

# Preliminary assessment of a two-phase direct cooling of Lithium-Ion battery pack for e-bike mobility

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**Abstract.** Electric mobility is playing an increasingly central role in emission reduction policies to mitigate climate change effect. During the operation of electric vehicles, the batteries may be subject to high variation of the required current, which can lead to a sudden increase in the cell temperature. If this condition occurs repeatedly, there would be a reduction in battery capacity and useful life, and autonomy reduction of the electric vehicle. In the worst case, this problem can lead to the thermal runaway. Therefore, cooling of electric vehicle propulsion systems is a fundamental issue for the electric mobility development. In this article we propose an innovative cooling system using a dielectric low boiling fluid in which the batteries are directly immersed. The system was tested on an electric bicycle under real operative conditions. A special test bench was realized, consisting of a real electric bicycle, a training roller to simulate the load due to road slope and an external electric motor to simulate the pedaling of the cyclist. The results show a substantial decrease in the temperature of the cells with the proposed cooling system and there was a marked improvement in the temperature uniformity of the cells inside the battery pack.

## 1. Introduction

Electric vehicles (EVs) are keeping increasing attention by the transport manufacturer because of the central role they play in the reduction of fossil fuel consumption. This trend is even more emphasized by the common interest in the global warming and environmental pollution. Over the last years there was a wide diffusion of electric vehicles not only in the automotive sector, but also other applications, such as electric bike, scooter, and marine transport [1].

Lithium batteries (Li-ion) is the most common power supply option for EVs. They have several advantages: lower weight, higher specific power and energy density, longer life cycle, and lower self-discharge rates [2, 3]. However, they could be subjected to high temperature increase during their functioning due to electrochemical heat generation. The consequence is a reduction in electrical performance and lifetime. Furthermore, a very dangerous consequence is the thermal runaway that could occur if the batteries work at extreme temperatures, or if subjected to electrical or mechanical abuse [4].

In this context, the batteries thermal management is a fundamental topic in the development of EVs and to overcome safety problem of EVs. Several studies addressed this problem focusing on the design of an effective battery thermal management system (BTMS).

Due to their simplicity and cost-effectiveness, air cooling systems are often adopted, both in natural and forced convection, in low power applications. They are usually combined with system to enhance heat transfer such as heat sinks, pin-fins, pulsating heat pipe (PHP) [5-7]. However, air systems have a lower heat transfer coefficient and heat capacity. Using a liquid could be a solution to this problem since the higher thermal capacity. Indirect liquid cooling, single-phase or two-phase, were deeply studied [8, 9]. The problem of this solution is the limited surface contact area, and the thermal resistance between the surfaces in contact.

