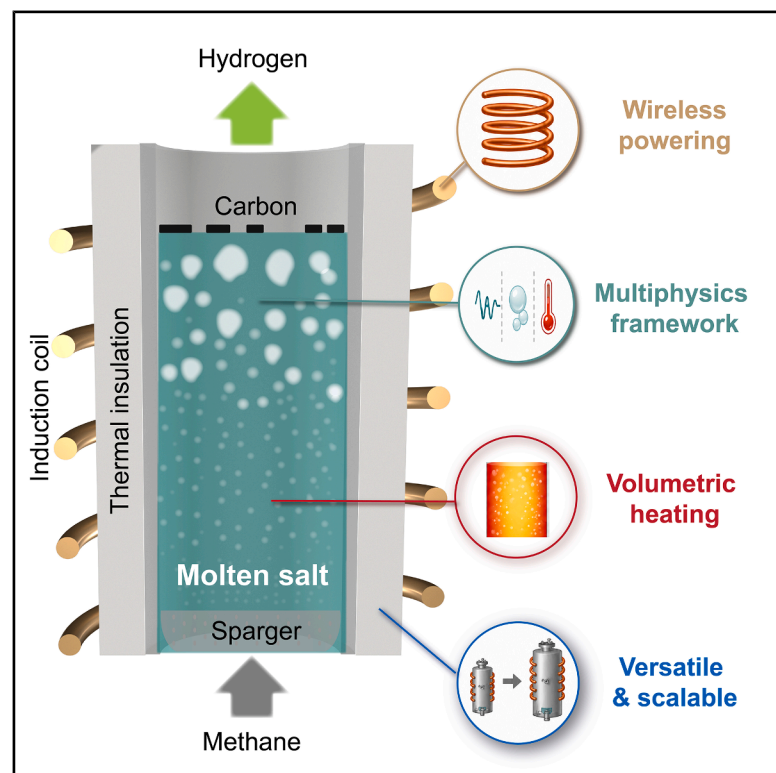


High-frequency inductively heated molten salt bubbling beds for methane pyrolysis

Graphical abstract



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In brief

Methane pyrolysis can produce hydrogen while sequestering solid carbon, but efficient high-grade heat delivery and coking management remain challenging. This study shows that high-frequency magnetic induction directly and volumetrically heats molten salt bubbling beds with stable power delivery, providing a scalable route for methane pyrolysis while managing solid carbon formation. These principles have applicability more broadly to molten salt chemical conversion and thermal energy storage systems.

Highlights

- High-frequency magnetic induction enables direct, volumetric molten salt heating
- Heating concept is scalable and can drive salt bed temperatures to 1,000°C+
- Induction-heated molten salt bubbling beds can be used for methane pyrolysis
- Multiphysics modeling reproduces experimental bubbling bed power profiles

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Article

High-frequency inductively heated molten salt bubbling beds for methane pyrolysis

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CONTEXT & SCALE Methane pyrolysis is a promising and economic route to clean hydrogen production that involves converting low-cost methane into hydrogen and solid carbon, providing a natural route to sequestering carbon. To address challenges associated with pyrolysis kinetics and the uncontrolled deposition of solid carbon within the reactor, molten salts have been proposed as a promising reaction medium capable of catalyzing pyrolysis and simultaneously separating produced hydrogen and solid carbon in a stable manner. However, its practical implementation still requires a mechanism for efficiently delivering sustainable, high-grade heat in a scalable and volumetric manner while mitigating challenges related to corrosion resistance and carbon deposition on internal heating components.

This work introduces the high-frequency magnetic induction of molten salt bubbling baths as a direct and wireless power delivery strategy for methane pyrolysis. We present operating regimes in which the co-design of high-frequency power electronics with bubbling bed characteristics supports efficient and volumetric heating, and we demonstrate methane pyrolysis in a bubbling chloride salt bed heated to over 1,000°C. Experimental analysis and numerical modeling indicate and explain how wireless power delivery to the bubbling bed is stable in time despite the dynamic nature of the bubbling bed.

Our concept provides a natural scaling pathway for molten-salt-based pyrolysis reactors, as magnetic induction is an intrinsically volumetric phenomenon and has been industrially scaled in the context of metallurgical induction furnaces. For molten salt baths, volumetric and efficient energy delivery can be readily achieved in scaled systems with proper specification of the induction frequency, working medium conductivity, and bubbling conditions. Our proposed heating principle can be applied to other high-temperature chemical conversion and thermal energy storage processes beyond methane pyrolysis that utilize electrically conductive fluids.

SUMMARY

Methane pyrolysis is a promising bridge technology for clean hydrogen production, but it remains a challenge to efficiently and volumetrically deliver heat to the reaction while managing carbon deposition. We introduce a molten salt bubbling bed reactor that utilizes high-frequency magnetic induction to heat molten salts in an efficient, volumetric, wireless, and direct manner. We describe the heating process using a circuit model and discuss power-dissipation dynamics as a function of the effective medium of the bubbling bed, dynamic bed height variations from bubbling, and bubble-induced hotspots. With the model and experiments, we show that the heating efficiency is high and nearly time independent, despite the stochastic nature of bubble dynamics. We additionally demonstrate that our method can heat eutectic salts to temperatures exceeding 1,000°C for catalyst-free methane pyrolysis. We anticipate that these concepts can be adapted to scaled, high-temperature multiphase reactors utilizing electrically conductive liquid.

