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Comparison of Conventional and Microwave Heating

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Abstract. Carnot batteries (or Power-to-Heat-to-Power systems) are capable of increasing the use of electricity from photovoltaic or wind power plants to achieve decarbonisation of the electricity sector. To decouple electricity production from demand, these renewable power plants can be connected to the thermal energy storage system of a concentrated solar thermal power plant via electric heaters. As an alternative to electric heaters, microwaves are studied as a volumetric and selective heating method, avoiding the limitations of the Joule effect conventional heating when having solar salt (non-eutectic mixture of 60 $_{wt}$ % $NaNO_3$ and 40 $_{wt}$ % KNO_3), which is a storage medium with low thermal conductivity, working at a temperature very close to its affordable maximum temperature without degradation. In this work, the two heating methods are compared both experimental and numerically. At experimental level, a microwave oven and a muffle furnace are used to record energy consumption and time for a common objective. Additionally, different crucible materials were used to test their suitability with microwaves. Only quartz glass was validated for microwave heating, while the porcelain and alumina based materials (Corundum and Alsint 99.7) failed while exposed to microwaves. At numerical level 3D physical models are built and validated with experiments.

Keywords: Carnot Battery, Microwave Heating, Solar Salt, Thermal Storage, Hybridization

1. Introduction

Electricity generation is a major contributor to greenhouse gas emissions (GHGs) [1]. Increasing the contribution of renewable energy source (RES) plants, such as solar photovoltaic and wind, is seen as a need in order to reduce fossil fuel power generation. Decarbonisation is only possible with electrical energy storage (EES) systems capable of addressing the intermittency of these RES, absorbing the energy surplus in periods where production exceeds demand, so that it is available when required [2].

Carnot battery (CB) or Power-to-Heat-to-Power (P2H2P) represents the combination of renewable plants such as photovoltaic or wind power plants with thermal energy storage (TES) systems. Based on commercially existing technology [3], CB have a great potential for installation, enabling new use cases, e.g., by exploiting components of decommissioned coal-fired power plants [4]. In addition, although the cost of Li-ion batteries is predicted to fall to half their current value around 2030, CB are still a more cost-effective solution using them as combined heat and power (CHP) or achieving higher efficiencies [5].

These systems using a direct Power-to-Heat system are of great interest because of their compact, simple and economical design with high storage temperatures [6]. With solar salt being the most commonly used storage medium in TES [7], for concentrating solar power plants (CSP) the method proposed to date for heating this liquid is conventional heating with electrical heaters. Despite the high efficiency of the electricity-to-heat conversion of the Joule effect, molten solar salt (290 ºC-565 ºC) has a low thermal conductivity, less than 0.7 W/m ºC in the liquid state with working temperatures (between 290 ºC and 565 ºC) [8], being a handicap even when the heat transfer is by convection. Additionally, the working temperatures of the molten salt are quite close to its current degradation temperature (600 ºC), so superficial heat transfer may likely include degradation of the molten salt in the thermal boundary layer.

Microwave heating is proposed as an alternative method for heating solar salt from an electrical energy source. Microwaves are electromagnetic waves in the frequency band between 300 MHz and 300 GHz. They interact directly with matter at the molecular level, varying its electric and magnetic field, which produces heat. Therefore, this volumetric and selective heating, as it depends on the dielectric properties of the material to be processed, avoids the limitations of heating based on superficial heat transfer in a medium with low thermal conductivity, and offers the possibility of an electronic control with a high response speed of the heating medium to system start-ups and shutdowns [9].

Solar salt is a dielectric material that, electromagnetically, can be described by its relative electrical permittivity (ε_r):

$$\varepsilon_r = \varepsilon' - j\varepsilon'' \quad (1)$$

Where the dielectric constant (ε') determines the spatial distribution of the microwave electric field inside the material, and the loss factor (ε'') is responsible for the conversion of the microwave energy into thermal energy. These parameters change with both operating frequency and material temperature. From these, both the penetration depth (Dp) and the loss tangent (tan δ) are calculated, which indicate whether the material is susceptible to microwave heating [10].

