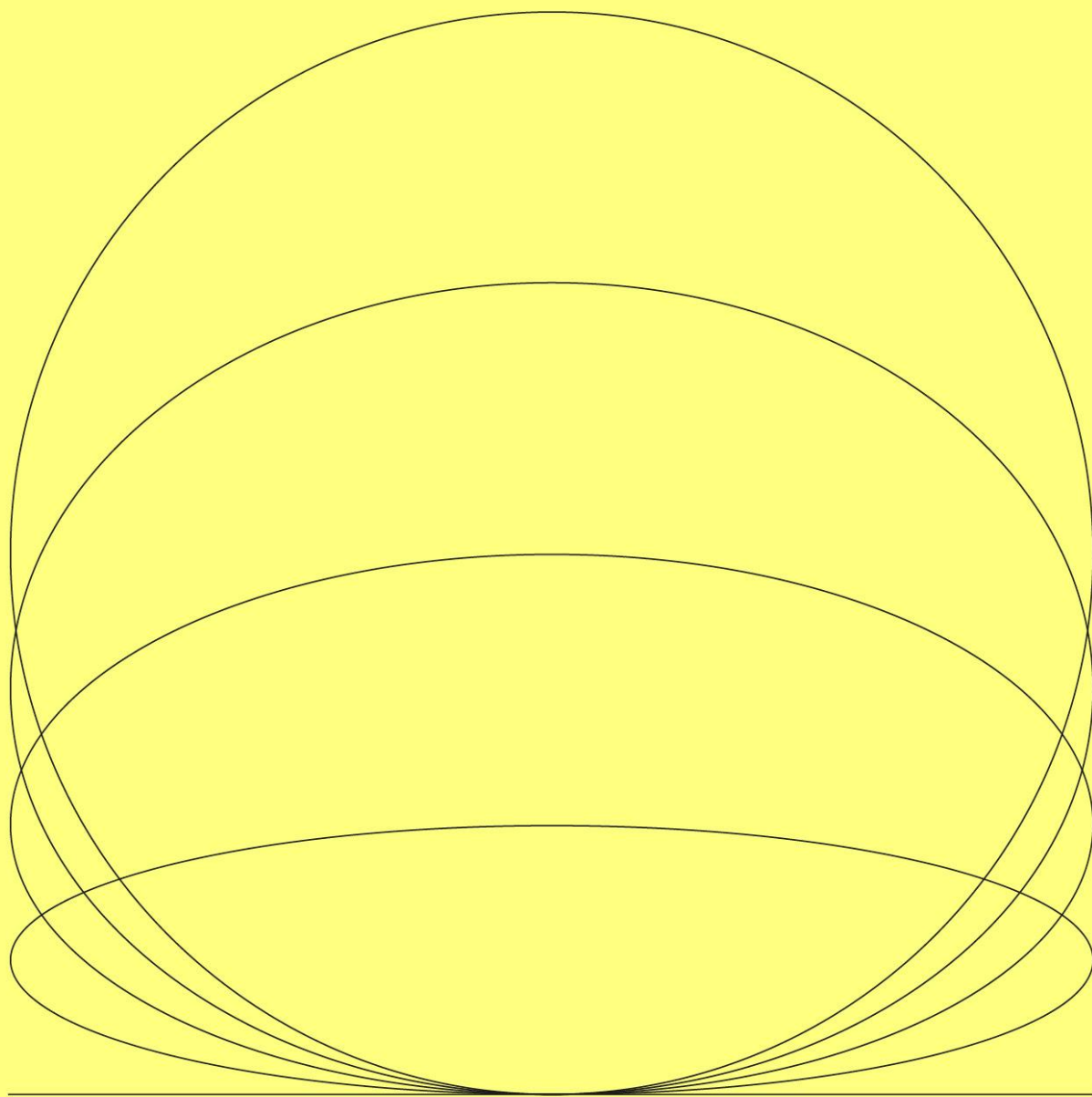




Report

H₂UpScale

Deliverable 7.2

Coolant formulations

Version: 1.0
YYYY-MM-DD
HORIZON-JTI-CLEANH2-2024-03-02



H₂UpScale



Clean Hydrogen
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Co-funded by
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Dissemination Level (Security)

- Public

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Restricted to the consortium and including the European Commission Services
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EU classified (EUCI) under Decision No 2015/444:

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Dissemination Level (Security)

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Project

Project acronym	H2UpScale
Project title	High-power hydrogen fuel cell system balance of plant component up-scale and optimization
Project number	101192481
Work programme topic	HORIZON-JTI-CLEANH2-2024-03-02
Work Package	WP7: Coolant path BoP component development
Deliverable number	D7.2
Deliverable type	Report
Dissemination level	Public
Due date	30-06-2026
Document date	15-09-2026
Keywords	Cooling fluids; Heat transfer; Nanomaterials; Thermal conductivity; Volumetric heat capacity; Biodegradability

Revision history

Date	Description	Author & organisation
28-08-2026	First draft	Laura Batlle (LEI)
09-09-2026	Quality assurance	Peter Cheadle (CMS-LTD) Gabriela Macías (LEI)
14-09-2026	Final version	Emma Castellanos (LEI) Laura Batlle (LEI)

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Acknowledgement
The project is supported by the Clean Hydrogen Partnership and its members.



