HEAT TRANSFER ENHANCEMENT IN AN IMMERSION COOLING BATTERY THERMAL MANAGEMENT SYSTEM USING LINEAR VORTEX GENERATORS

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ABSTRACT

Battery thermal management systems (BTMSs) for electric vehicles are of primary importance to the efforts for further market penetration of electric vehicle (EV) technology, as thermal safety and performance issues of Li-ion batteries persist. Different battery cooling approaches have been developed to address the issues of maximum temperature and temperature uniformity. In this paper, a novel, immersion-cooling BTMS concept is proposed where oil-based, dielectric fluids are employed. The cooling performance is further improved by incorporating linear vortex generators (LVGs) to enhance mixing close to the battery cell consequently heat transfer. The proposed BTMS is tested under three different rates of discharge (1C, 5C, 10C) with air and dielectric-fluid cooling. The results indicate that the use of a dielectric fluid along with LVGs leads to a significant drop of the maximum battery cell temperature and a temperature uniformity of 1° C across the battery cell.

INTRODUCTION

One of the most promising technological developments to reduce global carbon footprint in transportation is power train electrification, with lithium-ion (Li-ion) batteries being widely used in electric vehicles due to their high energy-density and power-energy attributes. These attractive attributes however naturally lead to increased heat generation rates affecting the thermal performance and safety of the battery packs. Temperature control and management of the Li-ion battery packs are vital for long-term performance, life cycle and durability [1,2]. Cell performance varies significantly with temperature, while the electrochemical phenomena occurring within the battery cells are also temperature dependent [3]. The suggested window of operation for the temperature of a Li-ion battery is between 15° C – 60° C, with the optimum temperature being below 40° C. Temperature uniformity within each battery cell and among different cells of the same battery pack is also of great importance, with a maximum of 5° C being the target [4]. Battery thermal management systems (BTMS) play an important role in maintaining temperature levels within the desired window and promoting temperature uniformity, thus promoting battery life cycle and preventing issues like thermal runaway and battery degradation [5,6].

Today's commercial EVs employ BTMSs that mainly use air cooling [7,8], water/glycol cooling systems in an indirect cooling approach through channels [9], phase-change materials (PCMs) [10,11], or complex combinations of the above [12]. Air-cooling systems carry decades of development and application in many different sectors (e.g. integrated circuits, ICE vehicles). However, their cooling capacity is limited and can hardly meet the tight temperature limits of EV battery packs. Indirect, liquid BTMSs employ working fluids (usually water or water/glycol mixtures) that flow through channels attached to jackets or plates in contact with the battery cells. Although the cooling capacity of the liquids increase the cooling performance of the indirect BTMS compared to air-cooling systems, the cooling channels result in complex topologies that do not promote temperature uniformity, while leading to increased system weight and manufacturing costs. Finally, PCMs are designed to absorb any surplus heat from the battery cells though melting/solidification processes. Their main drawback is the relatively moderate thermal conductivity, which cannot meet the thermal requirements of a modern EV BTMS. Their applicability is however an active field of research, especially in combination with other forms of cooling.

A different cooling approach that takes advantage of both the surface area of the battery cells and the increased thermal conductivity of liquids is immersion/direct cooling [13]. The main scope of this study is to present a novel approach for an immersion/direct cooling BTMS employing dielectric, oil-based coolants in conjunction with linear vortex generators (LVGs). Dielectric oil-based coolants are suitable for direct cooling approaches using the total surface area of the battery cells. Despite having lower thermal conductivity than water, they also present significantly lower electric conductivity that practically renders them as insulators. To further increase the cooling capacity of the proposed BTMS, LVGs are used to create a coherent secondary flow pattern of linear vortices promoting laminar mixing between the battery cells. Vortex generators have been previously used in many fields, especially in the ones of heat exchangers and aerodynamics. They are well-known for their ability to increase heat transfer and benefit macro-mixing [14].

The proposed immersion/direct cooling BTMS is modelled through a coupled approach comprising the electrochemical/

thermal performance of the battery and the cooling capacity of the dielectric coolants to quantify the effects of the coolant thermal properties and the linear vortices in enhancing heat transfer.

CONCEPT DESCRIPTION

The proposed immersion-cooling BTMS concept is developed for and tested on a battery pack consisting of prototype prismatic battery cells. Characteristic cell dimensions are given in **Figure** 1. The cell chemistry is Lithium-Iron-Phosphate (LFP) and the nominal capacity and voltage for each cell is 40Ah and 3.2V, respectively.