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \quad (2)$$

$$Dp = \frac{\lambda_0}{\pi\sqrt{2\varepsilon'}\sqrt{\sqrt{(1+(\tan\varepsilon')^2)}-1}} \quad (3)$$

A material with a very large penetration depth or low value for tan δ is considered a transparent material as the energy is poorly absorbed, whereas materials with high dielectric losses or high values for tan δ, and thus low penetration depth, act as microwave reflectors.

Rodríguez-García et al. [11] showed a first measurement of these dielectric properties in solar salt at a frequency of 2.45 GHz with a dual-mode cavity for microwave heating and in situ dynamic measurements with two different microwave sources. A cross-coupling filter provides high isolation between the signals from the two sources. The complex permittivity (ε) is obtained from changes in the cavity resonance using an improved cavity perturbation method (CPM) with an overall accuracy of 1.3% [12]. The results obtained for solar salt around its working temperature (Table 1) demonstrate that this sensible liquid storage medium can be efficiently heated with microwaves.

Table 1. *Linear approximations of the dielectric parameters of solar salt (290–565 ºC)*

Parameter	**Value**	**Coefficient of determination (R^2)**
Relative dielectric constant, ε'	$0.01363 \times T + 12.04$	0.9973
Dielectric loss, ε''	$-0.001711 \times T + 1.578$	0.9591

Among the container materials in microwave applications, glass quartz or alumina-based ceramics are well known. Although transparent to microwaves, the formation of hot spots during heating can increase the stress in these materials [13]. The reason for this phenomenon is the strong temperature dependence of the dielectric loss of most ceramics at 2.45 GHz microwaves [14]. Therefore, thinking in the application considered in this paper, as molten solar salt container, it is needed a material, not only transparent to microwaves, but also high resistant to thermal shock, as well as mechanically and chemically resistant.

The aim of this work is to make a first comparison between microwave and conventional heating of solar salt, both experimental and numerically. Considerations of the container material using microwaves are also given.

2. Material and methods

The equipment available for the experiments consists of a muffle furnace for conventional heating and an industrial microwave oven, as shown in Figure 1.

Figure 1. *Industrial microwave oven (left) and muffle furnace (right)*

The characteristics of both devices are, for the muffle furnace Nabertherm L 40/11 with heating wires on the sides and an electrical power of up to 6000 W. It reaches a maximum temperature of 1100 ºC in the chamber with dimensions 320x490x250 mm. In the case of the microwave oven, this is the Phoenix Black model with two magnetrons. The maximum electrical power it can withstand is 3500 W with a frequency of 2.45 GHz. The electromagnetic energy conversion efficiency is about 60%, capable of reaching a maximum temperature up to 1200 ºC. Its dimensions are 400x730x305 mm.

To measure the temperature in the microwave oven, as metallic sheathed thermocouples can induce a current, resulting in erroneous measurements, a thermographic camera was used, which sees the top surface of the sample (Figure 2). In the case of the muffle furnace, a Datalogger with K-type thermocouples was used to measure the temperature in the solar salt sample.

To obtain the energy consumption of the microwave oven, an ESP8266 Wemos D1 Mini microcontroller with WiFi connection and the SCT-013 sensor were used. As the experiments were running, AC current, and therefore power consumption, values were sent to the ThingSpeak IoT platform. The muffle furnace has a three-phase power supply, so this AC sensor could not be used. However, the furnace controller itself incorporates the option of exporting the consumption data for each experiment

Figure 2. *IR camera allocated on the microwave oven, looking at its interior from above.*

The materials used for the crucibles were glass quartz, corundum, Alsint 99.7 and porcelain. (Figure 3).