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1 Introduction

1.1 Context

The deliverable D7.2 is the outcome of Task T7.2 “*Advancement of cooling fluids for PEMFC heavy duty systems*” within Work Package (WP) 7 “*Coolant path BoP component development*” of the H₂Upscale project. WP7 focuses on the development of coolant path BoP components for high-power PEMFC systems, including a modular 3D-printed heat exchanger and an innovative coolant formulation. The work aims to improve thermal management, enhance heat transfer performance, and ensure system durability, while enabling scalability across 250 kW to MW-scale applications. Task 7.2 builds on system specifications and requirements defined in WP2 and WP3, including thermal design targets, operating conditions, and environmental constraints for high-power PEMFC systems. It focuses on the development of three innovative coolant formulations using biodegradable and non-toxic compounds, optimized for enhanced heat transfer, volumetric heat capacity and low electrical conductivity. These candidates’ formulations are comparatively evaluated against the project requirements through a screening process, enabling the identification of the most suitable formulation (OC) for subsequent detailed characterization presented in this deliverable. Within the framework of WP7, D7.2 contributes to the achievement of the work package objectives, specifically Objective 7.2:

- Obj. 7.1: Fabricate a modular 3D printed H₂ dissipator for a min. 250kW system with an efficiency above 50 %.
- Obj. 7.2: Develop an innovative cooling formulation with enhanced heat transfer capacities: reduction on waste heat generation around 20%, achievement of electrical conductivity <2μS/cm and thermal conductivity > 0.4 W/m·K.
- Obj. 7.3: A 20 % increased durability of cooling system (coolant and H₂ dissipator) through the utilization of an ion filter.
- Obj. 7.4: Re-use of a 50 % of the heat captured by the coolant within the system.

1.2 Purpose and outline of the document

The document is organized to ensure clear and logical progression from the definition of system constraints to the validation of the selected coolants.

Firstly, the requirements and target specifications governing the coolant development are presented. Subsequently, the screening and selection process of base fluids, nanoparticles and additives is described, together with the methods and dispersion strategies studied.

The following sections describe the characterization techniques employed to evaluate the thermal, electrical and physicochemical properties of the developed coolant formulations. In addition, the stability study of the main fluid is also presented.

In accordance with the Grant Agreement, this deliverable is intended for public dissemination (PU). However, it should be noted that part of the work performed within the project has generated highly promising results with significant potential for future exploitation.

At the current stage, Leitao is conducting an internal assessment of the patentability and intellectual property protection strategy related to these results. In line with Horizon Europe’s principles on the protection of results with potential commercial and innovation value, and to ensure that no premature disclosure may compromise future intellectual property rights, certain technical details related to potentially exploitable results have been intentionally generalized or omitted in this document.



The information included in this deliverable, therefore reflects the state of progress, methodology, and key findings at a level of detail that is sufficient for public dissemination, while avoiding the disclosure of sensitive data, proprietary know-how, or enabling technical details that could negatively impact ongoing IP protection activities.

Leitat remains fully committed to complying with the Grant Agreement requirements, while ensuring that the project's outcomes can achieve maximum impact through appropriate protection, valorization, and future exploitation. In this context, all results included in this deliverable are sufficient to validate the achievement of the project's technical objectives and KPIs, while avoiding the disclosure of sensitive or proprietary information.

2 Coolant fluids requirements

Coolant fluids for high-power Proton Exchange Membrane Fuel Cell (PEMFC) systems represent a critical enabler for effective thermal management, particularly for applications above 250 kW. Conventional coolants, originally developed for lower power ranges, present limitations in terms of heat transfer performance, electrical insulation, and long-term stability under demanding heavy-duty operating conditions.

To address these challenges, advanced coolant formulations are being developed within H₂UpScale as part of the coolant path BoP. These fluids are designed to operate under application-specific and Fuel Cell system boundary conditions defined in WP2 and WP3. These include high thermal loads, transient operating profiles, controlled pressure and flow regimes, as well as strict requirements on electrical conductivity, material compatibility, and system stability.

