# Novel battery thermal management enabling near zero temperature gradient for fast charging while improving safety

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**Abstract**:

Lithium ion batteries are powering a revolution in emission-free transport, but a significant opportunity exists in the improvement of their charging time. Fast charging will change the usage of the electric vehicles by enabling several charge and discharge cycles per hour. This will lead to an increased heat load on the cells and thus require an improved cooling system design. The main focus of the paper will be on aspects of immersion cooling and the performance assessment of the dielectric fluid that comes directly into contact with the cells to remove excessive heat generated by them.

**Keywords**:

battery, BEV (battery electric vehicle), fast charge, direct cooling, immersion cooling, thermal management

## 1. Introduction

As the industry is pushing for ultra-fast charging [1], thermal management of the battery is critical to safety. Significant temperature differences between adjacent cells as well as the profile of a singular cell can result in premature aging of battery performance and the potential overheating which can lead to a thermal runaway. One of the strategies being developed to manage temperature as well as mitigating a thermal runaway is immersion cooling [2], which consists of a direct contact of a cold dielectric fluid with the cells, the electrodes and the busbar. The present session will disclose comparative performance tests and abusive tests done in both air and dielectric fluids. As a first step, the heat transfer rate was evaluated according to the heat flux on a heat resistor wall. This preliminary work was presented in a previous paper [3]. Then, a representative battery module with prismatic cells was designed and tested in immersion to assess the cell gradient. In parallel, nail penetration tests were performed in different configurations to determine the capacity to prevent a thermal runaway propagation. A clear status of the potential of the immersion technology from a technical point of view will be established.

## 2. State of the art battery thermal management

Tier 1 automotive manufacturers are developing new products in battery thermal management (BTM) areas ranging from forced air cooling, used in the first electric cars such as the Renault Zoé, to the immersion cooling, now used in concept cars such as the Taiwanese “Miss R” of Xing Mobility. To improve these thermal management systems allowing for faster charging, Tesla Model S uses a water-glycol pumping system and the BMW i3 uses refrigerant boiling in cold plates. As there is an increased heat density removal required for the battery thermal systems, the question of whether OEMs will converge to a single preferred solution collectively or will they operate independently with their own separate cooling strategy? Each of the BTM systems has both positive and negative attributes for their potential use, these pros and cons are illustrated in Table 1.

Table 1: Comparison of BTM systems vs Forced Air

| | Pros | Cons |
|---|---|---|
| Forced Air | - No secondary cooling loop<br>- No leak potential<br>- Simple design<br>- Low cost<br>- Low maintenance | - Low heat transfer<br>- Large temperature variations<br>- Battery vent potential into cabin<br>- No fast charging<br>- Thermal runaway potential |
| Water glycol/cold plate | - Better heat transfer<br>- Better thermal control<br>- Low volume, compact<br>- Known technology | - Low charging rate<br>- Requires system integration<br>- Conductive fluid<br>- Thermal runaway potential<br>- Non-uniform temperature profile |
| Immersion cooling | - Best heat transfer<br>- Uniform temperature profile<br>- Increased battery lifetime<br>- Ultra-fast charging rates<br>- Limits runaway<br>- Potential<br>- Non-flammable<br>- Non-conductive<br>- Increased Packing density | - Higher density fluid<br>- Higher potential cost<br>- Design complexity<br>- Requires a heat sink |

The addition of immersion as a cooling strategy appears to be the latest and most novel approach being applied yet to address this problem. And as such, there are only a limited number of projects to date actively investigating immersion on both its merits and benefits over existing alternatives. The key advantages would make one believe that implementation could happen very soon especially in premium cars designed for fast charging and high performances. This technology adoption would then eventually trickle down to the mass EV market. Indeed, this solution has the unique capability to directly cool all the battery components, not only the cells: electrodes, bus bars, wires, electronics (balancing resistors…) etc. and does not require extra space inside the battery pack. There are no additional requirements of heat exchangers or large ducts, only inlet and outlet ports for the fluid. This will allow other BTM components to be positioned in the most desirable locations to reduce the car's overall footprint.