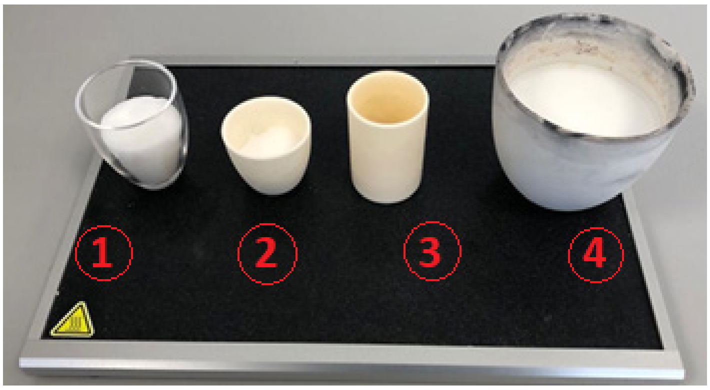

Figure 3. *The different crucibles used in the experiments: (1) glass quartz-50 mL, (2) corundum-30 mL, (3) Alsint 99.7-50 mL and (4) Porcelain-300 mL*

2.1 Numerical simulations

For the numerical simulations, three-dimensional models of both devices, the muffle furnace and the microwave furnace, were built with COMSOL Multiphysics, considering their dimensions and the location of the magnetrons or heating wires.

The simulations were performed for solar salt in liquid state, defining the dielectric and thermal parameters of the sample, and applying the following conditions:

- The meshes of the sample are predefined as extra fine meshes and finer meshes for the rest of the geometry. The averaged element quality is 0.6708 for the microwave and 0.6982 for the muffle furnace.
- Electromagnetics is solved within the cavity, but microwave heating only occurs within the molten solar salt.
- The impedance boundary condition is considered on external walls.
- The natural convection within the molten salt is calculated considering a Newtonian fluid with incompressible flow.
- No slip condition is considered at the walls of the crucible.
- Heating wires are ideal heat sources as the temperature is constant over the entire surface, and the walls of the muffle furnace are thermally insulated

In the case of the microwave heating, its simulation is based on a transient approach as the dielectric parameters of solar salt are affected by the temperature. The electromagnetic module calculates the electric field distribution through Maxwell equations and the total volumetric power, Q (W/m^3).

The temperature distribution is obtained iteratively from the Fourier thermal balance equation applied in the heat transfer module, and due to density differences in the molten solar salt, free convection is considered. Therefore, the Navier-Stokes incompressible flow is solved along the mass continuity equation.

To represent the physics of the muffle furnace, the equations of conservation of fluid flow, heat transfer and mass are solved under a fully coupled nonisothermal flow approach which solves the three modes of heat transfer: conduction, convection and radiation.

3. Results

3.1 Suitability of the container material

After heating the solar salt in the different crucibles, both in the muffle furnace and in the industrial microwave, only the quartz glass was valid for both processes as the porcelain broke after a few seconds of starting the microwave heating, and in the case of the Alumina-based crucibles, these showed cracks through which the solar salt leaked during microwave heating (Figure 4).

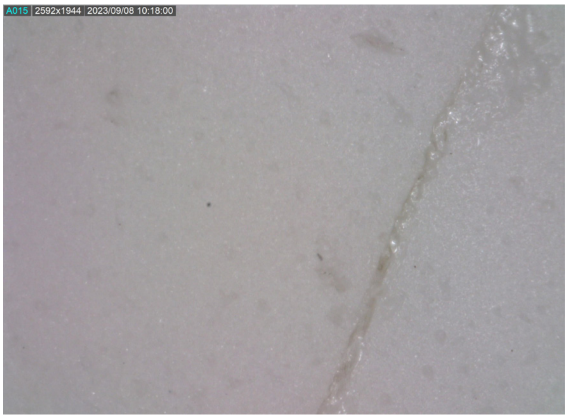

Figure 4. *Large crack in Alsint 99.7 crucible (left) and leakage of solar salt in corundum crucible (right)*

3.2 Experimental results

The comparison of both conventional and microwave heating was done with 87.5 g of Solar Salt in a glass quartz crucible. For both experiments, a single heating cycle was performed in which a temperature ramp from room temperature to the limit temperature of 565 °C was programmed. In the case of the muffle furnace, this set point is programmed for the air inside the chamber, while the temperature of the solar salt in the microwave is observed with the IR camera.