INTRODUCTION

The high carbon intensity of the chemical and fuel economy is a significant contributor to global warming, necessitating decarbonization strategies in these industries. To this end, the hydrogen economy has been proposed as a clean energy strategy in which hydrogen serves as a carbon-free chemical feedstock and energy carrier.¹ There exists a wide range of techniques for producing hydrogen with a low carbon footprint. One is the utilization of carbon capture infrastructure with conventional hydrogen production methods via steam methane reforming, partial oxidation, or auto-thermal reforming.² It is relatively mature and immediately deployable but requires collocation with a carbon dioxide sequestration site.^{3–5} A second is the utilization of green electricity to perform water splitting via electrolysis.⁶ While this technology is modular and deployable anywhere there is water and green electricity, the high energy requirements and capital cost of electrolyzers present economic bottlenecks for immediate widespread deployment.^{3,7}

A third route to hydrogen production, and the focus of this study, is methane pyrolysis. Methane pyrolysis is considered a promising and economic bridge solution to clean hydrogen production, as it combines the use of low-cost carbon feedstocks, relatively low energy requirements with the pyrolysis process itself, and sequestration of carbon in the solid form.⁸ While promising, there remain numerous technical challenges to implementation. The solid carbon produced from pyrolysis can accumulate in uncontrolled ways on all surfaces within a chemical reactor.^{9,10} Strategies for producing higher-value carbon products are required to further enhance the economics of the process,¹¹ thereby requiring the development of new classes of catalysts¹² and mechanisms^{13,14} for separating formed carbon products from the catalysts. Concepts need to be developed that can inject high-grade heat, generated using clean energy processes, into the reactor in a volumetric and efficient manner.¹⁵

To address these challenges, many reactor concepts have been proposed, including those based on fluidized beds,^{14,16} packed beds,^{17,18} moving beds,¹⁹ plasmas,^{20–22} and molten media.^{23–25} While no singular reactor technology addresses all issues, molten salt reactors address many of the critical problems. In molten salt reactors, methane is bubbled through high-temperature molten salt media, which is heated to approximately 1,000°C, and the methane decomposes into hydrogen and solid carbon. The solid carbon floats to the top of the molten bed and is removed for disposal or utilization, while the hydrogen gas bubbles out of the molten media and is collected.^{13,25,26} Catalysts compatible with molten salts have been developed^{24,27–29} and have been demonstrated to produce high-value carbon products such as graphene.^{30–32} It has been further shown that the molten salt media itself can facilitate the separation of formed carbon products from the catalysts.^{25,33} A major issue, however, is the efficient and volumetric delivery of energy into the molten salt reactors at scale.¹⁵ Conventional wall heating methods are limited by heat transfer and do not scale effectively,³⁴ and the use of internal heaters or heat exchangers is complicated by the corrosive molten salt environment³⁵ and issues pertaining to long-term solid carbon deposition.⁹

We propose an electrified heating concept for molten salt reactors in which high-frequency magnetic induction of molten salt media facilitates the efficient, internal, wireless, and volumetric high-temperature heating of a molten salt bubbling bed. This approach takes advantage of the fact that all molten salts are electrically conductive^{36–38} and can directly couple with alternating high-frequency magnetic fields, leading to the induction of eddy currents within the molten salts that dissipate as heat (Figure 1A). Our concept addresses many of the unique heating issues posed by molten salt pyrolysis reactors. The wireless heating of molten salt eliminates the need for any immersion heating infrastructure, thereby overcoming issues pertaining to heater compatibility with the corrosive molten salt environment and solid carbon deposition onto heating infrastructure. The concept can be tailored to support a volumetric heating profile across the full reactor diameter for reactor sizes spanning lab to commercial scale,³⁹ providing a clear path for scaling.⁴⁰ Volumetric heating, together with mixing within the bubbling bed, ensures that the reaction environment features small radial temperature gradients even in scaled systems. Our particular use of high-frequency power electronic sources, with frequencies specified by the electronic properties of the molten salt bath itself, enables highly efficient power delivery. While this study focuses on methane pyrolysis, our concept broadly applies to electrically conductive bubbling and slurry beds, including thermal energy storage systems utilizing solar salts,^{38,41,42} CO₂ conversion systems utilizing molten carbonate salts,^{37,43} and hydrogen production and nuclear systems applications utilizing molten halide salts^{36,42} (Figure 1A).

RESULTS

Bubbling beds are heterogeneous multiphase systems featuring multi-scalar material distributions that vary as a function of time, making electromagnetic modeling of the bed and optimization of the induction heating process non-trivial. Our general approach is to treat the molten salt bed as a homogenized, time-averaged effective medium with an effective electrical conductivity that is a function of vertical position (Figure 1B, right). In the limit where the bubbling bed features low gas-phase volume fractions, homogenization can be performed using the Maxwell-Eucken effective medium theory (EMT).^{44,45} The dependence of effective conductivity on vertical position reflects the evolution of the gas-phase volume fraction as the bubbles rise through the bed, during which the bubbles grow, change shape, and change velocity. Upon bubbling, the molten salt bed height increases (Δh in Figure 1B, right), leading to an increase in susceptor size and subsequent enhancement in power dissipation.

Power dissipation is primarily driven by eddy current losses in the homogenized bed. These losses can be parameterized as power dissipated in the i^{th} homogeneous cylindrical subsection and can be quantified using established analytic formalisms.⁴⁶ Briefly, power dissipation in a homogeneous cylindrical susceptor has a frequency-dependent alternating current (AC) resistance that is a function of the bubbling bed skin depth, $\delta = \sqrt{1/\pi\mu_0 f \sigma_{\text{eff}}}$, where f is the induction frequency and σ_{eff} is the effective electrical conductivity of the cylinder. The AC

