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Thermal Direct Oil Management of Power Electronics in Electric Mobility

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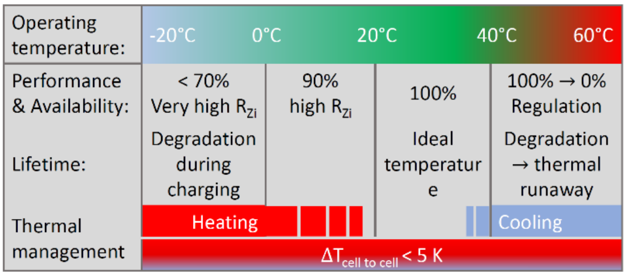
Abstract
Efficient thermal management technologies in electric mobility promote sustainable transportation. The energy-efficient and lightweight direct cooling and heating of batteries, inverters and motors are enabling principals to achieve high power densities in the powertrain. Silicone oil is a key resource in terms of thermal, viscous and dialectical characteristics. The target is to integrate the necessary cooling through direct contact with the cooling liquid and the electrical conducting parts. This direct contact eliminates the need for a thermal conductor and electrical insulator between the metal and liquid and uses the sealed battery housing as a reservoir. The outlined concept is based on silicone oil direct cooling and heating in the housing of lithium-ion 18650 battery cells with an integrated thermoelectric element. The proposed setup is validated in two electrical motorcycles ethec alpha and ethec city from ETH Zurich.

Keywords: Direct oil cooling, battery, thermal management, motorcycle

1. Introduction

According to the European Green Deal [1], transport-related greenhouse gas emissions should be reduced by about 90% by 2050. To achieve these ambitious targets, further improvements in climate-neutral transportation are necessary. Electric mobility is one key asset in this plan. Electrical systems that are operated at high power have to be cooled to dissipate the power losses in the form of heat. The choice of the cooling medium is usually a liquid, which is superior to air, thanks to its heat capacity and heat conduction properties. For example, Ushakov et al. [2] stated that transformers between 10 to 630 kVA are cooled with oil. The oil used in such transformers is either mineral oil-based or synthetic insulating fluids as described by Küchler [3]. Due to the advantages of synthetic insulating fluids over mineral oils, such synthetic fluids are considered. More precisely, due to their properties, particularly suitable silicone oils will be taken into account.

Lithium-ion (Li-ion) batteries are used for electric vehicles (EVs) and hybrid electric vehicles (HEVs) because of their high power density, high energy density, and low self-discharge rate compared to other battery technologies. The optimal operating temperature of a Li-ion cell is around 25°C. As can be seen in Figure 1, the internal resistance increases at temperatures below 20°C, which leads to a strong reduction in performance and degradation as described by Jaguemont et al. [4]. Furthermore, at temperatures above 50°C, the electrolyte in the cell begins to evaporate, which contributes to cell ageing. In addition, at even higher temperatures, oxygen can be released from the active material, which together with the electrolyte can cause the cell to ignite. This process is called thermal runaway. Ma et al. [5] described the temperature distribution inside the Li-ion cells itself for a better understanding of the resulting effects in cylindric cells. The temperature gradient inside the cell should also be as low as possible to enable the best electrochemical reaction. Furthermore, cylindrical cells have different heat transfer coefficients in the axial and radial directions due to their layer distribution. Cen et al. [6] also described the integration of the thermal management of the battery module in the vehicle's air conditioning. Therefore, the maximum temperature difference of 64 pieces of 18650 cells is around 2 K.



Operating temperature:	-20°C	0°C	20°C	40°C 60°C
Performance & Availability:	< 70% Very high R_{Zi}	90% high R_{Zi}	100%	100% → 0% Regulation
Lifetime:	Degradation during charging		Ideal temperature	Degradation → thermal runaway
Thermal management	Heating			Cooling
	$\Delta T_{\text{cell to cell}} < 5$ K			

Figure 1: Relationship between operating temperature, thermal management and lifetime according to Korthauer [7]

Patil et al. [8] discussed the mineral oil direct cooling simulation for pouch cells. Chen et al. [9] compared the direct liquid cooling with mineral oil to air, indirect liquid and fin cooling for Li-ion pouch cells. Whereas pouch cells have a bigger surface and better geometry for cooling. The results show that due to the direct contact between the coolant and the battery the lowest mass flow rates are necessary. Trimbake et al. [10] reported experimental results of the mineral oil bath and full immersion cooling of 18650 cells in a 4S1P circuit with different C-rates. Furthermore, Camilleri et al. [11] analysed the arrangement influences on the heat transfer coefficient for direct cooled 18650 battery packs. Especially the flow direction of radial and axial to the cylindric cells are discussed.

