

Powering Mobile Sensor Nodes in Fluidized Beds: A Non-Invasive RF Energy Harvesting Proof-of-Concept

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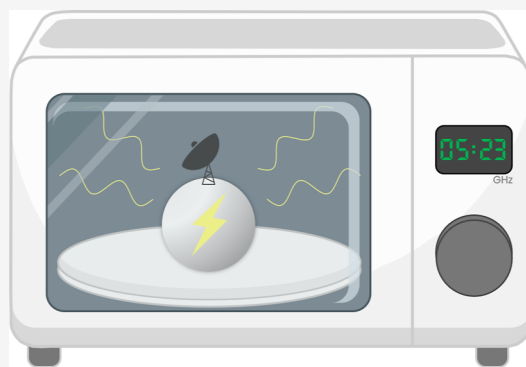
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ABSTRACT: Real-time monitoring within industrial processing vessels is essential for advancing process analytical technology. Flow-following sensors represent an ideal approach for delivering continuous, in-line data from the process stream. However, deploying these mobile sensors is constrained by the physical barriers of sealed metallic vessels and harsh, battery-hostile environments. To overcome these limitations, a non-invasive, retrofittable wireless power transfer system is presented. The metallic vessel is structurally repurposed into a 5.23 GHz multi-mode microwave cavity resonator by coupling microwave energy through existing standard flanges. Electromagnetic simulations validate that this method generates continuous energy coverage throughout dynamic flow zones, demonstrated using a fluidized bed granulator as an application example. To harness this energy, an omnidirectional antenna and a compact RF-to-DC rectifier prototype were developed. By enabling the continuous operation of autonomous, battery-free mobile sensor nodes, this framework provides a practical, scalable foundation for high-density spatial analytics and data-driven industrial optimization.



INTRODUCTION

Even though chemical processes for industrial applications have been developed and investigated for centuries, their execution often still relies on experience and existing experimental data. Details about chemical, physical, and mechanical phenomena occurring throughout the process at different scales, however, remain unknown or not sufficiently understood. Reliable monitoring and control of the process are crucial for ensuring a consistently high product quality and process stability. Nevertheless, conventional approaches rely on a limited number of stationary sensors and off-line measurements of small samples, which often fail to capture localized or transient phenomena inside the process. Without real-time data about critical process variables, such as composition or temperature in a chemical plant, disturbances may be detected too late or not at all, leading to reduced yields, deficient products, or safety risks.¹ Off-line tests introduce additional delays, which contribute to the late detection of deviation from the desired process, resulting in inconsistent product quality and inefficient reprocessing.² Therefore, capturing real-time in-line data would offer the possibility of instant reaction to anomalies, increasing process robustness and enabling the application of advanced control strategies.

One approach to address these challenges involves the development of mobile, autonomous sensors designed to be immersed within the process medium. This approach has been successfully demonstrated in different process environments. For instance, in liquid-phase applications, neutrally buoyant sensor spheres have been engineered to track flow paths and quantify hydrodynamic stress in large-scale stirred tank reactors.^{3–5} Bisgaard et al.⁶ provide an additional overview of flow following sensors in bioreactors. Furthermore, mobile sensors have been developed and applied to bioreactors and stirred tanks to track the flow and measure process variables, such as temperature and pH value.^{7,8} Rath et al.⁹ demonstrate how to enable full 3D tracking of mobile sensors based on accelerometer and magnetometer data using filtering algorithms with a bespoke dynamical model. In addition, mobile sensors for gas-solid processes have been introduced, providing

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Table 1. Comparison of Lagrangian Sensor Particle Designs Deployed in Process Vessels

reference	vessel/process	size/shape	power supply	sensing/telemetry	year
Higashida et al. ¹¹	gas-fluidised bed	Ø 30 mm sphere	on-board battery	3-axis fluid force and Lagrangian acceleration	2016
Harada et al. ⁴⁰	liquid settling/sedimentation	Ø 30 mm sphere	on-board battery	fluid force (3-axis accelerometer + magnetometer)	2011
Zhang et al. ¹⁰	gas-fluidised bed	Ø 60 mm stainless-steel sphere	on-board battery; USB data logger	3D Lagrangian acceleration; in situ phase-structure analysis	2009
Zhu et al. ¹⁴	conical hopper (granular flow)	Ø 42 mm polyformaldehyde sphere	rechargeable polymer battery (3.7 V)	3D translational + rotational tracking (accel. + gyroscope, 200 Hz); Wi-Fi + flash	2020
Cai & Qiu ¹²	gas-fluidised bed	Ø 30 mm sphere	on-board battery	translational/rotational kinematics (velocity, displacement, posture)	2016
Lauterbach et al. ¹³	bioreactor	Ø 7.9 mm sphere	inductive charging/battery	local temperature (sens-o-spheres)	2019
Buntkiel et al. ⁸	biogas fermenter	Ø 40 mm sphere	on-board battery	orientation-resolved 3D acceleration with pressure sensor	2023
Bisgaard et al. ⁶	large-scale bioreactors (review)	7.9–60 mm (multiple)	battery/inductive	review: <i>T</i> , pH, DO, pressure, acceleration	2020
Zimmermann et al. ⁷	laboratory mixer/turbulent flow	Ø 25 mm PEEK sphere	on-board coin cell	3D Lagrangian acceleration; real-time RF wireless (316 Hz)	2013
Geläsus et al. ¹⁵	biochemical reactor	Ø 10–15 mm sphere	battery	IMU and optical data transmission	2025
Reinecke et al. ³	industrial vessels (multi-type)	flow-following sphere	on-board battery	multi-parameter process characterisation	2022
Hofmann et al. ⁴	stirred tank (15000 L)	Ø 40 mm sphere	on-board battery	hydrodynamic lifeline analysis	2024
Haringa et al. ⁵	pilot-scale bubble column (2 m ³)	32–55 mm PEEK sphere	on-board battery	Lagrangian lifeline mapping; pH, DO, pressure, <i>T</i> , accelerometer	2025

data from different regions of fluidized beds.^{10–12} These established examples prove the value of gathering data from a Lagrangian or flow-following perspective, providing unprecedented insight into local conditions as they are experienced along the material's trajectory through the system. However, in these works, energy is provided by non-rechargeable battery cells. In contrast, Lauterbach et al.¹³ and Zhu et al.¹⁴ present mobile sensors that can be recharged inductively outside of the process. To advance mobile sensor techniques even further, this work presents a non-invasive RF energy harvesting proof-of-concept for in-process powering of the sensors. The possibility of using an energy harvester for power management in future versions of miniaturized mobile sensors was also mentioned by Geläsus et al.¹⁵ Table 1 presents an overview of different Lagrangian sensor implementations in process engineering.

To be effective, these sensor elements must not significantly alter the process dynamics. This imposes strict requirements on their physical properties, such as size, density, and shape, to ensure that their movement is representative of the surrounding process fluid or particulate phase.⁵ In addition to those restrictions, key sensor functionalities, such as data acquisition and transmission, must be guaranteed.

One process with the demand for reliable in-line measurements is fluidized bed spray granulation or coating. It is an established process for the production of high-quality granular solids across various industries, such as pharmaceuticals, food, and chemicals. Benefits of applying a coating layer on solid particles include improved handling, taste and odor masking, or providing a protective barrier against environmental influences.¹⁶ To obtain this coated form, the particles are fluidized by heated air while a solid-containing liquid is sprayed onto them. The droplets collide with and spread on the particle surface. As the liquid is evaporated, a solid shell is formed around the core particle.¹⁷

Traditional methods for monitoring and control of fluidized bed granulation rely on stationary sensors measuring the state

of the fluidization air at the inlet, in the process chamber, and at the outlet. Additional information about product properties are obtained from off-line analysis of samples.¹⁸ While other non-invasive process analytical technology (PAT) tools have been explored, such as acoustic emission sensors,¹⁹ electrical capacitance tomography (ECT)²⁰ and magnetic resonance imaging (MRI),²¹ they often provide spatially averaged data, have limited resolution or require complex setups. Based on this data, the process is evaluated and parameters are adapted. However, real-time information from inside the particle bed is severely limited in its spatial resolution and often relies on interpolation (e.g. stationary sensors) or projections (e.g. ECT, MRI), which is non-ideal for precise process control.