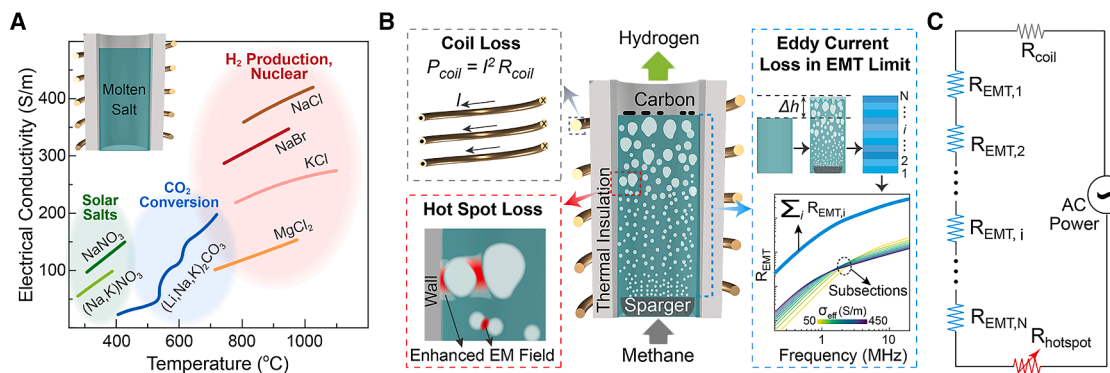


Figure 1. Molten salt bubbling bed as a dynamic, effectively conductive electromagnetic system

(A) Electrical conductivity of different molten salt compositions as a function of temperature, grouped in terms of representative applications.

(B) Schematic of the pyrolytic molten salt bubbling bed. The bubbling liquid-gas system serves as a susceptor that is volumetrically heated by high-frequency magnetic induction. Power losses in the system arise from ohmic losses in the coil (top left), hotspots arising from localized electromagnetic fields (bottom left), and eddy current losses in the molten salt bed described in the effective medium limit (right). For the latter, bubbling leads to bed expansion by Δh and enlarging of the susceptor. The total bed can be divided into N subsections, each of which can be modeled as a homogeneous conducting cylinder, and the total dissipated power is the summation of power from each subsection.

(C) Circuit model describing power dissipation in the molten salt bubbling bed system. Losses in the system are due to eddy current dissipation in the subsections of an effectively conductive bubbling bed with dynamic bed height expansion ($R_{EMT,i}$), electromagnetic hotspots ($R_{hotspot}$), and parasitic coil losses (R_{coil}).

resistance, which correlates with power dissipation, has a frequency-dependent curve that features an inflection point when $\delta \sim R/2$, where R is the reactor radius. This point represents an ideal operating regime in which the heating profile of the cylinder is volumetric and the heating efficiency is near a maximal value.⁴⁰ For lab-scale reactors with a radius of 4.2 cm, which is the topic of this study, the transition point occurs in the megahertz-frequency range. In addition to eddy current losses in the homogenized bed, contributions to power dissipation also arise from the presence of electromagnetic hotspots in the bed, which arise when small gaps between adjacent bubbles and the bubble and reactor wall are formed (Figure 1B, lower left).

Total power dissipation within the molten salt reactor can be modeled using an electronic circuit picture (Figure 1C). AC resistance terms from eddy current dissipation in homogeneous subsections are represented by $R_{EMT} = \sum_i R_{EMT,i}$ and account for power dissipation in all subsections in the expanded bubbling bed. Electromagnetic hotspot dissipation is represented by $R_{hotspot}$. There also is a parasitic AC resistance term, R_{coil} , which arises because currents flowing through the helical magnetic coil, used to produce the AC magnetic field, dissipate as heat (Figure 1B, top left panel). The heating efficiency is defined as the relative amount of power dissipated in the molten salt bed compared with the total power dissipated in the salt and drive coil and is $(R_{EMT} + R_{hotspot}) / (R_{EMT} + R_{hotspot} + R_{coil})$. Molten salt systems have ideal electrical conductivity values for supporting highly efficient induction heating when driven by a high-frequency power source in the transition region, and the heating efficiencies for our lab-scale systems are typically in the 80% range.

In this study, we take a systematic theoretical and experimental approach to examine molten salt beds of increasing complexity to understand the origins of these different terms and how they impact the induction heating process. We first consider the inductive heating of a molten salt bed with no

bubbling. In this limit, the molten salt susceptor is homogeneous, and σ_{eff} in all subsections is the conductivity of the molten salt, leading to a simplified circuit picture (Figure 2A). We consider a eutectic salt system comprising sodium chloride and potassium chloride, which is a typical salt composition for pyrolysis³³ and which has a suppressed melting point of around 656°C. Images of the setup are shown in Figure 2B. The reactor consists of a 10 cm-diameter quartz tube surrounded by 5 cm-thick aluminosilicate thermal insulation and a water-cooled helical copper coil. The cooling water flow rate is set to 0.2–0.3 L/min, which ensures the coil is near room temperature during reactor operation. A total of 1.5 kg of salt is added to the reactor, which corresponds to a static molten salt bed height of about 18 cm. To heat the system from room temperature, a custom-made resistive heater surrounding the quartz tube is initially used to melt the solid salt to the molten state, as solid salts are not electrically conductive. The resistor layout is carefully designed to ensure that it minimally couples with AC magnetic fields produced from the induction coil (see Note S3). The salt is confirmed to be fully molten after extended heating prior to induction heating and reactions (see Note S12). Once the salt is in the molten state, the resistive heater is turned off and the power amplifier connected to the induction coil is turned on. Temperature measurements used for feedback and temperature profiling are performed using K-type thermocouples sheathed in quartz thermowells.

