Case 2: Flow as incompressible, laminar and unsteady (with temperature effect)

Here, a uniform mesh was constructed throughout without dividing the enclosure into multiple regions as Case 1. Region being, this single block is further subdivided into various regions while using chtMultiregion solver. Here along with fluid region, metal enclosure and heater also get added. For demonstration purpose two battery modules in an enclosure with horizontal and vertical configuration are used for simulation study.

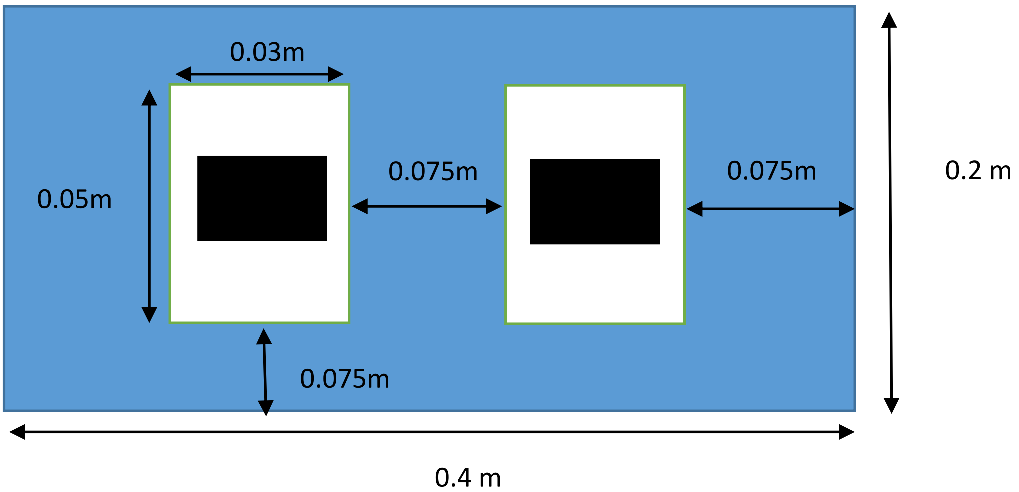


Figure 7: Geometry for 2 Battery pack enclosure

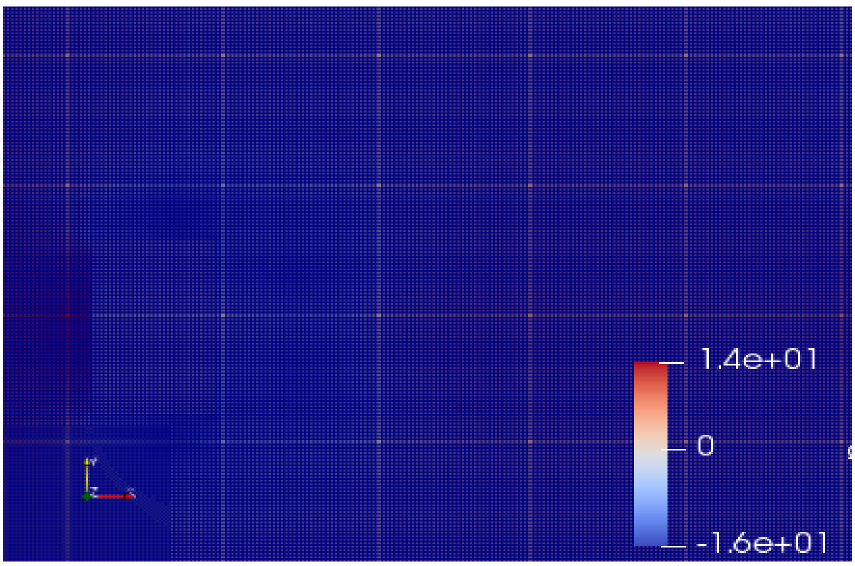


Figure 8: Uniform mesh strategy throughout (fluid, metal and heater)

```
Writing polyMesh
----------------
Mesh Information
----------------
  boundingBox: (-0.1 -0.1 0) (0.3 0.1 0.01)
  nPoints: 161202
  nCells: 80000
  nFaces: 320600
  nInternalFaces: 159400
----------------
Patches
----------------
  patch 0 (start: 159400 size: 200) name: fluidInlet
  patch 1 (start: 159600 size: 200) name: fluidOutlet
  patch 2 (start: 159800 size: 800) name: Walls
  patch 3 (start: 160600 size: 160000) name: frontAndBack
```

Figure 8: Mesh information and patches

The geometry was split into following regions in toposet:

1. Fluid {1 2 3 4 5 6 7}
2. Metal1 {8 9 10 11}
3. Metal2 {12 13 14 15}
4. Heater1 {16}
5. Heater2 {17}

The regions split in Toposet are as follows:

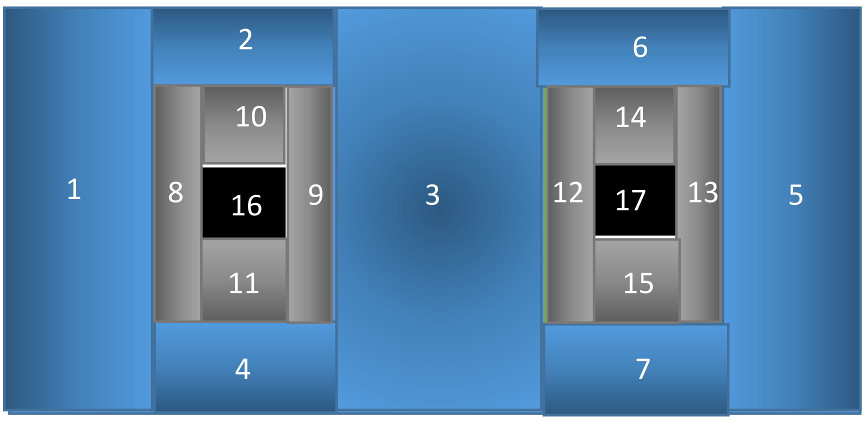


Figure 9: Region nomenclature for Toposet

4.2 Initial and Boundary Conditions

The initial and boundary conditions are included in the 0 folder as p, U, T, p_rgh

For fluid:

	Velocity U (m/s)	Pressure p(m2/s2)	Temperature (K)	Fixedfluxpressure P_rgh
Fluid Inlet	0.5 m/s	Uniform 0	300	0
Fluid Outlet	Int. Field	Uniform 0	300	0
Fluid-Metal1 Int.	noSlip	zeroGrad	300	0
Fluid-Metal2 Int.	noSlip	zeroGrad	300	0
Top	noSlip	zeroGrad	300	0
Bottom	noSlip	zeroGrad	300	0
Fixed Walls	noSlip	zeroGrad	300	0

Table 1: Fluid IC and BC

For heater1:

	Pressure p(m2/s2)	Temperature (K)
Heater1-Metal1	Uniform 0	300

Table 2: Heater1 IC and BC

For heater2:

	Pressure p(m2/s2)	Temperature (K)
Heater2-Metal2	Uniform 0	300

Table 3: Heater2 IC and BC

For Metal1:

	Pressure p(m2/s2)	Temperature (K)
Metal1-Fluid	Uniform 0	300
Metal1-Heater1	Uniform 0	300

Table 4: Metal1 IC and BC

For Metal2:

	Pressure p(m2/s2)	Temperature (K)
Metal2-Fluid	Uniform 0	300
Metal2-Heater2	Uniform 0	300

Table 5: Metal2 IC and BC

4.3 Solver

There were to models followed, first the test model where the simulation was for incompressible, turbulent and unsteady fluid flow without temperature effect. So here PisoFoam Solver was used. The results of this model clarified that turbulence (vortex) effect isn't prevalent and this assumption can be neglected. So in the next case we fix our model to incompressible, laminar and unsteady flow problem with temperature effect. So for this, we choose chtMultiRegionFoam Solver to get the simulation for all three regions fluid, metal and heater. Residual control criteria was set as 10^{-7} for all parameters.