Due to the liquid injected into the process chamber, process variables, such as temperature and moisture, are not constant throughout the particle bed. In the spray zone near the nozzle, for example, the temperature of the particles is comparatively low, while the moisture is high as particles come into contact with injected droplets. In contrast, the drying zone, usually in the outer regions, is characterized by higher temperatures and lower particle moisture. In extreme cases, over-wetting or hot spots can occur, which are not necessarily detected early on by traditional monitoring equipment. This affects process stability as well as product quality and can lead to collapse of the fluidized bed and disposal of the product.

In case of a fluidized bed, a mobile sensor could be integrated in the form of a particle, that is moving along with the surrounding bulk particles. To achieve this fluidization behavior and avoid segregation, the size and density of the sensor node have to be carefully chosen.

For deployment of immersive, mobile sensors in fluidized bed granulation processes, design limits are defined and converted into mechanical and electrical constraints. Restrictions on sensor size imposed by product sizes ≤ 2 mm,²² process temperatures around >100 °C for typical model materials such as sodium benzoate^{23,24} and sensor mobility

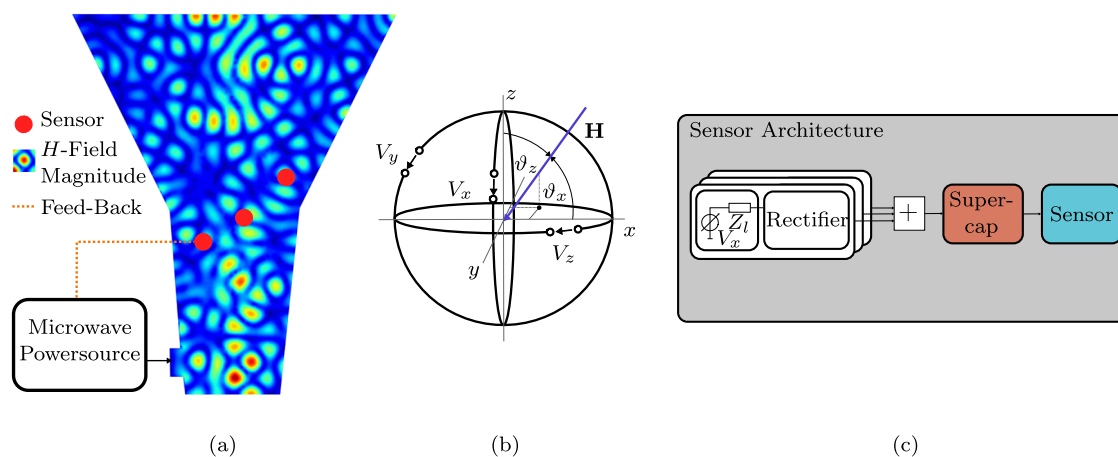


Figure 1. System overview of the microwave-powered fluidized bed concept. (a) Cross-section of the reactor vessel acting as a multi-mode cavity resonator, illustrating the simulated magnetic field (*H*-field) distribution, the microwave power supply, and the distribution of mobile sensor nodes. (b) Schematic of the orthogonal three-loop antenna ensuring omnidirectional energy harvesting. (c) Block diagram of the sensor node architecture, detailing the individual rectifiers, the energy buffer (supercapacitor), and the sensor payload.

create challenges for electrical modules, especially on the power supply.

Mobile power solutions range from on-board storage to active and passive energy harvesting, with the optimal choice dictated by the surrounding environment and on-board energy demand. For example, solar, kinetic and thermoelectric generators exploit ambient motion or temperature gradients to power wearables and industrial monitors.^{25–28} In signal-dense environments, ambient RF harvesting scavenges existing Wi-Fi or cellular frequencies for low-power nodes.^{29–31} However, the low power densities of these ambient sources often make them insufficient for continuous monitoring applications, justifying the use of a dedicated source.^{25,32} When ambient sources are insufficient, such as in enclosed or remote settings, dedicated RF transmission provides reliable, active wireless power.^{33,34}

In the context of fluidized bed reactors, most of these approaches prove unfeasible due to optically opaque particle beds, predominantly steel chamber walls, and practical implementation limits regarding size and density.

Approaches of near-field inductive coupling and high frequency electromagnetic field transfer are both capable of penetrating typical, dense particulate phases without requiring line-of-sight or adding weight-intensive harvesting mechanisms while offering potential for miniaturization. This penetrative behavior holds true for many typical fluidized bed materials, including lactose, microcrystalline cellulose, and polymers, which are generally non-conductive and non-ferromagnetic in their dried state. Nevertheless, both principles require physical integration into the reactor to bypass its steel walls.

Despite its physical feasibility, the magneto-inductive approach offers limited efficiency due to the size differences between receiver and transmitter coil, while requiring high integration effort including a cooling system directly into the process chamber. Alternatively, an external generator can introduce a microwave field into the process chamber via a standard waveguide, where internal reflections establish a standing wave. Conceptually, this configuration operates analogously to a conventional microwave oven, utilizing the metallic process chamber as a resonant cavity, a methodology previously demonstrated for wirelessly powering multiple small receivers throughout a large metallic volume.^{35,36} A key

challenge, however, is the frequency shift caused by moving equipment or materials within the cavity, which can be addressed with compensation techniques.³⁷

Despite the clear physical advantages of the resonant cavity approach, there remains a lack of practical hardware capable of harvesting energy in the transient environment of a fluidized bed, especially in the range around 6 GHz, that enables short antennas and a high resonance density inside the process chamber. At such high frequencies, achieving high efficiency in miniaturized rectifying antennas (rectennas) is a significant challenge. However, recent advancements in highly sensitive, miniaturized CMOS rectifiers demonstrate the feasibility of powering small devices in low-power environments.^{38,39} Addressing this existing hardware deficit, this work focuses on two core objectives. Empirical performance data for a prototype receiver board designed for miniaturization and integration into mobile sensor nodes is presented. Alongside this hardware validation, a generalized conceptual framework detailing how to non-invasively transform a standard process chamber into a microwave resonance cavity using existing mechanical infrastructure is provided.