Direct oil cooling is also applied to other components of the electric powertrain. High power densities in electric motors bring new challenges for thermal management due to their high loss densities. Gai et al. [12] compared the different cooling methods of traction motors and states one of the highest heat transfer coefficients of a direct forced liquid-cooled motor. However, there are challenges in the manufacturing of these cooling arrangements in stator and housing. Axial-flux permanent magnet (AFPM) motors are becoming relevant, especially in electric mobility due to their high-torque-density and high efficiency. Liu et al. [13] described the analysis and design of such an AFPM with oil-immersed stator cooling. The challenges in the design of such a compact motor cooling system are validated and the effectiveness of the oil-immersed stator cooling is elaborated.

2. Method

The efficient thermal management of batteries is achieved through oil, integrated into a suitable direct cooling circuit. Therefore, it is important to have good electrical strength and good insulating properties. The advantages of synthetic insulating fluids over mineral oil are mainly their thermal resistance, low flammability, environmental compatibility and non-hazardousness to water. An example of such a synthetic insulating fluid is silicone oil. It consists of linear polymers, which have a limited length and are without spatial cross-links. Furthermore, it is characterised by a high flash point of usually more than 300°C and a high burning point of more than 335°C. In addition, it is chemically stable in terms of ageing and heat and has a low viscosity range available. It is also chemically stable and thus resistant to ageing, even in the presence of air. Compared to mineral oil, however, the heat transfer properties are less favourable, but it is considered ecologically harmless. The following section elaborates on the required principles in depth.

2.1 Silicone oil

Silicone oils are mainly characterised by their kinematic viscosity as shown for a 5 mm^2/s oil in Table 1. This kinematic viscosity is given in the production of the oils by the length of the molecules. In addition, the volatility and thus also the flashpoint is directly coupled with the viscosity. The lower the kinematic viscosity, the more volatile the oil and the lower the flashpoint. For example, the point at which an ignitable vapour-air mixture can form. The electrical or insulating properties of the oils are mainly constant across the different viscosities. In addition, the dielectric strength, dielectric constant and contact resistance values are suitable for high voltage applications. The thermal properties, such as specific heat capacity and thermal conductivity, are less suitable for cooling compared to water. However, compared to air, they are still much higher and therefore more suitable for efficient cooling and heating. There are also some other critical properties to consider. The surface tension is directly coupled with the creep ability. Thus, thin-bodied oils are creeping and volatile. This must be taken into account when designing the housing. In addition, the low-viscosity oils are also not optimally compatible with the environment, in particular, they have aquatic toxicity. In conclusion, it can be stated that an optimal silicone oil for use in direct oil application has a viscosity of approx. 1-5 mm^2/s. The negative properties of low-viscosity oils are largely eliminated and viscosity properties similar to those of water prevail.

Viscosity at 25°C	5 mm^2/s
Specific gravity at 25°C	0.91 g/cm^3
Flashpoint at (closed cup)	120 °C
Surface tension	19.7 mN/m
Expansion coefficient	$1.15 \cdot 10^{-3}$ cm^3/cm^{3}K
Specific heat	>1.63 J/g
Thermal conductivity	0.12 W/mK
Dielectric strength	14 kV/mm
Volume resistivity at 25°C	$1 \cdot 10^{15}$ ohm/cm

Table 1: Characteristics of the proposed silicone oil

2.2 Battery cooling

Battery cells always have an inner power loss. The cell must be possible to dissipate this heat. Figure 2 shows five basic cooling concepts based on pouch cells as described by Korthauer [7].

Air cooling is one of the simplest methods of tempering. Here, the cooling air flows around the free surfaces of the cell. Handling the cooling medium air and the cell is relatively unproblematic. The cooling capacity of the system is limited by the heat capacity of the air and the heat transfer coefficient.