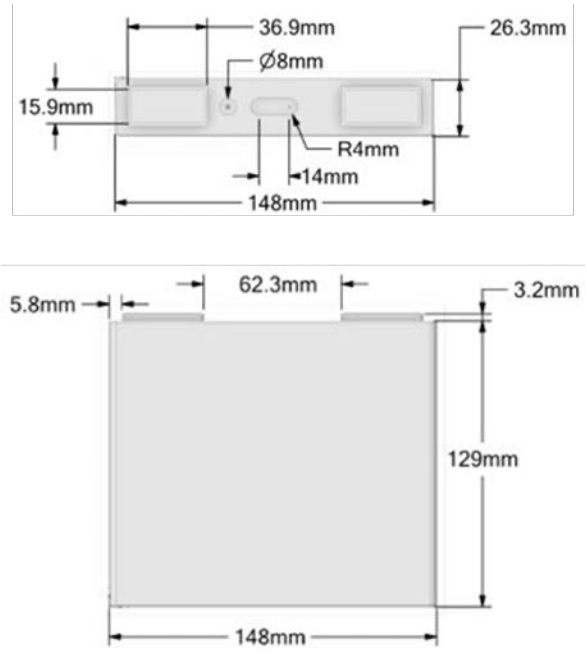


Figure 1 Top- and side-view and dimensions of the prototype battery cell used to test the novel BTMS.

The battery cells are placed side-by-side, separated by a gap of 1cm. The battery cell has been defeatured and, to further simplify the investigation at this stage, only one cell and its associated LVGs are simulated by exploiting lateral symmetry. **Figure 2** presents the defeatured prototype battery cell and the two pairs of LVGs placed upstream of the cell. Each LVG has height and length equal to 2cm and width equal to 0.1mm. The angle between the LVGs of each pair is equal to 9° and their respective distance is 0.8mm (on the converging side). Each pair is placed 2.6cm upstream of the battery cell and 2mm from the battery sides. Finally, the centre of mass of each LVG is vertically aligned with the centre of mass of the battery cell.

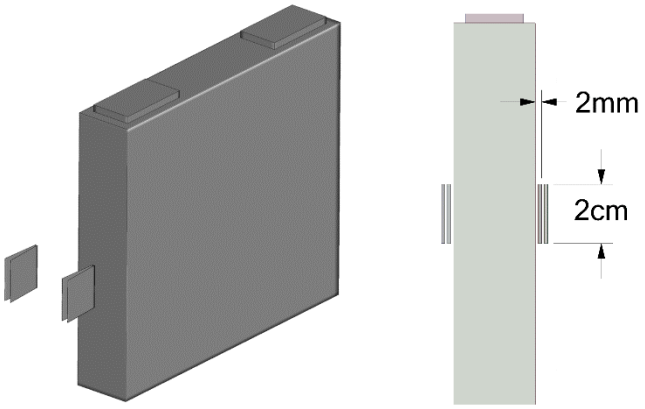


Figure 2 Isometric (left) and front (right) view of the battery cell and the LVGs placed upstream.

NUMERICAL MODELLING

The proposed immersion/direct cooling concept is implemented in ANSYS Fluent through the dedicated Battery Module [15]. The module allows for thermal analysis and heat rate computations by coupling of the electrochemical and thermal phenomena that take place during the operation of battery cells. There are various approaches to this coupling, with each offering specific advantages with respect to the level of detail and the phenomena of interest. For the purposes of this work, where along with the electrochemical/thermal coupling there is also interest in the flow features that affect the cooling performance of the proposed BTMS, the Multi-Scale Multi-Domain (MSMD) approach is selected [16].

One of the most challenging aspects with regards to the modelling of realistic battery cells and packs is the different length scales and the different physics that take place in such domains. In this case, the temperature distribution on each battery cell is determined first at the battery length scale via the electrochemical/thermal coupling. Then, the flow solver is employed at the flow length scales to account for heat transfer between the battery cells and the surrounding fluid. The MSMD approach computes the battery electrical and thermal fields at the battery cell scale by solving the following set of equations:

$$\frac{\partial \rho c_p T}{\partial t} - \nabla(k\nabla T) = \sigma_+|\nabla\varphi_+|^2 + \sigma_-|\nabla\varphi_-|^2 + \dot{q}_{ECh} \quad (1)$$

$$\nabla(\sigma_+\nabla\varphi_+) = -j_{ECh} \quad (2)$$

$$\nabla(\sigma_-\nabla\varphi_-) = j_{ECh} \quad (3)$$

Equations 2 and 3 are used to determine the positive and negative phase potentials φ for the positive and negative electrodes respectively. The volumetric current transfer rate and the electrochemical reaction heat manifest themselves through the terms j_{ECh} and $\dot{q}_{ECh}$, respectively. The terms that are concerned with internals short-circuits and thermal abuse conditions are currently neglected.