The time required to melt the solar salt and reach this temperature limit was 1 hour 3 minutes and 15 seconds in the muffle furnace, compared to 9 minutes and 17 seconds in the microwave oven. Regarding the electricity consumption, the muffle oven consumption was 4.39 kWh while the microwave oven consumption was 0.3 kWh. These results are shown in the following Figure 5.

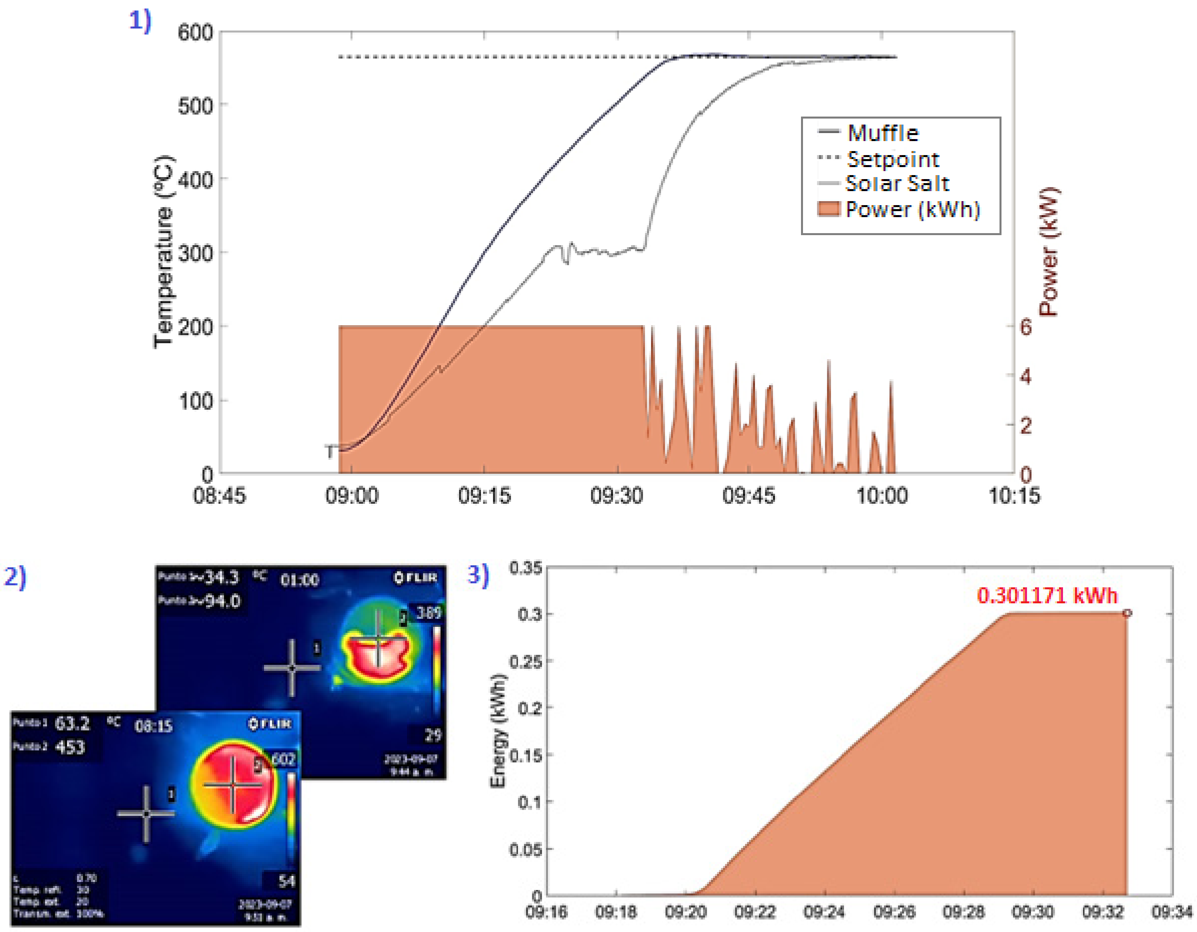

Figure 5. *1) Time graph of muffle furnace set point temperature, chamber temperature, solar salt temperature and electrical power required, 2) images captured with the IR camera, and 3) temporal graph of energy consumed by the microwave oven*

In conventional heating, the temperature inside the chamber increases continuously, but the temperature inside the solar salt stops when it reaches 300°C, at which point it begins to melt. Once it has melted, it continues to increase its temperature up to the maximum programmed temperature. The time between the air in the chamber reaching the maximum temperature of 565 °C and the molten solar salt increasing its temperature to this maximum is about 24 minutes.

