

Article

Microwave Power-to-Heat for Solar Salt: Multiphysics Analysis and Design Constraints

Cristóbal Valverde ^{1,*} , Alejandro Díaz-Morcillo ² , José Fayos-Fernández ² , Juan Monzó-Cabrera ² ,
Margarita-Manuela Rodríguez-García ¹  and Esther Rojas ¹ 

¹ CIEMAT–Plataforma Solar de Almería, Ctra. de Senés km 4.5, 04200 Almería, Spain; marodriguez@psa.es (M.-M.R.-G.); esther.rojas@ciemat.es (E.R.)

² Departamento de Tecnologías de la Información y las Comunicaciones, Universidad Politécnica de Cartagena (UPCT), 30202 Cartagena, Spain; alejandro.diaz@upct.es (A.D.-M.); jose.fayos@upct.es (J.F.-F.); juan.monzo@upct.es (J.M.-C.)

* Correspondence: cvalverde@psa.es

Abstract

Thermal energy storage using suitable materials is a strategic solution for integrating renewable energy and decarbonising industrial processes. Current Power-to-Heat systems using solar salt rely on electric heaters; however, the low thermal conductivity of molten solar salt promotes localised hot spots, leading to material degradation and reduced performance. Microwave heating is a promising alternative due to its volumetric heating capability and compatibility with renewable electricity. Nevertheless, dielectric characterisation shows that molten solar salt behaves as a highly conductive ionic medium with significant dielectric losses, limiting microwave penetration and resulting in predominantly surface-localised heating. To investigate this limitation, two cavity configurations were analysed using multiphysics simulations and parametric design studies: a single-mode elliptical cavity operating at 915 MHz with an iris, and a quasi-cylindrical multimode cavity operating at 2.45 GHz for scalable applications. The coupled electromagnetic, fluid-flow, and thermal behaviour was evaluated through the resulting field distributions and heating patterns. Complementary experiments assessed microwave-transparent container materials and determined the emissivity of molten solar salt from thermographic measurements, highlighting key engineering considerations for integrating microwave heating into next-generation Power-to-Heat technologies. The results demonstrate that microwave heating of highly conductive molten solar salt is fundamentally constrained by the limited electromagnetic penetration depth, defining practical design limits for its integration into next-generation Power-to-Heat systems.

Keywords: Power-to-Heat; solar salt; microwave heating; multiphysics simulation; microwave-transparent materials; infrared thermography



Academic Editors: Tiago Santos, Vítor António Ferreira da Costa and Susana Devesa

Received: 3 June 2026

Revised: 29 June 2026

Accepted: 3 July 2026

Published: 12 July 2026

Copyright: © 2026 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the [Creative Commons Attribution \(CC BY\)](https://creativecommons.org/licenses/by/4.0/) license.

1. Introduction

Electricity production represents a major source of global greenhouse gas (GHG) emissions and is therefore a key driver of climate change [1]. In response, international energy policies increasingly prioritise the decarbonisation of the power sector by promoting the integration of renewable energy sources (RES), particularly solar photovoltaics (PV) and wind energy, into the electricity mix due to their technological maturity, cost competitiveness, and scalability [2]. The global installed capacity of renewable electricity generation continues to grow rapidly, with solar PV experiencing the fastest expansion and projected

to significantly increase its contribution by 2030 [3]. However, as the penetration of PV and wind power increases, the inherent intermittency of these RES results in increasingly pronounced temporal mismatches between electricity generation and demand. A well-known manifestation of this challenge is the so-called “duck curve”, characterised by excess PV generation during midday followed by steep ramping requirements in the evening as solar output declines. These rapid transitions are typically met by dispatchable generation. Although part of this generation may be supplied by dispatchable RES, such as biomass, hydropower, or concentrated solar power (CSP), it often remains fossil-based, thereby limiting the overall decarbonisation potential [4]. Consequently, the large-scale integration of PV and wind technologies requires the deployment of energy storage systems (ESS) capable of providing flexibility, balancing supply and demand, and ensuring grid stability.

Electrochemical energy storage, also known as battery energy storage systems (BESS), has been widely adopted, particularly for short-duration and small-scale applications, owing to its high efficiency and fast response times [5]. However, the currently high cost of these systems, together with the growing demand for batteries in electric vehicles, limits their widespread deployment in large-scale applications such as centralised power generation and energy-intensive industrial processes. Within this context, thermal energy storage (TES) systems, whose reliability for energy storage in power generation applications has been widely demonstrated in CSP plants, emerge as a promising alternative for large-scale applications owing to their cost-effectiveness, scalability, and operational suitability [6]. When TES is integrated with systems that convert electricity into heat and subsequently reconvert it into electricity, the resulting configurations—commonly referred to as Carnot batteries (CBs) or Power-to-Heat-to-Power (PtHtP) systems—represent promising solutions for long-duration electricity storage [7].

Molten nitrate salt-based TES has become a cornerstone technology for large-scale, high-temperature applications, particularly in CSP systems, where nearly half of the installed capacity incorporates TES solutions [8]. The molten nitrate salt commonly employed is known as solar salt, a non-eutectic mixture composed of 60 wt% sodium nitrate (NaNO_3) and 40 wt% potassium nitrate (KNO_3). This fluid is typically operated as a sensible heat storage medium within a safe temperature range of 290 °C to 565 °C [9]. Its widespread use is attributed to several advantageous characteristics, including high energy density, low vapour pressure, chemical stability, non-flammability, and relatively low cost [10].

To date, Power-to-Heat (PtH) charging in molten salt-based systems has primarily relied on electric resistance heaters, which transfer heat from their surface to the bulk of the storage medium [11]. Under these conditions, heat diffusion governs the thermal transport process and, given the low thermal conductivity of molten solar salt, may exacerbate internal temperature gradients and accelerate thermal degradation phenomena, thereby reducing overall system efficiency and operational lifetime [12]. In this context, microwave heating has emerged as a promising alternative [13], owing to its ability to provide direct volumetric energy transfer within the material and thereby improve temperature uniformity. Furthermore, interest in microwave heating for industrial processes has grown significantly in recent years, driven by advances in material science and applicator design that have enabled its implementation across a broad range of industrial sectors [14].

The effective implementation of this technology requires a comprehensive understanding of the dielectric properties of the storage medium and their temperature dependence, as these parameters govern the interaction between electromagnetic fields and the material [15]. Valverde et al. [16] characterised the dielectric behaviour of solar salt using the cavity perturbation method (CPM) at the industrial, scientific and medical (ISM) frequencies of 915 MHz and 2.45 GHz, complemented by electrochemical impedance spectroscopy (EIS) over the frequency range from 100 Hz to 1 MHz. Their results showed that

the solid–liquid phase transition is associated with a marked increase in dielectric losses, thereby enhancing microwave absorption. However, in the liquid state, the high dielectric loss factor (ϵ'') significantly reduces the electromagnetic penetration depth (D_p), causing energy deposition to be predominantly confined to near-surface regions. Consequently, effective volumetric heating is limited, making it difficult to achieve uniform temperature distributions throughout the bulk of the storage medium.

In this work, the microwave heating of solar salt is analysed in two cavity configurations with distinct electromagnetic field distributions using multiphysics simulations, with the aim of evaluating the feasibility and fundamental limitations of microwave-based Power-to-Heat systems employing highly conductive molten salts. First, an elliptical single-mode cavity operating at 915 MHz is examined. Second, a quasi-cylindrical multimode cavity operating at 2.45 GHz is considered, in which electromagnetic energy is coupled into the solar salt through a waveguide connected to the cavity by means of a series of slots. In both configurations, the molten salt flows continuously through the cavities via applicator tubes made of microwave-transparent material, absorbing electromagnetic energy and increasing in temperature. Prior to this analysis, suitable cavity geometries were identified through parametric design studies to maximise microwave power absorption within the molten solar salt.

Other key aspects addressed in this work include the experimental evaluation of mechanically robust, microwave-transparent materials for containing molten solar salt in future system implementations. For this purpose, a multimode microwave oven was employed. In addition, the emissivity (ϵ) of solar salt was experimentally determined using a contact thermometer method in order to enable accurate temperature estimation through infrared thermography, which is particularly relevant for temperature monitoring and process control in microwave heating systems. Overall, this study identifies the key electromagnetic and thermal constraints governing the integration of microwave heating technologies into next-generation PtH systems, thereby establishing fundamental design considerations for the efficient utilisation of highly conductive molten solar salts.

2. Materials and Methods

2.1. Thermal and Dielectric Properties of Solar Salt

Commercial multiphysics finite-element software, CST Studio Suite 2025, was used to simulate the heating of molten solar salt under various microwave configurations [17]. Within this framework, the non-eutectic nitrate mixture was defined as the material under test (MUT) under operating conditions, with an inlet temperature of 290 °C. Table 1 summarises the thermophysical properties used in the multiphysics simulations.

To evaluate the electromagnetic field distribution and the associated power dissipation, the dielectric properties of molten solar salt must first be defined. These properties were obtained from Valverde et al. [16], in which solar salt was characterised using CPM and EIS. Although both techniques showed a marked increase in the effective loss factor (ϵ''_{eff}) upon melting, the EIS measurements indicated that this behaviour is primarily caused by the sharp increase in the real part of the electrical conductivity (σ') associated with ionic transport. Because the high effective losses in the molten phase violate the small-perturbation assumption of CPM, the direct determination of ϵ''_{eff} by this technique becomes unreliable under these conditions.

The interaction of a non-magnetic material with an alternating electric field is described by its complex relative permittivity,

$$\epsilon^* = \epsilon' - j\epsilon''_{eff} \quad (1)$$

where $j = \sqrt{-1}$ is the imaginary unit, ϵ' is the dielectric constant, which describes the material's ability to store electric energy and influences microwave propagation, and ϵ''_{eff} is the effective loss factor, which quantifies the dissipation of electromagnetic energy as heat, expressed as

$$\epsilon''_{\text{eff}} = \epsilon''_{\text{diel}} + \frac{\sigma'}{\omega\epsilon_0} \quad (2)$$

where ϵ''_{diel} represents the intrinsic dielectric losses associated with polarisation mechanisms, σ' is the real part of the electrical conductivity, ω is the angular frequency of the applied electromagnetic field, and ϵ_0 is the vacuum permittivity. For molten solar salt, conductive losses are assumed to dominate over dielectric polarisation losses; therefore, ϵ''_{diel} is neglected.

Table 1. Thermophysical properties of molten solar salt, adapted from [18].

Property	Expression/Value (T in $^{\circ}\text{C}$)
Crystallization temperature [$^{\circ}\text{C}$]	238
Maximum operating temperature [$^{\circ}\text{C}$]	565
Heat of fusion (based on the average of heat of fusion of each component) [kJ/kg]	$h_{\text{sl}} = 161$
Change in density upon melting	$\Delta V/V_{\text{solid}} = 4.6\%$
Density [kg/m ³]	$\rho = 2090 - 0.636 T$
Specific heat capacity [J/kg $^{\circ}\text{C}$]	$c_p = 1443 + 0.172 T$
Thermal conductivity [W/m $^{\circ}\text{C}$]	$k = 0.443 + 1.9 \times 10^{-4} T$
Absolute viscosity [mPa s]	$\mu = 22.714 - 0.120 T$ $+ 2.281 \times 10^{-4} T^2 - 1.474 \times 10^{-7} T^3$

Based on the available experimental data, σ' was estimated to be 160–170 S m^{−1} by extrapolating the EIS measurements to the GHz frequency range, whereas the available CPM measurements indicated ϵ' values between 30 and 56. The corresponding D_p , defined as the distance at which the electric-field amplitude decays to $1/e$ of its surface value [19], was then calculated as

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

where $\lambda_0 = c/f$ is the free-space wavelength, c is the speed of light in vacuum, f is the microwave frequency, and $\tan \delta = \epsilon''_{\text{eff}}/\epsilon'$ is the loss tangent. From these values, D_p was estimated to be approximately 1.3 mm at 915 MHz and 0.8 mm at 2.45 GHz.