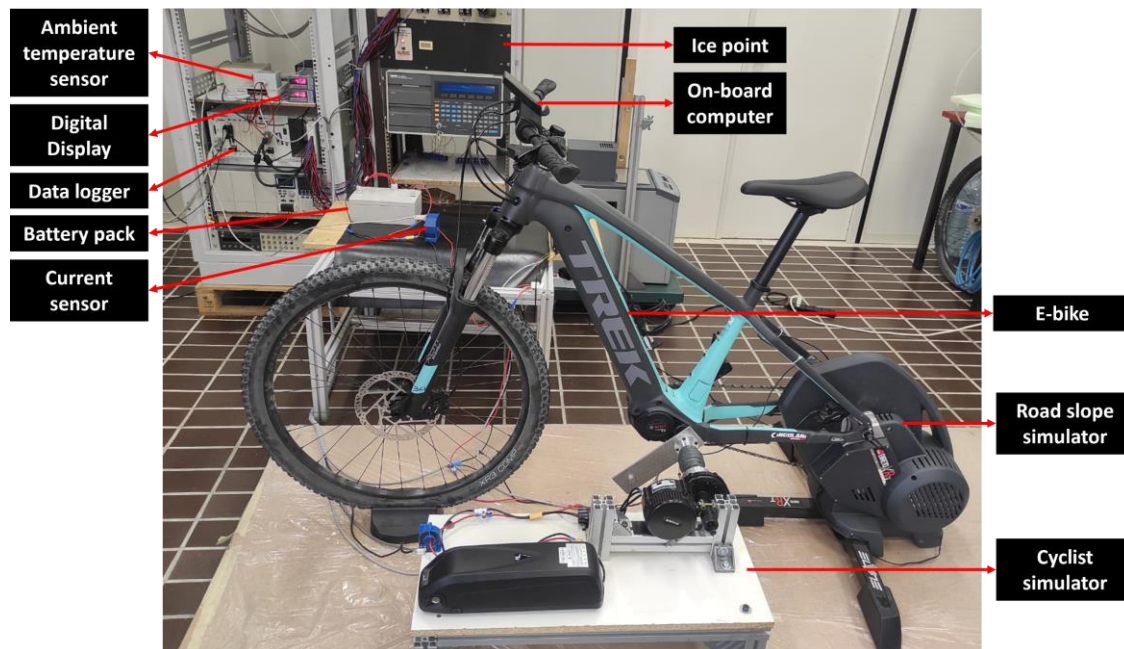
Direct contact liquid cooling is a promising solution since the batteries are directly immersed in a dielectric fluid. In this case the advantages are: (i) thermal power generated is directly transferred to the coolant avoiding the thermal contact resistance problem, (ii) larger heat transfer surface area [10]. Wu et al. [11], used a silicon oil and obtained a temperature 20% lower than the indirect liquid cooling. Patil et al. [12], study the effect of static and flowing condition on a large-format pouch cell. Wu et al. [13], noted a substantial reduction of maximum temperature and a higher temperature uniformity by submerging a pouch cell into a low boiling dielectric liquid. Jithin and Rajesh [14], numerically show the effect of three different dielectric coolants on a 1P4S battery pack. Williams et al. [15] experimentally investigated a direct liquid cooling on a small battery pack under several discharge rates and both in single and double phase natural convection.

The system proposed in this paper is based on three fundamental points: (i) the batteries are directly submerged in a dielectric fluid ensuring the maximum heat transfer surface; (ii) the fluid has a low boiling point in order to create a thermal buffer for the heat power peaks generated by high electric power requirement; (iii) the system is totally passive, avoiding any other electric consumption to move the fluid inside the battery pack. A passive cooling system is particularly attractive for electric vehicle. Indeed, the energy requirements of the battery cooling system weighs on the battery itself, resulting in a higher discharge rate and a lower range for the EVs. Furthermore, the battery undergoes a higher number of charge-discharge cycle reducing the operative life and thus must be disposed and replaced earlier, with clear environmental consequences. In previous works the system was tested on a single cylindrical cell [16] and on a small battery pack [17] under several rates of discharge using an electronic load. However, the discharge current was always set to a specific and constant value. Instead, in this paper, our aim is to test the system in real operating conditions for the first time. For this purpose, a special test bench was realized, consisting of a real electric bicycle (e-bike), a training roller to simulate the load due to road slope and an external electric motor to simulate the pedaling of the cyclist. A 5P10S battery pack was realized with similar dimensions and electrical characteristics to a real e-bike battery and it was tested with the dielectric low boiling fluid inside the container. The results were compared with the case without dielectric fluid.

## 2. Experimental setup

Four macro elements composed the test bench (Fig. 1): the e-bike, the battery pack, the road slope simulator, and the simulator of the cyclist pedaling.