In bottom cooling, a liquid is used as the cooling medium, which absorbs the heat via the bottom of the cell. The relatively good heat conduction coefficient of the metallic current conductors can be used to transport the heat in the axial direction via this. The interface with the cooling system is more complex, as the cooling apparatus is best located in direct contact with the electrical components of the battery. As the highest temperature arises around the poles, this method is less efficient.

Side cooling can be implemented actively or passively. In this case, the heat is transported to the outside via the different layers of the cell. This direction of heat transport is not as efficient as in the axial direction. The layers of the separator and the active materials, which do not conduct heat as well as the current conductors, must always be overcome. However, due to the usually larger surface area of the sides, a large heat flow can also be transported away.

Arrester cooling takes advantage of the direct contact with the electrical conductor and its good thermal conductivity. It thus uses the same principle as bottom cooling but is also more complex to implement.

These methods are usually used in combination, since, for example, in a cylindrical cell the sidewalls of the cell also form the arresters. In this case, both the sidewalls and the arresters are cooled in parallel.

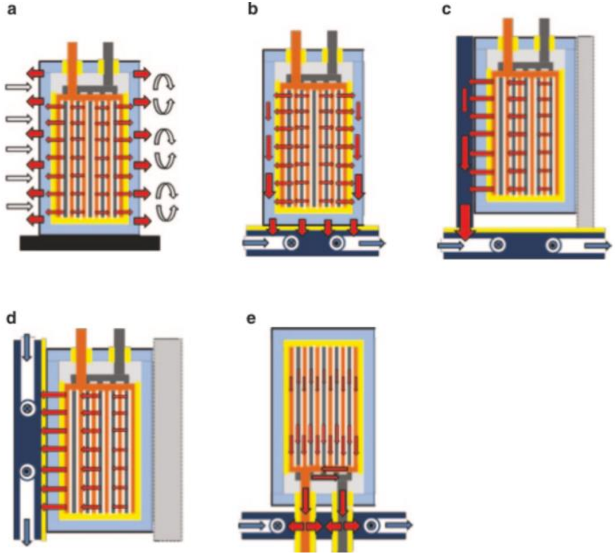


Figure 2: Principle concepts of cell cooling according to Korthauer [7]: a) air cooling, b) bottom cooling, c) side cooling (passive), d) side cooling (active), e) arrester cooling

2.3 Flow analysis in the battery

The battery cells are arranged hexagonally, as this achieves around 13 % better space utilisation than a square arrangement. A uniform flow around the cell must be achieved so that heat can be dissipated from all cells uniformly. As can be seen in Figure 3, there are still discontinuities in the flow velocities in the lower rows of the battery cells. Due to the influence at the front of the battery, the velocities in the rear part of the battery are higher than in the front. Nevertheless, the velocities are also higher in the front part, at the bottom left of the figure, than in the middle of the battery. This is also due to the asymmetric shape, as the average flow velocity is reciprocal to the flow cross-section due to the conservation of mass of an incompressible fluid. The narrower lower part of the battery, therefore, increases the average velocity. After a few rows of cells, a uniform flow is established and the velocity between the cells is constant across the entire width. A close examination of the data shows that the average velocities over the cell surfaces are 95+/-2 mm/s for all cells. To achieve a more uniform flow in the edge areas, inlet areas are constructed from polymethylmethacrylate.