We measure the frequency-dependent AC resistance of the molten salt and coil at different salt temperatures using a vector network analyzer (VNA) (Bode 100, OMICRON LAB), and the results are summarized in Figure 2C. The coil resistance is independent of salt temperature, as it remains at room temperature from water cooling. At low frequencies, the coil resistance scales as the square root of frequency, which is due to skin depth and proximity effects in the coil itself, and the shoulder arising at higher frequencies is due to resonances in the coil system. The salt resistance curve shows a profile typical of induction heating

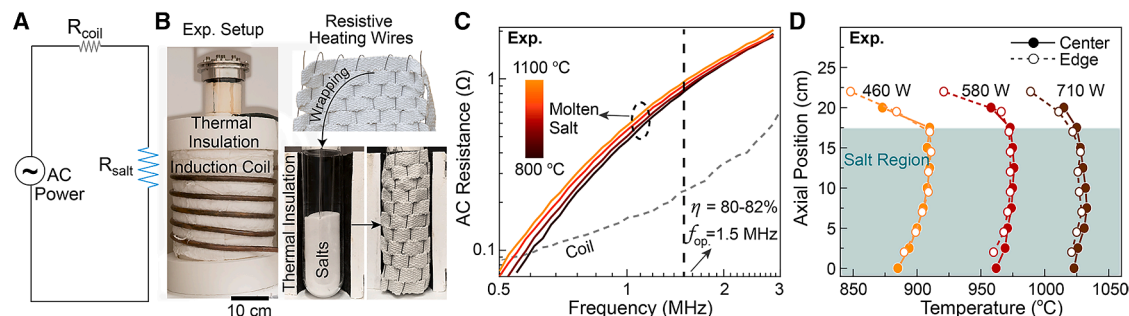


Figure 2. Experimental setup and heating of a static molten salt bed

(A) Circuit model describing power dissipation in the static molten salt bed. Bed height expansion and hotspot contributions to dissipation are not present in this static system.

(B) Images of the reactor setup. The reactor consists of a four-inch-diameter quartz tube surrounded by resistive heating wires (see Note S2), thermal insulation, and a helical induction coil.

(C) Experimental AC resistance of the induction coil and static molten salt bed at different temperatures near the transition region of the impedance curve. The operating frequency is 1.5 MHz, at which point the heating efficiency is approximately 80%.

(D) Axial temperature profiles measured at the center and edge of the molten salt bed under different input power levels, showing minimal radial temperature gradients.

of a homogeneous cylinder, with a transition region connecting high- and low-sloped regions. The slight temperature dependence of these curves is due to the weak dependence of molten salt electrical conductivity on temperature. With curve fitting, the electrical conductivity of the molten salts is experimentally measured to be approximately 328 S/m at 800°C, which is consistent with known values. The transition point frequency is measured to be approximately 1.5 MHz, which we set as our operating frequency moving forward. At this frequency, the heating efficiency is measured to be 80% at 800°C and 82% at 1,100°C. Vertical temperature profiles at the center and edge of the reactor are plotted in Figure 2D for different input powers. The profiles show a slight temperature gradient along the vertical direction, which is due to heat loss from the bottom of the reactor setup. In all cases, the axial temperature profiles along the reactor center and edge nearly overlap, indicating minimal radial temperature gradients in the salt system (see Note S11).

We next bubble nitrogen gas at different flow rates into the molten salt and analyze the corresponding AC resistance of the bubbling bed system. In this limit, the circuit diagram (Figure 3A) now includes a height fluctuation term, and the sub-sections each have unique effective conductivity values. An image of the setup (Figure 3B) shows three inlet tubes for inert gas flow, which serve as a basic gas distributor scheme that can be readily adapted to our reactor setup. Our use of only three inlet tubes here for gas flow minimizes interactions between bubbles; hence, we neglect power dissipation from hotspots. Measurements of the frequency-dependent AC resistance of the bubbling bed for different gas flow rates are plotted in Figure 3C and indicate that the resistance curves increase with increasing gas flow rate, leading to an enhanced heating efficiency (Figure 3C, inset). This increase in AC resistance correlates with an increase in gas-phase volume fraction in the molten salt bed, which has two effects. One effect is the physical rise of the bubbling bed, which corresponds to an increase in molten salt bubbling bed volume, an enlargement of the susceptor, and enhanced power dissipation that is captured by the

series of $R_{EMT,i}$ in the circuit model. We further validate such bed height increases by room temperature experiments using salt water, which shares a similar density, surface tension, and viscosity with our molten salt system, under varying gas flow rates. The experimental results agree well with our fluidic simulations (see Note S4). The second is a reduction in effective electrical conductivity in the bulk bubbling bed. For our particular operating frequency and reactor geometry, this reduction actually leads to a slight reduction in AC resistance, though it is possible for a reduction in electrical conductivity to enhance the AC resistance when higher induction frequencies are used (see Figure 1B, bottom right).

Time-dependent measurements of power dissipated in our bubbling bed at our operating frequency, which is normalized to power dissipated in a static bed, confirm that the amount of dissipated power in the system increases with increasing gas flow. Interestingly, we observe that in spite of the time-varying nature of the bubbling bed, power dissipation in the system experiences relatively small dynamic fluctuations (Figure 3D). For flow rates up to 100 standard cubic centimeters per minute (SCCM) (i.e., superficial velocity of 3×10^{-4} m/s), the dissipated power exhibits fluctuations on the order of 0.05% or less, and for a 4,000 SCCM flow rate (i.e., superficial velocity of 1×10^{-2} m/s), these fluctuations are on the order of 0.15%. In these calculations, baseline fluctuations due to noise in the network analyzer, which is reflected in the noise floor for the case of no gas flow, have been subtracted out. This nearly time independent power dissipation is important, as it ensures that the amount of power transferred to the molten salt bed is approximately constant in time. It also simplifies impedance matching infrastructure between the power electronics and molten salt reactor.