2.2. Numerical Modelling

This section presents the geometries considered in this study, together with the parametric design and tuning strategies used to maximise power absorption, the mesh settings, and the adopted multiphysics simulation approach. The governing equations, as well as the initial and boundary conditions, are also described. All simulations were performed within the same computational environment.

2.2.1. Geometry of the Microwave Cavities

The first step in the model development was the definition of the microwave cavity geometries. Two configurations were considered, differing primarily in their size relative to the operating wavelength. The single-mode cavity, with characteristic dimensions on the order of the operating wavelength, supports a unique three-dimensional electromagnetic field distribution, whereas the larger multimode cavity enables the superposition of several

field patterns, leading to spatially uneven and variable electromagnetic field maxima and minima. The operating frequencies of 915 MHz and 2.45 GHz correspond to the two principal ISM bands employed in industrial microwave heating, for which mature high-power microwave sources are commercially available and experimental dielectric-property data for solar salt are available.

Elliptical Single-Mode Cavity

Figure 1 illustrates the first microwave cavity configuration analysed in this study. The system consists of a single-mode cavity connected to the microwave feeding subsystem through a WR975 tapered waveguide, which provides a transition between rectangular cross-sections of 247.65×51 mm and 247.65×123.83 mm. An iris is incorporated to improve impedance matching. The feeding waveguide operates in the fundamental transverse electric TE_{10} mode at 915 MHz [20].

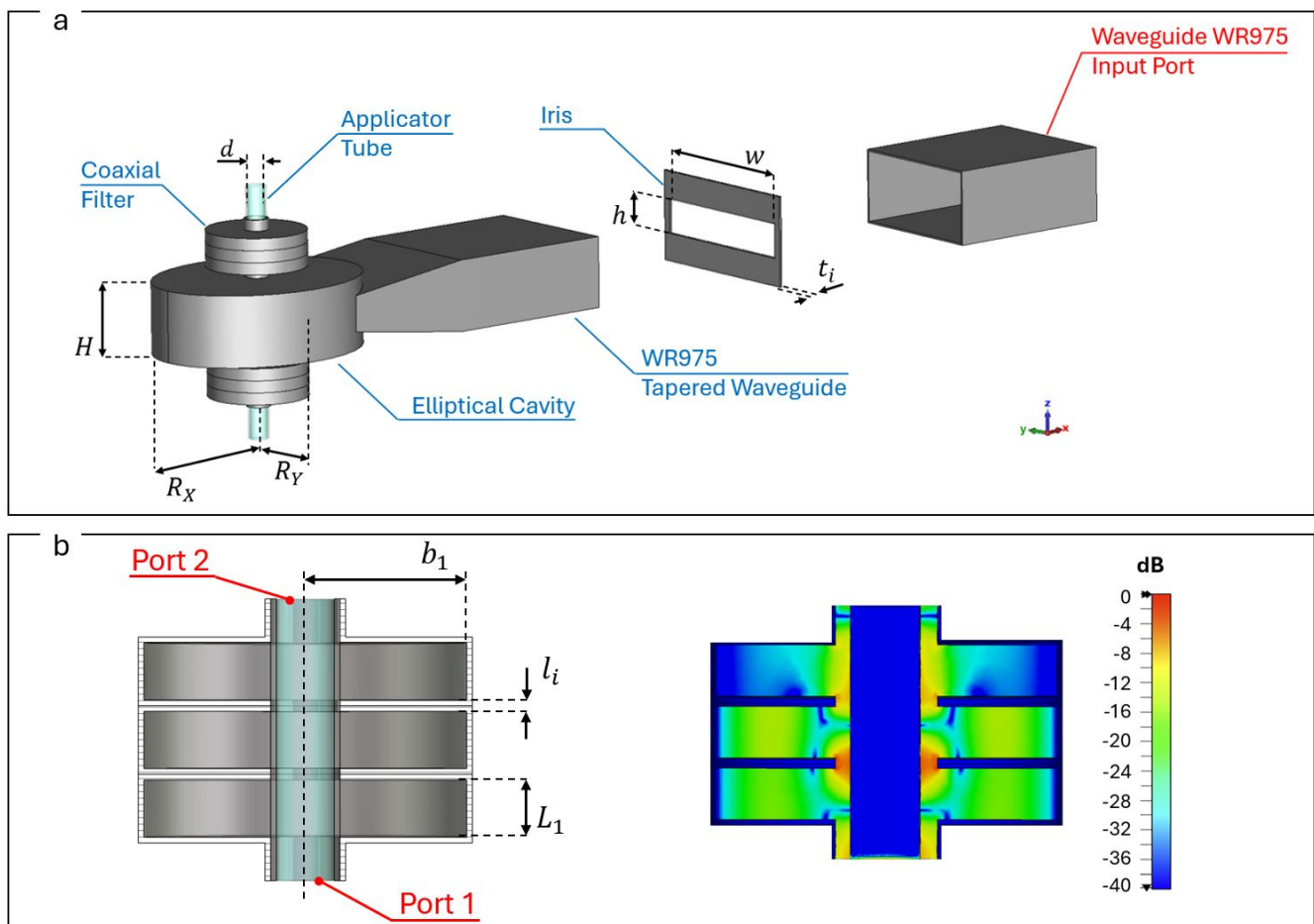


Figure 1. Single-mode elliptical cavity model: (a) exploded view of the main components, including the elliptical cavity, WR975 tapered waveguide, iris, quartz applicator tube, and three-stage coaxial cavity filter; (b) geometry of the coaxial filter and simulated attenuation distribution illustrating the suppression of electromagnetic propagation through the applicator tube ports.

The cavity geometry and feeding system were designed by systematically varying selected geometrical parameters to maximise microwave absorption within the molten solar salt (see Table 2). In particular, different iris aperture sizes were evaluated by simulation, although only the selected configuration is reported here. The cavity cross-section is defined by the X- and Y-axis radii (R_X and R_Y), where R_X is varied within 128–205 mm while R_Y is fixed at 154 mm. Under these conditions, both elliptical and circular geometries are analysed, with a constant cavity height (H) of 125 mm. The molten solar salt flows through

the cavity via a quartz applicator tube with internal diameter (d) between 30.4 mm and 55.7 mm and a wall thickness of 3 mm.

To prevent microwave leakage through the applicator tube inlet and outlet, three-stage coaxial cavity filters based on the design proposed by Monzó-Cabrera et al. [21] are incorporated at both ends of the cavity. Owing to the high electrical conductivity of molten solar salt, the salt column may behave as the inner conductor of a coaxial structure, while the cavity walls act as the outer conductor, enabling potential microwave leakage. The coaxial filters provide strong attenuation at the operating frequency, thereby suppressing field propagation through the ports. Figure 1 shows the geometry of the three-stage coaxial cavity filter employed in this work. The selected configuration provides effective suppression of microwave leakage at the operating frequency of 915 MHz.

Table 2. Geometrical parameters of the elliptical single-mode cavity model.

Symbol	Description	Value [mm]
d	Applicator diameter	30.4–55.7
R_x	Cavity X-axis radius	128–205
R_y	Cavity Y-axis radius	154
H	Cavity height	125
h	Iris height	25–100
w	Iris width	62–186
t_i	Iris thickness	3
b_1	Filter inner radius	87
l_i	Filter intracavity thickness	6
L_1	Filter height	16

Quasi-Cylindrical Multimode Cavity

The multimode microwave oven model for scalable, pre-industrial heating of solar salt is based on the patented design by Monzó-Cabrera et al. [22]. As illustrated in Figure 2, the microwave applicator consists of a rectangular resonant cavity with curved longitudinal edges, resulting in a quasi-cylindrical geometry. This geometry concentrates microwave energy along the central axis and improves efficiency compared with conventional rectangular cavities. The flat cavity walls enable the integration of slotted rectangular waveguides, ensuring stable excitation of multiple resonant modes. This feeding configuration also allows the magnetron antenna to be positioned away from the applicator tube, thereby reducing the risk of electrical arcing.

The molten solar salt flows through a quartz applicator tube aligned with the axis of symmetry and supported by quartz holders. Quartz is effectively transparent to microwaves, with a real relative permittivity of $\epsilon' \approx 3.75$ and negligible ϵ'' . The cavity may also incorporate adjustable tuning elements (e.g., screws or posts) to control the resonant mode distribution. Finally, the design is inherently scalable through the cascading of multiple modules, allowing stage-wise tuning adjustments to accommodate variations in fluid temperature and dielectric properties.

As in the single-mode elliptical cavity, microwave leakage through the applicator tube ports is prevented by incorporating three-stage coaxial cavity filters. For the present multimode configuration, the filter dimensions were scaled to match the applicator geometry while preserving their leakage-suppression function.