6. Results and Discussions

Case 1: (Using PisoFoam solver)

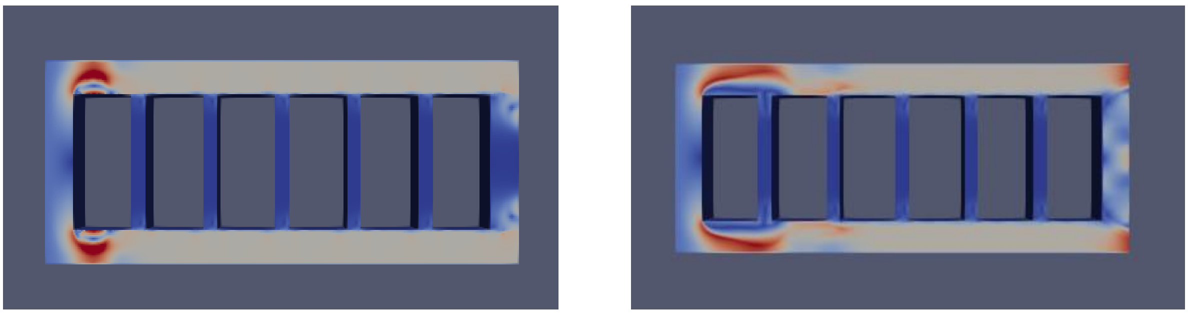


Figure 10: Two instances for Velocity Plots in turbulent model

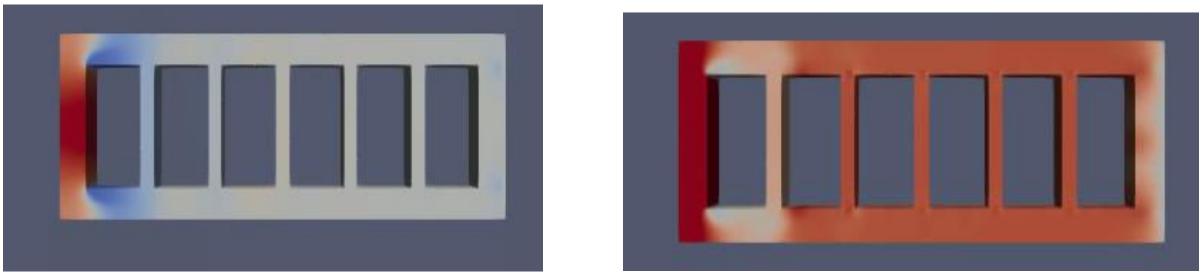


Figure 11: Two instances for Pressure Plots in turbulent model

From this we see that, vortex formation effect is negligible. So we can neglect the assumption of turbulent model in immersion cooling.

Case 2: (Using chtMultiRegionFoam solver)

For this simulation, as mentioned above, two configurations were simulated to find the one providing the most efficient cooling for electric batteries.

a) The vertical configuration, where the fluid flows X direction, considering the coordinate system of simulation space.
b) The horizontal configuration, where the fluid flows along Y direction, considering the coordinate system of simulation space.

Also, as mentioned in the introduction, along with configuration, the choice of dielectric medium driving away the heat also plays a crucial role.

From one such analysis in a White Paper [5] provided by Schneider Electric, the different dielectric cooling media used are of two categories viz. Oils and Fluorocarbons:

1) Oils:
    a. Mineral / white oils
    b. Synthetic poly alpha olefins (PAOs)
    c. Synthetic gas to liquids (GTLs)
    d. Synthetic esters
    e. Silicone oil
2) Fluorocarbon Fluids:
    a. Perfluorocarbons (PFCs)
    b. Perfluoropolyethers (PFPEs)
    c. Hydrofluoroethers (HFEs)
    d. Fluorketones (FKs)

From the analysis presented in the paper it has been mentioned that, in the Oils category, Synthetic PAOs have slightly better dielectric and heat driving characteristics, although all Synthetic oils have nearly the same performance.

From the Fluorocarbon Fluids category, Perfluoropolyethers (PFPEs) have better cooling characteristics compared to all others.

So based on this, the two fluids that were selected for Simulation were Synthetic Oils and Perfluoropolyethers. The properties for the same used in simulation are:

Dielectric Fluids	Synthetic Oils	PFPEs
Molar Mass	200	156
Density (kg/m3)	900	1800
Heat Capacity (J/kgK)	2200	2300
Kinematic Viscosity (m2/s)	959e-5	650e-5
Prandlt No.	9	12.3

Table 6: Property values for different dielectrics

For Li-Ion batteries, typically a single charging cycle, the amount of heat generated (heating effect of electric current) is 32 W. The other typical Li-ion electric characteristics are:

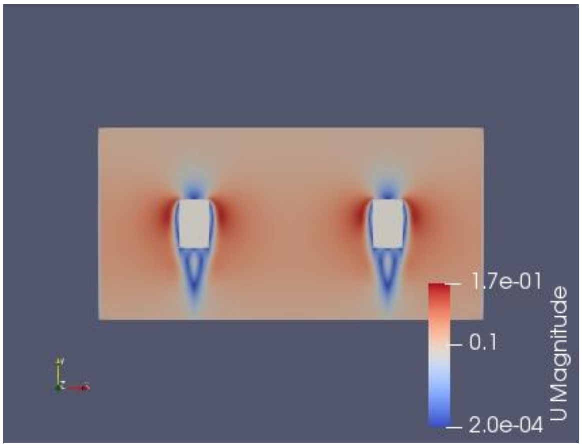
Parameters		Values
Nominal voltage	(V)	3.2
Nominal capacity	(Ah)	10
Internal resistance	(mΩ)	$\approx$10
Charging current	(A)	≤ 10
Continuous discharge current	(A)	≤ 20
Maximum discharge current	(A)	50
Upper cut-off voltage	(V)	3.65 ± 0.05
Lower cut-off voltage	(V)	2.5
Cycle life	(/)	≥ 2000
Weight	(g)	275 ± 5
Dimension	(mm)	$131 \times 65 \times 16$

Figure 12 : Li-Ion Characteristics [5]

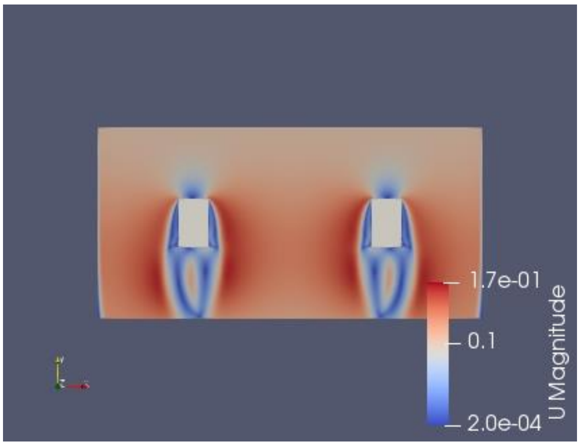
Also a typical fluid velocity maintained in the immersion cooling technique as per Schneider is 0.1 m/s [5].