To better understand the spatial and temporal power-dissipation profile within the bubbling bed, we perform multiphysics simulations that combine computational fluid mechanics (OpenFOAM) and electromagnetics (COMSOL Multiphysics) analyses. Briefly, dynamic bubbling bed simulations are carried out for our experimental reactor configuration for different gas

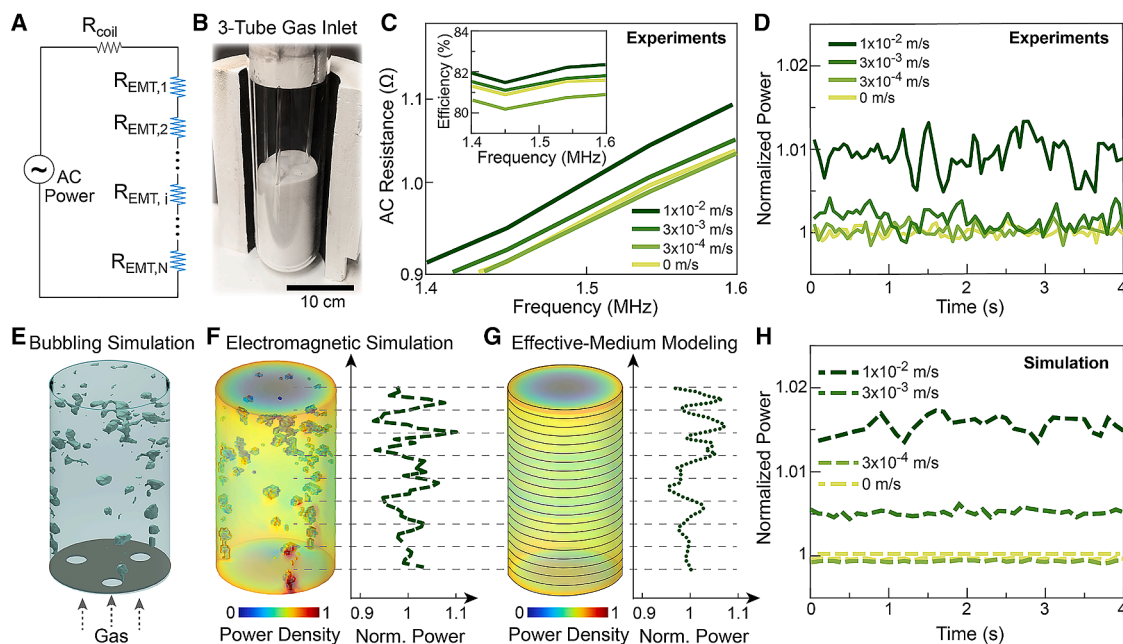


Figure 3. Characterization of an inductively heated molten salt bubbling bed

(A) Circuit model describing power dissipation in the experimental molten salt bubbling bed. Dissipation due to bed height expansion is considered, but hotspot contributions are neglected as the bubbles minimally interact with each other and the reactor walls.

(B) Image of the experimental bubbling setup, where nitrogen gas is injected through three quartz tubes embedded in the salt bed.

(C) Measured AC resistance of the bubbling bed at 1,000°C under different gas flow rates. The AC resistance increases slightly as the flow rate increases, leading to enhanced heating efficiency (inset).

(D) Normalized time-dependent power dissipation at the operating frequency (1.5 MHz). Despite the dynamic nature of the bubbling bed, fluctuations in power dissipation are small ($\leq 0.05\%$ – 0.15%).

(E) Snapshot of a computational fluid simulation of the bubbling bed using the experimental reactor geometry and a superficial velocity of 1×10^{-2} m/s.

(F) Electromagnetic simulation of the system in (E) showing the volumetric power-dissipation profile of a bubbling bed at a superficial velocity of 1×10^{-2} m/s, along with the plot of the normalized axial power profile.

(G) Axial power profile of the system in (F), where the bubbling bed has been converted into an effective medium using the Maxwell-Eucken model (see [Note S5](#)). This profile and that in (F) have a correlation of 0.70.

(H) Simulated time-dependent total power dissipation in the bubbling bed for different flow rates. The increase in power dissipation as a function of flow rate and the dynamic variation in power dissipation are consistent with experimental results in (D).

flow rates, and the bubble configurations as a function of time are recorded ([Figure 3E](#)). Magnetic induction simulations are subsequently performed on each frame of the fluid simulations to quantify the volumetric power-dissipation profiles in the reactor as a function of time. Additional details are provided in [Note S4](#). A snapshot of the bubbling bed with a superficial gas injection velocity of 1×10^{-2} m/s, overlaid with the volumetric heating profile, is shown in [Figure 3F](#), together with an effective medium description of the bubbling bed, including both effective conductivity change and bed expansion. Plots of the instantaneous axial power-dissipation profiles for both descriptions of the bubbling bed are in [Figure 3G](#) and display variations that capture the stochastic nature of the bubbling process. These plots show good agreement and have a correlation value of 0.70, indicating that the effective medium description of the bubbling bed is generally valid. Additional analysis of power dissipation in our experimental setup is shown in [Figures S5](#), [S6](#), and [S9](#). Total bubbling bed power dissipation as a function of time is calculated from the fluid mechanics simulations for different bubbling flow rates and is shown in [Figure 3H](#), and

they are consistent with the temporal power-dissipation profiles in [Figure 3D](#).

The effective medium picture for bubbling beds, together with the incompressible nature of molten salts, helps to explain why power dissipation in the bubbling bed is nearly independent as a function of time. In particular, the incompressibility of the salts, together with the nearly constant salt phase fraction in the bed, serves as a constraint to the bubbling bed effective medium profile in a manner where local fluctuations within different subsections are correlated and produce nearly constant spatially averaged responses. In fact, it can be shown that in the limit where the salt phase fraction is constant and variations in effective conductivity are small, the total power dissipation in the bubbling bed is nearly constant (see [Note S8](#)). We attribute the observed variations in total power dissipation to minor dynamic variations in the total salt phase fraction, deviations of the bubbling bed from the effective conductivity limit, and dynamic fluctuations in the bed height arising from turbulence (see [Note S6](#)).

The outlet gas composition is measured using a calibrated mass spectrometer 10 min after the start of gas bubbling.