## 3. Target of this work

The key performance criteria for a battery pack can be established by simultaneously trying to minimize temperature variations (within the cell and between the cells) and maximizing the heat removal capability. To characterize this behavior, with given heat transfer coefficients and surface area, it is necessary to measure heat flowrates, liquid flowrates and cell temperatures across the battery pack for the fluids. The overall thermal resistance essentially dictates both temperature variations that can be observed and heat removal that can be calculated. As seen from these experiments, immersion cooling is capable of significantly improving most of these parameters and enable ultra-fast charging.

This work has been financed by The Chemours Company in order to increase the level of knowledge on their fluid portfolio for the new application that is direct cooling of batteries. In the work presented in this paper, four refrigerant fluids are considered. Three of them are new chemistries, known as Hydrofluoro-Olefins (HFOs), developed specifically as lower global warming potential (GWP) options than the previous HFCs and PFCs for heat transfer applications. Interestingly these fluids show a range of boiling temperature from 33 to 110°C. In addition to these fluids, we benchmarked their cooling performance with an oil having a rather low cinematic viscosity down to 5.1 mm²/s at 40°C

## 4. Cooling performance assessment

### 4.1 Test rig description

A mobile test rig has been developed (Fig. 1 and 2) so that it can be placed in a climatic chamber to assess the performances of the fluids in a wide range of ambient temperatures. In this rig, the dielectric fluid is pumped through a hermetic battery housing containing several dummy cells and one actual cell. After having been in direct contact these cells, the fluids exhaust the battery module, it is then cooled in a plate heat exchanger connected to a chiller. An expansion vessel is used in order to set the pressure in the loop to a desired value: under, above or equal to the atmospheric pressure.

Table 2: Refrigerant fluids from Chemours

| **Property** | **Opteon SF33** | **Vertrel XF** | **Opteon SF70** | **Opteon SF10** |
|---|---|---|---|---|
| | HFO | HFC | HFO | HFO |
| Boiling Point °C | 33.4 | 55 | 70.6 | 110 |
| Freeze Point °C | <-80 | <-80 | <-80 | < -80 |
| Density @25°C g/cm3 | 1.36 | 1.62 | 1.63 | 1.58 |
| Viscosity @25°C cP | 0.38 | 0.58 | 0.75 | 1.12 |
| Heat of Vaporization @BP kJ/kg | 169 | 130 | 98 | 96 |
| Liquid Thermal Conductivity W/m/K | 0.077 | 0.096 | 0.093 | 0.065 |
| Liquid Specific Heat @25°C Kj/kg/K | 1.20 | 0.77 | 0.75 | 1 |
| Coefficient of Expansion 1/K | 0.0019 | 0.0013 | 0.0014 | 0.0015 |
| Flash Point. CC ASTM D56 | none | none | none | none |
| Dielectric Strength. 0.1" gap kV | 11.5 | 32 | 37 | 29 |
| Volume Resistivity Ohm.cm | 5.8E8 | 3.8E10 | 2.1E15 | 2.2E11 |
| Dielectric Constant | 18 | 7.1 | 1.82 | 5.16 |
| Ozone Depletion Potential (ODP) | 0 | 0 | 0 | 0 |
| Global Warming Potential (GWP) | 2 | 1650 | < 20 | 2.5 |

Regarding the battery module, an intermediate approach between testing a unitary cell and testing a complete large battery pack was applied. Thermal behaviors are largely dependent of the scale at which they are studied. Testing a representative sub-assembly of a complete pack was then required and a module with 36 prismatic cells was constructed.