The e-bike is the Trek model Powerfly 4 Gen 3 equipped with a Bosch power train. The electric motor (Bosch Performance CX Line) has a maximum torque of 85 Nm, a maximum continuous power of 250 W, and a power peak of 600 W. It is supplied by the Bosch PowerTube



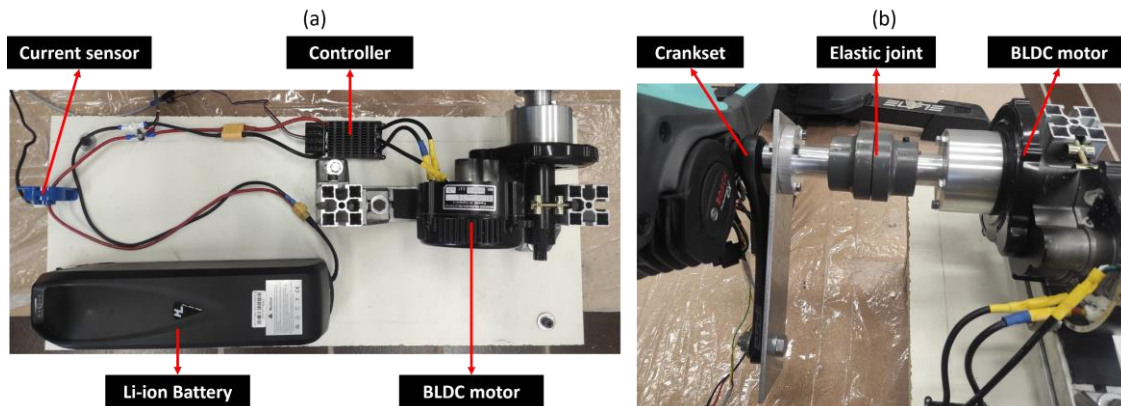
**Figure 1.** Experimental setup.

625 with a nominal voltage of 36 V and a capacity of 16.7 Ah. The on-board computer (Bosch Nyon) allows to monitor the performance of the cyclist in terms of cadence, mechanical power to the pedal, and travel speed. These data are acquired by the on-board computer every second and transferred to the software eBike Connect by bluetooth connection. Furthermore, it is possible to set four different levels of electric support.

The battery pack was composed by 50 cells arranged in a 5P10S configuration in order to obtain the same voltage and similar capacity of the original battery of the bicycle without overcome the volume occupied by the original battery. The cell is a cylindrical NMC (Lithium nickel cobalt manganese oxide) battery model 18650 (height 65 mm and diameter 18 mm) with a weight of 46 g. The nominal cell voltage, maximum voltage, and nominal capacity were 3.7 V, 4.2 V, and 2.85 Ah, respectively. The battery pack is composed of 10 cells in series and 5 cells in parallel resulting in a nominal voltage of 37 V and a capacity of 14.25 Ah. The battery pack was placed inside a hermetic container. The gap between the battery pack and the internal wall of the container is 10 mm on each side, while the ratio between the external surface of the container and the battery pack is equal to 0.6.

The road slope was simulated by an Elite training roller model Direto XR-T. It allows to replicate a maximum road slope of 24% that can be set to a fixed value, according to a variable cycle or following the real conditions of a route. The system has an integrated power meter and cadence sensor. The power meter allows to measure the total mechanical power of the cyclist and the e-bike motor. The roller can be managed by the relative software (My E-Training) which allows to set the road slope and acquires the sensor data (mechanical power, cadence, and travel speed) once per second.

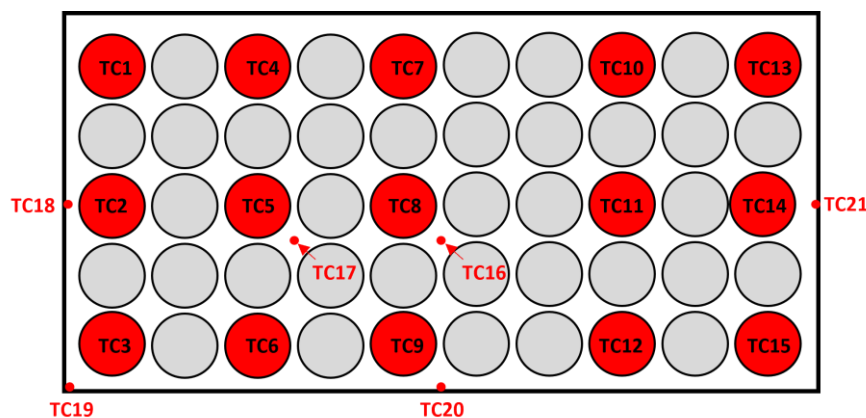
The cyclist's pedaling simulator is composed of an external DC brushless electric motor (Bafang model BBS02B) and an electronic controller. The motor has a nominal power of 500 W and a maximum torque equal to 110 Nm. It is supplied by a lithium battery pack of nominal