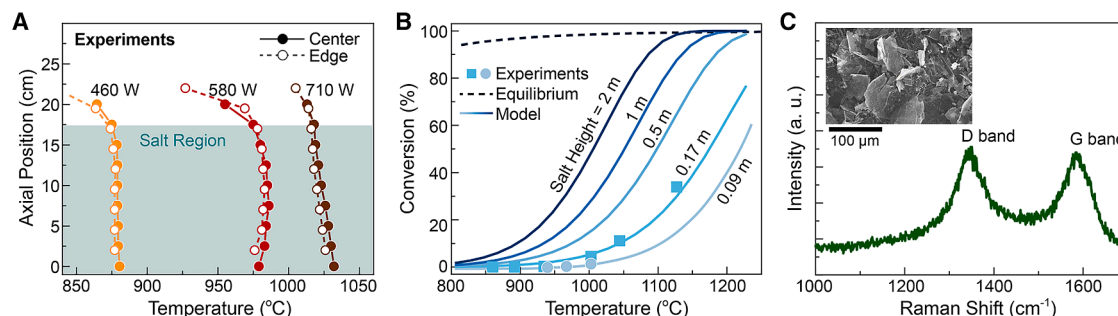


Figure 4. Methane pyrolysis in an inductively heated molten salt bed

(A) Measured vertical temperature profiles at the center and edge of the molten salt bed during gas bubbling. The superficial velocity is 3×10^{-3} m/s. (B) Methane conversion measured with two molten salt bed heights, with the temperature ranging from 875°C to 1,130°C. The methane is flowed at a total rate of 1,000 SCCM (i.e., superficial velocity of 3×10^{-3} m/s), and argon is flowed into the space above the molten salt as a sweep gas at rates of 1,000 SCCM and 2,000 SCCM for bed heights of 17 and 9 cm, respectively. Experimental data (square markers) are fitted with a simple kinetic flow model (solid curves). More details on our kinetics modeling are included in [Notes S9](#) and [S10](#). (C) SEM and Raman spectrum of the carbon products formed in the bed at 1,025°C.

K-type thermocouples are used for measuring the vertical temperature profile at the center and edge of the bubbling bed. The induction coil was shut off prior to taking temperature measurements to avoid electromagnetic interference with the thermocouple reading. The measured temperature profile during pyrolysis is shown in [Figure 4A](#), showing minimal radial temperature gradients within the reactor, and is consistent with those obtained from the static molten salt bed in [Figure 2D](#). The conversion is plotted in [Figure 4B](#) and increases as a function of temperature, which is expected for this endothermic reaction. These conversion values are far below equilibrium values (dashed line in [Figure 4B](#)) due to the limited kinetics of our non-catalytic system and the limited residence time set by our finite bed height.

To extrapolate the performance of our pyrolysis system to taller bed heights, we fit these data using an elementary kinetics model, developed previously for non-catalytic pyrolysis reactions,^{26,47–49} and couple it with a simple flow reactor model (see [Notes S9](#) and [S10](#)). Conversion as a function of temperature for different bed heights is plotted in [Figure 4B](#). These plots show good agreement between the experimental data and model, and they further indicate that conversion can be substantially enhanced as bed height increases. Ultimately, these models are simple and at best approximate, and a more detailed description of bubbling bed dynamics and the pyrolysis reaction is required to accurately describe these reactions in the high-conversion regime. Nonetheless, these results suggest the promise of scaled molten salt reactor systems for pyrolysis, and a more thorough analysis will be performed in future work. A scanning electron microscopy (SEM) and Raman analysis of the solid carbon products from the molten salt bed heated to 1,025°C shows that the carbon has a flake morphology and is amorphous ([Figure 4C](#)). These observations are consistent with prior studies on catalyst-free methane pyrolysis.³³

In the final part of this study, we perform a multiphysics analysis of bubbling beds utilizing gas spargers that are designed to produce ideal bubble distributions at high flow rates.⁵⁰ The sparger has gas inlets in a square array alignment, consistent

with industrial sieve plate sparger designs (see [Note S4](#)). Dynamic bubbling simulations are conducted with equal gas velocities at each inlet, and total superficial velocities as high as 2×10^{-2} m/s, which correspond to the turbulent flow regime, are simulated. A circuit model describing power dissipation in the system is presented in [Figure 5A](#) and shows a complete model combining contributions from eddy current dissipation in each subsection, bed height fluctuations, and hotspot dissipation. To understand how each of these terms manifests in this bubbling bed system, we first analyze a snapshot of the bubbling bed with a gas injection superficial velocity of 2.4×10^{-2} m/s ([Figure 5B](#)). Its normalized electromagnetic power-dissipation profile and axial power plot are presented in [Figure 5C](#). Power dissipation contributions from R_{EMT} are calculated by converting the fully expanded bubbling bed profile into an effective medium picture, which includes both effective conductivity change and bed expansion. We note that the change in the bed height expansion due to bubbling has been independently validated by experiments. Specifically, the bed expansion is confirmed by direct visualization in a salt water analog system (see [Note S4](#)). The power-dissipation profile and axial power plot are presented in [Figure 5D](#), and we see that this axial power plot correlates with that of the detailed bubbling system. However, its power-dissipation plot deviates from the detailed plot and has generally lower values.

This difference in power dissipation between the detailed and effective medium bubbling bed descriptions can be attributed to hotspots, which can be clearly visualized as points in the electromagnetic profile in [Figure 5C](#) that have substantially larger power densities than the background. These localized hotspots arise from nearly bridging bubbles or bubbles in close proximity with the reactor wall, and they lead to enhanced localized heating. Similar hotspot phenomena have been generally observed with electromagnetic interactions involving heterogeneous metal-based systems, including visible light interactions with plasmonic metal composites⁵¹ and the microwave heating of conductive particulate systems.⁵² In our system, hotspots form in a transient manner, preventing the substantial buildup of