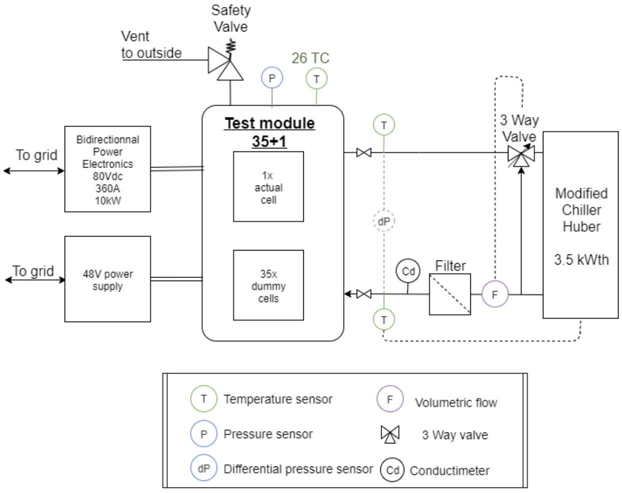

Figure 1: Test rig layout

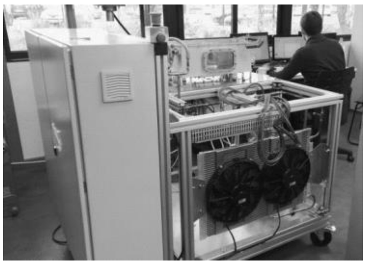

Figure 2: Photo of a version of the test stand equiped with a radiator with fans

35 of the prismatic cells were dummy cells that enclosed heat resistors. One is an actual cell, a 10Ah LTO Toshiba cell. This will allow for a representative thermal behavior without incurring potential safety issues with the use of lithium cells and simplifying the monitoring of the voltage having only one cell to monitor. The heat resistors are supplied with a controlled power supply with adjustable voltage. Having mapped the internal DC resistance of the actual cell, we could reproduce the heating power of the actual cell on the 35 dummy cells.

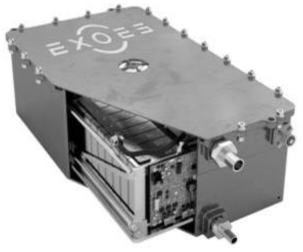

Figure 3: Battery module equipped with prismatic dummy cells

The module is equipped with an inlet and an outlet port to circulate the liquid (Fig 3, 4, 5 and 6). Inside the module the fluid cools the 4 small surfaces of the cells in 1 to 2 mm layers. Hermetic connectors are used for the electric power connection as well as for the numerous temperature sensors. In addition to the sensors on the fluid loop, we use type-T thermocouples located on 4 different cells, including the actual one, so that we could map the module and the actual cell.

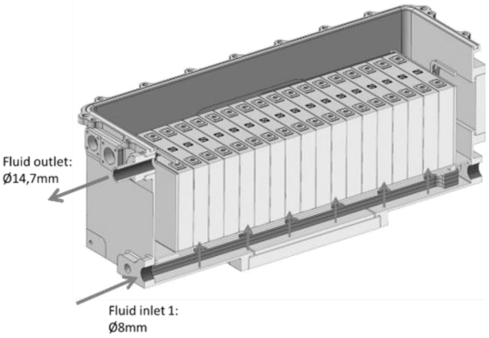

Figure 4: Internal flow pattern

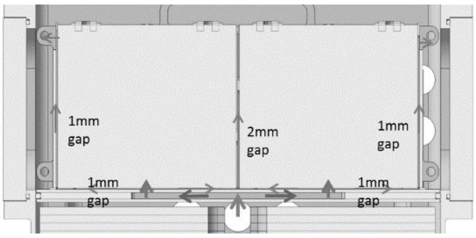

Figure 5: Internal flow pattern continued

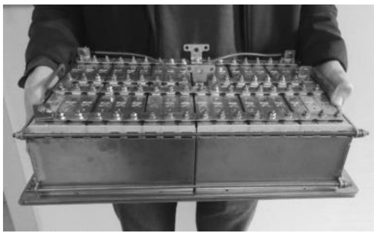

Figure 6: Picture of the cell assembly (notice the actual cell that has prominent busbars)

The electric cycle that has been used is an alternative charge and discharge between to state-of-charge at the same C-rate. The typical charge/discharge duration is between 10 to 60 seconds.