**Figure 2.** (a) Cyclist's pedaling simulator system; (b) motor shaft connection to the e-bike.

voltage 36 V and capacity 15.6 Ah. The motor is controlled by an ESC (Electronic Stability Control) FlyFun model HV130A OPTO V5 able to vary the power supply to the motor according to a PWM (Pulse Width Modulation) signal. The PWM signal was generated by the NI PXI-6289 device and allows to change the power supplied by the external electric motor. The motor shaft was finally connected to the crankset of the e-bike by means of an elastic joint. The system used to simulate the cyclist's pedaling is shown in figure 2.

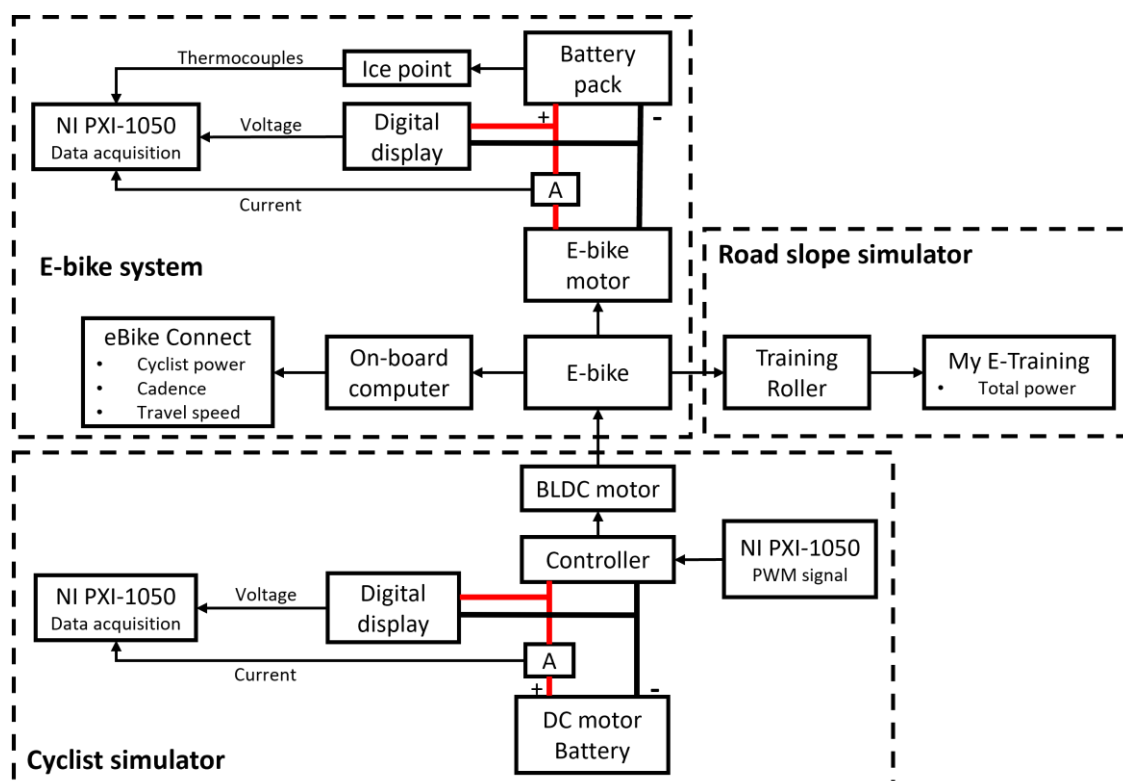
Two current transducers were used to measure: the operating current supplied by the e-bike battery and that sunk by the external electric motor. The first has an uncertainty is  $\pm 0.02$  A in the range  $\pm 85$  A; the second has an uncertainty of  $\pm 2\%$  of full scale in the range  $\pm 100$  A. The Turnigy Reaktor charger manages the charge of the battery, balancing the charge of the cells and applying a typical constant current constant voltage charge (CCCV). Ambient temperature was measured with an uncertainty of  $\pm 0.6$  °C. The voltages of the batteries of the e-bike and external motor were measured by two digital displays equipped with a high voltage module with an uncertainty of  $\pm 0.1\%$  of the reading. The temperature of the cells surface was measured by 15 T-type thermocouples bonded in the middle height of the cells with a high conductive adhesive. Other 6 thermocouples were placed in the fluid between the cells and near the wall of the container at the