A key innovation is the investigation of novel additives to improve thermal properties, promoting a **more efficient heat transfer**. However, **ensuring stable dispersion** of these nanomaterials is essential to avoid agglomeration, sedimentation, and performance degradation. At the same time, maintaining **low electrical conductivity** is essential to avoid leakage currents through the coolant, which could negatively affect system efficiency and safety. Additionally, the coolant must be **compatible with system materials**, avoiding corrosion, deposit formation, or degradation when interacting with metallic components, polymers, and auxiliary systems such as the heat exchanger.

In line with the project's sustainability objectives, the developed coolants prioritize the use of biodegradable, non-toxic and environmentally friendly materials, reducing the carbon foot-print impact and safety risks associated with conventional fluids. The integration of supporting technologies, such as ion filtration systems or the use of antioxidant additives, is therefore considered by LEI and MHDE to mitigate degradation mechanisms and extend the operational lifetime of the coolant.

Based on these requirements and boundary conditions, the experimental KPIs in Task 7.2 for the coolants are defined as follows:

- KPI 1: Thermal conductivity > 0.4 W/m·K.
- KPI 2: Electrical conductivity < 2 µS/cm.
- KPI 3: Compatibility with PEMFC operating conditions ($T_{\max} = 88^{\circ}\text{C}$ defined in WP3).
- KPI 4: Use of biodegradable, non-toxic and environmentally sustainable components.

It should be noted that the 20% waste heat reduction target (described in Obj. 7.2) is considered a system-level KPI and therefore cannot be assessed exclusively through coolant characterization. Task 7.2 contributes to this objective through the development of an enhanced coolant formulation, while the final verification of the KPI will be performed during the integrated system validation in Task 7.4.

Detailed boundary conditions and system requirements are provided in previous deliverables (e.g. D2.1 or D3.4), which guide the development, optimization and validation of the coolant formulations.



3 Review of advanced coolant fluids strategies

The primary role of the coolant fluid in high-power PEMFC systems is to efficiently remove and transport heat generated within the system under demanding operating conditions. In practice, coolant systems are based on a base fluid combined with specific additives, allowing the adjustment of thermal, physical and chemical properties according to application requirements and system constraints. Consequently, the selection of the base fluid represents a fundamental step in the design of the coolant path BoP.

Within H₂UpScale, the focus is placed on coolant formulations suitable for **indirect cooling** systems in **high-power PEMFC applications**.

Water-based fluids are commonly selected due to their favorable thermal properties and high thermal conductivity; however, alternative solutions such as oil-based fluids or emulsions are also under investigation to achieve lower electrical conductivity among the system.

The following sections review the State-of-the-art (SoA) for the main components considered in this study. Based on this analysis, selection criteria are then defined in line with the boundary conditions established in WP2 and WP3.

3.1 Base fluids

As previously indicated, water, due to its properties, is the most globally used coolant, particularly effective in both heating and cooling applications as well as for sensible heat storage applications. However, the effective operating window of pure water remains restricted [1]. To expand this range, it is commonly mixed with organic compounds such as glycols or esters, which enable operation across broader temperature conditions. Nevertheless, several of these established formulations present concerns related to toxicity and environmental impact, promoting a growing interest in the development of safer and more sustainable alternatives [2].

In this context, a screening of various base fluids has been performed to identify potential environmentally friendly candidates. The selection is based on the assessment of key thermophysical properties, such as thermal conductivity and electrical conductivity, as well as viscosity, which are essential parameters for ensuring adequate system performance [3].

Based on this study, **water-organic base mixtures**, **oil-based** and **oil-in-water emulsions (O/W)** are selected by LEI as promising candidates for further study. Their selection is driven by their potential to meet both thermal ($>0.4 \text{ W/mK}$) and electrical performance requirements ($<2 \mu\text{S/cm}$), which represent the main critical challenge. In particular, the coolant must provide efficient heat removal while maintaining sufficiently low electrical conductivity to ensure safe and efficient operation. In general, formulations with a higher water content tend to exhibit superior thermal performance, whereas formulations containing a higher proportion of oil typically achieve lower electrical conductivity. Therefore, the development of the coolant formulation requires finding an optimal balance between both properties [4].

The initial screening demonstrates that water-based formulations containing organic additives constitute the most promising approach for further development. While oil-based fluids provide excellent electrical insulation properties, their thermal performance remains significantly below the targets established for the project. On the other hand, O/W emulsions offer an attractive compromise between thermal and electrical properties; however, concerns related to stability and compatibility with the defined operating temperature range currently limit their applicability. Consequently,

the study focuses primarily on water-organic formulations, which provide the most favourable balance between thermal performance, electrical conductivity, and system compatibility.