The electrical phase potentials are computed using the semi-empirical electro-chemical sub-model NTGK, developed by

Newman, Tiedemann, Gu and Kim (cite). The volumetric current transfer rate is given by:

$$j_{ECh} = \frac{Q_{nominal}}{Q_{ref} Vol} Y[U - V] \quad (4)$$

while the electrochemical reaction heat is given by:

$$\dot{q}_{ECh} = j_{ECh}[U - V - T\frac{dU}{dT}] \quad (5)$$

In the above equations, $Q_{nominal}$ is the battery capacity, Q_{ref} is the capacity of the battery used in experiments to evaluate the model parameters Y and U, while V is the battery cell voltage and Vol is the volume of the cell's active zone.

NUMERICAL SIMULATIONS

For the purposes of this study, a single, prototype, prismatic LFP battery cell is immersed into a fluid volume. The equations of mass, momentum and energy conservation are solved in an approach similar to [17], along with the electrochemical equations. Symmetry boundary conditions are used on the sides of the domain to account for the effects of the battery cells placed on 1cm away from each of the two sides of the battery cell. Wall boundary conditions are used for the casing of the battery and the LVG surfaces. A velocity inlet boundary condition is imposed upstream of the battery cell and the LVGs. The velocity magnitude corresponds to a Reynolds number $Re = uD/v = 1000$, where u is the inlet velocity, D is the hydraulic diameter of the inlet and v is the kinematic viscosity of the fluid. The fluid inlet temperature is 27° C for all cases. An outflow boundary condition is imposed at the domain's outlet.

Two working fluids are used to demonstrate the cooling performance of the proposed BTMS. The first is air at standard conditions. The second is a dielectric, mineral oil-based coolant. The density of this oil is 798.2 kg/m^3. The specific heat C_p is equal to 1834 J/(kg K), while the thermal conductivity is equal to 0.1373 W/(m K) and the dynamic viscosity is equal to 0.0071 kg/(m s). For both fluids, the inlet velocity is adjusted to correspond to a Reynolds number of 1000.

The proposed immersion/direct cooling BTMS is tested under three different discharge rates: 1C, 5C and 10C. C-Rate is defined as the inverse of the time in hours required to fully discharge the battery: C-Rate = 1 / h_{req}. For all three discharge rates, a baseline simulation is first performed where the battery cell is immersed into stagnant air, without cooling flow to demonstrate the magnitude of the cell heat generation rate. Then, the battery cell is first cooled with air and oil to evaluate the cooling performance of the novel dielectric fluid. Finally, simulations are conducted for both air and oil with the presence of LVGs to demonstrate their capabilities in further enhancing heat transfer.

RESULTS

The simulations of the battery cell under the different discharge rates for the two working fluids with and without the presence of the LVGs are summarized in Tables 1-3. The maximum temperature that was observed for the battery cell is reported in Table 1, while Tables 2 and 3 present the maximum temperature difference for the battery cell and the standard deviation of the cell's temperature respectively, as a measure of temperature uniformity. In Figure 3, contours of temperature are presented for the cases of stagnant air, oil cooling and oil cooling with LVGs for the case of 10C.

	Max Temperature				
	Stagnant	Re 1000		Re 1000, LVG	
C-Rate	Air	Air	Oil	Air	Oil
1	32.7	30.5	27.6	29	27.3
5	49.2	47.1	31.6	36.9	30.4
10	63.5	62.9	41	45.1	36.7

Table 1 Max temperature observed for the battery cell under different discharge rates and cooling configurations

	Max Temperature Difference				
	Stagnant	Re 1000		Re 1000, LVG	
C-Rate	Air	Air	Oil	Air	Oil
1	0.1	0.3	0.3	0.02	0.03
5	0.7	1.9	2.4	0.07	0.06
10	1.6	3.24	7.06	0.15	0.75

Table 2 Max temperature difference observed across the battery cell under different discharge rates and cooling configurations