Horizontal Configuration with Synthetic Oil as Dielectric (Fluid flow along +Y axis):

1. Velocity Plots (Figure 13):



Instance 1: Start



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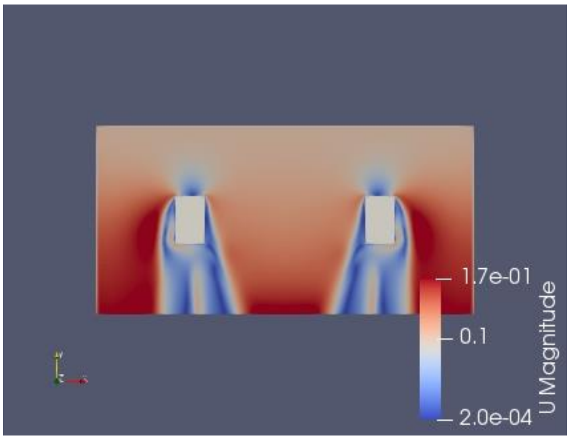
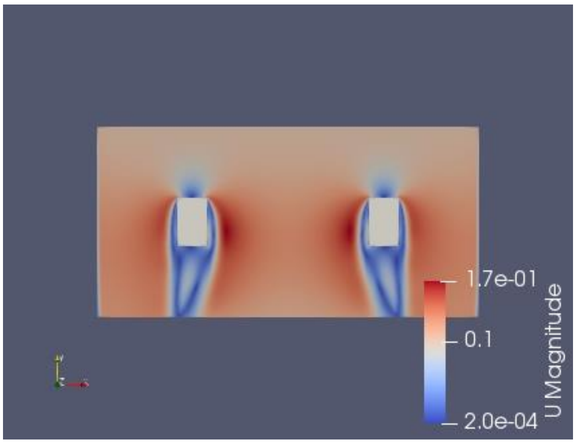
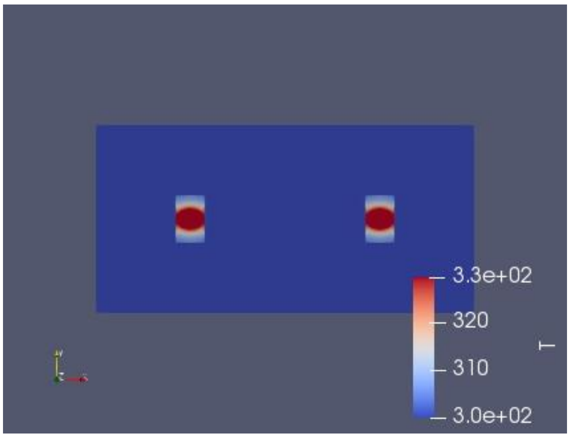


Instance 3: 9 sec

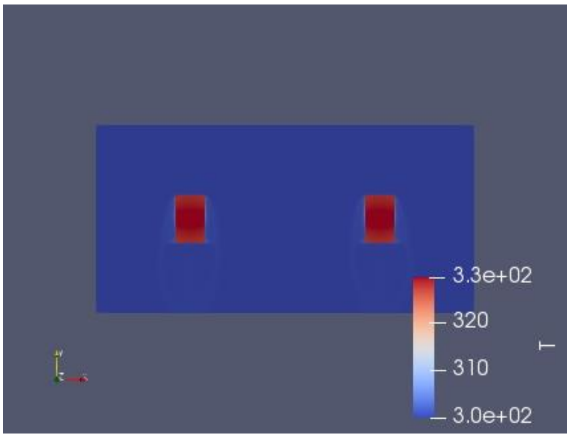


Instance 4: 14 sec

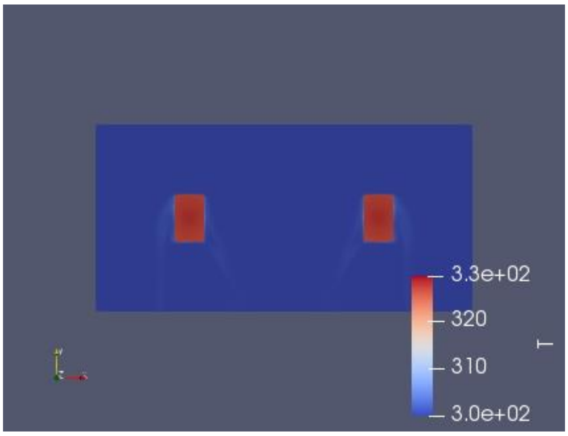
2. Temperature Plots (Figure 14):



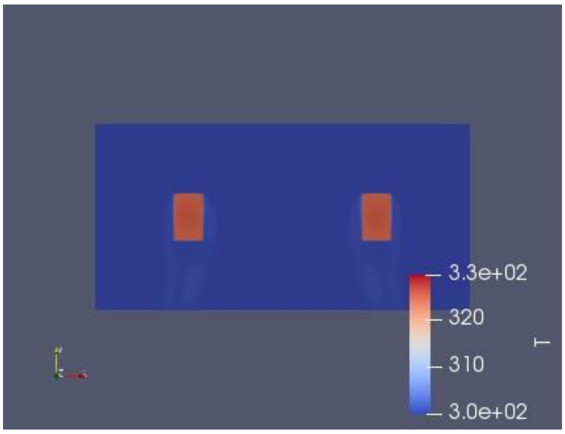
Instance 1: Start



Instance 2: 4 sec



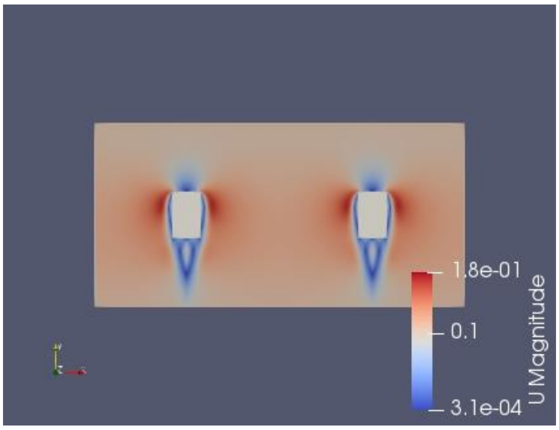
Instance 3: 9 sec

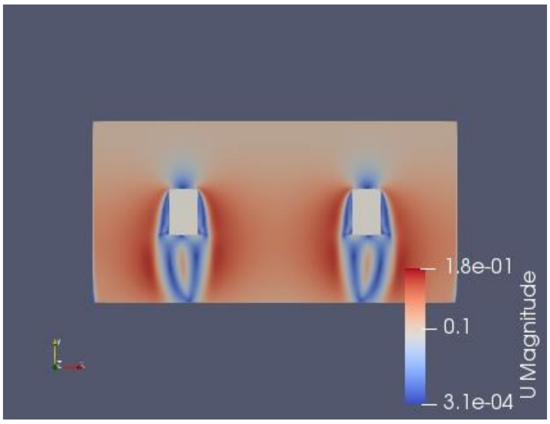


Instance 4: 14 sec

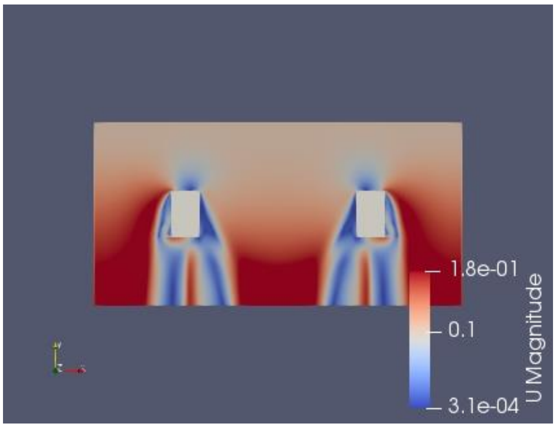
Horizontal Configuration with PFPE (Fluoro Carbon) as Dielectric (Fluid flow along +Y axis):