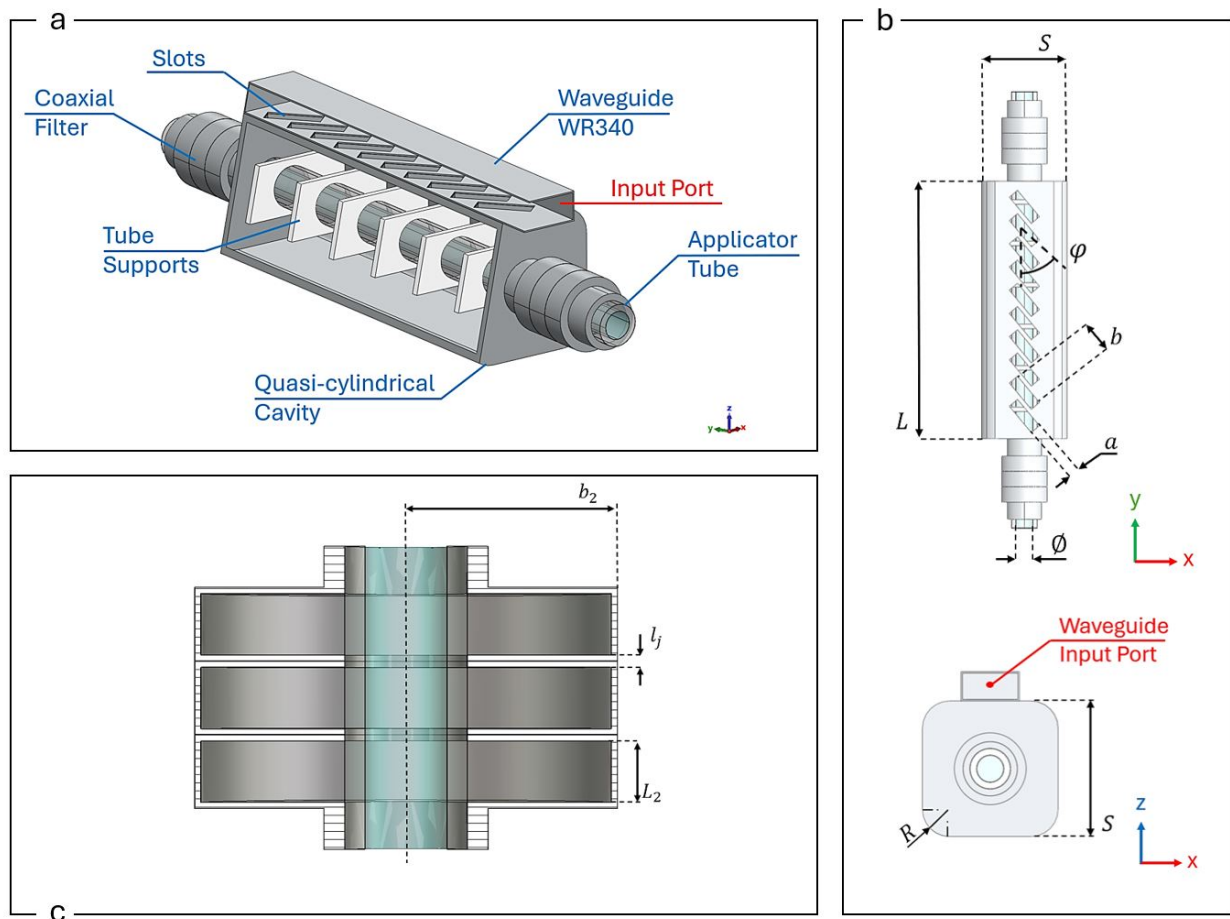


Figure 2. Geometry of the quasi-cylindrical multimode cavity model: (a) three-dimensional view of the main components, including the quasi-cylindrical cavity, slotted WR340 waveguide, quartz applicator tube, tube supports, and coaxial cavity filters; (b) side and end views showing the principal cavity dimensions, slot arrangement, and waveguide input port location; (c) geometry of the three-stage coaxial cavity filter.

This study proposes a multimode cavity operating at 2.45 GHz and fed by a slotted WR340 waveguide. The cavity design is primarily governed by the orientation of the coupling slots, defined by the rotation angle (φ) with respect to the longitudinal Y-axis. The internal diameter of the applicator tube ($\varnothing$) was varied from 30 to 50 mm. The cavity geometry is characterised by its length (L), width and height (S), and corner radius (R), while the slot dimensions are defined by their width (a) and length (b). The applicator tube is mechanically supported by tubular quartz supports spanning the width of the cavity. The geometrical parameters considered in the parametric design study are summarised in Table 3.

Table 3. Geometrical parameters of the quasi-cylindrical multimode cavity.

Symbol	Description	Value [mm]
L	Cavity length	600
S	Cavity width and height	200
R	Corner radius	40
a	Slot width	25
b	Slot length	80
$\varnothing$	Applicator tube diameter	30–50
φ	Slot rotation angle [°]	30–90
b_2	Filter inner radius	100

Table 3. Cont.

Symbol	Description	Value [mm]
l_j	Filter intracavity thickness	6
L_2	Filter cavity height	30

2.2.2. Governing Equations, Boundary and Initial Conditions

The numerical model is based on the coupled solution of the electromagnetic, fluid-flow, and heat-transfer fields through the exchange of electromagnetic power losses and temperature between the EM and thermal solvers. To reduce the computational cost, the dielectric properties of molten solar salt are assumed to be constant, and the problem is solved using a unidirectional EM–thermal coupling without iterative feedback. Under these assumptions, the electromagnetic power-loss density scales linearly with the incident microwave power while its spatial distribution remains unchanged. Although the dielectric properties vary with temperature after melting [16], EIS measurements indicate that σ' increases by approximately a factor of 2–3 over the molten temperature range, corresponding to an approximately 30–40% reduction in D_p . Extrapolation of these measurements to microwave frequencies yields an effective conductivity of $\sigma' \approx 160\text{--}170\text{ S m}^{-1}$, corresponding to a D_p of approximately 1.3 mm at 915 MHz and 0.8 mm at 2.45 GHz. Since these values remain much smaller than the characteristic dimensions of the applicators, incorporating temperature-dependent dielectric properties would primarily affect the local distribution of absorbed microwave power, while the principal conclusion of predominantly surface-localised heating remains unchanged.

The electromagnetic problem was solved in the frequency domain to determine the spatial distribution of the absorbed microwave power within the material. The electric field behaviour was described by Maxwell's equations in their frequency-domain formulation:

$$\nabla \times \left(\frac{1}{\mu_0} \nabla \times \vec{E} \right) - \omega^2 \epsilon_0 \epsilon^* \vec{E} = 0 \quad (4)$$

where $\vec{E}$ is the electric field intensity vector (V m^{-1}), μ_0 is the permeability of free space (H m^{-1}), ϵ_0 is the permittivity of free space (F m^{-1}), ω is the angular frequency (rad s^{-1}), and ϵ^* is the complex relative permittivity defined in Equation (1). Since molten solar salt is a non-magnetic material, its relative permeability was assumed to be $\mu_r = 1$, such that the magnetic permeability reduces to $\mu = \mu_0$.

The boundary conditions for the EM solver included perfect electric conductor (PEC) walls at the waveguide and cavity surfaces, implying that $\hat{n} \times \vec{E} = 0$.

The volumetric power generation (Q) due to microwave absorption was obtained from the electric field distribution as:

$$Q = 2\pi f \epsilon_0 \epsilon''_{\text{eff}} |\vec{E}|^2 \quad (5)$$

where $\vec{E}$ denotes the root-mean-square (RMS) electric field intensity vector.

The temperature evolution of the fluid was governed by Fourier's energy balance equation, including convective transport:

$$\frac{\partial T}{\partial t} + \vec{v} \cdot \nabla T = \frac{k}{\rho C_p} \nabla^2 T + \frac{Q}{\rho C_p} \quad (6)$$

where ρ is the density (kg/m^3), C_p is the specific heat capacity (J/kg K), k is the thermal conductivity (W/m K), and $\vec{v}$ is the velocity vector (m/s).

The fluid flow was described by the incompressible Navier–Stokes equations together with the continuity equation:

$$\rho \left(\frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} \right) = -\nabla P + \mu \nabla^2 \vec{v} + \rho \vec{g}, \quad (7)$$

$$\nabla \cdot \vec{v} = 0, \quad (8)$$

where P is the pressure (Pa), ρ is the fluid density (kg m^{-3}), μ is the dynamic viscosity (Pa s), $\vec{v}$ is the fluid velocity (m s^{-1}), and $\vec{g}$ is the gravitational acceleration (m s^{-2}).

A no-slip boundary condition was applied at the inner wall of the applicator tube. The inlet temperature of the molten solar salt was fixed at 290 °C, while the outlet pressure was set to atmospheric conditions. The Reynolds numbers associated with the investigated operating conditions indicate laminar flow in the single-mode cavity ($Re \lesssim 1400$), whereas the multimode cavity operates in the transitional regime ($Re \approx 2600$). Accordingly, the automatic turbulence model available in the CST Studio CHT solver was employed. Adiabatic boundary conditions were imposed at the applicator wall to isolate the effect of microwave heating on the solar salt and analyse the dominant physical mechanisms governing the process under idealised operating conditions. This assumption represents an idealised thermal configuration. In a practical system, heat exchange with the surroundings through conduction, convection, and radiation would depend primarily on the thermal management strategy, including the level of thermal insulation and any external temperature control applied to the cavity.

2.2.3. Electromagnetic Coupling Efficiency and Mesh Convergence

Both cavity configurations are excited through a single waveguide port. The fraction of incident power reflected at this port is characterised by the frequency-dependent scattering parameter S_{11} , which is obtained directly from the EM solver:

$$S_{11} = \frac{b}{a} \quad (9)$$

where a and b denote the complex amplitudes of the incident and reflected waves at the port, respectively.

The electromagnetic coupling efficiency (η), defined as the fraction of the incident microwave power accepted by the cavity, is given by

$$\eta = 1 - |S_{11}|^2 \quad (10)$$

Consequently, the cavity configurations were selected by minimising $|S_{11}|$. Metallic losses are negligible (<0.5%), indicating that nearly all accepted microwave power is dissipated within the solar salt. Unlike Joule heating, however, the overall electrical-to-thermal efficiency of a microwave system also depends on the efficiency of the microwave source and power delivery components.

To ensure numerical accuracy, a mesh convergence study was performed in the EM solver using an unstructured tetrahedral mesh. Due to the small D_p of molten solar salt, the grid discretisation is significantly finer than standard wavelength-based criteria, such as the Nyquist condition, which establishes that the maximum mesh element size should remain below half the wavelength ($S_{max} < \lambda/2$) [23], or the use of six cells per wavelength [24]. Accordingly, local mesh refinements were applied within the MUT domain, with two refinement levels (0.8 mm and 0.3 mm) evaluated. As shown in Figure 3, finer meshing led to shifts in resonance frequency and amplitude compared to coarse meshes, while the difference between the two refined cases was negligible despite a signifi-

cantly higher computational cost for the finest mesh. Therefore, adaptive mesh refinement was adopted for all simulations. In this approach, the mesh is iteratively refined based on an error estimator, with convergence assessed through the variation of the S -parameters between successive passes. This enables targeted refinement in regions with high field gradients, providing a balance between accuracy and computational efficiency.

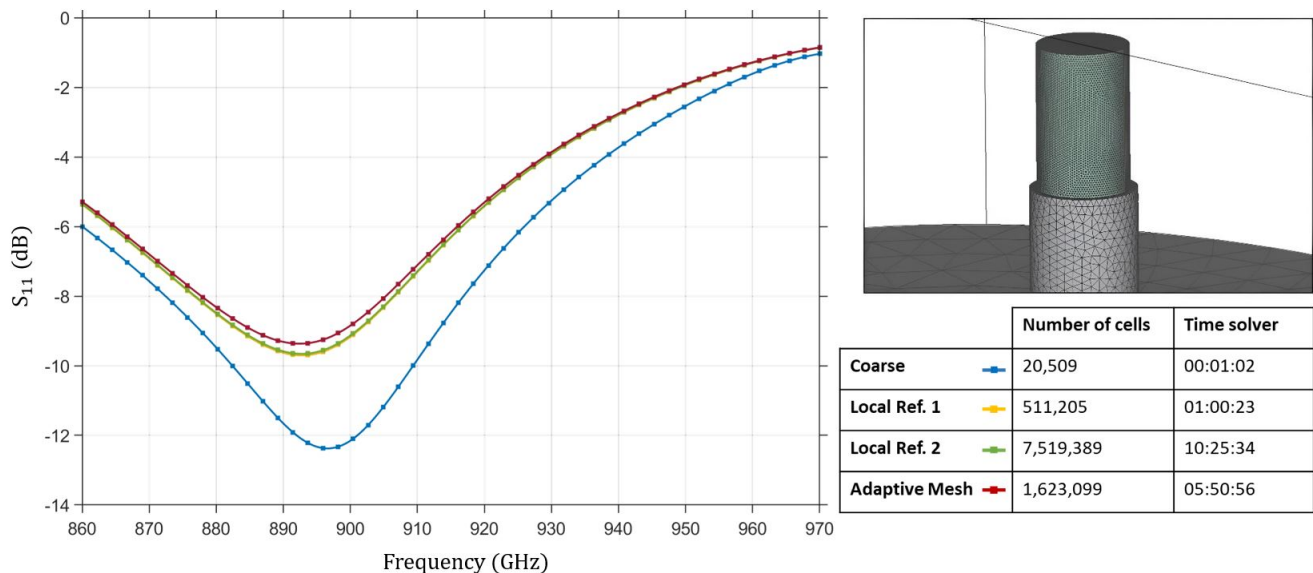


Figure 3. Mesh convergence analysis for the single-mode cavity: **(left)** reflection coefficient magnitude in dB as a function of frequency for different mesh configurations (coarse, locally refined, and adaptive); **(top right)** detail of the mesh refinement near the applicator tube; **(bottom right)** comparison of the number of cells and solver time for each mesh.