**Figure 3.** Thermocouples position inside the battery pack.

same height. The position of the thermocouples is showed in figure 3. Finally, one thermocouple was placed in the centre of the container in the vapour phase. An ice point reference was adopted for the thermocouples before the data logger acquisition. All the thermocouples were calibrated using a high precision bath, obtaining an uncertainty of  $\pm 0.06$  °C.

The on-board computer allows to measure the mechanical power of the cyclist using a torque sensor integrated in the e-bike motor with an uncertainty of  $\pm 1.5\%$  of the reading. The data logger is a NI PXI-1050 equipped with a data acquisition device for voltage signal (NI PXI-6289) and a device for thermocouples (NI SCXI-1303). The sensor signals of the current, battery voltage, and ambient temperature were acquired by the NI PXI-6289 device. The device has a resolution of 0.076 mV and the uncertainty is  $\pm 0.25$  mV. The cadence is measured by a magnetic sensor placed



**Figure 4.** Schematic diagram of the experimental setup.

on the back wheel and this data is used by the on-board computer to calculate the travel speed. The integrated power sensor of the training roller allows to measure the total mechanical power (cyclist and e-bike motor) with an uncertainty of  $\pm 1.5\%$  of measured value. Figure 4 shows a schematic diagram of the experimental setup.

The data measured by the on-board computer and the training roller were acquired at 1 Hz. Other parameters (i.e. thermocouples, ambient temperature, voltages and currents) were acquired at 25 Hz; then the mean values at 1Hz were calculated.

### 3. Results and discussion

The tests were performed with the following conditions: constant road slope equal to 12%, total weight (e-bike and cyclist) of 90 kg, and time duration of 1 h. The external electric motor was set

to a fixed power equal to about 70 W through the PWM signal controller, while the e-bike motor was set to the maximum level of support. The mean resulting cadence was 75 rpm and the mean C-rate of the battery discharge was 0.65C. The same ambient temperature (25 °C) was adopted for all the tests.

The battery pack was placed inside a hermetic container. The test described above was firstly performed on the battery pack with only air in natural convection. Then, the container was filled with the dielectric fluid (Novec 7000) to completely cover the cells, and the test was repeated with the same conditions. Between two tests the battery was charged with a low current CCCV cycle, and enough time was waited for the cells to return to ambient temperature.

Table 1 shows the mean mechanical power of the e-bike motor ( $P_{m,b}$ ), the mean mechanical power of the cyclist ( $P_{m,c}$ ) measured by the on board computer, the mean total mechanical power ( $P_{m,t}$ ) measured by the training roller, and the mean electrical power ( $P_{e,b}$ ) supplied by the battery for the two configurations. It is worth nothing that the e-bike motor mechanical power was calculated as  $P_{m,b} = \eta P_{e,b}$ , where the electrical power was calculated as the product between voltage and current supplied by the e-bike battery pack, and  $\eta$  is the overall efficiency defined as