■ PROOF-OF-CONCEPT VALIDATION: REACTOR SIMULATION AND HARVESTER PERFORMANCE

This section details the conceptual framework and hardware architecture of the proposed powering strategy by explicitly tracing the system's end-to-end energy flow. The power transfer initiates at an external microwave generator, which couples energy into the metallic reactor vessel, structurally repurposed here as a multi-mode cavity resonator, as depicted in Figure 1a. Within this cavity, the injected energy is available as a confined electromagnetic standing wave. On the receiver side, the mobile sensor node intercepts this field utilizing a miniaturized high-frequency energy-harvesting architecture. It consists of a triaxial loop antenna, depicted in Figure 1b, which converts the incident electromagnetic field into an alternating voltage. The captured alternating voltage is subsequently rectified into direct current (DC) and temporarily buffered to reliably drive the sensor payload. The stored energy is available for the sensor node. The harvesting architecture is summarized in Figure 1c. It eliminates the requirement of internal batteries, which otherwise impose significant mass, volume, and thermal

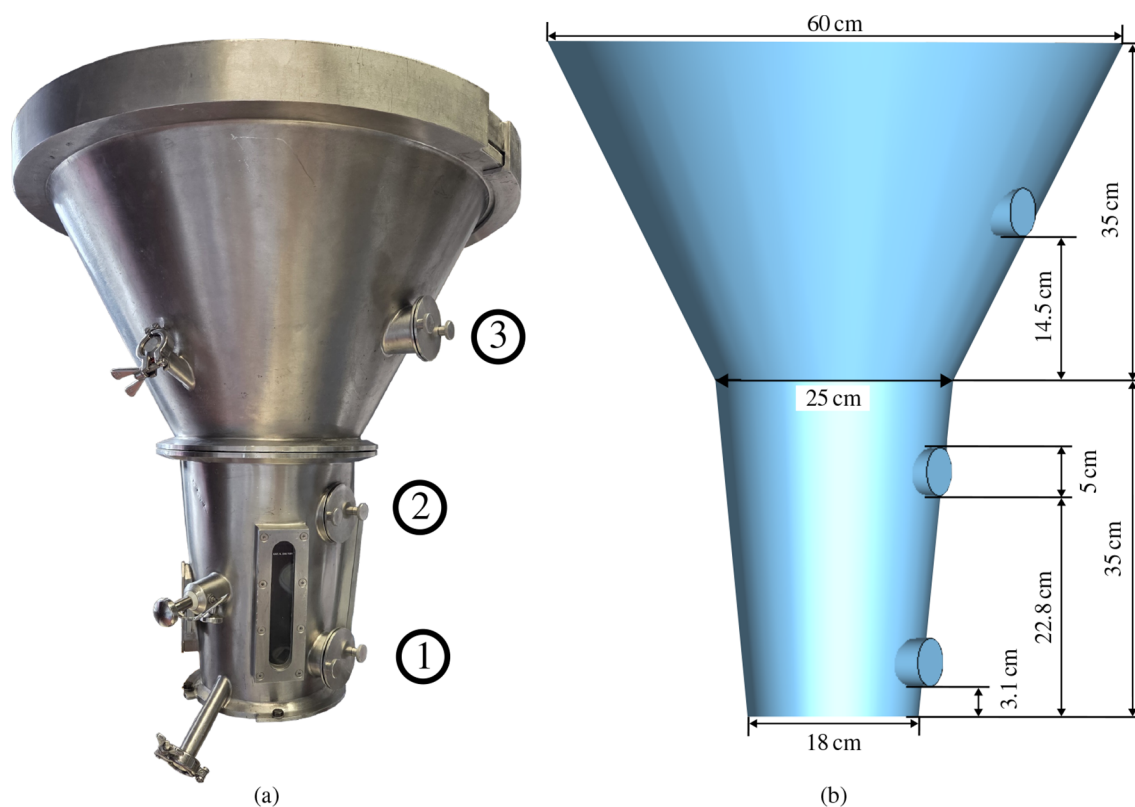


Figure 2. Granulator geometry and simulation setup. (a) Photograph of the exemplary fluidized bed process and expansion chambers, highlighting the three available standard flanges (①, ②, and ③) evaluated as microwave feed ports. (b) The corresponding reduced 3D simulation model utilized for the electromagnetic full-wave analysis, annotated with the primary internal dimensions.

constraints. The sensor nodes achieve a maintenance-free operating life with a minimal physical footprint. This work is separated into two main categories as follows.

- The process and expansion chamber:
 - **Electromagnetic resonance cavity:** Figure 1a depicts a typical fluidized bed process and expansion chamber acting as the propagation medium, inside which a standing wave pattern with high-field regions and nodal points (dead zones) is created.
 - **The microwave feed interface:** Electromagnetic waves are coupled into the process chamber via a standard flange (e.g. DN40/DN50), which acts as a waveguide aperture. This eliminates the need for structural modifications to the reactor. A microwave-power source feeds the flange as shown in Figure 1a. The microwave power source can react to yield the optimal input power, and therefore react to environmental changes due to the process.
- Harvesting electronics:
 - **3D Loop Antenna:** Figure 1b shows an omnidirectional alignment of three loops. This prevents an energy timeout due to misalignment of the loop to the magnetic field. For simplicity, the antenna was approximated as an electrically small loop antenna (ESLA).
 - **RF to DC converter:** Figure 1c shows the schematic of the power transfer of the sensor node. The sensor node is equipped with a compact rectification circuit. Although the stand-

ing wave pattern exhibits local minima, the hydrodynamic movement of the sensor ensures that it continuously traverses varying field strengths. This stochastic motion results in a sufficiently time-averaged energy intake, which is buffered in an onboard supercapacitor⁴¹ to bridge temporary dead zones and provide a constant power supply. The harvested and stored energy is made accessible to the sensor.

The Process and Expansion Chamber—Creating the Electromagnetic Resonance Cavity

Figure 2 depicts the investigated stainless steel laboratory fluidized bed setup. Analogous to typical models, it utilizes standardized flanges (e.g., DN40, DN50) as service ports for external media interaction and probe insertion. Another example of a possible interaction could be found in wireless energy transmission to power sensor nodes inside the reactor. For this, a flange would be used as a connection point for a circular waveguide to feed an externally generated electromagnetic field into the reactor's chamber, where said sensor nodes could harvest the field's energy. The propagation of electromagnetic energy through a flange is strictly governed by a geometry-dependent cutoff frequency f_c . The cutoff frequency for a circular waveguide is defined as

$$f_c = \frac{1.841 \times c_0}{2\pi r \sqrt{\epsilon_r}} \quad (1)$$

where c_0 is the speed of light in vacuum, r is the inner radius of the nozzle, and ϵ_r is the relative permittivity of the fill material.⁴² Dielectrics such as PTFE therefore lower f_c while

simultaneously providing process isolation, as illustrated in Figure 3 for air, PTFE, and quartz as a function of nozzle radius.

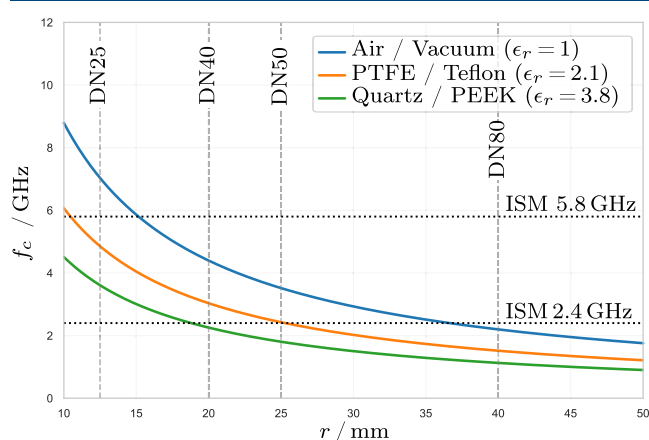


Figure 3. Calculated cutoff frequency versus nozzle radius for different dielectric materials, highlighting relevant standard flange sizes (DN) and ISM bands.

As standard practice often dictates operating within Industrial, Scientific, and Medical (ISM) bands to prevent electromagnetic interference (EMI), these frequencies are highlighted in Figure 3. Since the metallic reactor inherently functions as a Faraday cage and therefore confines the field inside, the operating frequency can be treated as an adaptable design parameter rather than imposing ISM standards.

It should be noted that industrial vessels frequently feature sight glasses for process observation (e.g. see Figure 2a). Since standard glass is transparent to microwaves, these windows can lead to electromagnetic leakage, resulting in both energy losses within the resonator and occupational safety hazards. To mitigate this issue, such windows must be electromagnetically sealed. In practice, this is achieved by integrating a conductive metal mesh into the glass, with a grid to block radiation while maintaining visual transparency. Yue et al.³⁶ introduced a meshed resonator cavity wall that still enables outside communication which is needed to enable in-line measurements of mobile sensor nodes with data transmission from inside the reactor.