	Temperature Standard Deviation				
	Stagnant	Re 1000		Re 1000, LVG	
C-Rate	Air	Air	Oil	Air	Oil
1	0.025	0.1	0.07	0.003	0.007
5	0.17	0.5	0.62	0.018	0.078
10	0.41	0.78	1.87	0.033	0.22

Table 3 Standard deviation of the temperature observed for the battery cell under different discharge rates and cooling configurations

The results from Table 1 clearly present an improvement in cooling capacity from the use of the dielectric, mineral oil. The maximum temperature is reduced by 10% for the case of 1C and 35% for the case of 10C. However, temperature uniformity is not improved, rather, it decreases with the use of oil cooling, as indicated by Tables 2 and 3, an effect that can be explained by the smaller thickness of the thermal boundary layer of the oil coolant.

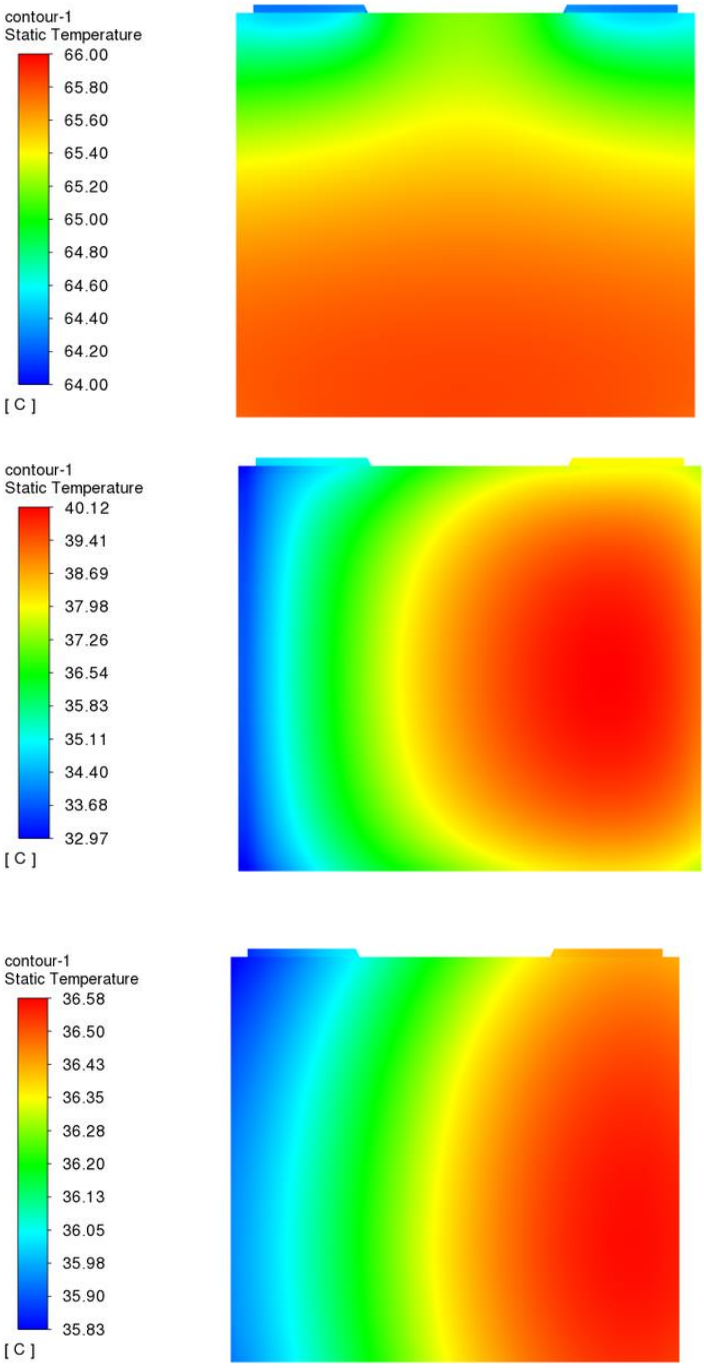


Figure 3 Temperature contours for stagnant air (top), oil cooling (middle) and oil cooling with LVGs (bottom). Discharge rate 10C.
(Colormap adjusted to local scale for each case)

To further improve the cooling capabilities of the proposed BTMS that employs a dielectric oil as the working fluid, the simulations are repeated with two pairs of LVGs placed upstream of the battery cell as described earlier. It is observed from the results reported in Tables 1-3 that the presence of LVGs acts in favour of both maximum temperature reduction and temperature uniformity, not only for the dielectric oil but also for air. Maximum temperature is reduced for air by 5% and 28% for the cases of 1C and 10C respectively. For the dielectric oil, the respective maximum temperature reduction is 2% and 10%. Although for the case of the dielectric oil further reduction of the maximum temperature is limited, especially for the low discharge rates, there is significant improvement with regards to temperature uniformity. For all cases, LVGs delivered a temperature uniformity of less than 1°C. As depicted in Figure 3 and reported in Table 2, for the case of 10C, the BTMS with dielectric oil and LVGs presented a maximum temperature difference of 0.75°C.