For the thermal solver, an octree-based Cartesian CFD mesh was employed, with local refinement in the near-wall region of the applicator tube. In this case, the mesh resolution was governed by geometric features and thermal gradients, ensuring element sizes smaller than D_p to accurately resolve the temperature field in the region where the absorbed power is concentrated. This dual-mesh strategy allows each physical problem to be discretised using the most appropriate numerical approach, combining geometric flexibility for the electromagnetic solution with computational efficiency for the fluid–thermal analysis.

2.3. Experimental Setup for Complementary Studies on Microwave Heating of Solar Salt

To investigate key practical aspects associated with the microwave heating of molten solar salt, including the suitability of container materials and ϵ of the storage medium for temperature monitoring, a modified multimode 3.5 kW power-rated microwave furnace (CEM Corporation, Matthews, NC, USA, Phoenix BLACK) operating in the 2.45 GHz ISM band was employed. An infrared thermographic camera (Optris PI 640i, Optris GmbH, Berlin, Germany) with a spectral range of 7.5–13 μm was integrated into the applicator to monitor the sample temperature during microwave heating. The camera was oriented towards the surface of the sample, placed inside a crucible, through a perforated plate with sub-wavelength apertures, thereby minimising microwave leakage while enabling thermal imaging of the solar salt. With the magnetrons switched off, ϵ as a function of temperature was determined using the contact thermometer method [25], by adjusting the ϵ setting of the infrared camera until the measured surface temperature matched that recorded by the thermocouples. Type-K Class 1 thermocouples, with a measurement uncertainty of approximately ± 1.5 $^{\circ}\text{C}$ according to IEC 584-2:1982 [26], were inserted approximately 3–5 mm below the molten salt surface to minimise the influence of ambient

air temperature while maintaining representative near-surface temperature measurements (Figure 4). The Optris PI 640i infrared camera has a specified measurement accuracy of $\pm 2\text{ }^{\circ}\text{C}$ or $\pm 2\%$ of the measured temperature, whichever is greater, according to the manufacturer's specifications [27].

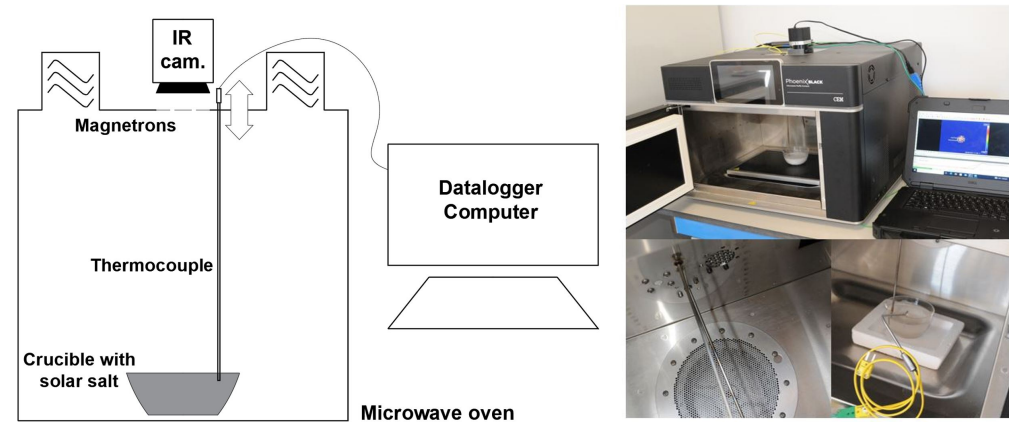


Figure 4. Schematic of the experimental setup (left) and the adapted multimode microwave furnace (right).

Materials for Solar Salt Containment

Materials with a very low, nearly negligible ϵ'' are considered essentially non-dissipative to microwaves [28]. Owing to their mechanical and chemical resistance, as well as their durability under thermal shock conditions—particularly in the presence of localised hot spots—such materials are suitable candidates for the fabrication of high-temperature microwave-heating containers. Typical examples include PTFE, whose maximum operating temperature is limited to $260\text{ }^{\circ}\text{C}$, together with fused quartz and alumina-based ceramics [29].

The materials used for the crucibles employed during microwave heating experiments with solar salt included commercially available quartz glass (320 mL), boron nitride (20 mL), and alumina-based ceramics, namely corundum (30 mL) and Alsint 99.7 (50 mL). These crucibles were evaluated under realistic molten salt operating conditions. Boron nitride typically exhibits $\epsilon' \approx 3.8$ to 4.4 and $\epsilon'' \approx 10^{-3}$ to 3×10^{-3} up to approximately $600\text{ }^{\circ}\text{C}$ [29]. Similarly, alumina-based ceramics present $\epsilon' \approx 3.8$ to 4.5 and $\epsilon'' \approx 10^{-3}$ to 10^{-2} up to about $600\text{ }^{\circ}\text{C}$, above which corundum undergoes a marked increase in dielectric losses [30].

3. Results

3.1. Numerical Simulation Results

The numerical simulation results are presented for the two cavity configurations under study: a single-mode elliptical cavity and a quasi-cylindrical multimode cavity. For each case, the electromagnetic performance is first evaluated in terms of impedance matching and field distribution, followed by the analysis of power absorption and the resulting thermal behaviour of the molten solar salt under representative operating conditions.

3.1.1. Elliptical Single-Mode Cavity

The cavity geometry was determined through a parametric sweep of selected geometrical variables. In particular, different configurations were analysed by varying the applicator tube diameter (d), the elliptical cavity radius (R_x), and the iris dimensions (h , w) within realistic and manufacturable ranges (see Table 2). The parameters were initially sampled using predefined step widths, generating approximately 50 different geometrical combinations. The parameter ranges were subsequently refined around the configurations

exhibiting the lowest S_{11} values near 915 MHz for molten solar salt at 290 °C, thereby improving the impedance matching conditions.

The final cavity configuration was selected as the one exhibiting the minimum S_{11} magnitude at the operating frequency. The resulting geometrical parameters are $d = 30.5$ mm, $R_x = 190.5$ mm, $h = 50$ mm, and $w = 232$ mm. This configuration ensures single-mode operation within the cavity and provides effective impedance matching, thereby maximising the electromagnetic power transferred to the molten solar salt. The corresponding electric field distribution (Figure 5) exhibits a well-defined standing-wave pattern, with field intensities concentrated around the applicator tube, indicating efficient energy localisation within the molten salt region. In addition, the field magnitude within the three-stage coaxial cavity filters remains negligible, confirming that electromagnetic energy is effectively confined within the applicator.

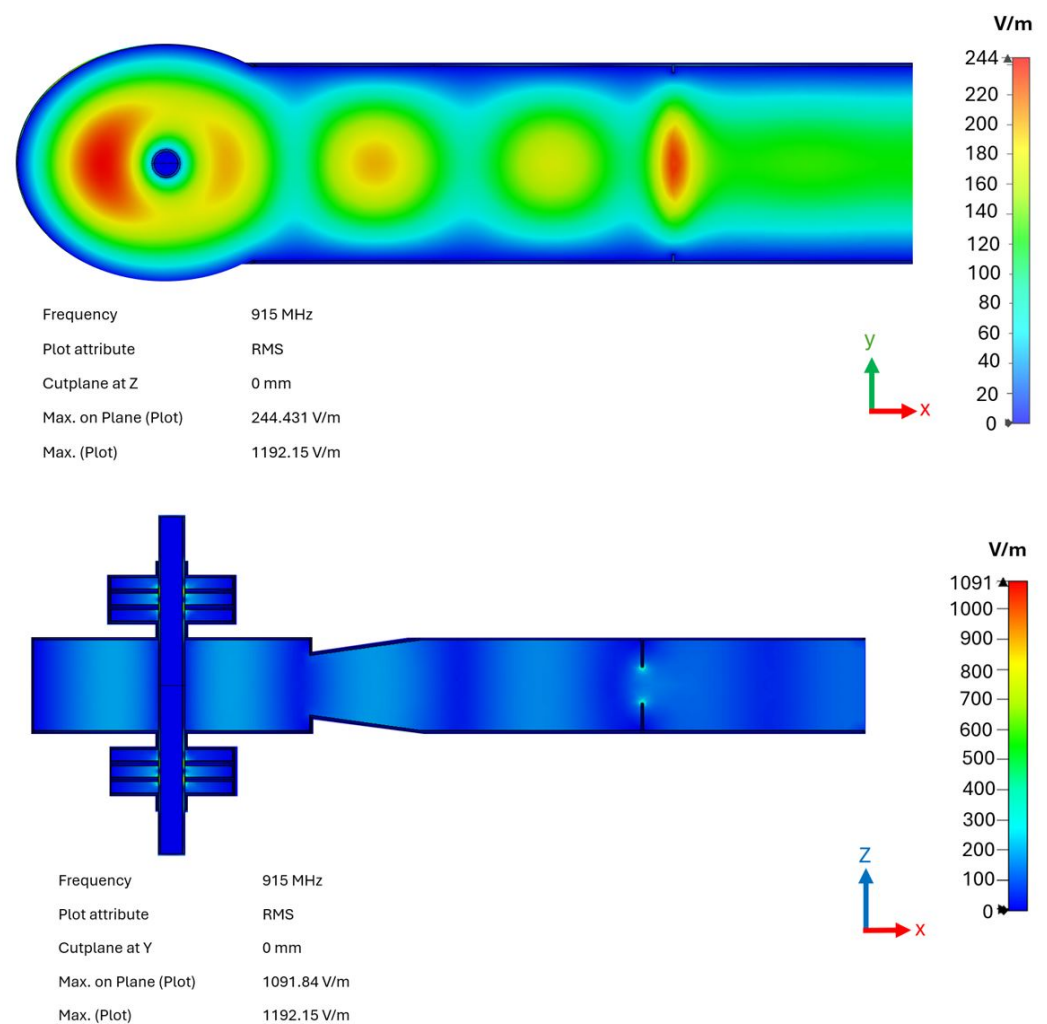


Figure 5. Electric field magnitude (RMS, V/m) distribution in the single-mode elliptical cavity at 915 MHz: **(top)** XY symmetry plane ($Z = 0$); **(bottom)** XZ symmetry plane ($Y = 0$).

The frequency response (Figure 6) exhibits a well-defined resonance centred at approximately 915 MHz. Among the 50 configurations evaluated during the parametric design study, the selected design (highlighted in red) achieves a minimum S_{11} magnitude of approximately -29 dB, corresponding to $\eta > 99.8\%$ according to Equation (10).

Figure 7 presents the spatial distribution of power loss density (W/m^3) obtained from the EM solver for an excitation power of 0.5 W, considering molten solar salt flowing through the applicator tube at an inlet temperature of 290 °C. A highly non-uniform distribution is observed, with electromagnetic energy predominantly absorbed within a

thin region near the inner wall of the tube. This behaviour is attributed to the high ionic conductivity of molten solar salt, which leads to a reduced D_p , thereby confining power deposition to the near-wall region and resulting in negligible absorption within the core of the flow.