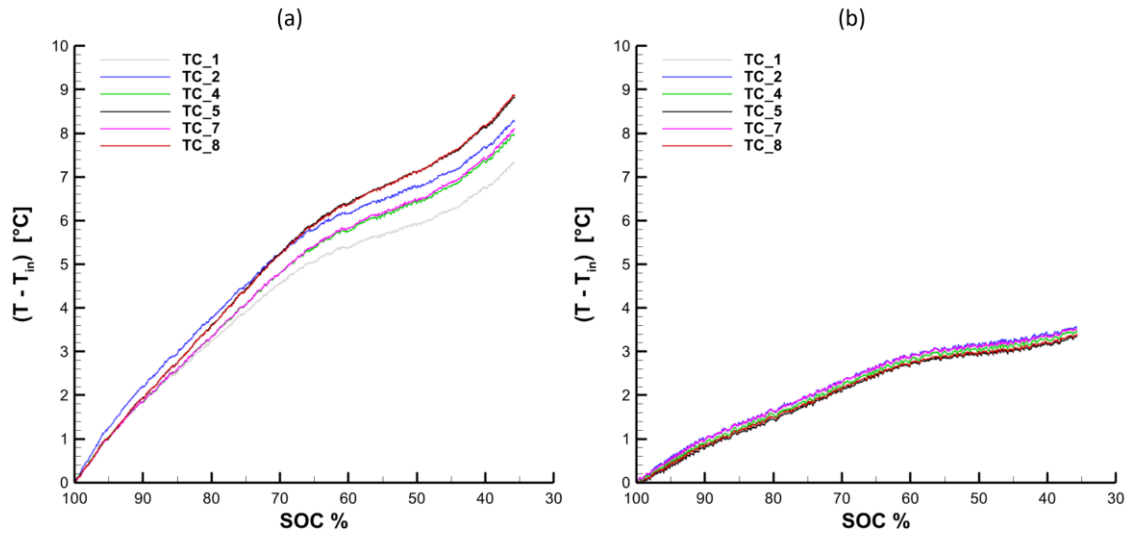
**Table 1.** Mean powers measured during the tests.

	Air	Novec 7000
$P_{m,c}$	70.6 ± 1.1	70 ± 1.1
$P_{m,t}$	347.9 ± 5.3	346.2 ± 5.2
$P_{e,b}$	331.8 ± 3.4	330.9 ± 3.7
$P_{m,b}$	277.4 ± 5.4	276.2 ± 5.3

$\eta = (P_{m,t} - P_{m,c})/P_{e,b}$ . The mean powers measured for the two tests (with and without dielectric fluid) are summarized in table 1. The power data highlight that the same load conditions were respected for the test with air and with dielectric fluid since the measured powers were approximately the same.

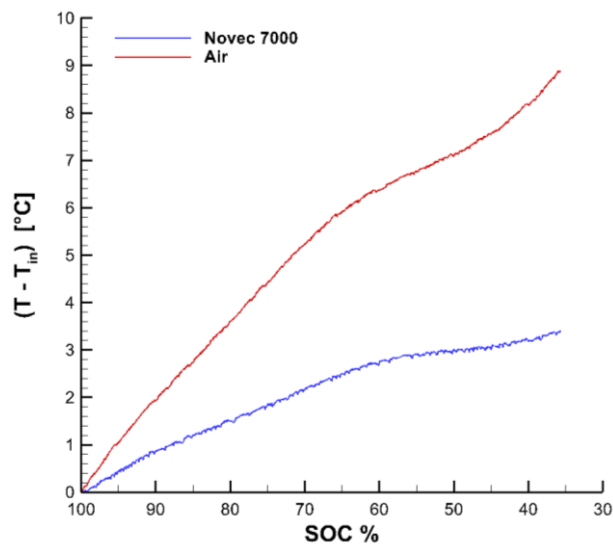
The temperature plot of the cells for the two cases under investigation is showed in figure 5. The temperature of the cells during the test was subtracted to their initial value, in order to avoid the influence of ambient temperature and highlights the temperature rise. Only 6 thermocouples were taken as reference and showed in the graphs. These thermocouples were chosen because the system has two axes of symmetry, and the behaviour of the symmetrical thermocouples was found to be the same. The maximum uncertainty obtained for the thermocouples was equal to ±0.07 °C. This value includes both the instrument uncertainty, and the random uncertainty based on the standard deviation of the measurements.