The benefits with regards to maximum temperature reduction and temperature uniformity due to the presence of the LVGs can be qualitatively explained by the contours of axial vorticity, presented in Figure 4. The LVGs create and sustain a secondary flow pattern of linear vortices that travel downstream, interacting with the laminar boundary layer developed around the battery. This interaction promotes mixing in the area close to battery walls, resulting in heat transfer enhancement. In the left part of Figure 4, the presence of the linear vortices is evident, especially compared with the BTMS that does not incorporate LVGs (right part of Figure 4).

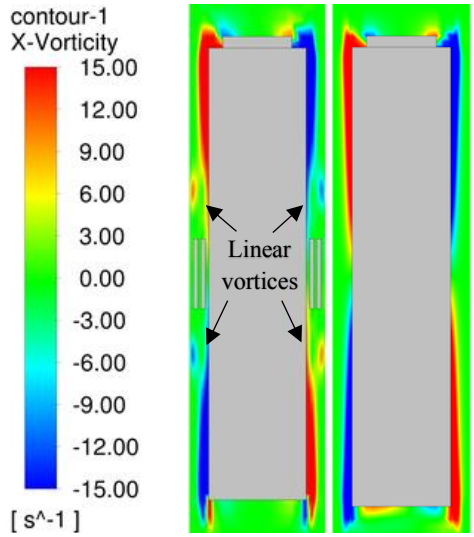


Figure 4 Contours of axial vorticity: BTMS with LVGs (left) and without LVGs(right).

The process of battery discharging (and charging, of course) and the associated electrochemical/thermal phenomena are transient. For that purpose, it also has merit to present the evolution of the maximum temperature with respect to time. These curves are given in Figure 5. The top part of the figure presents maximum battery temperature over time for the case of 1C, while the middle and bottom parts of the figure correspond to 5C and 10C respectively. As expected, air cooling without LVGs could only be a potential option only for very low discharge rates, as it cannot cope with the cooling requirements of increased C-rates. With the use of LVGs, however, even the