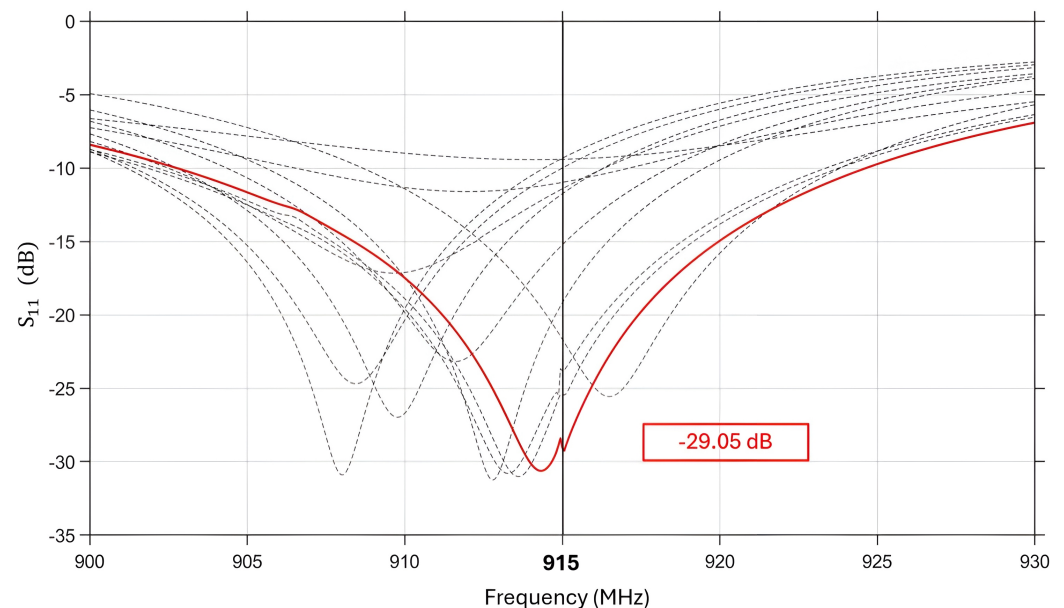


Figure 6. Reflection coefficient magnitude in dB as a function of frequency (MHz) for the evaluated single-mode elliptical cavity configurations. The optimised design is highlighted in red.

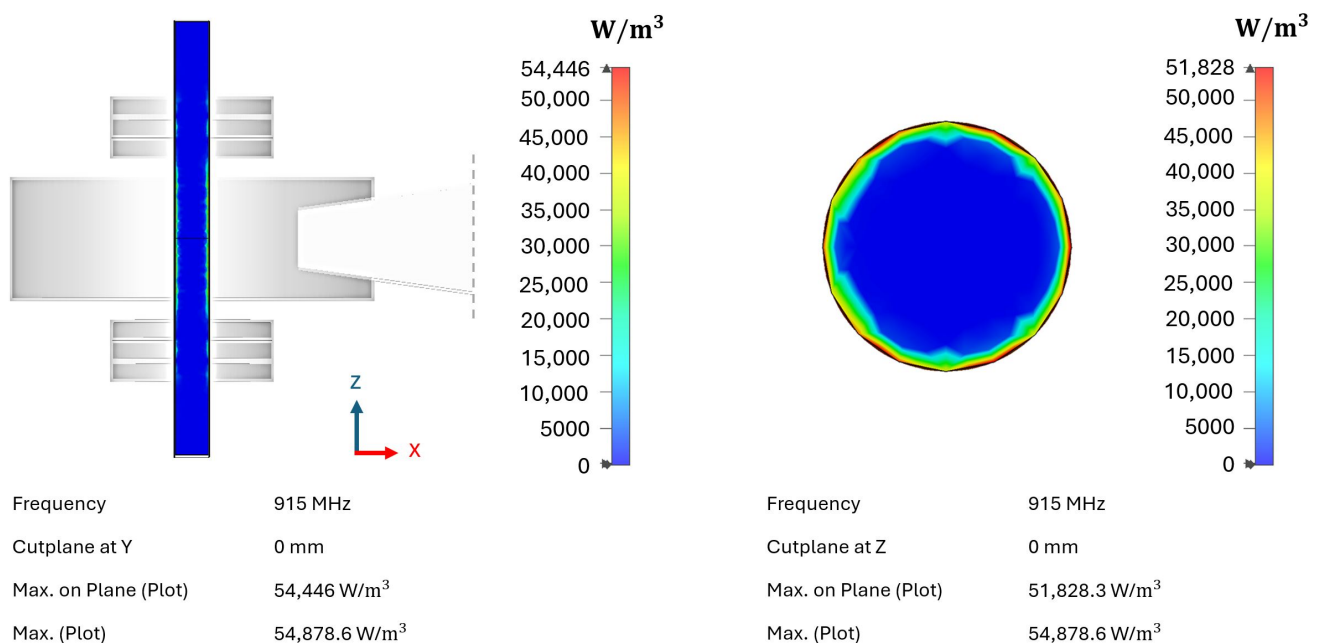


Figure 7. Spatial distribution of power loss density (W/m³) in molten solar salt at 915 MHz: (left) longitudinal cross-section ($Y = 0$); (right) transverse cross-section ($Z = 0$).

To evaluate the thermal performance, the power loss density was scaled up and coupled to the thermal solver, considering an input power of 4 kW and a flow rate of 2 L/min. The resulting temperature distribution is shown in Figure 8. Although the microwave applicator exhibits excellent electromagnetic coupling and most of the accepted power is absorbed by the molten solar salt, the absorbed energy is confined to a thin layer adjacent to the quartz tube wall because of the extremely limited electromagnetic D_p . Thermal

conduction and fluid motion partially redistribute this energy throughout the flow; however, pronounced radial temperature gradients persist, with temperatures approaching 550 °C near the salt–quartz interface while the central region remains substantially cooler. A similar radial temperature distribution is expected in conventional electrical resistance heating, where thermal energy is likewise generated at a solid–liquid interface and subsequently redistributed by thermal conduction and fluid motion [31]. Consequently, despite the different heat-generation mechanisms, both technologies are fundamentally governed by the same heat-transfer processes. These results therefore indicate that, although microwave energy is efficiently coupled into the molten solar salt, the heating process remains predominantly surface-localised, thereby limiting its volumetric heating capability.

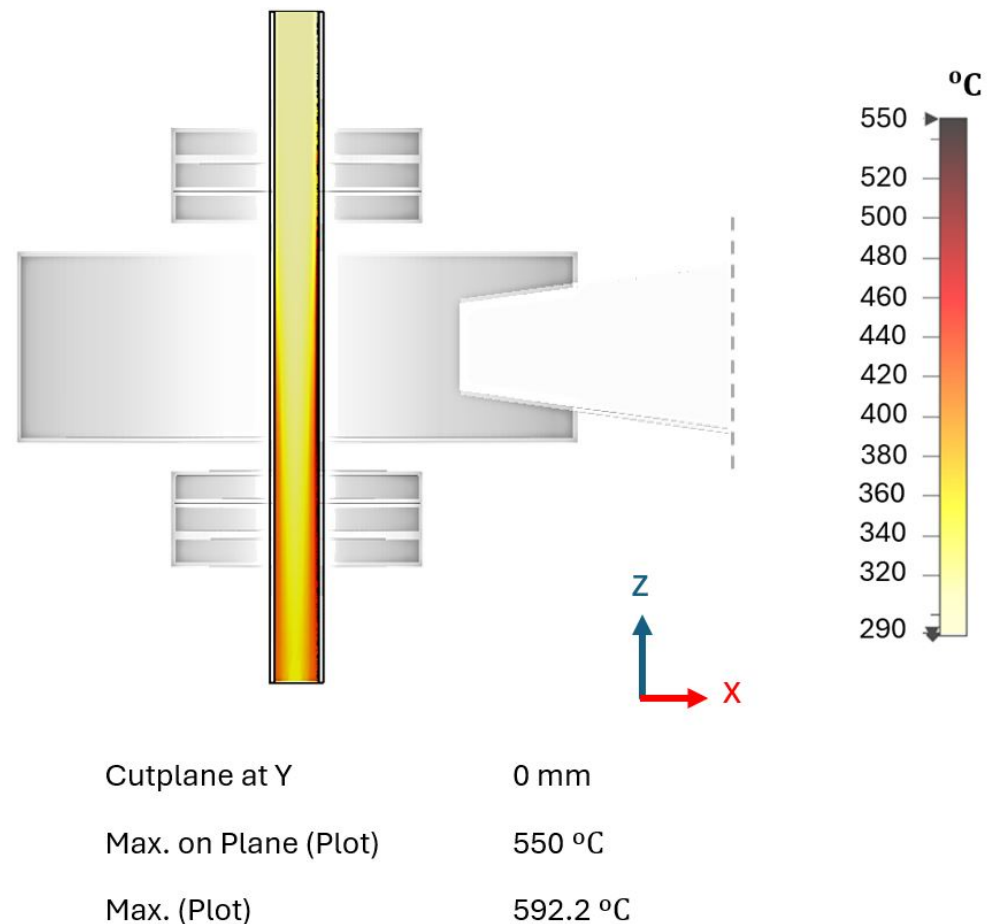


Figure 8. Temperature distribution (°C) in the single-mode elliptical cavity at 915 MHz for an input power of 4 kW and a molten solar salt flow rate of 2 L/min, shown in the longitudinal ZX plane ($Y = 0$ mm).

3.1.2. Quasi-Cylindrical Multimode Cavity

The quasi-cylindrical multimode cavity operates at 2.45 GHz and is fed by a standard rectangular waveguide through a series of coupling slots. Its electromagnetic behaviour is mainly governed by the slot orientation angle ($\varphi = 30$ – 50°) and the internal diameter of the quartz applicator tube ($\varnothing = 30$ – 50 mm). These variables were systematically varied through a parametric sweep using predefined step widths, and the cavity configuration exhibiting the minimum S_{11} at 2.45 GHz was selected.

The electric field distributions for the selected configuration are shown in Figure 9. Unlike the single-mode elliptical cavity, the quasi-cylindrical applicator exhibits a complex field pattern characterised by multiple local maxima and minima distributed throughout

the cavity volume, reflecting the simultaneous excitation of several resonant modes. Despite this multimode behaviour, appreciable electric field intensities are observed in the vicinity of the applicator tube, indicating that microwave energy is effectively coupled to the central heating region.