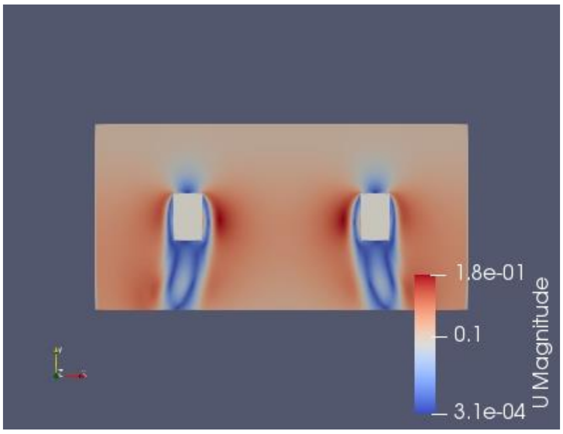
1. Velocity Plots (Figure 15):





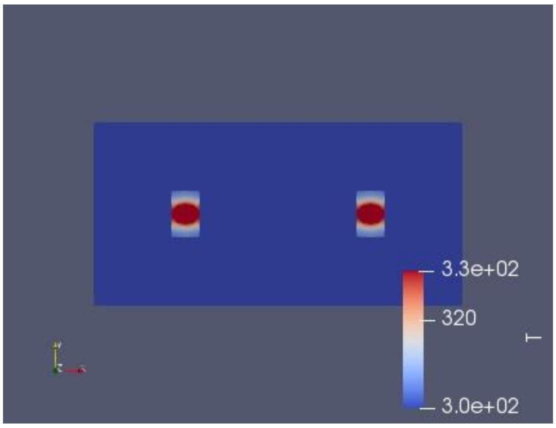
Instance 1: Start Instance 2: 4 sec

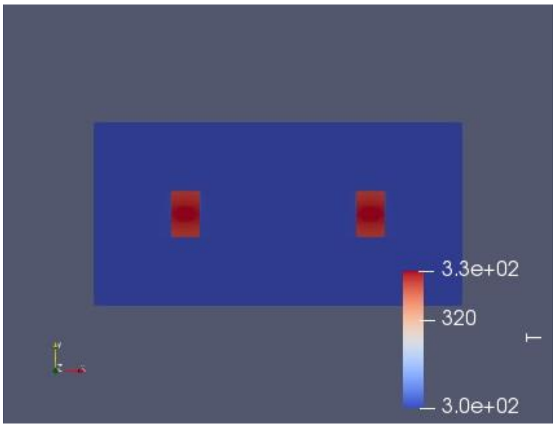




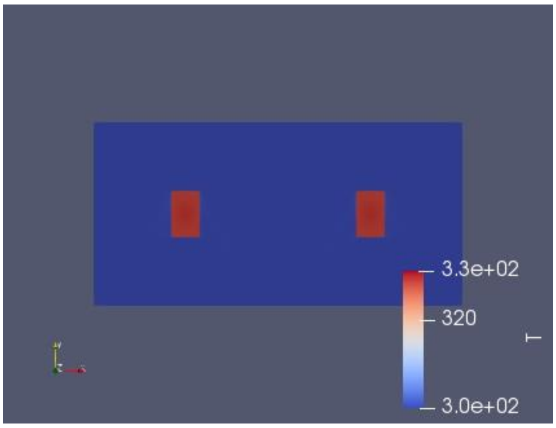
Instance 3: 9 sec Instance 4: 14 sec

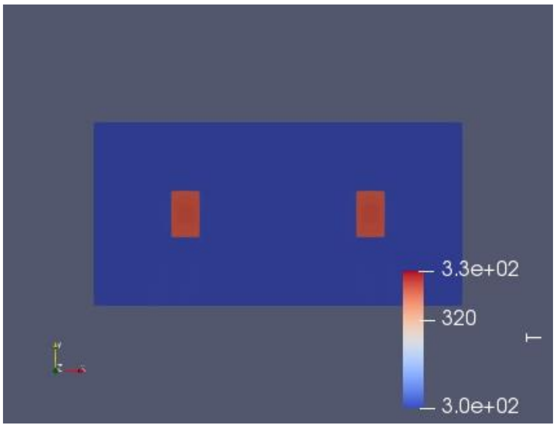
2. Temperature Plots (Figure 16):





Instance 1: Start Instance 2: 4 sec

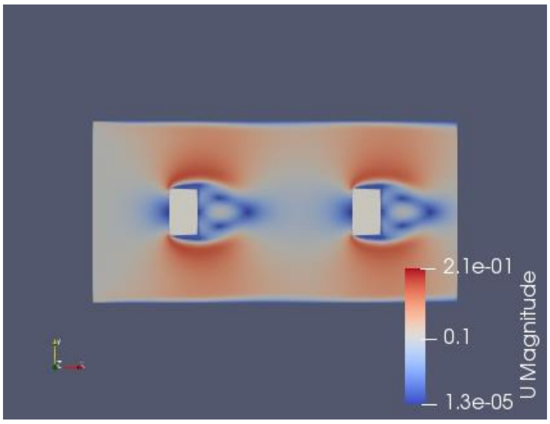




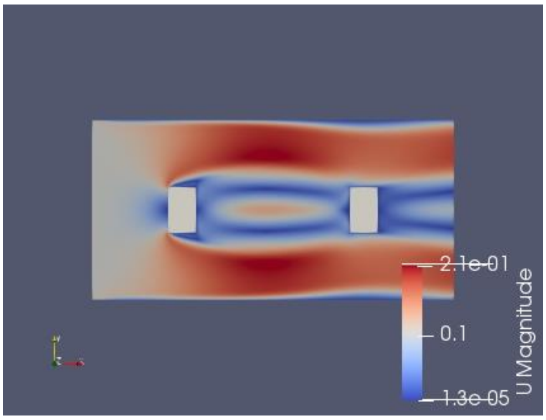
Instance 3: 9 sec Instance 4: 14 sec

Vertical Configuration with Synthetic Oil as Dielectric (Fluid flow along +X axis):

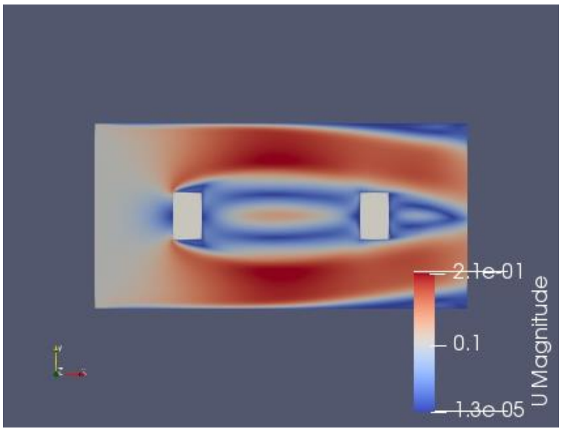
1. Velocity Plots (Figure 17):