4.2 Data analysis

Among the various results obtained, the focus will be cast on the heat transfer coefficients on different fluids. These coefficients are calculated based on the heat generated - calculated thanks to the internal resistance and the current - and their skin temperature measured in several places as show in equation (1).

$$h_{fluid} = \frac{R_{cell} \cdot I^2}{S_{cell} \cdot (T_{cell} - T_{fluid})} \quad (1)$$

with h heat transfer coefficient, $\dot{Q}$ heat power, S surface, R resistance, I current and T temperature

This heat transfer coefficient largely depends on the local speed and viscosity of the fluid.

### 4.3 Test results

On this test rig we benchmark two different types of fluids: a refrigerant type and an oil (see Table 3).

Table 3: fluid characteristics and performances

| | **unit** | **SF70** | **Oil** |
|---|---|---|---|
| Viscosity @25°C | mPa.s | 0.8 | 6 |
| Liquid conductivity | mW/m/K | 51 | 140 |
| Vol. heat capacity | kJ/L/K | 1.5 | 1.8 |
| Density @25°C | kg/m3 | 1650 | 800 |
| Reynolds @10L/min | - | 640 | 40 |
| Typical heat transfer coefficient - measured | W/m²/K | 200 | 100 |
| Cell superheat to inlet temp. @0.2W/cm² - measured | °C | 10 | 19 |
| Max heat flux to keep battery DT below 5°C - measured | W/cm² | 0.2 | 0.15 |

The refrigerant type fluid was found to have a better overall thermal performance. This was not expected. Using Colburn equation to estimate heat transfer coefficient (HTC), we calculated that, at the low Reynold considered, the oil should have the best behavior. On the contrary the tests showed that:

- Figure 7: At a heat flux of 0.2 W/cm², the refrigerant has a HTC of ~200 W/m²/K while the oil has a HTC of ~100W/m²/K

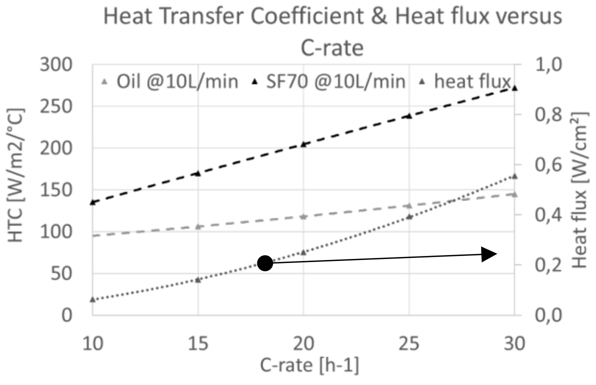

Figure 7: Heat transfer coeficient

- Figure 8: The superheat of the cell, defined as the averaged cell temperature minus the fluid inlet temperature, at 0.2 W/cm² is 10K for the refrigerant and 19K for the oil.

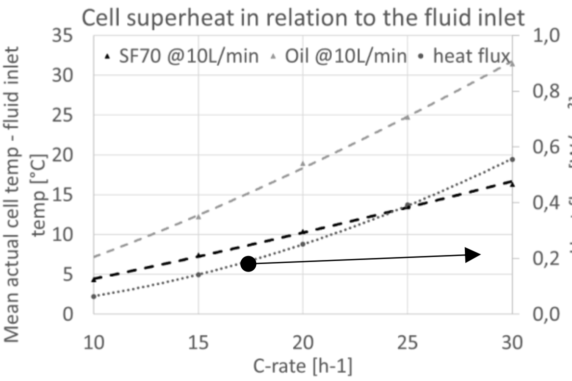

Figure 8: Cell superheat

- Figure 9: To keep the cell temperature uniformity (below 5K), defined as the maximal temperature minus the minimal temperature measured of the cell skin, the maximal heat flux should be below 0.2 W/cm² with the refrigerant and 0.15 W/cm² with the oil.