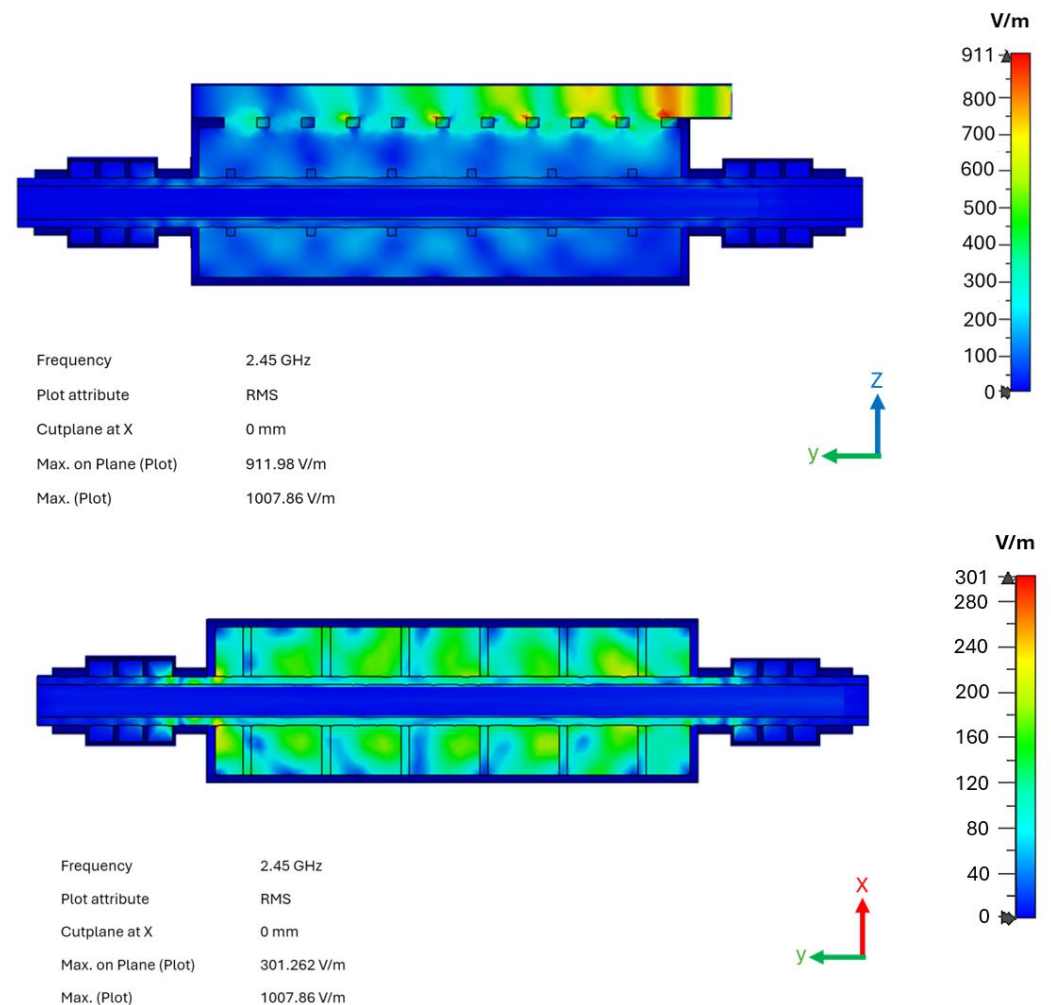


Figure 9. Electric field magnitude (RMS, V/m) distribution in the quasi-cylindrical multimode cavity at 2.45 GHz: **(top)** YZ longitudinal cross-section ($X = 0$); **(bottom)** XY cross-section ($X = 0$).

The frequency response for the analysed configurations is shown in Figure 10. Unlike the single-mode cavity, the S_{11} curves display no clear or predictable trend, reflecting the inherently complex impedance behaviour of multimode cavities. In this case, the resonant response arises from the interaction of multiple modes and is highly sensitive to small geometrical variations. The selected cavity configuration ($\varphi = 40^\circ$, $\varnothing = 40$ mm) yields an S_{11} magnitude of approximately -14.3 dB at 2.45 GHz, corresponding to $\eta \approx 96.3\%$. Although the matching is less pronounced than in the single-mode cavity, it still indicates acceptable electromagnetic coupling to the applicator.

Figure 11 shows the spatial distribution of power loss density (W/m^3) in the molten solar salt at different axial positions along the applicator tube. As in the single-mode case, the absorbed electromagnetic power is concentrated mainly within a thin outer region close to the tube wall, whereas the central core remains associated with much lower values of power deposition. This behaviour is again attributed to the reduced D_p , which confines the absorption of electromagnetic energy to the near-wall region. Therefore, although the surrounding cavity field exhibits multimode interference patterns, the local absorption mechanism inside the fluid remains predominantly superficial.

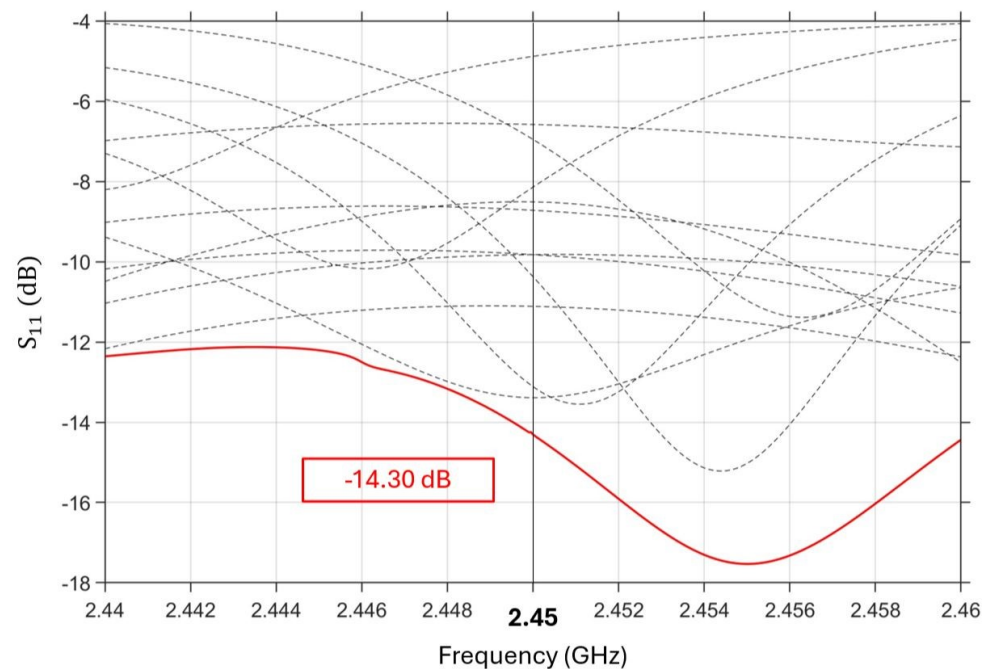


Figure 10. Reflection coefficient magnitude (S_{11}) in dB as a function of frequency for the quasi-cylindrical multimode cavity evaluated for different slot orientation angles (φ) and applicator tube diameters ($\varnothing$). The selected cavity configuration is highlighted in red.

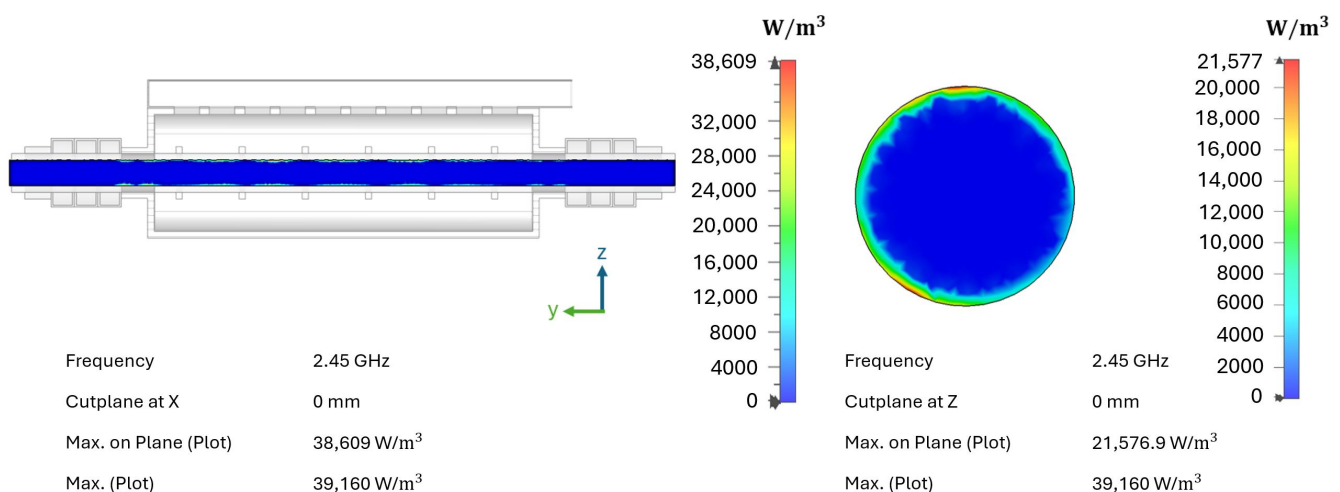


Figure 11. Spatial distribution of power loss density (W/m^3) in molten solar salt for the quasi-cylindrical multimode cavity at 2.45 GHz: (left) longitudinal YZ cross-section ($X = 0$), showing power absorption along the applicator tube; (right) transverse cross-section ($Y = 0$).

To evaluate the thermal performance of the multimode cavity, the electromagnetic power loss density was scaled up and coupled to the thermal solver, considering an input power of 10 kW and a flow rate of 6 L/min. The resulting temperature distribution is shown in Figure 12. Similar to the single-mode configuration, microwave heating remains predominantly surface-localised, resulting in significant radial temperature gradients within the molten solar salt. Despite the presence of multiple resonant modes and a more distributed electromagnetic field pattern within the cavity, no substantial improvement in thermal uniformity is observed. This behaviour is attributed to the extremely low electromagnetic D_p and low thermal conductivity of molten solar salt (see Table 1), which confine energy deposition near the tube wall and limit radial heat transfer toward the core of the flow. The slightly lower temperature gradients observed in the single-mode cavity (see Figure 8)

may be associated with the smaller diameter of the quartz applicator tube and stronger localisation of the electromagnetic field around the central heating region.

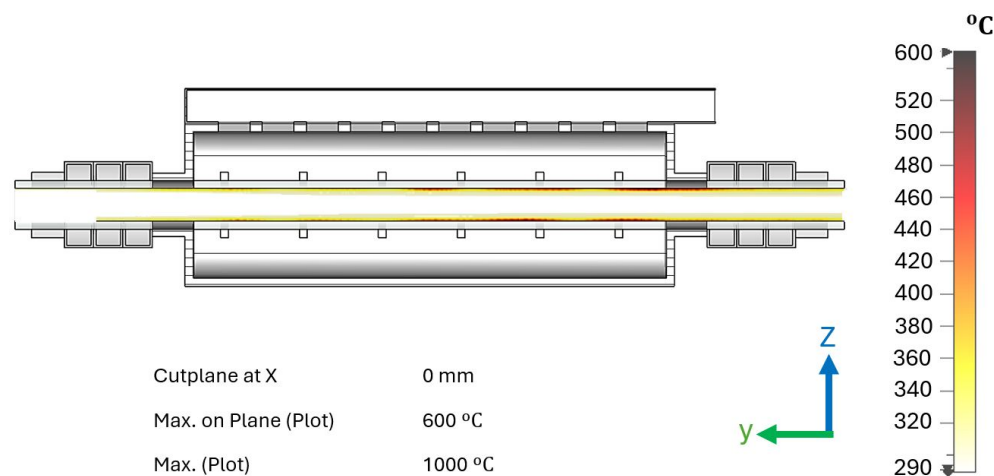


Figure 12. Temperature distribution (°C) in the quasi-cylindrical multimode cavity for an input microwave power of 10 kW and a flow rate of 6 L/min, shown in the longitudinal YZ plane ($X = 0$ mm).