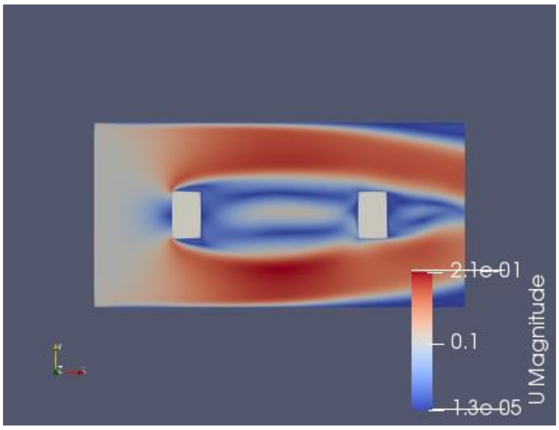
Instance 1: Start



Instance 2: 4 sec

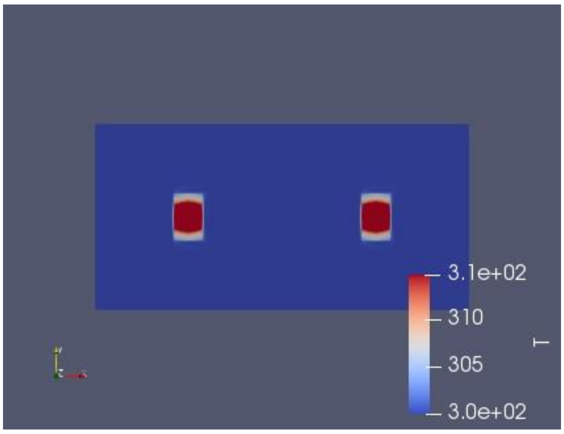


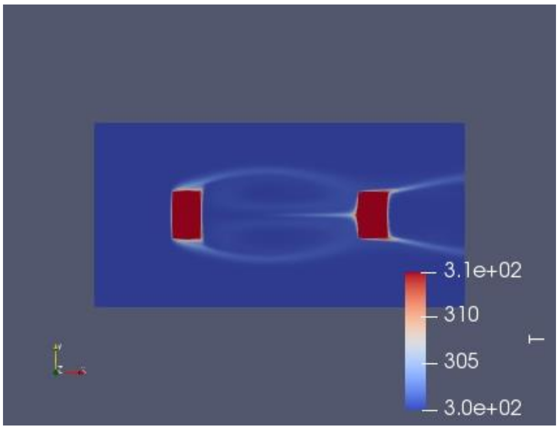
Instance 3: 9 sec



Instance 4: 14 sec

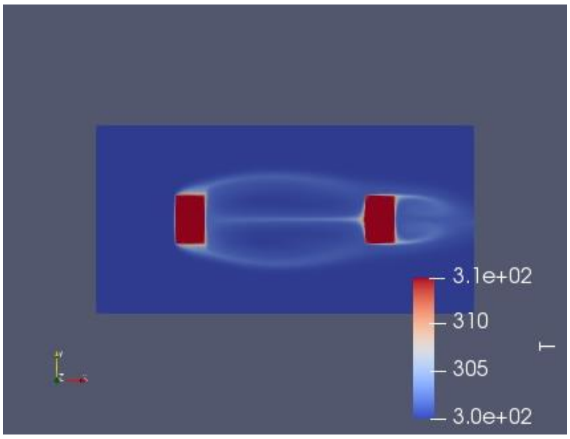
2. Temperature Plots (Figure 18):

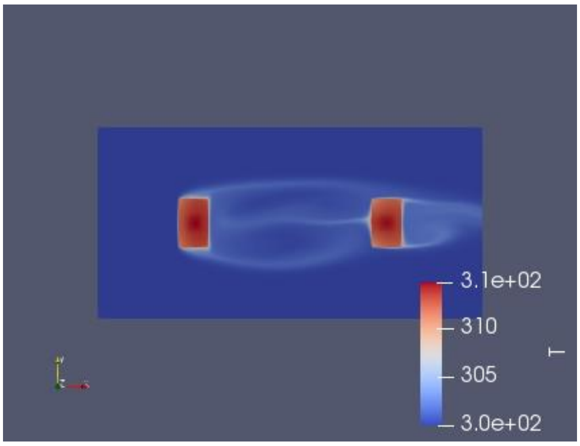




Instance 1: Start

Instance 2: 4 sec



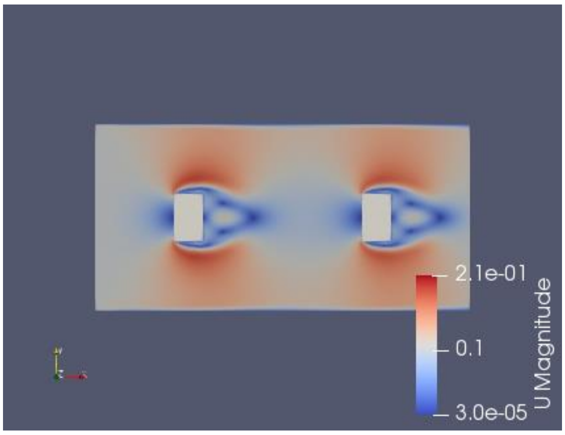


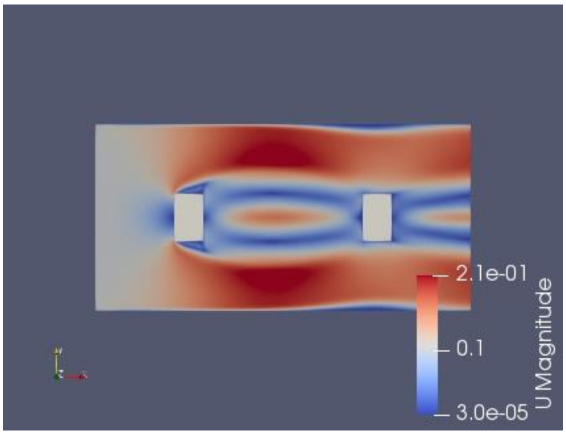
Instance 3: 9 sec

Instance 4: 14 sec

Vertical Configuration with PFPE (Fluoro Carbon) as Dielectric (Fluid flow along +X axis):

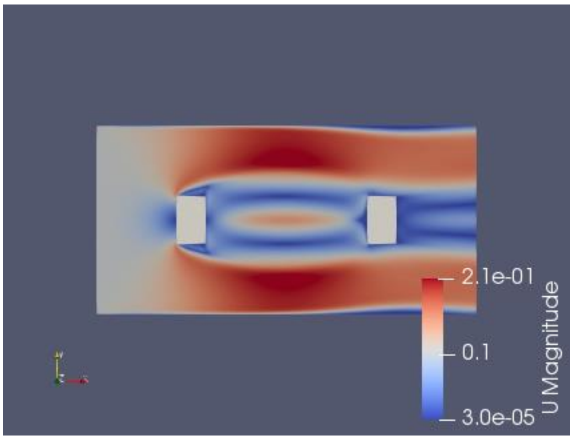
1. Velocity Plots (Figure 19):