For this fluidized bed reactor equipped with standard DN50 flanges, an operating frequency of 5.23 GHz was selected, as it

coincides with the resonance and peak conversion efficiency of the as-manufactured harvesting circuit. This operating point also operates safely above the waveguide cutoff frequency of the flange without requiring additional dielectric loading, while minimizing frequency-dependent dielectric losses within the processed materials.

Inside the reactor cavity, the injected energy reflected by the steel walls forms a complex standing wave pattern determined by the vessel geometry, the dielectric properties of the process medium, and the excitation frequency. The local field strength, hence the harvestable energy, can be directly controlled via the generator's output. Specifically, the electromagnetic field amplitude scales with the square root of the input power ($|E| \propto \sqrt{P_{in}}$), allowing precise adjustment of the energy levels to meet the sensor's requirements.

To predict the energy availability and to optimize the generator coupling, the electromagnetic field distribution inside the process chamber was simulated using the frequency domain solver in CST Studio Suite 2024 (Dassault Systèmes, Vélizy-Villacoublay, France).

The simplified simulation model is depicted in Figure 2b. A waveguide port excites the structure with an input power of 0.5 W at the supply nozzle. To reduce computational complexity while maintaining accuracy, the reactor walls were modeled as perfect electric conductors (PEC), and the interior was defined as a vacuum. To identify the optimal feed point, independent simulations were performed for each available flange (①, ②, and ③).

The simulated magnetic field strength distribution (H -field) reveals a non-trivial standing wave pattern (see Figure 4a–c), with local maxima reaching approximately 12 A m^{-1} . While the highest field intensity is concentrated in the lower central region of the vessel, several nodal points are clearly evident. Furthermore, comparative simulations demonstrate that flange ① provides the most efficient power coupling into the reactor cavity (see Figure 4a).

To quantify the utility of this field for the sensor, the volumetric “coverage”, defined as the percentage of the reactor volume where the field strength suffices for energy harvesting, was analyzed using the optimal feed ①. Although a precise spatial probability density function could be derived for a fixed and well-defined process, a uniform spatial distribution was assumed for simplicity. The reactor volume was partitioned into distinct spatial zones, as shown in Figure 5a, to evaluate the varying field conditions encountered by the sensor nodes.

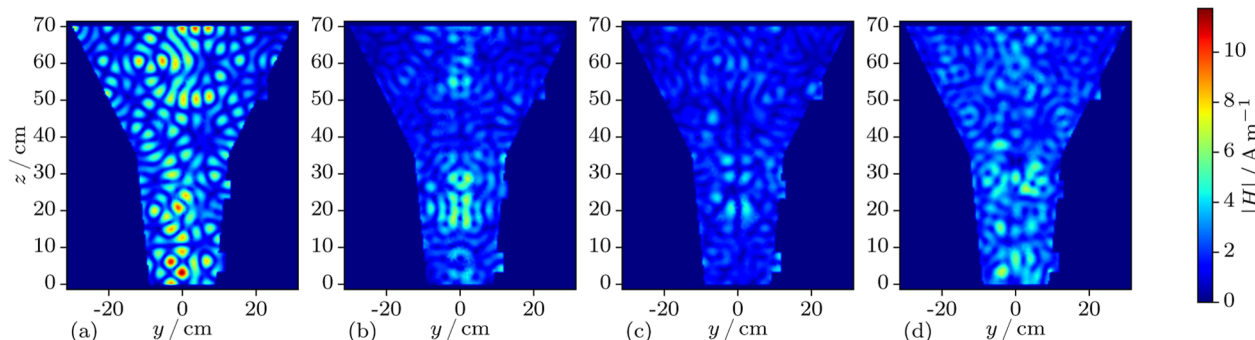


Figure 4. Simulated magnetic field strength distribution (H -field) in the yz -plane of the reactor cavity at 5.23 GHz. The panels illustrate the standing wave patterns generated when utilizing different standard flanges as the microwave feed point: (a) flange ①, (b) flange ②, and (c) flange ③. Panel (d) demonstrates the severe cavity loading and field attenuation when utilizing the optimal feed ① in the presence of a dense, lossy liquid spray cone ($\nu_f = 5\%$).

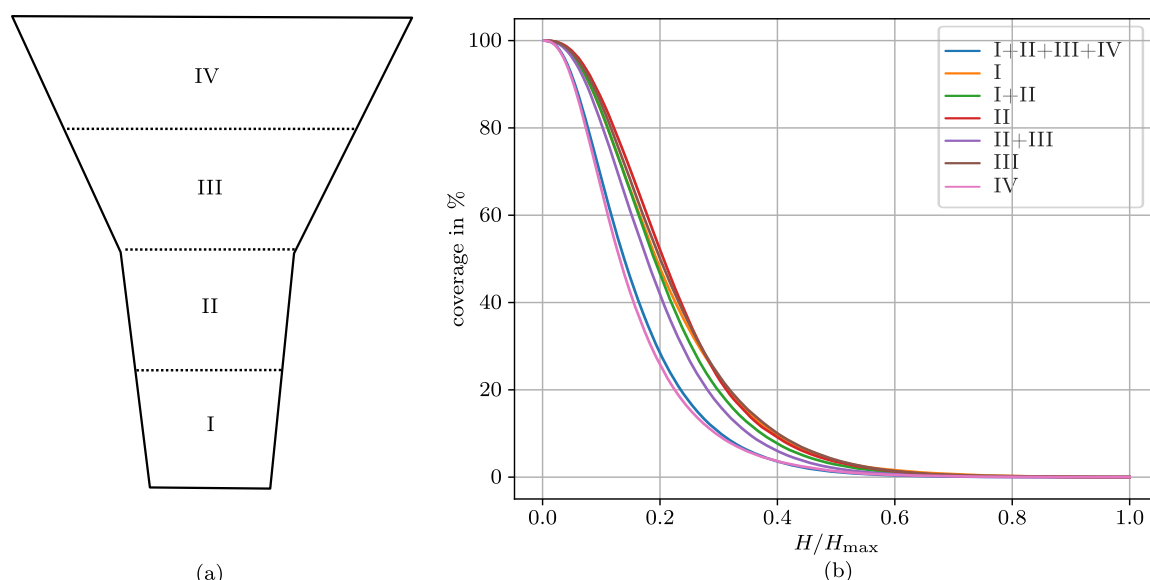


Figure 5. Spatial analysis of energy availability using feed ①. (a) Partitioning of the fluidized bed plant into four distinct evaluation zones. (b) Volumetric field coverage as a function of the normalized magnetic field threshold ($H/H_{\max}$ with $H_{\max}$ taken locally within each zone), demonstrating the highest energy availability in Zones II and III.

Figure 5b plots the volumetric coverage as a function of the normalized magnetic field threshold, with $H_{\max}$ taken locally within each zone. The analysis reveals that Zones II and III yield the best coverage, while Zone IV exhibits the poorest coverage, however, this region is not expected to be reached by the sensor sphere during normal operation. Crucially, under typical process conditions, the sensor nodes are expected to predominantly circulate within Zones I and II, ensuring a highly favorable overall energy availability.