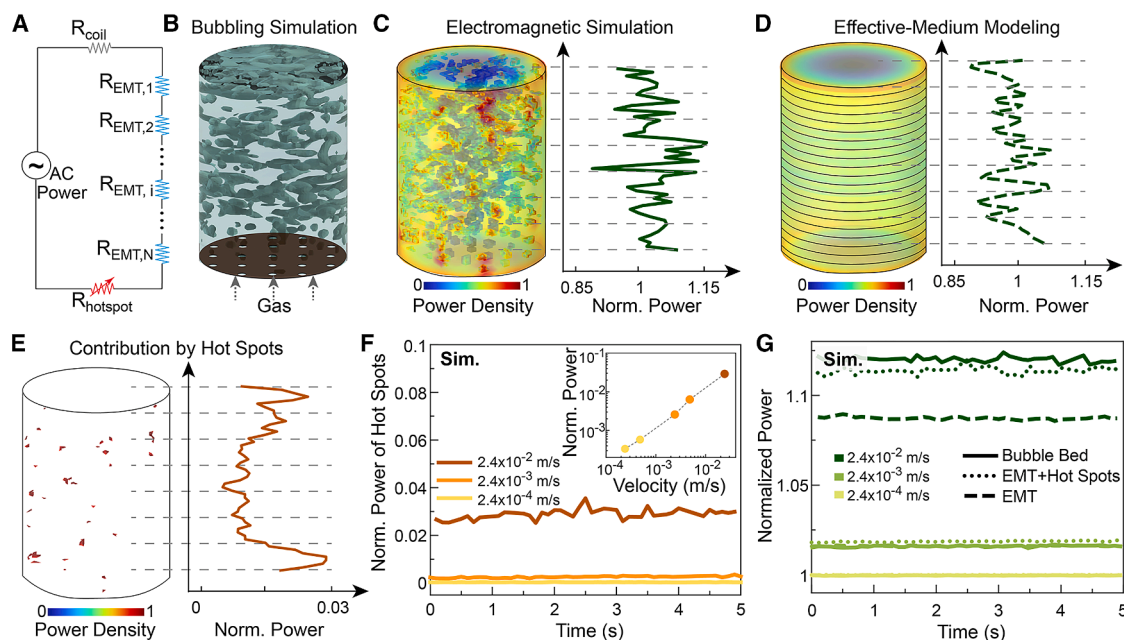


Figure 5. Analysis of a bubbling bed with a gas sparger

(A) Equivalent circuit model describing power dissipation in the molten salt bubbling bed with a gas sparger.
 (B) Snapshot of a fluidic simulation of the sparger-based bubbling bed. The superficial velocity is 2.4×10^{-2} m/s.
 (C) Electromagnetic simulation of the bubbling bed from (B), showing the instantaneous volumetric power-dissipation profile (left) and axial power profile (right). Both plots are normalized to those of a non-bubbling salt bed.
 (D) Axial power profile of the system in (C), where the bubbling bed has been converted into an effective medium using the Maxwell-Eucken model. This profile and that in (C) have a correlation of 0.75.
 (E) Hotspot contributions to power dissipation extracted from (C), using a method described in [Note S7](#).
 (F) Dynamic power dissipation from hotspots in the reactor for different gas velocities. Power dissipation minimally fluctuates as a function of time, and the time-averaged power scales with flow rate (inset).
 (G) Time-dependent power dissipation of the full bubbling bed (solid lines), of the bed-expanded system described in the effective medium limit (EMT, dashed lines), and from hotspots (dotted lines). The combined power dissipation from EMT and hotspot contributions approximates power dissipation in the full bubbling bed.

energy and measurable temperature gradients at a given hotspot and making their direct experimental observation challenging. We therefore resort to a computational analysis to quantify their energy dissipation properties (see [Note S7](#)). The resulting hotspot distribution and power contributions are summarized in [Figure 5E](#) and show that a sparse distribution of hotspots, representing 1.7% of the total bubbling bed volume, contributes to approximately 3% of the total power dissipation in the reactor system.

Interestingly, the contribution of hotspots to power dissipation is nearly time independent. Simulated power dissipation from hotspots for different inlet gas velocities is shown in [Figure 5F](#) as a function of time and indicates that while individual hotspots are highly sensitive to local bubble geometry and dynamically form and disappear over time, they collectively have a consistent statistical distribution within the full bubbling bed at all times. This weak time dependence of hotspot power dissipation, together with that of bed height fluctuations and eddy current dissipation in subsections in the effective medium regime, indicates that the total power dissipation in these bubbling bed systems is nearly time independent. This finding is confirmed in simulated plots of total power dissipation in the detailed

sparger-based bubbling bed as a function of inlet gas velocity ([Figure 5G](#)). The detailed power-dissipation plots match well with those calculated from the combined contributions of eddy current dissipation in an effective medium ([Figure 5D](#)) and hotspots ([Figure 5E](#)), indicating the validity of our approach and simplifications used in analysis.

DISCUSSION

We have shown that high-frequency magnetic induction can enable the efficient, volumetric, and wireless heating of molten salt bubbling beds to high temperatures suitable for methane pyrolysis. We present a comprehensive framework to describe power dissipation in the bubbling bed, in which we identify three primary sources: eddy current heating in the effective medium limit, bed height expansion and fluctuations, and electromagnetic hotspot contributions. We observe experimentally and numerically that the total dissipated power in the molten salt bed minimally fluctuates as a function of time, and this near time independence can be largely explained using our effective conductivity model of the bubbling bed and the incompressibility of the molten salts.

In our experimental demonstration, we achieved methane pyrolysis in an inductively heated molten salt reactor at temperatures exceeding 1,000°C, with conversions typical of non-catalytic systems. Our energy consumption of 17.9 kW h/Nm³ H₂ represents a 1–2 order of magnitude decrease over other reported lab-scale demonstrations.^{23,24,27,28,53–56} As solid carbon is the dominant carbon-containing product, the carbon yield can be approximated by methane conversion, giving an estimated carbon yield of 35%, which is higher than the typical 5%–20% conversion reported for many lab-scale molten salt methane pyrolysis systems.^{24,27,28,53–56} Our scale-up analysis³⁹ indicates that our design can improve the methane conversion to 0.97 kW h/Nm³ H₂ as it is scaled to 5 mm in diameter and 10 m in height, which approaches theoretical limits (see more detailed analysis in [Note S13](#)). Our concepts can be applied to other molten salt systems and applications relevant to chemical conversion and energy storage, serving as the basis for the co-design of induction frequency, effective system conductivity, and reactor dimensions.^{39,40}

We outline potential future research directions to further advance the theoretical analysis and experimental capabilities of this system. Theoretically, more comprehensive and scaled bubbling bed models can be developed to account for radial-dependent effective conductivities arising from wall effects, anisotropic conductivity profiles associated with bubble shape, and the presence of solid carbon and catalyst materials. The role of hotspots in enabling selective heating at catalysts or bubble interfaces can also be further explored. In addition, reactor models that accurately capture kinetics in high-conversion regimes and bubble growth driven by hydrogen generation represent important areas for future development in both catalyst-free and catalyst-mediated systems.