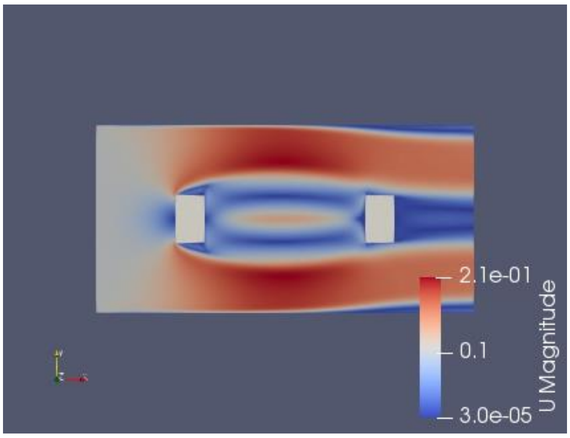


Instance 1: Start

Instance 2: 4 sec

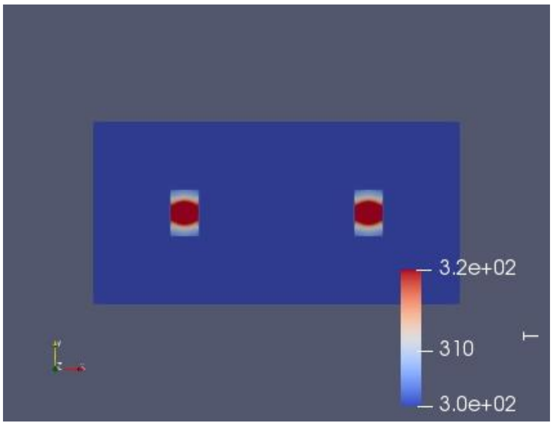


Instance 3: 9 sec

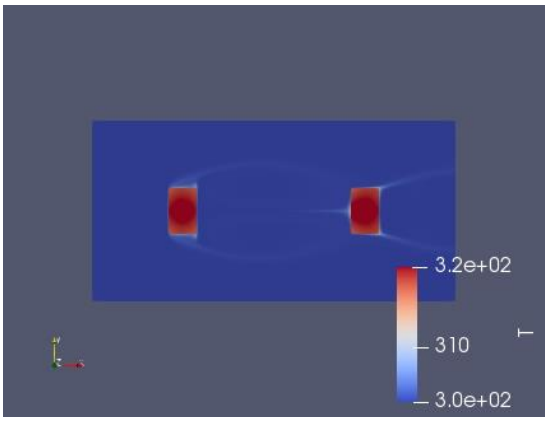


Instance 4: 14 sec

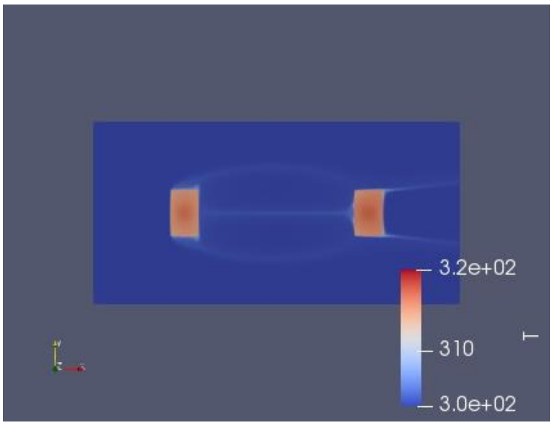
2. Temperature Plots (Figure 20):



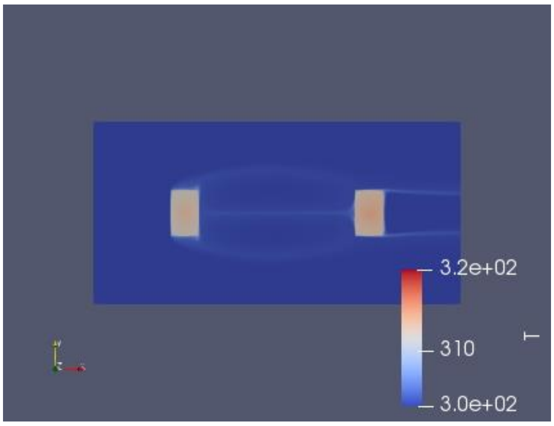
Instance 1: Start



Instance 2: 4 sec



Instance 3: 9 sec



Instance 4: 14 sec

Now, to compare the efficiency of each method, we check for Fluid-Battery Surface Average Interface temperatures. Interestingly, the surface temperatures vary slightly in both the batteries present in the same enclosure, because of the virtue of their position internally. Note that this can be obtained using GNUPlot, as the bash commands for the same can be found in the Case file. However for clarity on images, we plot on Excel, and the results for each are as follows:

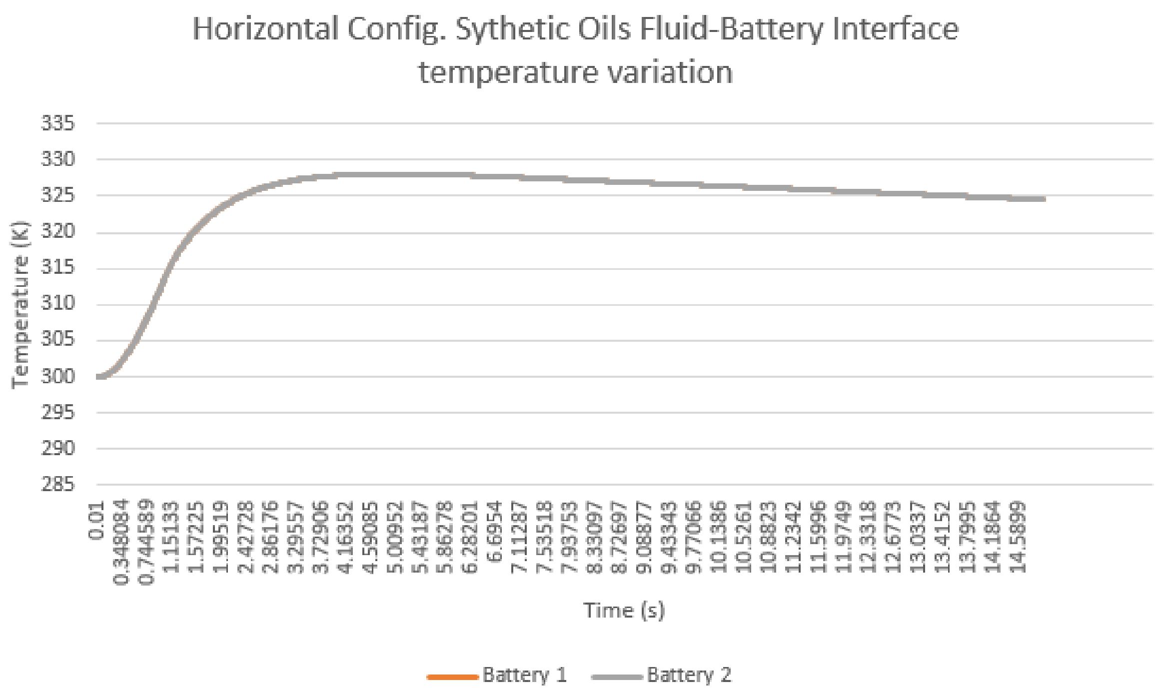


Figure 21: Horizontal Config. with Synthetic Oil

Here, we see that, both the batteries follow almost same temperature profile w.r.t time. This is because of the virtue of their position, as the fluid flow reaching to each of the batteries has almost same velocity profile. This is same for both Synthetic Oil and Fluorocarbons case.