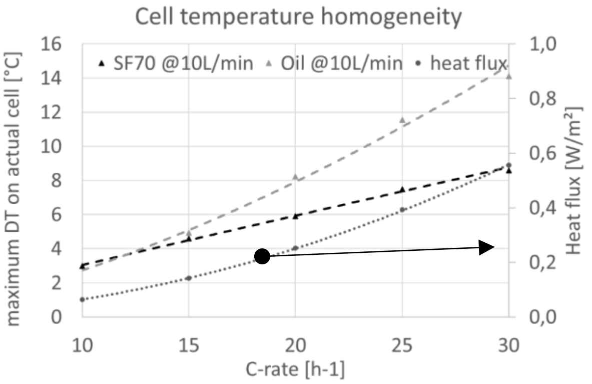

Figure 9: Cell uniformity

In terms of cooling performance, it’s clear that the refrigerant has an advantage.

## 5. Thermal runaway behavior

### 5.1 Test rig description

We wanted to investigate the capability of the refrigerant fluids to keep the battery safe in case of a cell thermal runaway. Indeed, a single cell failure cannot be excluded from the DFMEA. The designers have to build battery packs that prevents a single cell fire to propagate to the adjacent cells. We designed an experiment where eight small cylindrical cells (18650 type) are put as close as 0.5 mm from each other and welded to a massive busbar (without fuse). This cell assembly is flooded in a box full of refrigerant fluid. The box is equipped with a diaphragm so that a nail can move down and puncture one cell to initiate a thermal runaway (Fig. 10 and 11). The box is equipped with a sight glass to record what is happening inside. Eight temperature and one pressure sensors are located in the box and acquired at high frequency. The box is tight and equipped with a relief valve. No active cooling is provided to the box nor to the 3.2L of fluid enclosed.

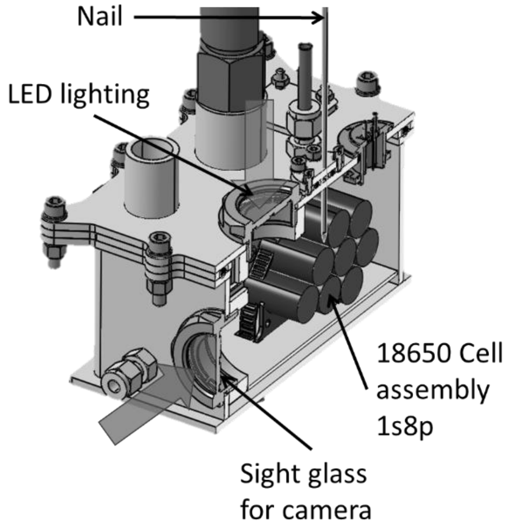

Figure 10: Abuse test box

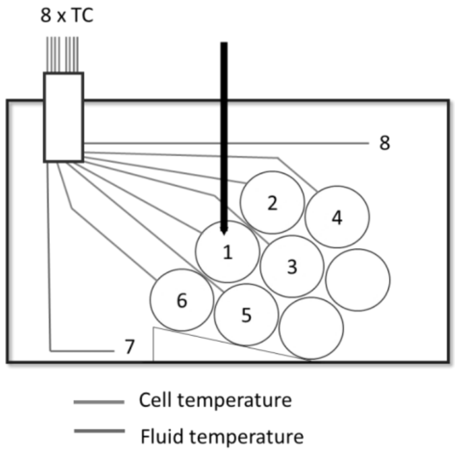

Figure 11: Layout of the test box featurig the temperature sensors location

The abuse test box is placed in a chamber where a pneumatic actuator can move the nail at a rated speed (Fig. 12). The chamber is secured, the atmosphere is monitored, and there is a direct link to firefighters so that workers can safely work despite the risks of explosion or pollutants in the air.