3.2 Nanomaterials

Once suitable base fluids have been identified, additional improvements can be achieved through the incorporation of nanomaterials, following the use of nanofluids as a promising approach for advanced thermal management applications. Depending on the targeted properties, several types of nanomaterials can be employed, including metallic particles, metal-oxides, carbon-based etc. The presence of nanomaterials can significantly modify the thermophysical properties of the base fluid, particularly by increasing its effective thermal conductivity and consequently enhancing heat transfer capabilities. However, these improvements are often accompanied by changes in viscosity or an increase in electrical conductivity, which must be carefully considered [5].

In addition, sustainability considerations must also be evaluated during the nanomaterial selection process. Certain nanomaterials may present concerns related to toxicity, environmental persistence, or limited biodegradability, making them incompatible with the sustainability targets established within H₂UpScale. Therefore, preliminary screening is required to identify and exclude those candidates that have not fulfilled the environmental and safety requirements [6].

Based on these considerations, the results show that metal-oxides and metal nanomaterials exhibit varying behaviour regarding electrical and thermal conductivity. Some provide a favourable balance between conductivity enhancement and overall performance, whereas others have been excluded from further consideration due to toxicity concerns or poor stability. In contrast, carbon-based nanomaterials, despite their high thermal conductivity, tend to increase electrical conductivity very significantly, making them unsuitable for this application.

3.3 Surfactants

The performance of a nanofluid has not only determined by the properties of the base fluid and the selected nanomaterials, but also by its ability to maintain these properties throughout the operational lifetime of the system. For this reason, the formulation of a high-performance coolant requires the incorporation of a suitable additive package capable of ensuring stability and preserving the targeted properties.

A key challenge in nanofluid development is maintaining nanoparticles homogeneously dispersed within the base fluid. Agglomeration and sedimentation phenomena can gradually reduce the beneficial effect of nanoparticles on heat transfer performance, while potentially affecting fluid circulation and system reliability. Therefore, the use of **surfactant agents** capable of promoting steric and/or electrostatic repulsion between particles is often required (Figure 1).

In parallel, particular attention should be given to the electrical conductivity of the coolant. Although certain additives can improve nanoparticle dispersion, they may also influence the ionic content of the fluid and consequently its electrical behaviour. Since maintaining low electrical conductivity is a critical requirement, the selection of surfactants must consider not only their stabilization efficiency, but also their impact on the electrical insulation performance of the formulation.

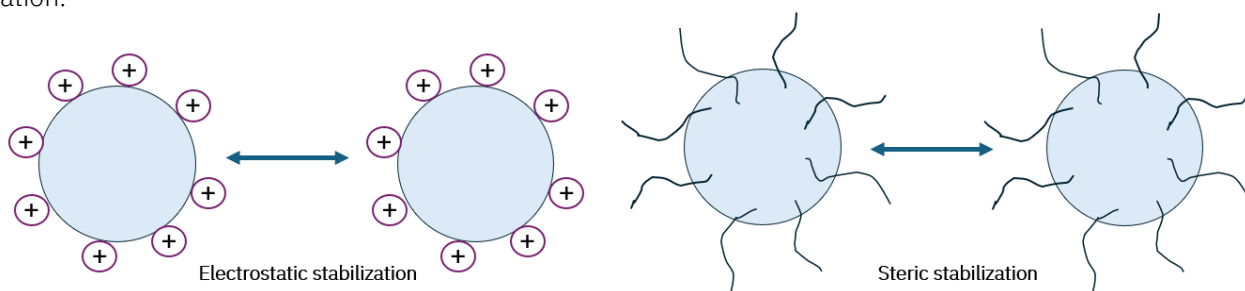


Figure 1. Schematic illustration of the electrostatic and steric stabilization generated by different surfactants

For this reason, the use of **steric stabilization surfactants** has been prioritized. Unlike electrostatic stabilization, which in most cases relies on pH adjustment and the presence of ionic species to generate repulsion between particles, steric stabilization is based on creating a physical barrier around nanomaterials. This mechanism allows colloidal stability to be decoupled from the fluid's ionic chemistry, enabling more precise control of electrical conductivity and minimizing the risk of unintended increases associated with changes in ionic strength [7].

3.4 Coolant formulations experimental procedure

After the screening study of the base fluids, nanomaterials and surfactants, different chemical formulations and dispersion strategies have been evaluated and optimized.