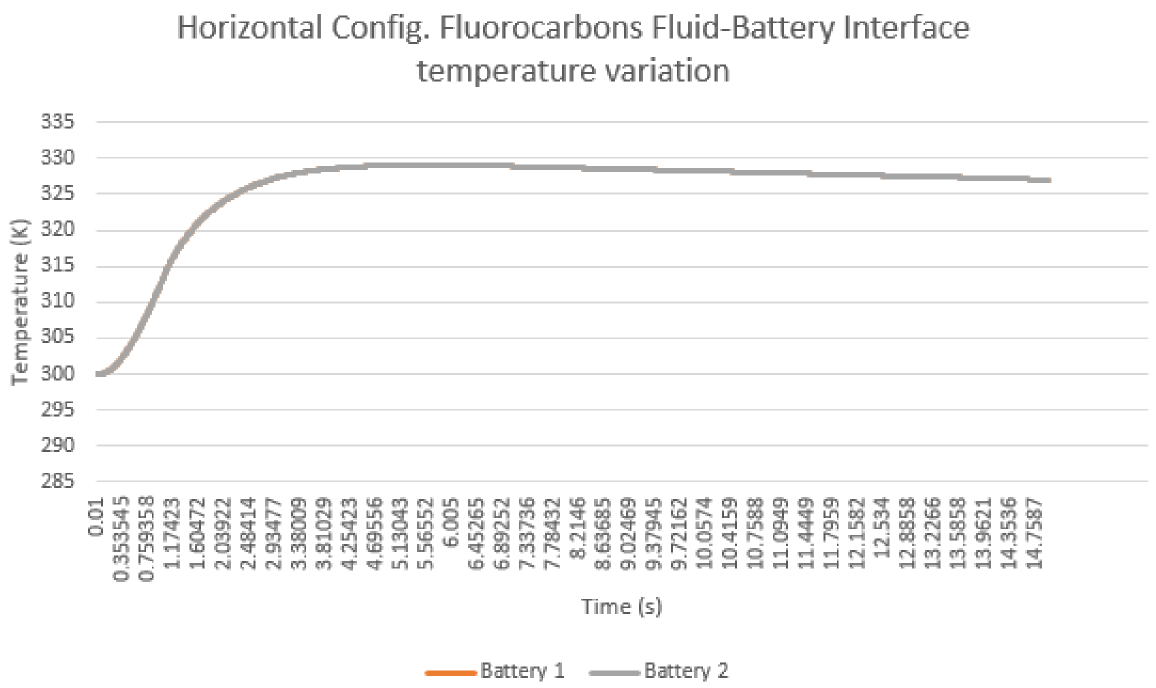


Figure 22: Horizontal Config. with (PFPE) Fluorocarbons

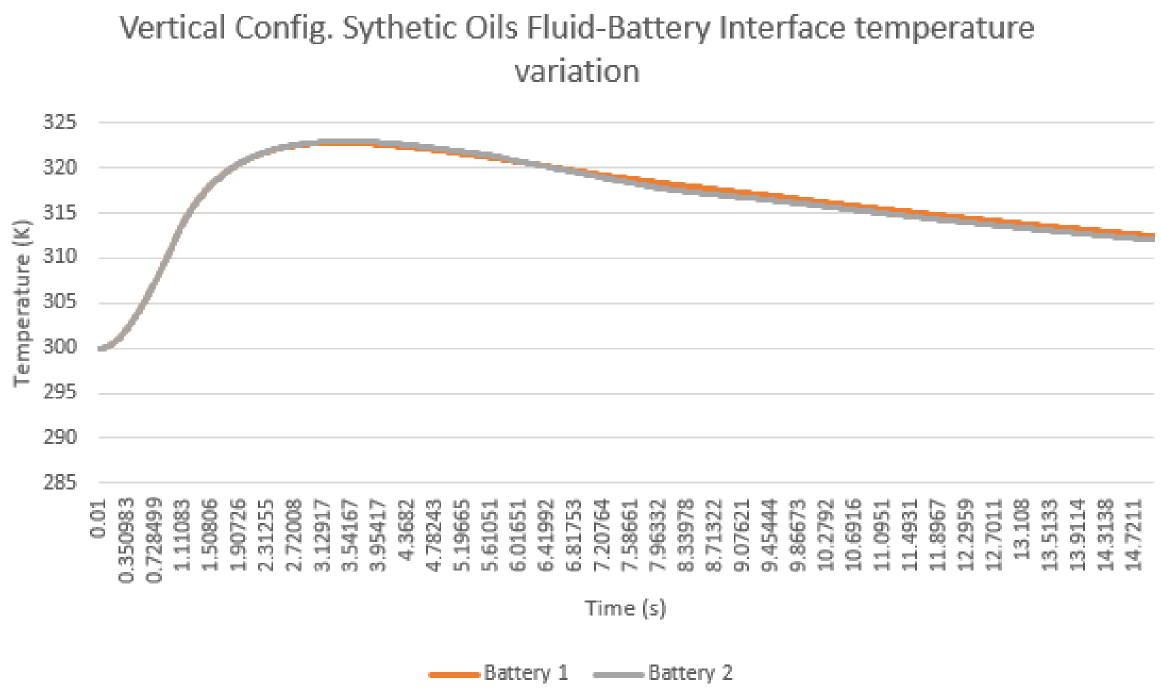


Figure 23: Vertical Config. with Synthetic Oils

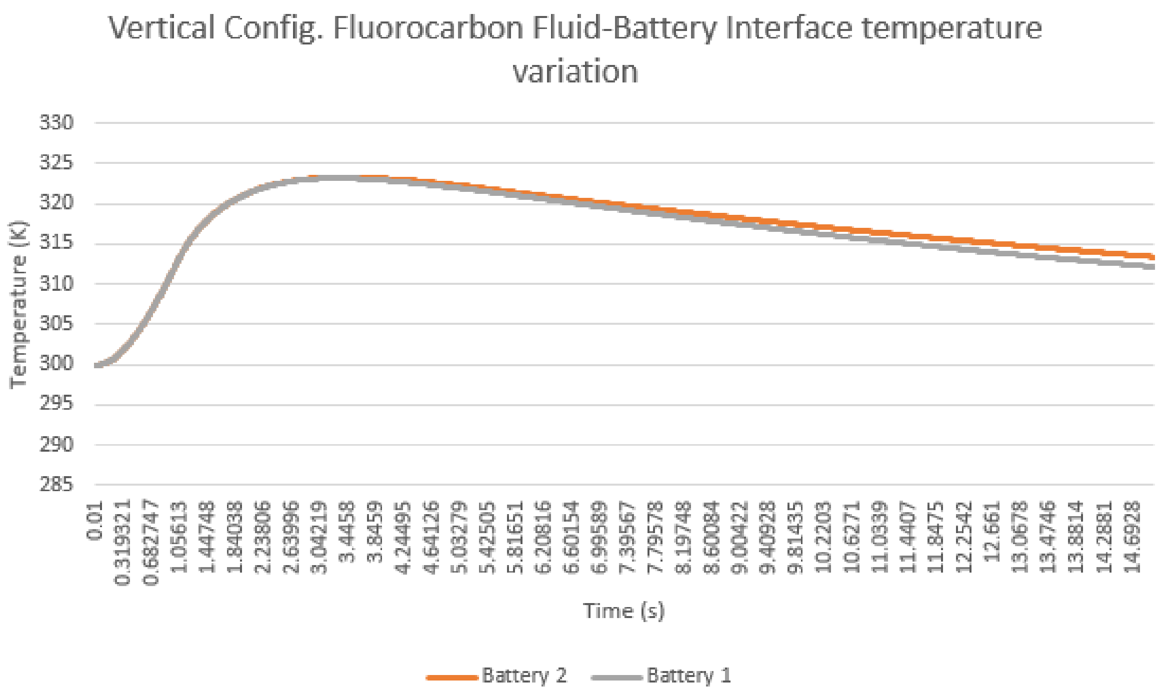


Figure 24: Vertical Config. with (PFPE) Fluorocarbons

In the vertical configurations, we see that temperature profiles of both batteries deviate w.r.t time. Battery 1 which is first in the path of fluid, has higher rate of cooling compared to Battery 2 behind it. This case is observed similar in Synthetic ils and Fluorocarbons, with slightly varying cooling rates.