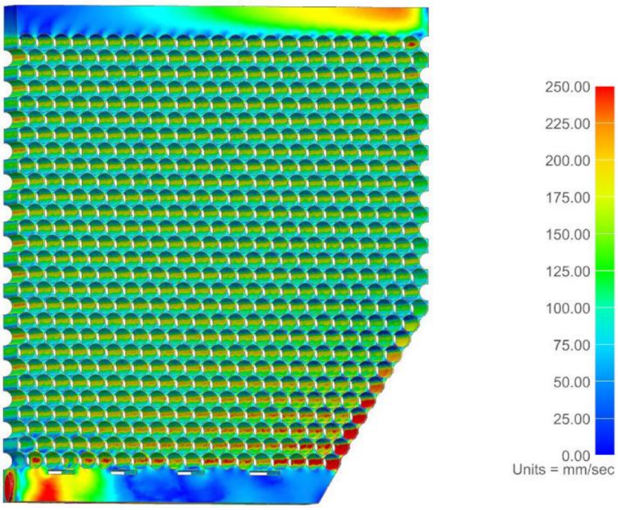


Figure 3: Flow rate of the silicone oil in the battery pack of ethec alpha

It is also necessary to consider the peripheral areas, as the degradation of the weakest cell in a parallel circuit is critical for the degradation of the entire battery. If the critical cell also has a minimum speed of cooling or heating flow, all cells age at about the same rate. Care must be taken to ensure that the cells have approximately the same temperature at the inlet and outlet. The black area in the left illustration of Figure 4 represents the insufficient velocity. This means that in these areas the oil flows only very slowly or not at all and therefore the cells are not conditioned sufficiently. This was adjusted by optimising the wall distance in the figure on the right.

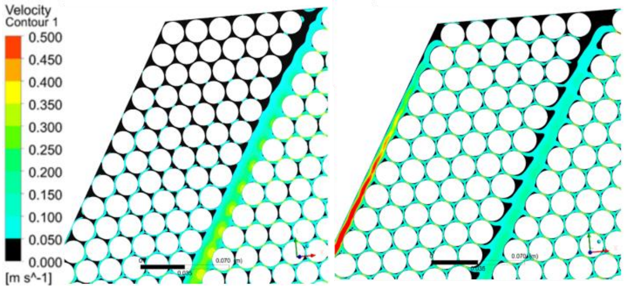


Figure 4: Comparison for different edge distances from 0 mm left to 5 mm right for ethec city

3. Results

The method is validated for the electric motorcycle prototype ethec alpha and ethec city. These motorbikes have a wheel hub motor on the front and rear wheel. The battery, the inverter and the other power electronics are located between the wheels under the seat, as can be seen in Figure 5. The battery of the ethec alpha with its 15 kWh capacity takes up most of the space. It consists of 1260 Samsung INR18650-35E cells in a 28S45P circuit. The battery cells are arranged in 28 rows with 23 columns each. This results in 644 possible cells per block, of which 630 are used. The lid is attached at eight points and the temperature is measured at six points within the block.

Figure 5: Electric motorcycle ethec alpha

3.1 Thermoelectric cooling and heating

Peltier elements generate a heat flow when the current is connected. The elements are placed in housing with a ribbed surface. Silicone oil flows around one side and a water-glycol mixture around the other. The direction of the current in the Peltier elements can be reversed, which means that the battery is no longer cooled but heated. The heat is also dissipated to the environment via a cooler. The cooler consists of 8 cooling channels with 3 Peltier elements per gap. The Peltier elements have dimensions of 50 mm x 50 mm x 3.75 mm. The inner sides of the cooling channels will be provided with cooling fins to enable a greater cooling capacity. The housing is additively manufactured from aluminium using a laser-sintering process. During design, the fins must therefore be angled at 45°, otherwise, the enclosure cannot be finished without support material. The Peltier elements are placed and connected from below in the enclosure. Four temperature sensors are also placed in the enclosure. The two fluids flow through the channels in opposite directions and have their inlet on the sides opposite each other and the outlets at the top.

3.1 Thermal management performance

The maximum load case of a motorway journey at an outside temperature of 30°C results in energy demand on the engine of 7.1 kW, which in turn requires a cooling power of 2 kW from the entire system to be able to keep it at the optimum temperature. Furthermore, the battery can be heated from 0°C to 21°C within about 4 minutes. This value again reflects the efficiency of the management system. With Peltier cooling, a lightweight and modular cooling concept without moving parts are found. The battery management system (BMS) is also integrated directly into the battery housing as shown in Figure 6.

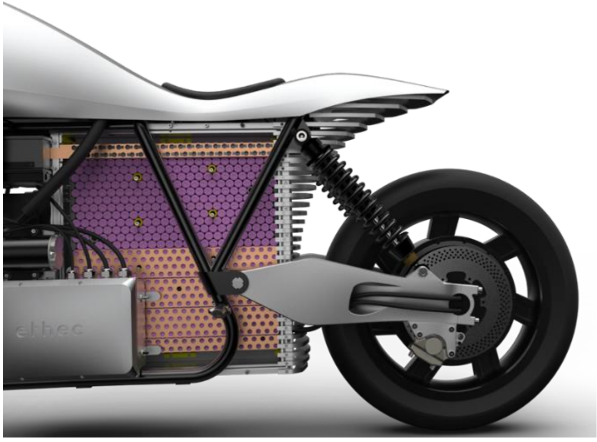


Figure 6: Battery cell placement in the module of the ethec alpha. The BMS is behind the inverter.