On the other hand, for microwave heating, despite not having the time graph of the temperature in the sample, it was observed that the solar salt needed much less time to melt. Since the heating does not depend on its transport mechanisms - conduction, convection and radiation - but rather the electromagnetic power is transformed into heat within the sample, it is logical that the heating requires less time and, in turn, less energy consumption.

3.3 Numerical Results

With the numerical simulation, the times required to heat the solar salt to its limit temperature of 565 °C are similar to the experimental results: 590 seconds with the microwave compared to 3600 seconds with the muffle furnace. Furthermore, as shown in the following Figure 6, these results give us an idea of how the temperature is distributed in both methods. While in the case of microwaves, the heating occurs in the centre of the sample where the maximum temperatures are found, in the case of conventional heating the high temperatures are found on the crucible wall where they are distributed throughout the entire volume of solar salt.

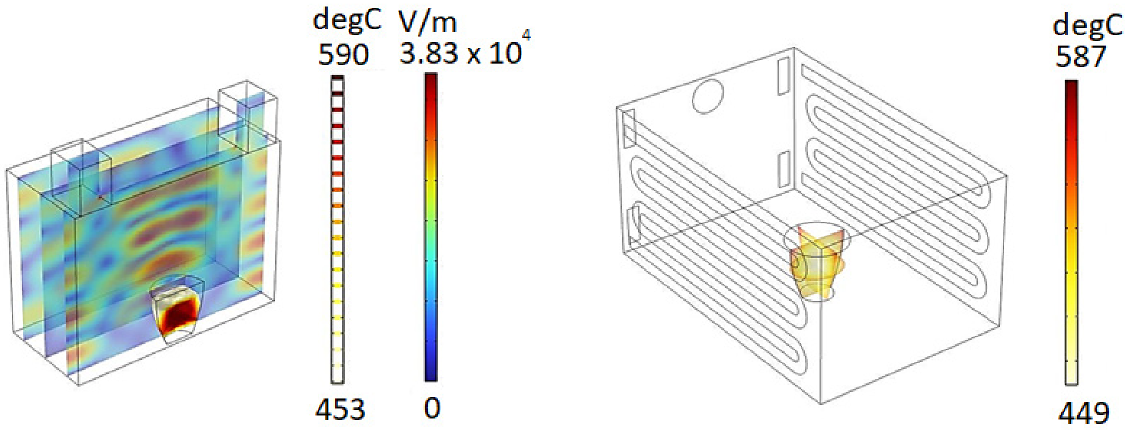

Figure 6. *Results of numerical simulations: electric field distribution and temperature of solar salt in microwave (left), and temperature of solar salt in muffle furnace (right).*

4. Conclusion

This work shows the feasibility of heating solar salt with microwaves, pointing out the advantages over conventional heating with a time saving of fifty minutes and consumption of ninety percent. It also highlights the importance of the container material in high-temperature microwave heating. Both porcelain and alumina-based ceramics presented failures, with quartz glass being the only valid material in these experiments. Finally, numerical simulation results in a useful tool to validate designs, showing the evolution of the physical process.

Data availability statement

The data needed to replicate the simulations are presented in the article itself. For more information, please contact the corresponding author.

Author contributions

Cristobal Valverde: Conceptualization, Investigation, Software, Writing-original draft; Margarita M. Rodriguez-Garcia: Conceptualization, Methodology, Supervision, Writing-review&editing; Esther Rojas: Conceptualization, Supervision, Writing-review&editing; Rocio Bayon: Project administration, Writing-review&editing

Competing interests

The authors declare that they have no competing interests.

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