These results suggest that additional strategies are required to improve thermal uniformity. In particular, applicator designs that increase the heated surface-area-to-volume ratio, such as bundles of smaller-diameter tubes operating in parallel or annular flow configurations, may reduce the characteristic heat-transfer distance and facilitate radial heat redistribution within the molten salt. Furthermore, flow-enhancing geometries could promote mixing between the heated boundary layer and the cooler core region. Advanced electromagnetic field-engineering approaches, including gradient-index metamaterials, may also offer opportunities to improve microwave energy concentration and utilisation [32]. It should be noted that the thermal results correspond to steady-state conditions and neglect radiative heat transfer effects, which could contribute to partial temperature homogenisation. Nevertheless, the extremely low D_p of molten solar salt remains a fundamental constraint that must be considered in future Power-to-Heat system designs.

3.2. Complementary Experimental Investigations

This section presents the experimental results obtained using the multimode microwave experimental setup described in Section 2.3, focusing on two key aspects: the suitability of different container materials for molten solar salt and the determination of ϵ values for temperature monitoring by infrared thermography.

3.2.1. Suitability of Container Materials for Solar Salt

Figure 13 shows the results of microwave heating of solar salt in crucibles made of advanced ceramic materials: corundum, Alsint 99.7 (both alumina-based), and boron nitride. These materials had previously been evaluated by Behrend et al. [29] in a single-mode microwave applicator containing oxide materials at temperatures up to 1600 °C. Under those conditions, the alumina-based crucibles exhibited cracking, whereas boron nitride, although it began to degrade above 900 °C, did not show cracking. In the present experiments, the crucibles were subjected to repeated microwave heating and cooling cycles in the multimode furnace. The maximum temperature reached during microwave heating was approximately 500 °C, as monitored by the thermal imaging camera. Under these conditions, both the alumina-based ceramics and the boron nitride crucibles exhibited cracking and solar salt leakage.

As previously discussed, multimode microwave cavities exhibit a highly non-uniform electromagnetic field distribution, resulting in spatially heterogeneous energy deposition. Despite their high resistance to thermal gradients, alumina-based ceramics and boron nitride may undergo local thermal runaway at temperatures above approximately 600 °C due to the increase in dielectric losses [29,30], leading to enhanced microwave absorption and local overheating. In addition, upon crystallization, molten solar salt remains attached to the container surface (see Figure 14b). During subsequent cooling and solidification, differential thermal contraction between the solidified salt and the crucible wall, together with the volumetric change associated with melting and crystallization ($\Delta V/V_{\text{solid}} \approx 4.6\%$) [18], may generate local mechanical stresses that promote crack formation.

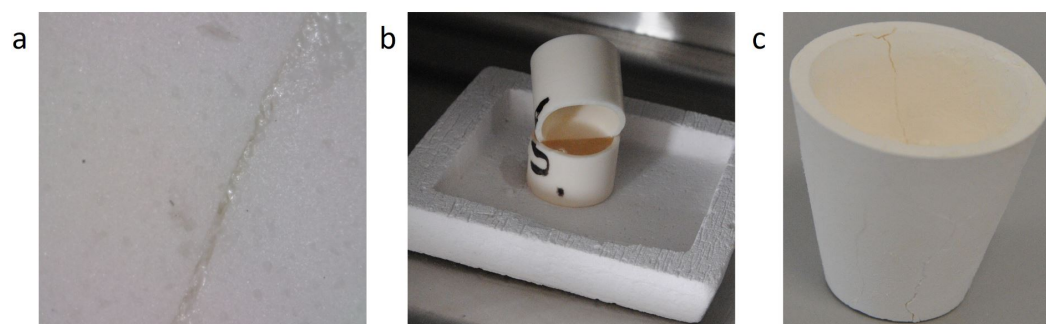


Figure 13. Images of crucibles containing solar salt after microwave heating: (a) microscopic image of a fracture in the corundum crucible, (b) breakage of the Alsint 99.7 crucible, and (c) fractures in the boron nitride crucible.

As shown in Figure 14, the 320 mL quartz crucible did not exhibit cracking or solar salt leakage. However, after solidification, the solar salt remained attached to the crucible walls, which may lead to the development of local mechanical stresses during cooling due to differential thermal contraction between the solidified salt and the quartz surface. This work involved up to three heating and cooling cycles using the quartz glass crucible. Therefore, the long-term stability of the system must be further investigated.

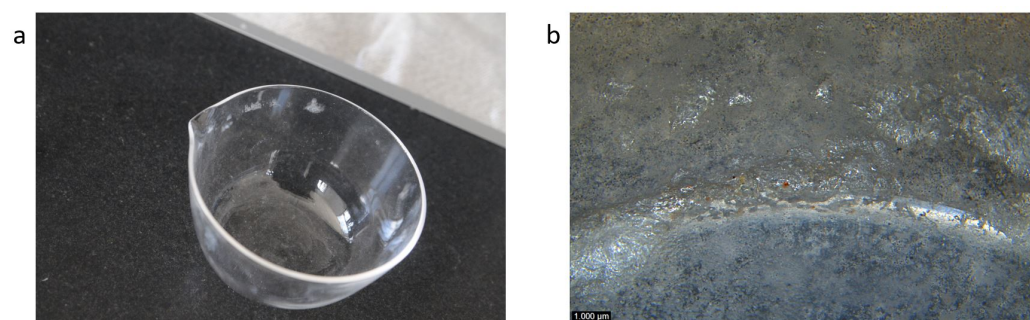


Figure 14. Images of quartz glass crucibles after heating solar salt inside: (a) photograph after emptying the crucible contents, and (b) microscopic image showing crystallized solar salt residue on the walls.

3.2.2. Emissivity Calibration Using the Contact Thermometer Method

To measure the temperature of solar salt by infrared thermography, its ϵ was estimated up to 500 °C using the contact thermometer method in the multimode microwave experimental setup described in Section 2.3, employing the quartz crucible configuration described above. The ϵ values configured in the Optris PI infrared camera were evaluated against the temperature- and wavelength-dependent emissivity data reported by Xie et al. [33].

In Figure 15, the continuous curves represent the temperature evolution measured by the infrared camera using different configured ϵ values (0.4–1.0), with the camera focused near the thermocouple location on the solar salt surface. The black curve corresponds to the thermocouple measurement. The inset shows the spectral variation of ϵ reported by Xie et al. [33], highlighting the 7.5–13 μm spectral range of the infrared camera. Both datasets indicate that ϵ reaches its maximum at 500 °C and progressively decreases during cooling and solidification, while remaining above approximately 0.55 within the operating temperature range of the salt.

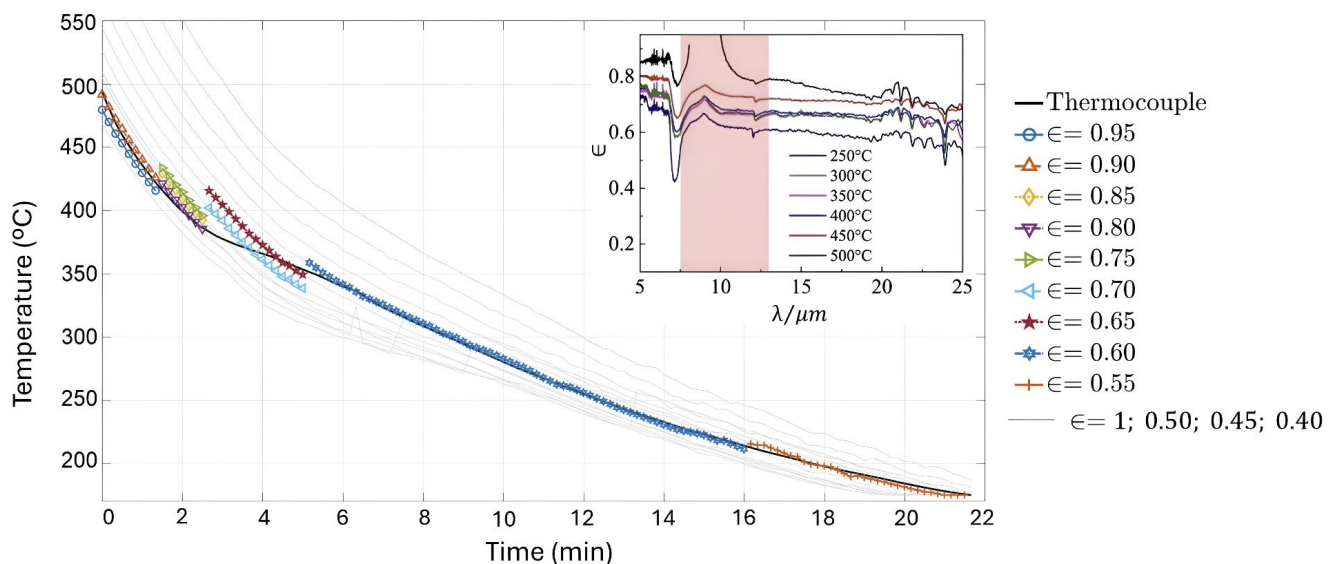


Figure 15. Temperature evolution of solar salt during cooling after microwave heating, measured by thermography for different emissivity (ϵ) values. The inset shows the spectral variation of ϵ for solar salt at different temperatures, adapted from Xie et al. [33].

Table 4 summarises the ϵ values obtained in this work and those reported by Xie et al. [33]. The reported values are rounded to the nearest 0.05 and correspond to the range of camera settings consistent with the thermocouple measurements within the combined measurement uncertainty of the thermocouple and infrared camera. Both datasets show the same general trend, with the best agreement observed between 250 and 350 °C, where the values determined experimentally in this work fall within the reported literature ranges. At higher temperatures (400–500 °C), the ϵ values obtained using the contact thermometer method are slightly higher, although they remain consistent with the upper range of the literature data.

Table 4. Effective emissivity (ϵ) values of solar salt in the 7.5–13 μm spectral range obtained using the contact thermometer method and comparison with the values reported by Xie et al. [33].

Temperature Range (°C)	This Work (Optris PI)	Xie et al. [33]
200	0.55	—
250	0.60	0.55–0.65
300	0.60	0.60–0.75
350	0.60–0.70	0.60–0.75
400	0.75–0.85	0.60–0.75
450	0.90–0.95	0.70–0.80
500	0.90–0.95	0.80–0.95

Unlike the approach of Xie et al. [33], in which the effects of radiation from the inner wall of the large crucible and the emission and reflection at the bottom surface of the smaller

crucible were minimized, the measurements obtained in the present setup were affected by these sources of error. Additional uncertainties arise from deformations of the free surface of the molten solar salt, which, in practice, tends to adopt a slightly convex shape due to surface-tension effects [34]. This surface curvature, together with reflections within the metallic cavity, affects thermographic measurements and introduces further uncertainty. Nevertheless, the method enables effective temperature monitoring and control of the thermal process and remains scalable for future industrial applications.

4. Conclusions

This work combined multiphysics numerical simulations with complementary experimental investigations to examine the feasibility of microwave heating of molten solar salt for PtH applications. The objective was to identify the fundamental design constraints associated with the microwave heating of highly conductive molten solar salt. The main findings are summarised as follows:

1. Both cavity configurations achieved favourable electromagnetic coupling ($S_{11} \approx -29$ dB at 915 MHz and -14.3 dB at 2.45 GHz, corresponding to $\eta > 99.8\%$ and $\eta \approx 96.3\%$, respectively). However, the high electrical conductivity of molten solar salt resulted in an extremely low electromagnetic D_p , confining microwave energy absorption to a thin region adjacent to the applicator wall.
2. Both cavity configurations produced predominantly surface-localised heating and pronounced radial temperature gradients despite their different electromagnetic field distributions.
3. Experimental evaluation of microwave-transparent crucible materials showed that quartz maintained its mechanical integrity during thermal cycling, whereas alumina-based ceramics and boron nitride exhibited cracking and salt leakage, demonstrating its suitability for microwave heating experiments with molten solar salt.
4. Estimated emissivity ϵ , obtained using the contact thermometer method, agreed well with literature values between 250 and 500 °C, supporting the use of infrared thermography as a reliable non-contact technique for temperature monitoring during microwave heating.