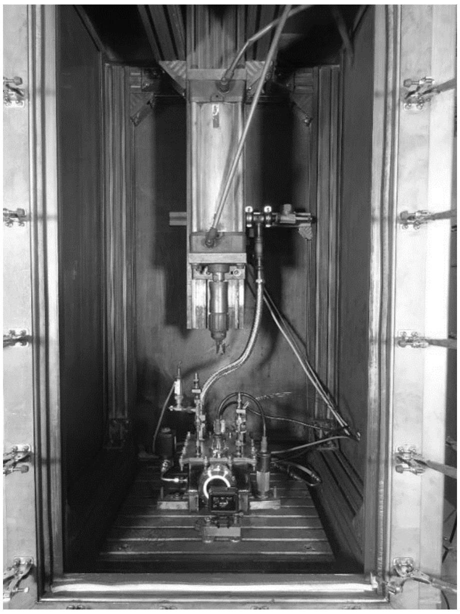

Figure 12: Nail penetration test rig

### 5.2 Results

To put it simply, the fluids prevented a thermal runaway propagation. This could be measured in the weight lost and in both the temperature and pressure profiles. In Figures 13 and 14, the impact of a single cell failure is shown. In air, all plastic parts were severely burnt and their jelly rolls were extruded out of the cans. With the fluorinated fluids, only the punctured cell exhibited degradation while all other adjacent cells remained unscathed.

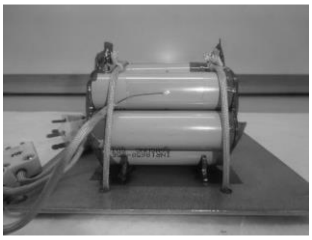

Figure 13: Cell assembly before test

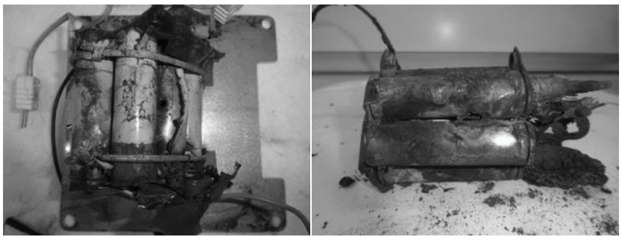

Figure 14: Cell assembly after test
left: in fluid ; right: in air

In Figures 15 to 18, temperature and pressure records are plotted. Peaks mean a thermal runaway event. You can see that, in air, the temperature drop is slow and a second wave of thermal runaways occurred 180 seconds after the first one. When immerged in fluids the peak temperature shifts very quickly below 100°C, which prevents the propagation from cell to cell.

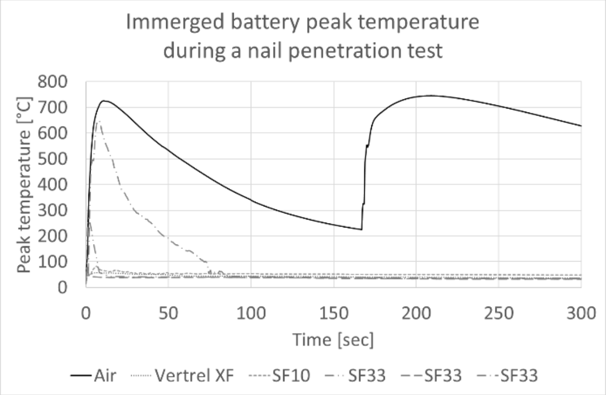

Figure 15: Temperature profile (300sec)

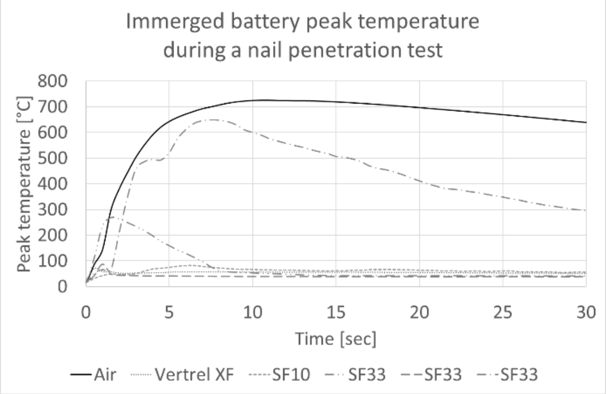

Figure 16: Temperature profile (30sec)