The figures put in evidence a better temperature uniformity distribution achieved with the dielectric fluid. In this case all the temperatures have similar value with a very small difference by each other. The maximum difference obtained with dielectric fluid was 0.29 °C. Otherwise, in the case without dielectric fluid there are higher differences between the cells. Furthermore, the difference of temperature between the cells measured in the case without dielectric fluid is consistent with the position of the cells: the highest temperature was measured for TC5 and TC8



**Figure 5.** Temperature difference of 6 cells with air (a) and with dielectric fluid (b).

that are in the middle of battery pack and surrounded by other cells on each side; intermediate values was found for TC2, TC4, and TC7 since they are on the side of the battery pack and surrounded on three sides; the lowest temperature is for TC1 which is placed on the corner. Indeed, if the cell is surrounded by other cells there is a mutual heat transfer, and the temperature rise more rapidly. Furthermore, the convective heat transfer is limited by the small space between the cells which are placed in the middle of the battery pack compared with the external cells. Finally, it could be notice that the temperature of TC2 initially rises at a higher rate. This could be explained since the positive terminal of the battery pack is solder near this cell. In both cases the temperature rise more rapidly in the first part of the test; then at about the 60% of SOC there is a change of slope in the curves; finally, the temperature rise again over the 40% of SOC. This



**Figure 6.** Comparison of TC8 temperature difference with air and with dielectric fluid.

behaviour is typical of Li-Ion battery discharge phase and is due to the battery internal reaction [16].

Figure 6 shows the comparison of the temperature measured by TC8 with and without dielectric fluid. It is very clear from the figure the positive effect of the cooling strategy since a lower temperature was reached by the case with dielectric fluid. In this case the maximum temperature difference was 8.5 °C; while, with the dielectric fluid, the maximum temperature difference lightly overcame 3 °C, obtaining a temperature increase reduction of 62% at the end of the test. The lower temperature at the end of the test obtained with the dielectric fluid can be explained by the higher heat capacity of the fluid and the higher convective heat transfer coefficient.

#### 4. Conclusions

In this paper a preliminary experimental assessment of a novel cooling method of Li-Ion battery packs for e-bike under real operative conditions was presented. The batteries are directly submerged in a low boiling dielectric fluid. The proposed system is completely passive since there is no flowing fluid inside the battery pack, avoiding any additional power consumption. Furthermore, the low boiling point creates a thermal buffer in case of high electrical power requirements.

A special test bench was realized, consisting of an e-bike, a road slope simulator and a cyclist simulator. The original battery pack of the e-bike was replaced with a customized battery in configuration 5P10S with volume and electrical characteristics similar to the original battery. The pack was instrumented with several thermocouples placed on cells surface and in the fluid. Other relevant parameters were also acquired to obtain the mechanical power supplied by the electric motor and the cyclist.

Compared with the case of air in natural convection, a significant decrease of the temperature increase during battery discharge was observed. The temperature rise reduction was equal to 62% with the dielectric fluid. Another important result regards the temperature uniformity of the cells inside the battery pack. Indeed, the temperature was more uniform in the case with dielectric fluid. In this case, all the thermocouples measure very close values. Otherwise, in the case without dielectric fluid, there is a higher difference between the cells, according to their position inside the battery pack. Despite the excellent thermal control, the system introduces an additional weight to the e-bike of approximately 1 kg due to the dielectric fluid. However, it is important to remark that the percentage impact on the whole e-bike is only 5%.

The proposed system is capable to effectively control the temperature of the cells in their optimal range. The system could be also applied in other types of electric vehicles such as automotive or lightweight aircraft. In order to face off the higher thermal power to dissipate, in these applications the system could be improved by properly optimize the geometry of the external surface of the container, for example by adding some fins to enhance heat transfer area and facilitating the condensation of the dielectric fluid or by integrating other passive system such as heat pipe or pulsating heat pipe.

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