While these initial simulations assume an empty cavity (air/vacuum) to establish the baseline mode distribution, the introduction of the actual process medium, specifically the injected liquid spray, significantly impacts the electromagnetic resonance. Depending on the liquid volume fraction, the spray can cause slight frequency detuning or severe cavity loading. To explicitly model the worst-case attenuation during the active spraying phase, the dense spray cone was approximated as an effective macroscopic medium with a fractional water volume of $v_f = 5\%$. The complex permittivity of the pure liquid water droplets at the operating frequency of 5.23 GHz and a nominal process temperature of 40 °C was determined using the double-Debye model proposed by Liebe et al.⁴³ Subsequently, the effective dielectric properties of the spray zone were calculated by applying the exact Maxwell-Garnett mixing rule for spherical inclusions within a host medium of air ($\epsilon_{\text{air}} = 1$). Assigning the resulting effective relative permittivity ($\epsilon_r \approx 1.1513$) and loss tangent ($\tan \delta \approx 0.001012$) to the modeled spray zone. This zone is modeled as a cone, with a centric injection point at a height of 500 mm and a cone height of 300 mm with a bottom radius of 80 mm. The spray damps the resonant standing wave pattern by 4 dB, as depicted in Figure 4d. The previously dominant magnetic field hotspots collapse, leading to a substantial reduction in the local field intensity compared to the empty state.

Operating frequency determines dielectric loading. The spray medium's loss tangent scales linearly with frequency across the 1–10 GHz range. For example, $\tan \delta \approx 2 \times 10^{-4}$ at 1 GHz and $\approx 1.9 \times 10^{-3}$ at 10 GHz. The relative permittivity, ϵ_r , remains constant. Lower frequencies minimize dielectric

attenuation. This improves energy delivery to distant high-field regions. However, standing-wave patterns scale with wavelength. Lower frequencies therefore enlarge dead zones within a fixed reactor geometry. The net impact on volumetric coverage remains unpredictable a priori. Frequency-specific electromagnetic simulations must evaluate these competing trends.

This methodology enables a physically rigorous emulation of the localized electromagnetic wave attenuation during the active spraying phase, which dictates the dynamic power requirements and hardware protection strategies for the mobile sensor node. While a simulative approach provides a promising initial estimate by approximating ϵ_r and $\tan \delta$, the precise material parameters in the final assembly remain unknown. This uncertainty introduces integration risks that necessitate experimental validation, where the group of Gutiérrez-Cano et al. introduced an approach to quantify the complex permittivity of dielectric materials at microwave frequencies.⁴⁴

RF HARVESTING ELECTRONICS

This section introduces a prototype of the RF-harvesting circuit, that once miniaturized is intended for integration into a mobile sensor node. As the sensor node requires a stable DC supply voltage, a rectification circuit was designed based on a shunt diode topology. This design consists of a receiving antenna (see Figure 1b) and a rectifying circuit, commonly combined to the term “rectenna”. In general, the antenna induces a high-frequency AC signal, which is subsequently converted to DC.

Three-Dimensional Harvesting via 3D Loop Antenna

The electromagnetic field distribution within the reactor is a complex vector field. Consequently, the energy transfer efficiency highly depends on the alignment between the field vector and the receiving antenna. Since the mobile sensor nodes are able to freely rotate within the dynamic process, a single-axis antenna would suffer from frequent polarization mismatches and power dropouts.

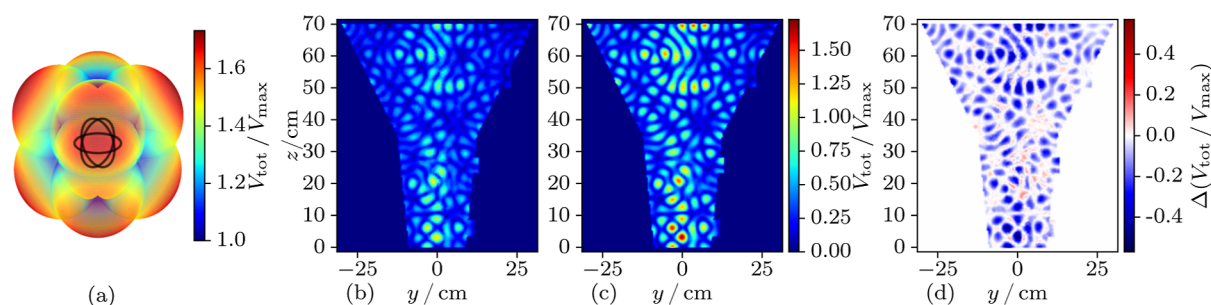


Figure 6. Spatial analysis of a virtual triaxial loop receiver in the reactor cross-section. (a) Theoretical sensitivity pattern of the triaxial loop as a function of the local H -field orientation. (b,c) Spatially resolved relative harvested voltage for (b) normal alignment (0° , 0°) and (c) rotated alignment (45° , 45°). (d) Difference between (b,c).

To maintain continuous power delivery during stochastic particle rotation, the antenna is designed as a triplet of mutually orthogonal loops (see Figure 1b). According to Faraday's law of induction, the voltage amplitude $|V_i|$ induced in loop i (where i denotes x , y , or z) is given by

$$|V_i| = \omega \mu_0 N \int_A \mathbf{H} \times d\mathbf{A} \quad (2)$$

since the dimensions of $a \leq 2$ mm particle to perfectly imitate the particle bed constraints²² and the corresponding wavelength at 5.23 GHz render the antenna approximately electrically small, (2) simplifies to

$$|V_i| = \omega \mu_0 |H| A N \cos \vartheta_i \quad (3)$$

where ω is the angular frequency, μ_0 is the vacuum permeability, $|H|$ is the local magnetic field strength amplitude, A is the loop area, N is the number of windings, and ϑ_i is the angle between the field vector and loop i and its surface normal. The maximal amplitude of a single loop is $V_{\max} = \omega \mu_0 |H| A N$.

The equivalent circuit diagram of a single shorted loop is shown in Figure 1c. The source impedance Z_s consists of the loop inductance L_1 and the wire resistance R_w , the latter comprising both the ohmic (DC) and skin-effect contributions, given as

$$Z_s = j\omega L_1 + R_w \quad (4)$$

For the considered dimensions ($R = 1$ mm, gold bond-wire feed, $a \approx 12.5$ – 25 μm), the loop self-inductance is $L_1 \approx 4.7$ – 5.6 nH, and the matching capacitance for series resonance lies in the range $C_{\text{match}} \approx 165$ – 196 fF, confirming that it is readily realizable in CMOS-processed circuits.

Ideal orthogonality prevents mutual magnetic coupling. Manufacturing tolerances introduce tilt angles α_{ij} between nominally orthogonal loops. Here, $i, j \in \{x, y, z\}$ and $i \neq j$. This tilt yields the mutual inductance

$$M_{ij} = M_0 \sin \alpha_{ij} \approx k L_1 \alpha_{ij} \quad (5)$$

M_0 is the coplanar mutual inductance. L_1 is the self-inductance from eq 4. The geometric coupling coefficient $k \ll 1$ for edge-sharing loops. Consequently, $M_{ij} \ll L_1$ for realistic tolerances. A nonzero M_{ij} shifts the reactive part of Z_i . This detuning remains negligible. The matching network's bandwidth absorbs the shift. Additional coupling is introduced by connecting the antennas to the rectifiers.