The formulation of nanofluids requires the selection of an appropriate dispersion strategy, considering the physicochemical properties of both the base fluid and the nanomaterials. The dispersion method employed applies a direct influence on the distribution of the nanomaterials used, their interactions with the medium and the tendency to agglomerate. This, in turn, determines both the final thermophysical properties and the colloidal stability of the system. Since particle aggregation and sedimentation may compromise homogeneity and reduce the effectiveness of the nanofluid, dispersion techniques should be carefully selected and adapted to the characteristics of the formulation. The efficiency of the dispersion process is strongly influenced by factors such as the applied energy, processing time, temperature, and the incorporation of suitable stabilizing agents. Therefore, it is essential to meticulously optimize the dispersion process parameters to ensure a homogeneous and stable formulation that meets the specified performance criteria [8].

A variety of dispersion techniques can be used individually or in combination to improve the distribution of nanomaterials and the stabilization of the surfactant within the fluid.

- Magnetic agitation is a process that promotes the macroscopic homogenization of suspension by generating convective currents. It is particularly useful in the preliminary stages of mixing.
- High-shear homogenizers (Ultra-Turrax) promote the mechanical deagglomeration of particles through intense velocity gradients and localized shear forces.
- High-energy probe sonication is based on acoustic cavitation phenomena, generating microbubbles that violently collapse and break up nanomaterial agglomerates, making it one of the most effective techniques for producing stable dispersions.

In practice, the sequential combination of several of these techniques, as well as the use of surfactants, tends to yield superior stabilization compared to their individual application. This allows for the simultaneous optimization of the target properties of the coolant [9].

Based on these considerations, several combinations of dispersion techniques have been applied to the promising coolants formulations. The obtained results demonstrate that the preparation methodology has a considerable impact on the final properties of the nanofluids, leading to noticeable variations in thermal performance, electrical conductivity and colloidal stability. Formulations exhibiting high electrical conductivity, insufficient thermal performance and/or stability issues have been excluded from the study.

As a result of this selection process, three coolant formulations (F1, F2 and F3) have been selected as representative candidates for PEMFC cooling applications, in accordance with the objectives of Task 7.2. Due to the potential intellectual property value of the developed formulations, detailed compositional information is not disclosed in this report. A comparative assessment of the three candidates was subsequently performed, leading to the development of a final optimized formulation (**optimized coolant, OC**) that integrates the best balance between the four main key parameters: high thermal performance, low electrical conductivity, reduced toxicity and exhibit stability, making it the candidate selected for detailed characterization in the following sections.



4 Coolant characterization and results

In this section, the nanofluid exhibiting the best thermophysical and performance characteristics (OC) is evaluated. The performance of the OC is subsequently benchmarked against one commercially available coolant formulation (CF1), as well as against the corresponding base fluid (BF) without nanomaterials.

4.1 Thermal Properties (TC and VHC)

In this section, the results of the thermal properties characterization of the studied fluids are presented.

4.1.1 Thermal Conductivity results

Thermal conductivity (λ) describes the ability of a material to transfer heat through its structure. For liquid samples, one of the most employed techniques to determine this property is the Transient Hot Wire (THW) method, performed according to ASTM D7896-19. This technique monitors the temperature response of the fluid as a function of time following the application of a controlled heat pulse, allowing the thermal transport properties of the sample to be accurately determined.

Heat transfer in the fluid is guided by Fourier's law of conduction. The temperature field generated around the heated wire can therefore be described using the heat conduction Equation 1:

$$\Delta T(t) = \frac{q}{4\pi\lambda} \ln \frac{4\alpha t}{r_o^2 e^\gamma}$$

Equation 1. Heat conduction equation.

Under constant heating conditions, the temperature increase exhibits a linear relationship with the natural logarithm of time. The thermal conductivity of the fluid is subsequently calculated from the slope of the temperature versus $\ln(t)$ curve.

The thermal conductivity of the formulations is assessed throughout the operating temperature window defined in WP2. In all cases, the measurements show the expected temperature dependence, with higher thermal conductivity values observed at elevated temperatures. Furthermore, **the incorporation of nanomaterials leads to an enhancement of the thermal conductivity relative to the BF**, confirming the positive contribution of the dispersed solid phase to the heat transfer performance of the coolant and enabling thermal conductivity levels comparable to those of the selected commercial reference fluid (CF1) while **fulfilling the experimental KPI 1 (>0,4 W/mK) of the Task 7.2.**

4.1.2 Specific and Volumetric Heat Capacity

The specific heat capacity (C_p) and volumetric heat capacity (VHC) of the different formulations have been evaluated over the relevant operating temperature range. Whereas thermal conductivity characterizes how efficiently heat is transferred through a material, volumetric heat capacity reflects the amount of thermal energy that a fluid can absorb and store before experiencing a temperature increase. Consequently, these parameters provide complementary information regarding the thermal management capabilities of the coolant.