Overall, the results demonstrate that the use of molten solar salt in microwave-based PtH systems is fundamentally constrained by its extremely low electromagnetic D_p . Consequently, microwave heating of molten solar salt cannot, by itself, be regarded as a truly volumetric heating process. Achieving a more uniform temperature distribution therefore requires additional measures to redistribute the generated heat within the fluid, such as enhanced mixing or applicator designs that increase the heated surface-area-to-volume ratio. These findings establish practical design guidance for the development of future microwave-assisted PtH systems.

Author Contributions: Conceptualization, C.V., M.-M.R.-G. and E.R.; methodology, C.V. and E.R.; software, C.V.; validation, C.V., A.D.-M., J.F.-F. and J.M.-C.; formal analysis, C.V.; investigation, C.V.; resources, M.-M.R.-G. and E.R.; data curation, C.V.; writing—original draft preparation, C.V.; writing—review and editing, A.D.-M., J.F.-F., J.M.-C., M.-M.R.-G. and E.R.; visualization, C.V.; supervision, M.-M.R.-G. and E.R.; project administration, M.-M.R.-G. and E.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data presented in this paper will be made available on request.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

BESS	Battery energy storage system
CB	Carnot battery
CFD	Computational fluid dynamics
CPM	Cavity perturbation method
CSP	Concentrated solar power
EIS	Electrochemical impedance spectroscopy
EM	Electromagnetic
ESS	Energy storage system
GHG	Greenhouse gas
ISM	Industrial, scientific and medical
MUT	Material under test
PEC	Perfect electric conductor
PtH	Power-to-Heat
PtHtP	Power-to-Heat-to-Power
PV	Photovoltaic
RES	Renewable energy sources
RMS	Root mean square
TES	Thermal energy storage

References

1. de Sisternes, F.J.; Jenkins, J.D.; Botterud, A. The value of energy storage in decarbonizing the electricity sector. *Appl. Energy* **2016**, *175*, 368–379. <https://doi.org/10.1016/j.apenergy.2016.05.014>.
2. IEA; NEA; OECD. *Projected Costs of Generating Electricity*; 2020 Edition; OECD Publishing: Paris, France, 2020.
3. International Renewable Energy Agency (IRENA). *Renewable Capacity Statistics 2025*; Technical Report; International Renewable Energy Agency: Abu Dhabi, United Arab Emirates, 2025. Available online: <https://www.irena.org/Publications/2025/Mar/Renewable-Capacity-Statistics-2025> (accessed on 23 March 2026).
4. Obi, M.; Bass, R. Trends and challenges of grid-connected photovoltaic systems—A review. *Renew. Sustain. Energy Rev.* **2016**, *58*, 1082–1094. <https://doi.org/10.1016/j.rser.2015.12.289>.
5. Feldman, D.; Margolis, R.; Denholm, P.; Stekli, J. *Exploring the Potential Competitiveness of Utility-Scale Photovoltaics Plus Batteries with Concentrating Solar Power, 2015–2030*; NREL Technical Report NREL/TP-6A20-66592; NREL: Golden, CO, USA, 2016.
6. Zurita, A.; Mata-Torres, C.; Valenzuela, C.; Felbol, C.; Cardemil, J.M.; Guzmán, A.M.; Escobar, R.A. Techno-economic evaluation of a hybrid CSP + PV plant integrated with thermal energy storage and a large-scale battery energy storage system for base generation. *Sol. Energy* **2018**, *173*, 1262–1277. <https://doi.org/10.1016/j.solener.2018.08.061>.
7. Dumont, O.; Frate, G.F.; Pillai, A.; Lecompte, S.; De Paepe, M.; Lemort, V. Carnot battery technology: A state-of-the-art review. *J. Energy Storage* **2020**, *32*, 101756. <https://doi.org/10.1016/j.est.2020.101756>.
8. Achkari, O.; El Fadar, A. Latest developments on TES and CSP technologies—Energy and environmental issues, applications and research trends. *Appl. Therm. Eng.* **2020**, *167*, 114806.
9. Bauer, T.; Odenthal, C.; Bonk, A. Molten salt storage for power generation. *Chem. Ing. Tech.* **2021**, *93*, 534–546.
10. Alva, G.; Liu, L.; Huang, X.; Fang, G. Thermal energy storage materials and systems for solar energy applications. *Renew. Sustain. Energy Rev.* **2017**, *68*, 693–706.
11. Novotny, V.; Basta, V.; Smola, P.; Spale, J. Review of Carnot battery technology commercial development. *Energies* **2022**, *15*, 647. <https://doi.org/10.3390/en15020647>.
12. Cordaro, J.G. Chemical perspectives on alkali and alkaline earth nitrate and nitrite salts for concentrated solar power applications. *Green* **2013**, *3*, 9–18.
13. Rodríguez-García, M.-M.; Bayón, R.; Alonso, E.; Rojas, E.; García-Baños, B.; Gutiérrez-Cano, J.-D.; Plaza-González, P.-J. Experimental and theoretical investigation on using microwaves for storing electricity in a thermal energy storage medium. *AIP Conf. Proc.* **2023**, *2815*, 060003. <https://doi.org/10.1063/5.0148703>.
14. Martín, Á.; Navarrete, A. Microwave-assisted process intensification techniques. *Curr. Opin. Green Sustain. Chem.* **2018**, *11*, 70–75. <https://doi.org/10.1016/j.cogsc.2018.04.019>.

15. Catalá-Civera, J.M.; Canós, A.J.; Plaza-González, P.; Gutiérrez, J.D.; García-Baños, B.; Peñaranda-Foix, F.L. Dynamic measurement of dielectric properties of materials at high temperature during microwave heating in a dual mode cylindrical cavity. *IEEE Trans. Microw. Theory Tech.* **2015**, *63*, 2905–2914. <https://doi.org/10.1109/TMTT.2015.2453263>.
16. Valverde, C.; Link, G.; Soldatov, S.; Catalá-Civera, J.M.; Plaza-González, P.; Dimitrakakis, G.; Singh, B.; Cachot, A.; Del Campo, L.; Malki, M.; et al. Dielectric characterisation of solar salt for volumetric heating applications in Power-to-Heat-to-Power systems. *Energy Convers. Manag.* **2026**, *353*, 121205. <https://doi.org/10.1016/j.enconman.2026.121205>.
17. Dassault Systèmes. CST Studio Suite. 2025. Available online: <https://www.3ds.com/products/simulia/cst-studio-suite> (accessed on 13 May 2026).
18. Zavoico, A.-B. *Solar Power Tower Design Basis Document, Revision 0*; Sandia National Laboratories Technical Report; Sandia National Laboratories: Albuquerque, NM, USA, 2001.
19. Chandrasekaran, S.; Ramanathan, S.; Basak, T. Microwave material processing—A review. *AIChE J.* **2012**, *58*, 330–363. <https://doi.org/10.1002/aic.12766>.
20. Cheng, D.K. *Field and Wave Electromagnetics*; Addison-Wesley: New York, NY, USA, 1992.
21. Monzó-Cabrera, J.; Díaz-Morcillo, A.; Martínez-González, A.; Lozano-Guerrero, A.; Fayos-Fernández, J.; Pérez-Campos, R.; Pedreño-Molina, J.L. A novel bandstop filter based on two-port coaxial cavities for the installation of metallic mode stirrers in microwave ovens. *Electronics* **2022**, *11*, 1989. <https://doi.org/10.3390/electronics11131989>.
22. Monzó-Cabrera, J.; Álvarez Martín, A.; Cocero-Alonso, M.J.; Fayos Fernández, J.; Mato Chaín, R.B. Horno Microondas para el Calentamiento de Flujos Continuos de Líquidos y Semisólidos. ES Patent ES2698150 B2, 31 January 2019. Available online: <http://hdl.handle.net/10317/5485> (accessed on 25 January 2024).
23. Mirabito, C.; Narayanan, A.; Erez, D.; Stone, B.; Weekes, S.; Yakovlev, V. FEMLAB Model of a Coupled Electromagnetic–Thermal Boundary Value Problem. Technical Report (Research Experience for Undergraduates Project). 2005. Available online: https://www.researchgate.net/publication/228586320_FEMLAB_Model_of_a_Coupled_Electromagnetic-Thermal_Boundary_Value_Problem (accessed on 19 July 2023).
24. Zhang, H.; Datta, A.K.; Taub, I.A.; Doona, C.J. Electromagnetics, Heat Transfer, and Thermokinetics in Microwave Sterilization. *AIChE J.* **2001**, *47*, 1957–1968. <https://doi.org/10.1002/aic.690470907>.
25. ASTM E1933-14; Standard Practice for Measuring and Compensating for Emissivity Using Infrared Imaging Radiometers. American Society for Testing and Materials: West Conshohocken, PA, USA, 2018.
26. IEC 584-2; Thermocouples—Part 2: Tolerances. IEC: Geneva, Switzerland, 1982.
27. Optris GmbH. *Datasheet: Infrared Camera Optris PI 640i*; Optris GmbH: Berlin, Germany, 2023. Available online: https://www.ateg.de/en/frontend/media/datasheets/Datenblatt_OPTPI640ILT_en.pdf (accessed on 6 March 2024).
28. Sutton, W.H. Microwave processing of ceramic materials. *Am. Ceram. Soc. Bull.* **1989**, *68*, 376–386.
29. Behrend, R.; Dorn, C.; Uhlig, V.; Krause, H. Investigations on container materials in high temperature microwave applications. *Energy Procedia* **2017**, *120*, 417–423.
30. García-Baños, B.; Catalá-Civera, J.M.; Peñaranda-Foix, F.L.; Plaza-González, P.; Llorens-Vallés, G. In situ monitoring of microwave processing of materials at high temperatures through dielectric properties measurement. *Materials* **2016**, *9*, 349.
31. Pavón-Moreno, M.C.; López, A.; Paúl, A.; Gallardo, J.M.; Prieto, C. Dynamic corrosion behaviour of stainless steel in molten salt electric heaters: Influence of film temperature under realistic flow conditions. *J. Energy Storage* **2026**, *154*, 121321. <https://doi.org/10.1016/j.est.2026.121321>.
32. Xu, C.; Shu, W.; Ye, J.; Yang, Y.; Huang, K.; Zhu, H. Electromagnetic black hole for efficiency microwave heating based on gradient-index metamaterials in multimode cavities. *IEEE Microw. Wirel. Compon. Lett.* **2022**, *32*, 1235–1238. <https://doi.org/10.1109/LMWC.2022.3174580>.
33. Xie, M.; Zhu, Y.; Liu, Y.; Yuan, Y.; Tan, H. Measurement of spectral radiative characteristics of molten salt at high temperature using emission method. *Appl. Therm. Eng.* **2019**, *149*, 151–164.
34. Grosu, Y.; González-Fernández, L.; Nithiyantham, U.; Faik, A. Wettability control for correct thermophysical properties determination of molten salts and their nanofluids. *Energies* **2019**, *12*, 3765. <https://doi.org/10.3390/en12193765>.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.