Three serial rectennas using this geometry ensure that the total harvested power is proportional to the amplitude of the magnetic coupling across all three axes. Effectively, the

orthogonal arrangement spans the three-dimensional space, ensuring that the superposition of the antenna patterns eliminates the "null points" (blind spots) typically associated with a single-axis magnetic dipole, as illustrated in Figure 6a. By integrating three orthogonal loops, the system eliminates angular dead zones summing to $V_{\text{tot}} = \sum_i |V_i|$. The minimum $V_{\text{tot, min}}$ occurs when the field vector is aligned with one of the three axes, while the maximum occurs when the field vector is aligned equidistantly to all three axes (at $\pi/4$), resulting in a harvesting gain G_{harv} between $|V_i|$ and $\sqrt{3} |V_i|$, i.e., a factor of up to $\sqrt{3}$ relative to a single loop. This spatial dependence and the resulting orientation-dependent gain are confirmed by the field simulations shown in Figure 6b–d: panels (b) and (c) show the spatially resolved relative harvested voltage $V_{\text{tot}}/V_{\text{ref}}$ for normal alignment (0° , 0°) and rotated alignment (45° , 45°), respectively, while panel (d) shows their difference, highlighting regions where the harvested voltage is particularly sensitive to sensor orientation.

It should be noted that the lumped-element simplification in eq 3 is only valid for electrically small loops. Once the loop circumference exceeds approximately 0.1λ , the field can no longer be assumed uniform over the loop area. Moreover, since the antenna operates in the reactive near field of the resonant cavity rather than under classical far-field conditions, the surface integral of eq 2 must be evaluated directly.

Performance of the 5.23 GHz Energy Harvesting Interface

Since the induced signal operates at the system's microwave frequency of 5.23 GHz, a rectification circuit is required. Figure 7a shows the considered Shunt Diode Rectifier.⁴⁵ This circuit short-circuits the negative part of the sine wave and smoothes the remaining positive half wave. This topology avoids placing any diode in series with the load path, thereby avoiding an additional forward voltage drop at the output. At the low input power levels considered here, where the signal amplitude is comparable to the diode's threshold voltage, such a drop would reduce the PCE.

This approach prevents the destructive interference that would occur if the phase-shifted AC signals were combined directly prior to rectification, although at the expense of an increased component count and footprint. Not further discussed in this paper is the application specific energy density optimization, where a global optimum for the ratio of energy storage size to harvesting architecture size (including antennas, rectifiers and buffers) can be found.

To bridge the "dead zones" (nodes of the standing wave pattern) encountered during the sensor's trajectory, the system employs a supercapacitor as an intermediate energy buffer.

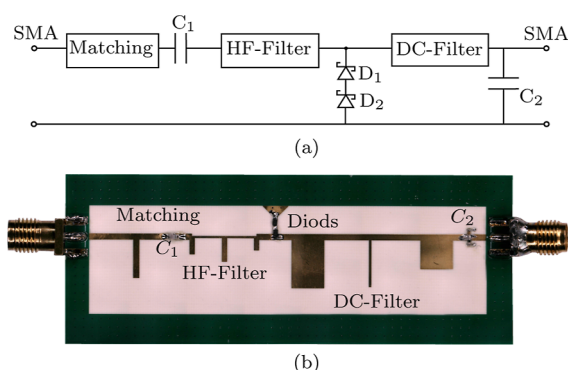


Figure 7. Microwave energy harvesting rectification circuit. (a) Schematic diagram illustrating the input impedance matching network, DC-blocking capacitor (C_1), HF filter, double-diode shunt rectifier (D_1 , D_2), DC filter, and output smoothing capacitor (C_2). (b) Photograph of the fabricated prototype on a Rogers RO4350B substrate, with the corresponding functional blocks annotated.

This ensures continuous sensor operation, data logging, and data transmission, even when the instantaneous harvested power drops below the required consumption threshold, while introducing only a small energy storage for short term power supply.

Instead of a single diode, a double-diode arrangement utilizing Silicon Schottky barrier diodes D_1 and D_2 (Skyworks SMS7630) is implemented to extend the maximum input power capability and enhance overall efficiency. The selected diodes enable operation at frequencies up to 24 GHz while introducing restriction on the maximum voltage (breakdown voltage ≤ 2 V per diode).

To ensure signal purity, a high-frequency (HF) lowpass filter with a cutoff frequency of approximately 8 GHz is utilized to suppress the 2nd, 3rd, and 4th order harmonics generated by the nonlinear diode characteristics. Finally, a DC lowpass filter ($f_{\text{cutoff}} \approx 1$ GHz) blocks any residual radio-frequency (RF) power from flowing into the load. A spectral investigation of the rectifier output revealed measurable spurious components only at 5.23 and 10.46 GHz, both more than 36 dB below the DC power. Due to their high frequency, these are irrelevant to the powered system.

Due to the operation in the gigahertz range, precise impedance matching is critical to minimize reflections and maximize power conversion efficiency (PCE) η_{PCE} , on a size of approximately 30 mm $\times$ 80 mm. Therefore, the rectification circuit was designed on a Rogers RO4350B substrate ($\epsilon_r = 3.48$, thickness 0.51 mm). It employs an input matching network to adapt the diode impedance to the 50 Ω antenna system, followed by a DC-blocking capacitor to isolate the RF input. The fabricated prototype is shown in Figure 7b.

To characterize the manufactured board, a conducted measurement setup, as depicted in Figure 8, is used. An RF signal generator (MG3694B, Anritsu, Atsugi, Japan) mimics the antenna signal, while a variable load resistance (Manger Electronic) and a multimeter (VC608, Voltcraft, Hirschau, Germany) capture the rectifier's output V_{DC} across the relevant power range.

Figure 9 illustrates the PCE calculated from the measured output voltage as a function of the input RF power and the

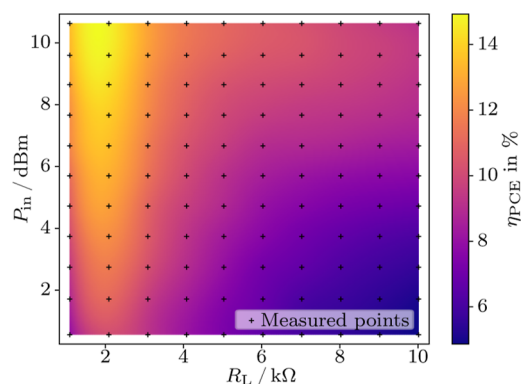


Figure 9. Power conversion efficiency (η_{PCE}) as a function of input power P_{in} and load resistance R_L , bicubic-spline interpolated from the measured points (black crosses).

connected load resistance. The heatmap reveals a distinct optimal operating region for the harvesting circuit. The peak efficiency is consistently achieved at an optimal load resistance of approximately 2 k Ω . Notably, this optimal load point remains highly stable across the entire swept input power range from 1 dBm to 10 dBm. At this matched load condition, the rectifier reaches a maximum PCE of over 14% at 10 dBm input power. Deviating from this optimum, particularly towards higher resistance values above 5 k Ω , results in a significant drop in conversion efficiency, which can be attributed to an increasing impedance mismatch between the rectifying diode network and the load. The achieved PCE of 14% reflects the proof-of-concept nature of this work. The primary contribution is not the maximization of rectifier efficiency, but the non-invasive, cavity-based wireless powering concept for mobile sensor nodes in metallic process vessels. Any resulting reduction in available power can be compensated by increasing the generator output, which is negligible compared to the overall process energy demand. To reduce size and increase PCE in future iterations, different approaches are summarized and compared in Table 2 operating in the 2.4–5.8 GHz range. Considering those approaches,⁴⁶ appears particularly promising for miniaturization, reducing size below 2 mm due to the applied CMOS manufacturing by yielding a PCE of 52%.

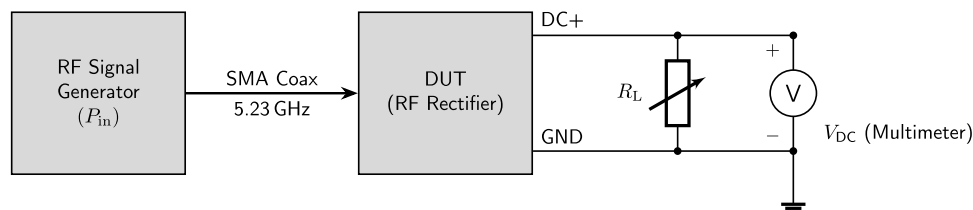


Figure 8. Schematic of the conducted measurement setup used to characterize the rectifier. The RF signal generator emulates the harvested antenna power (P_{in}), while the rectified DC voltage (V_{DC}) is measured across a variable load (R_L).