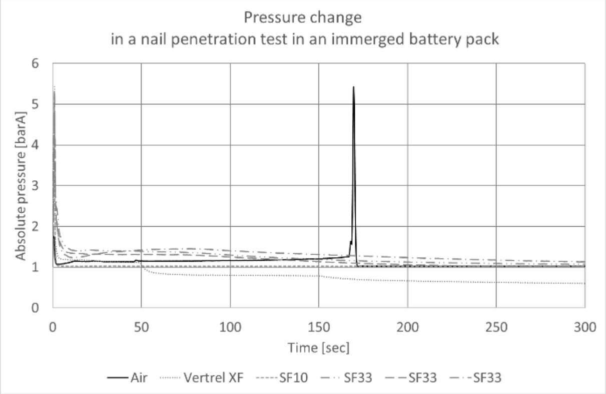

Figure 17: Pressure profile (300sec)

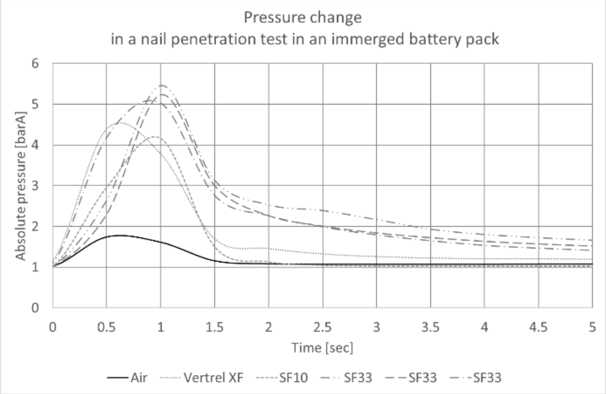

Figure 18: Pressure profile (5sec)

The initial pressure peak in air is low contrary to the ones in fluids. It seems that additional gases are produced when immerged in refrigerants due to the boiling of these refrigerants.

The test was repeated three times with SF33 due to erratic measures. It seems that on one test in SF33 the thermal runaway propagated to a few cells which seems to be confirmed by the weight loss (fig. 19). The weight loss during a thermal runaway is due to fact that plastics and graphite burns forming carbon oxides expelled from the box.

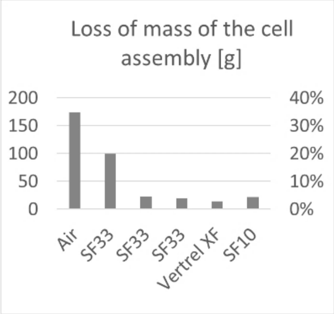

Figure 19: Weight loss of the cell assembly

## 6. Conclusion

Immersion cooling using dielectric fluids allows for direct contact on the battery cells and busbars and potentially offers an enhancement in both safety and performance versus other battery thermal management strategies. Increased surface area on the cell for cooling provides a lower cell superheat, better cell uniformity and prevents the propagation of a thermal runaway event.

Fluorinated working fluids, specifically HFOs, are very good candidates for this application. They provide increased performance thanks to their low viscosity and increased safety with their non-flammable characteristics.

Even though the tests presented in this paper had some defined limitations, the conclusions are easily derived. Future experiments will be developed to improve overall perspective and comparative basis for these fluids in their use as thermal management solution. Also, an acceptable weight and cost balance while maintaining similar or improved performance should be evaluated.

## 7. Acknowledgement

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## 8. References

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## 9. Glossary

| | |
|---|---|
| *HFO* | *Hydro-Fluoro-Olefin* |
| *HFC* | *Hydro-Fluoro-Carbon* |
| *ODP* | *Ozone Depletion Potential* |
| *GWP* | *Global Warming Potential* |
| *HTC* | *Heat Transfer Coefficient* |

## 10. Authors

Rémi DACCORD, founder of EXOES (2009) and e-mersiv (2019). He leads the technical development in battery thermal management. Rémi has applied for more than 20 patents since 2009. Rémi is an engineer graduated from University "Centrale Paris" in applied physics in 2006. He is a serial entrepreneur devoted to reduce the carbon footprint of our society.

Jason R. Juhasz, Chemours, Technology Leader for Thermal Management. Previous experience in leading Process Development and Research activities in both Semiconductor and Chemical Manufacturing industries. For the last 15 years, he has been working with Fluorochemical Division with the main focus in developing the next generation HFOs as sustainable products for the environment. He has B.S. degrees in Chemistry and Chemical Engineering from the University of Florida.