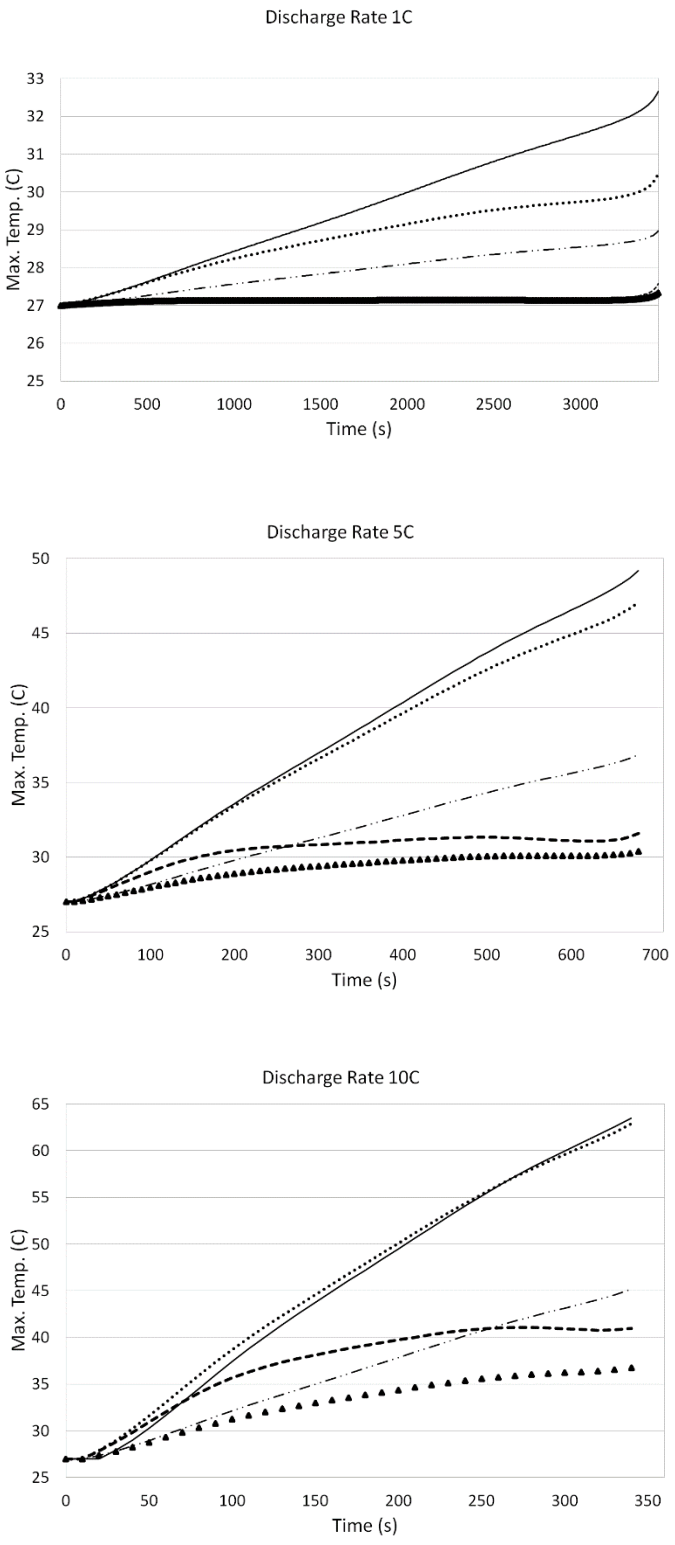


Figure 5 Variation of max temperature for 1C (top), 5C (middle) and 10C (bottom).
(Stagnant Air: ▬, Air at Re 1000: ●, Oil at Re 1000: ▬ ▬, Air at Re 1000 with LVGs: ▬ ●●, Oil at Re 1000 with LVGs: ▲)

cooling performance of air is increased for low and medium C-rates. For the case of the mineral oil, the cooling capabilities are evident for all discharge rates. The cooling performance is maximized with the presence of LVGs, rendering the respective BTMS an excellent choice for all C-rates. Finally, an important observation is the increased battery cell temperature that is reported during the first 200-300s for the case of the oil flow with and without LVGs and is evident in the temperature curves of 5C and 10C. Especially for the case of the oil without LVGs, the battery cell shows higher temperature during this time compared to the case of air with LVGs. The line plots indicate that, for the specific oil-based coolant, the battery cell reaches its maximum temperature at a relatively early stage and maintains this temperature until it is almost fully discharged, with small variations.

CONCLUSION

The work presented in this paper summarizes the first steps of the IBAT project towards a novel immersion/direct cooling BTMS employing dielectric, oil-based coolants with additives and LVGs to enhance heat transfer and increase the overall cooling performance. For the purposes of this study, a single, prototype, prismatic battery cell, immersed in an oil-based coolant was examined numerically within ANSYS Fluent, with and without the presence of LVGs. The results were compared with air cooling for three different battery discharge rates (1C, 5C, 10C) in terms of maximum temperature, temperature uniformity and temperature standard deviation.

First, the use of an oil-based coolant greatly lowered the maximum temperature on the battery cell. Especially for the case of 10C, the maximum temperature due to the oil-based coolant was reduced by 35%. However, temperature uniformity was not sufficient, and, in fact, air cooling presented better temperature uniformity despite the higher temperatures.

The use of LVGs offered significant benefits to the temperature uniformity for both coolants, while also offering some additional temperature reduction. The LVGs created and maintained a flow pattern of linear vortices that disturbed the boundary layer close to the battery cell, promoting flow mixing and enhancing heat transfer. The use of LVGs resulted in a temperature variation of less than 1° C in all reported cases. LVGs contributed to further reduction of the maximum temperature of the oil-based cooling BTMS by an additional 10% for the case of 10C, while significantly assisting in its temperature uniformity.

FUTURE WORK

The next steps of the IBAT project with regards to the numerical investigation of the novel immersion/direct cooling BTMS include the addition of the viscoelastic effects of the oil-based coolants through dedicated numerical models, the application of the methodology in a module of prototype battery cells corresponding to the battery pack arrangement and the design optimization of the shape, number and position of the LVGs to maximize heat transfer.

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