Table 2. Comparative Summary of Representative RF Energy Harvesting and Rectenna Designs^a

ref	freq (GHz)	antenna type & size	pol./orient.	topology	P_{in} (dBm)	R_L (k Ω)	η_{PCE} (%)	application
Mohamed et al. ⁴⁷	4.0–5.5	CP leaky-wave (297 × 70 mm ²)	circ., ±21° scan	volt. doubler (SMS7630)	0.0	2.5	53.8	free-space 5G midband
He et al. ⁴⁸	2.45	dual-pol. patch (67.6 × 67.6 mm ²)	all lin. pol. (2D fixed beam)	dual-port (HSMS282)	23.3	0.4	82.2	free-space WPT
Deng et al. ⁴⁹	5.80	CP microstrip slot (45 × 45 mm ²)	circ., fixed	V. doubler (HSMS-286C)	5.91	1.8	60.0	free-space WPT
Shi et al. ⁵⁰	2.50	broadband slotted patch (35 × 50 mm ²)	lin., fixed	V. doubler (HSMS-2852)	5.0	4.0	70.0	ambient LTE (2.0–3.1 GHz)
Reed et al. ⁵¹	2.40	patch (36 × 32 mm ²)	lin., fixed dir	shunt schottky (SMS7630)	5.2	2.0	69.3	free-space WPT
Wang et al. ⁵²	5.80	CP stacked patch array (25.9 × 25.9 mm ²)	circ., fixed	parallel subrect. (HSMS286F)	~13	0.24	80.6	free-space WPT (CubeSat)
Assimonis et al. ⁵³	0.868	strip-SSRR ($d = 19.2$ mm, $h = 52.1$ mm, $ka = 0.53$)	omni-az., lin. vert	half-wave (HSMS285B)	−4.9	2.2	36.6	ambient batteryless sensor
Dang et al. ⁴⁵	5.80	—(conducted)	N/A	lateral GaN Schottky	34.0	0.3	71.0	circuit benchmark
Dehghani et al. ⁴⁶	5.75	—(chip, 0.35 mm ²)	N/A	class-DE sync. CMOS rect. (65 nm, bidir.)	5.0	0.4	52	chip benchmark (50 Ω port)
this work	5.23	triaxial loops (R30 × 80 mm PCB)	Full 3-D isotropic	shunt double-SBD (SMS7630)	10.0	2.0	14.0	metallic cavity; fluidized node

^aEntries are ordered by decreasing antenna footprint.

While the current proof-of-concept focuses on maximizing the core RF rectification efficiency, deploying the sensor in a highly dynamic fluidized bed introduces overvoltage risks. Process-induced variations in relative permittivity, such as those from liquid injection, can temporarily alter the cavity's resonant modes, causing spikes in local field strength. To protect sensitive microelectronics in future fully integrated sensor nodes, two complementary strategies are proposed. On a hardware level, a miniaturized transient voltage suppression (TVS) diode at the DC output could provide robust voltage clamping without introducing parasitic capacitance at 5.23 GHz. On a system level, a closed-loop power control mechanism could be implemented. By establishing a wireless communication link, the sensor could provide real-time voltage feedback to the microwave generator, enabling adaptive regulation of the transmitted power to mitigate transient variations and ensure stable operation. This communication link might also be used for transmitting sensor data.

Due to the highly dynamic nature of the fluidized bed, the continuous motion of the sensor nodes relative to the microwave feed introduces a frequency deviation via the Doppler effect. To accurately assess the impact of this phenomenon on the PCE, the maximum expected particle velocity must be evaluated. Pietsch et al.⁵⁴ analyzed the vertical particle velocity in a spouted bed, demonstrating that for the majority of particles, the velocity does not exceed 2 m s^{−1}. Because particles in spouted beds typically experience higher velocities than those in standard fluidized beds,⁵⁵ even lower particle velocities are expected for the process considered in this work.

The maximum Doppler shift Δf is determined by the relationship

$$\Delta f = f_0 \frac{v}{c} \quad (6)$$

where f_0 is the 5.23 GHz carrier frequency, v is the relative particle velocity of ≈ 2 m s^{−1}, and c is the speed of light. Assuming a conservative upper-bound velocity of $v = 2$ m s^{−1}, the resulting maximum frequency deviation is approximately 34.89 Hz.

Because this deviation is orders of magnitude smaller than the carrier frequency, the detuning effect is physically

negligible. Consequently, it is concluded that the hydrodynamic motion of the particles does not degrade the stability or efficiency of the high-frequency wireless energy transfer.

Performance Analysis for In-Line Energy-Harvesting

A key requirement for applying microwave energy harvesting in this context is a low input power demand, which ensures the overall energy efficiency and safety of the setup. To demonstrate that the designed system meets this criterion, the power requirements of the miniaturized single-loop antenna ($R = 1$ mm, $A \approx 3.14$ mm², $N = 1$) operating at 5.23 GHz were evaluated, and the resulting safety margin against diode breakdown was assessed.

First, the system's operational boundaries are determined by the induced voltage requirements of the rectifier's Schottky diodes (Skyworks SMS7630). The circuit requires a minimum operation voltage of 60 mV, while the maximum breakdown voltage is 4 V (comprising two diodes in series, each with a 2 V maximum breakdown voltage).

Second, these voltage thresholds define the necessary local magnetic field strengths, defined by (3). To maintain the minimum operational voltage within the nodal regions, a field strength of at least $|H_{\text{dead}}| \approx 462.5$ mA m^{−1} is required. Conversely, to prevent diode breakdown, the local magnetic field must not exceed $|H_{\text{max}}| \approx 30.833$ A m^{−1}.

These field limits can then be related to the simulated magnetic field distribution inside the fluidized bed reactor. At a nominal simulated input power of 0.5 W (27 dBm), the baseline peak field reaches 12 A m^{−1}. Because the injected power scales with the square of the field strength ($P \propto |H|^2$), increasing this simulated peak field to the maximum allowable 30.8 A m^{−1} corresponds to a power increase factor of approximately 6.6 (≈ 8.2 dB).

Consequently, an actual input power of roughly 3.3 W (35.19 dBm) is sufficient to drive the miniaturized sensor node. This assessment shows that the system meets the low-power requirements for microwave energy harvesting, allowing for continuous operation using standard, low-cost microwave signal sources.

Furthermore, system planning must account for additional power losses. Pre-diode losses, such as flange coupling, cavity, process-medium, and antenna mismatch losses, allow com-

pensation via increased generator input power. The diode breakdown voltage bounds this compensation to $|H_{\max}|$. Post-diode losses, including diode junction capacitance, switching, and supercapacitor storage losses, resist input power compensation. Circuit and system design must minimize these downstream losses. Considering the maximum output voltage per rectifier of 4 V and the system gain of $\sqrt{3}$, the available power reaches up to 23 mW at the optimal load resistance of 2 k Ω . This is sufficient to supply a wide range of miniaturized sensors, including temperature, IMU, and pressure sensors, which typically consume between 100 μ W and 5 mW during active measurement,^{56–58} noting that continuous measurement is not expected to be required in the target application.