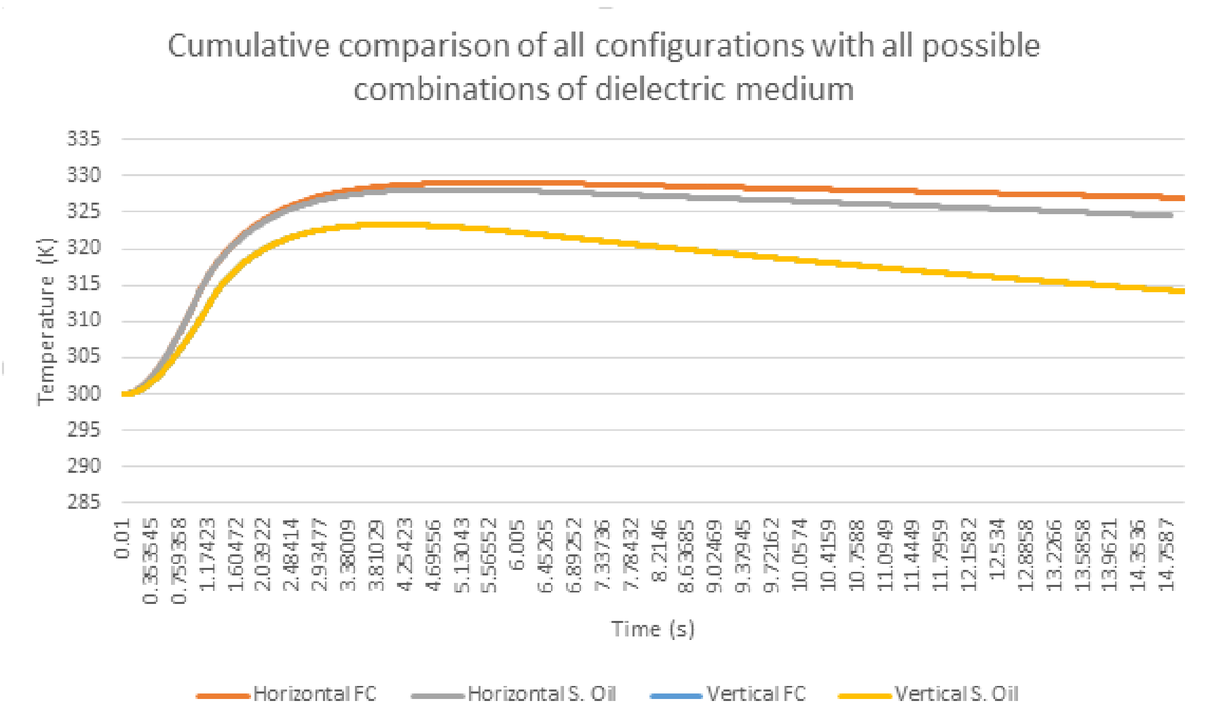


Figure 25: Comparison overall Surface Average Interface temperatures

The above plot provides a better understanding of all 4 combinations in a single frame. Note that, only temperatures from Battery 1 are taken for plotting.

Also, the Maximum fluid temperature attained in every configuration, based on the amount of heat driven can be seen below:

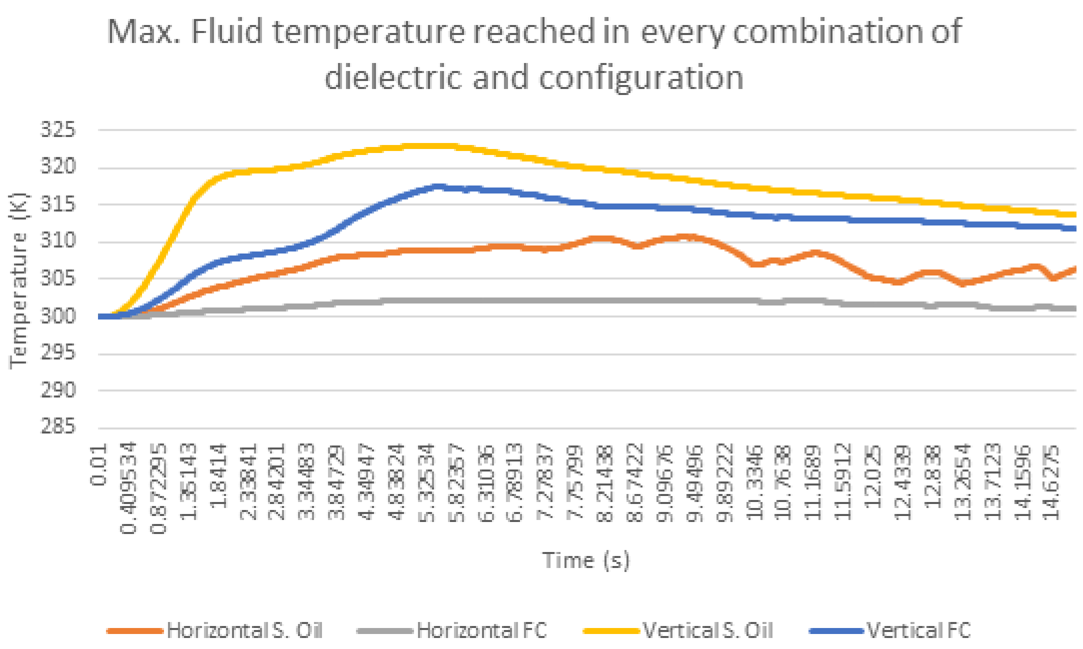


Figure 26: Comparison overall Max. fluid Interface Temperatures

End of simulation (15 sec)	Interface Fluid-Battery1 Temp (K)	Interface Fluid-Battery2 Temp (K)	Max Fluid Temp. (K)
Horizontal | S. Oil	325.3796	325.3796	306.3598
Horizontal | FC	327.0021	327.0021	301.379
Vertical | S. Oil	312.1737	313.4158	312.3202
Vertical | FC	312.4762	313.5642	311.3525

Table 7: Overall simulation stats

The results are close to the analytical values that we can obtain using the heat transfer equation between the three bodies (Battery 1, Battery 2 and Fluid)

$\boldsymbol{c}_{fluid} \times \boldsymbol{V}_{fluid} \times \boldsymbol{Density} \times$ (Max. Fluid Temp. – Initial Temp.) =

$\boldsymbol{c}_{Battery\ encl.} \times \boldsymbol{m}_{Battery\ encl} \times$ (Fluid-Battery1 Interface Temp.– Initial Temp.) +

$\boldsymbol{c}_{Battery\ encl.} \times \boldsymbol{m}_{Battery\ encl} \times$ (Fluid-Battery2 Interface Temp.– Initial Temp.)

Following are the observations:

1. Vertical configurations (both) have a faster cooling rate compared to horizontal.
2. Both Synthetic oils and Fluorocarbons have almost similar cooling rate (however Synthetic oils are slightly faster in cooling).
3. In horizontal configurations, the Synthetic Oil cooling is faster compared to Fluorocarbons.

Conclusions:

1. From all the above simulation studies it can be seen that, the effect of Vortex formation (In Case 1) wasn’t that significant, and so it is better to neglect the turbulence assumption
2. From both the configurations, Vertical and Horizontal, Vertical configuration has a faster cooling characteristic compared to Horizontal. Following are the reasons:
   a) The wall effect experienced during the path of horizontal configuration is more. So the flow velocity, although initial at the start for both configurations decreases more in case of horizontal configuration. So is the effect of forced convection less compared to vertical one.
   b) However, this effect is prevalent only in case with few battery modules (here 2). In case with many battery modules, the horizontal configuration will outperform vertical.
   c) In case of Dielectric fluids used, both the fluids perform very close in many cases

d) They have almost same cooling characteristics in Horizontal configuration
e) However, comparing the max. Temperature achieved by the fluid at the end of simulation, Synthetic oil has more temperature compared to Fluorocarbons. Although this doesn't necessary mean it has better cooling characteristics.
f) To back this up, the Surface average Fluid-Battery interface temperature is more in case of Fluorocarbons, in both the configurations as compared to Synthetic Oils family.
g) So from all the above points, we see that for Single Phase Immersion cooling in batteries, the vertical configuration (in case of few battery modules) and horizontal (in case of many battery modules) with Synthetic Oils (Synthetic poly alpha olefins (PAOs), Synthetic gas to liquids (GTLs), Synthetic esters) will be the recommended Thermal Management system for Li-Ion batteries in EVs.

References

[1] https://www.3m.com/3M/en_US/oem-tier-us/applications/propulsion/ev-battery/novec-for-ev-battery/

[2] D. W. Sundin and S. Sponholtz, "Thermal Management of Li-Ion Batteries With Single-Phase Liquid Immersion Cooling," in IEEE Open Journal of Vehicular Technology, vol. 1, pp. 82-92, 2020, doi: 10.1109/OJVT.2020.2972541.

[3] https://evannex.com/blogs/news/could-tesla-benefit-from-this-new-battery-cooling-approach

[4] "Comparison of Dielectric Fluids for Immersive Liquid Cooling of IT Equipment", White Paper by Robert Bunger and Tony Day, Schneider Electric.

[5] https://www.electronicsworld.co.uk/immersion-cooling-for-electric-vehicles-enables-super-fast-charging-and-improves-range-anxiety/16687/