Specific heat capacity measurements have been performed using Differential Scanning Calorimetry (DSC) following ASTM E1269-11. Measurements have been conducted over a temperature range from 25 to 100 °C using 40 μ L aluminium crucibles filled with the sample and fitted with micro-perforated lids (DSC1/500 Mettler Toledo). The VHC is subsequently calculated from the measured C_p values and the corresponding fluid density.

Results show that **the incorporation of nanomaterials have not compromise the formulation's volumetric heat capacity**. Despite the presence of a dispersed solid phase, which could potentially reduce the fluid's thermal energy storage capacity, the OC maintains values comparable to those of the BF and CF1 throughout the studied temperature range. This is particularly relevant, as the observed improvements in thermal conductivity have been achieved without a significant drawback to the heat capacity, allowing for a combination of more efficient heat transfer with a high capacity for thermal energy absorption.

4.2 Electrical conductivity

As outlined in the preceding sections, electrical conductivity is one of the most critical parameters in the development of cooling fluids for PEMFC systems. In order to ensure safe and efficient operation, it is crucial that the coolants meet the strict electrical conductivity requirements.

In systems where there is direct contact with electrically active components, the conductivity should be below 5 $\mu\text{S}/\text{cm}$. For indirect contact configurations, the conductivity should be below 100 $\mu\text{S}/\text{cm}$ [10, 11]. The primary challenge lies in achieving a balance between these limitations and maintaining optimal thermal properties.

The electrical conductivity of the OC has been determined using a ProfiLine Cond 3110 portable conductivity meter equipped with a TetraCon™ 325 four-graphite-electrode probe following ASTM D1125. The measurements have been carried out directly on the liquid samples, ensuring high precision and repeatability in the assessment of electrical conductivity.

The obtained electrical conductivity values of the OC remain below 10 $\mu\text{S}/\text{cm}$, which is above the H₂UpScale target KPI 2 of <2 $\mu\text{S}/\text{cm}$ defined for Task 7.2. Therefore, the project KPI has been approached but not yet fully reached at the current stage of development.

This result is consistent with the formulation strategy adopted, which prioritizes the enhancement of thermal performance through the incorporation of functional additives and nanomaterials, reflecting the trade-off between EC and TC. While these components contribute positively to heat transfer, they also introduce a limited increase in electrical conductivity compared with highly deionized coolant formulations.

Although the project KPI 2 has not been fully achieved, the obtained EC values for OC satisfies the operational requirements associated with indirect cooling systems (<100 $\mu\text{S}/\text{cm}$, selected for the project). The results therefore demonstrate that an **appropriate balance between thermal performance and electrical safety has been achieved** without compromising their suitability for high-power PEMFC applications.

Further optimization will be addressed in subsequent project activities. In particular, the potential influence of this EC parameter on the overall coolant path performance, scalability and system-level optimization will be assessed within Task 7.4 (*Coolant path, scalability and optimization*).

4.3 Boiling and Freezing Point

The boiling point and the freezing point are two essential parameters in the evaluation of coolants intended for high-power PEMFC systems. Accurate knowledge of these phase transition temperatures ensures safe and reliable performance by preventing undesired vaporization at high temperatures and solidification at low temperatures.

Accordingly, these parameters are experimentally determined for the OC, the corresponding BF, and the selected CF1 under equal conditions.

To determine the boiling point of the fluid, DSC is employed using a DSC1/500 Mettler Toledo instrument. The boiling point is identified from the thermal event associated with fluid evaporation during a temperature ramp. The measurements have been performed from Room Temperature (RT) up to 300 °C at a heating rate of 10 °C/min under an air atmosphere.

On the other hand, to determine the freezing point of the fluid, a controlled cooling setup following the ASTM D97 has been employed. The samples have been subjected to gradual cooling to ensure thermal equilibrium throughout the system. The onset of solidification is defined as the temperature at which the fluid ceased to flow and no longer responded to mechanical agitation, indicating the transition from liquid to solid phase under atmospheric pressure conditions.

The results obtained for the three formulations under investigation (CF1, BF and OC) have been analysed and compared. Regarding the boiling point, the OC exhibits **values comparable to those of the reference fluid**, remaining well above the maximum operating temperatures defined ensuring safe operation. In contrast, the **OC achieves the lowest freezing point** (best performance) among all the evaluated formulations, extending the operating window towards lower temperatures and providing improved protection against coolant solidification.