Voltage measurement can therefore be carried out quickly and accurately and ensure the safe operation of the cells. By using self-developed and optimised circuit boards, the required installation space could be drastically reduced. Heat dissipation during the balancing is significantly simplified on the voltage measurement circuit board, as balancing also takes place directly in the oil.

3.2 Reliability

An important point in the cooling of drives in electromobility is reliability and sustainability. The entire system as shown in Figure 7 must be able to fulfil its function for the entire service life and lifetime. Another consideration when cooling with silicone oil is potential particles in the liquid. These particles are substances or materials that affect the insulating properties of the oil. This failure can occur due to a specific action or due to the ageing of the system. The most important thing to detect such a fault is to measure the electrical breakdown and resistance of the silicone oil. Based on this measurement, measures such as filtering the oil in the circuit or replacing the oil completely can then be derived.

Environmental compatibility always plays a role in mobility applications. In the event of an accident, larger quantities of silicone oil may be released into the environment. The viscosity of the silicone oil should be selected so that there is no acute danger to the environment. Furthermore, the cooling circuits should be planned in such a way that in the event of an accident, not all the liquid can leak out. This is also desirable from a thermal engineering point of view, as otherwise there is a risk of the cells heating up considerably without oil.

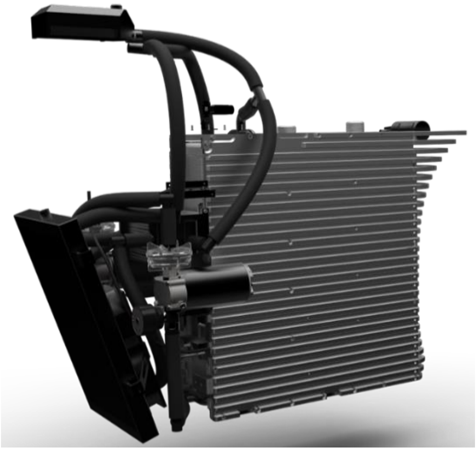


Figure 7: Visual representation of the whole battery cooling system of ethec alpha

The sealing is a manufacturing difficulty when cooling directly with oil. To seal the housing of the ethec city as illustrated in Figure 8, a different method was used than for the ethec alpha. The housing could only be opened from the top, whereas the covers of the ethec alpha are mounted on the side walls. With the ethec city, it is therefore still possible to open the battery after the oil has been let in. With the ethec alpha, the silicone oil tries to escape from the housing, whereas with the ethec city, the oil only wants to escape when the pump is switched on.

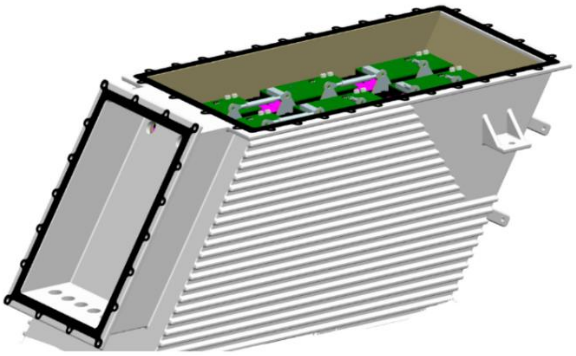


Figure 8: Necessary seals for the direct oil cooling in ethec city

4. Discussion and Outlook

The thermal management of a Li-Ion battery in electric mobility is elaborated. The properties of silicone oil in the direct cooling circuit are shown for electric motorcycles. One main challenge is the long-time compatibility between the oil and the components in the circuit. Furthermore, the main goal is efficient cooling and heating of the power electronics and to ensure a low degradation of the 18650 cells. There are also alternatives available as silicone oil. Wu et al. [14] also describe liquids like Novec700 for the direct cooling of electronics. Sustainability goes hand in hand with the environmental compatibility, lifetime and carbon footprint of the used components, methods and the whole system.

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