Experimentally, there are ample future opportunities to enhance both reaction performance and carbon value. The recovered carbon in this study is mainly amorphous, with an I_D/I_G ratio around 1, indicating a lower graphitization degree. Future work can improve conversion and promote the formation of higher-value carbon structures by utilizing catalysts within the molten salt bed.^{27,31,57} The post treatment of amorphous solid carbons can also serve as an alternative route to upgrading the carbon products.³¹ Another research direction is the development and selection of materials used for reactor construction. We used quartz as the reactor wall material in this study due to its electromagnetic transparency and chemical inertness; however, quartz is brittle and difficult to implement in scaled systems, and it can suffer from impurity-driven corrosion. Alternative materials such as ceramics (e.g., alumina^{58,59}) and metallic alloys (e.g., nickel-based alloys⁶⁰) offer complementary advantages in corrosion resistance and mechanical strength, and it remains an open opportunity how to adapt our heating methods with these materials. One other important topic of future research is understanding how to manage salt loss in these systems. Molten salt loss can occur through evaporation and bubble-driven entrainment. Based on the vapor pressure of eutectic NaCl–KCl at our operating temperature and gas-flow conditions, the salt loss rate is estimated to be on the order of approximately 40 g h^{−1}. Mitigation strategies, such as increased disengagement space and off-gas treatment using filtration or molten salt

scrubbing,⁶¹ need to be studied and implemented. Sparger optimization may also help reduce salt loss by generating smaller bubbles and suppressing bubble coalescence to minimize entrainment.^{62,63}

METHODS

Reactor setup

Methane pyrolysis was performed in an inductively heated molten salt bubbling bed reactor. A eutectic NaCl–KCl salt mixture with a 1:1 molar ratio was loaded into a round-bottom quartz tube and used as both the reaction medium and induction susceptor. 1.5 kg of salt was used, corresponding to a molten salt bed height of approximately 17 cm. The quartz reactor was surrounded by alumina-silica insulation and a water-cooled helical copper induction coil connected to a megahertz-frequency power amplifier.

Because solid NaCl–KCl is electrically insulating, the salt was first melted using a custom resistive heater. After the salt became fully molten and conductive, the resistive heater was turned off, and the molten salt was heated directly by high-frequency magnetic induction. The operating frequency was selected to be approximately 1.5 MHz based on impedance measurements, where efficient volumetric heating of the molten salt bed was achieved.

Impedance and temperature measurements

Frequency-dependent AC resistance was measured using a VNA (Bode 100) to quantify power coupling between the induction coil and molten salt susceptor. Static molten salt measurements were performed at different temperatures, and bubbling experiments were conducted using nitrogen at controlled flow rates. Temperature profiles were measured using K-type thermocouples protected by quartz thermowells. To avoid electromagnetic interference, temperature values were recorded immediately after switching off the induction field.

Methane pyrolysis reaction

Methane was introduced through three quartz inlet tubes positioned near the bottom of the molten salt bed, while argon was supplied above the salt surface as a sweeping gas. The outlet gas stream passed through a condenser and was analyzed by a calibrated mass spectrometer (MKS Cirrus 3). Methane conversion was calculated from the outlet methane concentration using argon as an internal reference. A simplified kinetic flow model was used to fit methane conversion and project performance at different molten salt bed heights. Solid carbon products were recovered by dissolving the salt in water, followed by filtration and drying. The recovered carbon was characterized by SEM (Thermo Fisher Scientific Apreo S LoVac) and Raman spectroscopy (Horiba Jobin Yvon LabRAM Aramis) with a 633 nm laser.

Modeling and simulations

Gas-liquid bubbling was simulated using a volume-of-fluid model in OpenFOAM 12, and the resulting bubble geometries were imported into COMSOL Multiphysics 6.2 for electromagnetic power-dissipation calculations. The bubbling bed was

also approximated as an effective medium using the Maxwell-Eucken model, where the local effective conductivity was determined by the gas volume fraction.

RESOURCE AVAILABILITY

Lead contact

Requests for further information and resources should be directed to, and will be fulfilled by, the lead contact, Jonathan A. Fan (jonfan@stanford.edu).

Materials availability

This study did not generate any new materials.

Data and code availability

This study does not report original code. Any additional information required to reanalyze the data reported in this paper is available from the [lead contact](#) upon request.

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AUTHOR CONTRIBUTIONS

Z.R., conceptualization, data curation and analysis, investigation, methodology, software, and writing – original draft; C.W., conceptualization, data analysis, investigation, methodology, software, visualization, and writing – review & editing; C.C., methodology and software; C.H.L., methodology and software; A.B.H., visualization; D.L.M., visualization; P.M., conceptualization; J.R.-D., supervision; J.A.F., conceptualization, funding acquisition, investigation, project administration, resources, supervision, visualization, writing – original draft, and writing – review & editing.

DECLARATION OF INTERESTS

The authors declare no competing interests.

DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE MANUSCRIPT PREPARATION PROCESS

During the preparation of this work, the authors used ChatGPT in order to improve the writing. After using this tool, the authors reviewed and edited the content. The authors take full responsibility for the content of the publication.

SUPPLEMENTAL INFORMATION

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