In conclusion, KPI 3 is achieved.

4.4 Kinematic Viscosity

Kinematic viscosity is another key parameter in the development of coolants for PEMFC systems, as it directly influences pressure drop, pumping requirements and the energy efficiency of the cooling circuit. This parameter, defined as the ratio of the dynamic viscosity to the fluid density, describes the internal resistance of the coolant to flow. Consequently, an increase in viscosity leads to a greater energy demand to maintain fluid circulation, which can negatively affect the overall performance and operating costs of the system.

To determine the kinematic viscosity, a Cannon-Fenske viscometer has been employed (Figure 2). The capillary viscometer measures kinematic viscosity by recording the time needed for a defined volume of liquid to pass through a calibrated capillary under gravity. The analysis has been carried out according to ASTM D445, ensuring accurate and reproducible measurements under controlled temperature conditions.



Figure 2. Cannon-Fenske viscometer setup (ASTM D445).

Results show that the OC has a slightly higher viscosity than that of the commercial fluids at intermediate temperatures. However, this difference decreases progressively with increasing temperature and becomes practically negligible within the system's operating range (>58°C). This indicates that the incorporation of nanomaterials has not significantly penalize the hydrodynamic behaviour of the coolant under the expected operating conditions. Therefore, the observed improvement in heat transfer properties has been achieved by maintaining viscosity values comparable to those of the CF1 during normal system operation.

4.5 Flammability

Although thermal management is the primary objective of the coolant, its behaviour under abnormal conditions should also be considered. For this reason, the flammability of the formulation developed (OC) has been evaluated through **Manifold Test** as part of their validation for PEMFC applications.

This method has been used to evaluate the combustion behaviour of OC when brought into contact with a heated metallic surface (multi-junction tube), according to the principles described in ISO 20823:2003. The test has been performed using a manifold tube positioned beneath an extraction hood. Once the desired temperature has been reached, 10 mL $\pm$ 5 mL of sample have been dispensed onto the middle area of the heated tube from a height of 310 $\pm$ 5 mm over a dispensing period of 50 $\pm$ 10s. During the test, the occurrence of flashes, ignition or sustained combustion has been monitored.

In this case, the study has been conducted at temperatures both **below and above 400 °C** with the aim of determining the product’s ignition temperature. There are three possible outcomes:

- There are flashes, combustion or ignition of fluid on the tube, but these have not continued when the fluid is collected in the drip tray: **I(T)**.
- There are flashes, combustion or ignition of fluid on the pipe, which continues into the collection tray: **I(D)**.
- At no point do flashes, ignition or combustion of fluid occur: **N**.

According to the results summarized in Table 1, no flashes, ignition or combustion events have been observed below 400 °C. Ignition has been only detected above 400 °C, where combustion remains confined to the manifold surface and has not been continued once the fluid reaches the collection tray.

Table 1. Manifold test results of OC.

Manifold temperature (°C)	Classification
<400	N
> 400	I(T)

These results indicate that the OC presents a low flammability risk and maintains a favourable safety profile.

4.6 Biodegradability

The biodegradability of the optimized coolant (OC) has been assessed using the Manometric Respirometry Test (OECD 301F). The microbial inoculum has been obtained from activated sludge collected at the municipal wastewater treatment plant in Terrassa (Barcelona, Spain). Prior to use, the sludge is conditioned through a 24-hour aeration step followed by sedimentation, after which the supernatant is separated from the settled solids. Approximately 30 mL of the resulting supernatants have been added per liter of mineral medium used in the test.

The study has been performed twice, using a mixture of glucose and glutamic acid (1:1) as the reference compound. In parallel, an inoculum blank has been included to account for endogenous respiration and background oxygen consumption. The test substance has been assessed at a concentration of 60 mg·L⁻¹. The test has been conducted over 28 days at 20 °C under dark conditions to prevent any potential interference from light exposure to the biodegradation process.



Based on the results obtained, the OC fulfils the **ready biodegradability** criteria established in OECD 301F, reaching the 60% biodegradation threshold within the required 10-day window after the lag phase. Furthermore, the formulation achieves a biodegradation level of 97% after 28 days, **confirming its biodegradable nature and favourable environmental profile**. Consequently, experimental KPI 4 of Task 7.2 (reported in Coolant fluids requirements) is successfully achieved, demonstrating that the environmental objectives of the project are achieved without compromising the functional requirements of the coolant.

4.7 Stability tests

As already mentioned, the stability of the coolant is another essential parameter, as it directly affects its thermal properties and long-term behaviour. To assess the stability of the formulations developed, centrifugation tests and particle size distribution analyses have been carried out. These techniques make it possible to study both the tendency towards sedimentation and the degree of dispersion of the nanomaterials within the fluid.

4.7.1 Centrifugation tests

Centrifugation tests are used as an accelerated method for assessing stability, enabling the identification of nanomaterials sedimentation phenomena at different rotational speeds. Furthermore, they make it possible to distinguish between nanomaterials that remain adequately dispersed and linked to the surfactant and those that tend to precipitate under centrifugal stress.

Centrifugation tests have been performed using a Digicen 21 equipment centrifuge, applying rotation speeds between 400 and 4000 rpm. No precipitation is found between 400 and 3000rpm. However, results show that, at speeds above 3000 rpm, some of the nanomaterials sediment due to the presence of aggregates or insufficiently stabilized particles. Nevertheless, the thermal and electrical properties of the supernatant remain practically unchanged. Rotational speeds above 3000 rpm will not be representative of the H₂UpScale system.

Since centrifugation represents an accelerated and more severe stability screening condition than normal storage or operation, the observed sedimentation should not be directly interpreted as instability under ambient conditions. The absence of significant changes in the thermophysical and electrical properties of the supernatant suggests that the sedimented fraction has a limited contribution to the overall coolant performance. However, additional studies will be necessary to confirm this behaviour and to further optimize the long-term stability of the formulation.

4.7.2 Dynamic Light Scattering: Size distribution

The Dynamic Light Scattering (DLS) technique is used to determine the hydrodynamic size and size distribution of particles in various formulations. This analysis provides information on the degree to which a nanomaterial is dispersed and enables the detection of aggregates or secondary particle populations that could appear with time (either in static or dynamic state).

The measurement of particle size allows the detection of possible increases in the hydrodynamic diameter, indicative of aggregation or coalescence processes. Likewise, the polydispersity index (PDI) provides information on the homogeneity of the size distribution: PDI values below 0.3 are generally indicative of relatively monodisperse dispersions, whereas higher values suggest heterogeneity and possible presence of aggregates [12].

To assess the colloidal stability of the OC, DLS measurements have been conducted at room temperature over a one-month period. The results show no significant changes in particle size and maintain PDI values below 0.3 throughout the



study, indicating a stable and relatively monodisperse dispersion without evidence of secondary particle populations. In addition, no relevant variations in fluid's properties have been observed during the evaluation period. These observations **confirm the colloidal stability of the formulation under ambient storage conditions**.

Future work within Task 7.3 will focus on evaluating the stability of the OC across the operating temperature range.

5 Conclusions

In conclusion, a novel coolant fluid has been successfully developed and validated within the framework of the H₂UpScale project. The OC formulation exhibits competitive thermophysical properties compared with commercial reference fluids while simultaneously improving the environmental profile of the coolant.

Based on the results obtained in Task 7.2, the status of the project objectives and experimental KPIs can be summarized as follows:

- KPI 1: The thermal conductivity target of $>0,4 \text{ W/mK}$ is achieved.
- KPI 2: The electrical conductivity target of $<2 \text{ }\mu\text{S/cm}$ is not achieved. The OC exhibits electrical conductivity values below $10 \text{ }\mu\text{S/cm}$, remaining above the project target but well within the limits typically accepted for indirect cooling systems ($<100 \text{ }\mu\text{S/cm}$). No issues will be foreseen in subsequent activities when using the final coolant.
- KPI 3: The compatibility with PEMFC operating conditions ($T_{\text{max}} = 88 \text{ }^{\circ}\text{C}$) is achieved, exhibiting an improved freezing point, a boiling point well above the expected operating temperature range, and a favourable flammability profile.
- KPI 4: The use of biodegradable, non-toxic and environmentally sustainable components is achieved, demonstrating that OC is ready biodegradable and being formulated from non-toxic compounds.

Furthermore, OC has demonstrated colloidal and functional stability, remaining stable at room temperature over a period of one month with no evidence of aggregation or degradation. In addition, its thermal conductivity remained unchanged throughout the storage period.

Based on these results the selected product for the compatibility assessment within Task 7.3 is OC. The study will evaluate the interaction of the cooling fluid with all relevant components and materials of the refrigeration system. The compatibility results, together with the outcomes obtained in this task (7.2), will support the optimization of the OC formulation through the incorporation of suitable additives, with the objective of enhancing its performance, stability, and compatibility with system components. In addition, the system-level objective related to the reduction of waste heat generation ($\sim 20\%$) will be assessed during the integration and validation activities of Task 7.4 (using CFD modeling), as its verification depends on the combined performance of the coolant, the heat exchanger and the overall cooling loop architecture.

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