CONCLUSIONS

This work establishes the feasibility of a wireless power transfer system for mobile sensor nodes within metallic apparatuses by treating the vessel as a resonant cavity. The concept was validated through electromagnetic simulations, which indicated that an input power of 3.3 W could be sufficient for powering a sensor node, suggesting a highly efficient power transfer mechanism. A hardware prototype of the energy-harvesting rectenna was also developed and characterized, achieving a power conversion efficiency of about 14% at 5.23 GHz confirming the viability of the core components. The comparably low PCE can be improved by more precise impedance matching.

For practical implementation, several aspects warrant further development. The current findings are based on simulations and laboratory measurements, making testing within an environment as close to a real dynamic process environment as possible the next necessary step. The study notes that process dynamics, such as liquid injection, can introduce transient loading and frequency shifts, though the underlying assumptions for this water spraying require validation. These effects underscore the need for future designs to incorporate robust overvoltage protection and a closed-loop power control system to ensure stable and reliable operation. A closed-loop power control system would additionally increase the robustness of the concept across a wider range of process conditions and reactor configurations.

Scaling the proposed concept to larger reactor geometries primarily requires an increased generator power to maintain the local field strength $|H_{\max}|$, as the same standing-wave pattern is distributed over a larger volume. Both, a change in reactor size, and a change in reactor geometry alter the resulting mode pattern and therefore require a dedicated electromagnetic simulation, following the methodology presented in this work. Beyond fluidized beds, the underlying requirements, a metallic, resonance-capable enclosure and a mobile sensor node traversing the field, are not specific to this process type and could in principle extend to other agitated or flow-following sensing applications, provided the process medium does not introduce excessive dielectric loss, as discussed. Consequently, possible applications include for example solids mixing and high-shear granulation processes as well as flow of bulk materials such as discharge from a hopper.

Furthermore, this investigation was focused on the power-harvesting unit. A fully functional system will require the future integration of sensor payloads and a data transmission module. Miniaturizing all subsystems into a single particle with

appropriate physical properties to match the process medium also remains a key objective for future work.

In summary, this research provides a strong foundation for a novel wireless powering application. By addressing the outlined areas for future work, such as system integration, miniaturization, and the implementation of control and protection circuits, this approach has the potential to enable advanced in situ process monitoring for improved process control and contribute to the development of self-regulated reactors.

ASSOCIATED CONTENT

Data Availability Statement

The experimental measurement data and electromagnetic simulation models generated and analyzed during this study are openly available in the TUHH Open Research (TORE) repository at [10.15480/882.16850](https://doi.org/10.15480/882.16850)

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Notes

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REFERENCES

- (1) Lee, J. H.; Lee, J. M. Progress and challenges in control of chemical processes. *Annu. Rev. Chem. Biomol. Eng.* **2014**, *5*, 383–404.
- (2) Kołodziejczak-Radzimska, A.; Rukowicz, B.; Davin, S. Real-time quality control for chemical and biotechnological processes: a brief review. *J. Med. Sci.* **2023**, *92*, No. e901.
- (3) Reinecke, S. F.; Buntkiel, L.; Kipping, R.; Hampel, U. Process Characterization in Industrial Vessels by Flow-Following Sensor Particles. *Meas. Sci. Technol.* **2022**, *33*, 095106–096501.
- (4) Hofmann, S.; Buntkiel, L.; Rautenbach, R.; Gaugler, L.; Ma, Y.; Haase, I.; Fitschen, J.; Wucherpennig, T.; Reinecke, S. F.; Hoffmann, M.; Takors, R.; Hampel, U.; Schlüter, M. Experimental Analysis of Lifelines in a 15,000 L Bioreactor by Means of Lagrangian Sensor Particles. *Chem. Eng. Res. Des.* **2024**, *205*, 695–712.
- (5) Haringa, C.; Tajsoliman, T.; Van Winden, W. A.; Dong, D.; Gladue, R. M.; Wu, L.; Rasmussen, T.; Noorman, H. J. Flow-Following Sensor Technology, a Route to Validated CFD Models. *Biochem. Eng. J.* **2025**, *215*, 109623.
- (6) Bisgaard, J.; Muldbak, M.; Cornelissen, S.; Tajsoliman, T.; Huusom, J. K.; Rasmussen, T.; Gernaey, K. V. Flow-following sensor devices: A tool for bridging data and model predictions in large-scale fermentations. *Comput. Struct. Biotechnol. J.* **2020**, *18*, 2908–2919.
- (7) Zimmermann, R.; Fiabane, L.; Gasteuil, Y.; Volk, R.; Pinton, J.-F. Measuring Lagrangian accelerations using an instrumented particle. *Phys. Scr.* **2013**, *T155*, 014063.
- (8) Buntkiel, L.; Ma, Y.; Reinecke, S. F.; Hampel, U. Orientation resolved measurements of accelerations with sensor particles in bioreactors. *tm - Technisches Messen* **2023**, *90*, 835–845.
- (9) Rath, V.; Sehar, F.; Sommer, F. L.; Götschel, S.; Steuwe, E.; Kameke, A. v.; Ruprecht, D. Tracking in-silico Lagrangian sensors in a lab-scale stirred tank reactor. *arXiv* **2026**, arXiv:2606.13099.
- (10) Zhang, Q.; Huang, C.; Jiang, D.; Wei, X.; Qian, Z.; Wei, F. Particle Measurement Sensor for in situ determination of phase structure of fluidized bed. *Particuology* **2009**, *7*, 175–182.
- (11) Higashida, K.; Rai, K.; Yoshimori, W.; Ikegai, T.; Tsuji, T.; Harada, S.; Oshitani, J.; Tanaka, T. Dynamic vertical forces working on a large object floating in gas-fluidized bed: Discrete particle simulation and Lagrangian measurement. *Chem. Eng. Sci.* **2016**, *151*, 105–115.
- (12) Cai, R.; Qiu, J. Position and posture determination of a large dense object in a fluidized bed. *Flow Meas. Instrum.* **2016**, *51*, 40–48.
- (13) Lauterbach, T.; Lüke, T.; Büker, M.-J.; Hedayat, C.; Gernandt, T.; Moll, R.; Grösel, M.; Lenk, S.; Seidel, F.; Brunner, D.; Bley, T.; Walther, T.; Lenk, F. Measurements on the fly—Introducing mobile micro-sensors for biotechnological applications. *Sens. Actuators, A* **2019**, *287*, 29–38.
- (14) Zhu, Y.; Yang, H.; Li, R.; Zhang, Y.; Chen, Q.; Hua, Y.; Sun, Q.; Kong, P. Wireless detector for translational and rotational motion of spherical-particle flow. *Powder Technol.* **2020**, *360*, 882–889.
- (15) Geläsus, A. U.; Haack, M.; Sulecki, J. V.; Trieu, H. K. Miniaturized Lagrangian Sensor-Systems for Position Detection in (Bio-) Chemical Reactors In *MikroSystemTechnik Kongress 2025*; VDE: Duisburg, Germany, 2025 DOI: .
- (16) Dewettinck, K.; Huyghebaert, A. D. Fluidized bed coating in food technology. *Trends Food Sci. Technol.* **1999**, *10*, 163–168.
- (17) Uhlemann, H.; Mörl, L. *Wirbelschicht-Sprühgranulation*; Springer Berlin Heidelberg: Berlin, Heidelberg, 2000.
- (18) Burggraef, A.; Monteyne, T.; Vervae, C.; Remon, J. P.; Beer, T. D. Process analytical tools for monitoring, understanding, and control of pharmaceutical fluidized bed granulation: A review. *Eur. J. Pharm. Biopharm.* **2013**, *83*, 2–15.
- (19) Tsujimoto, H.; Yokoyama, T.; Huang, C.; Sekiguchi, I. Monitoring Particle Fluidization in a Fluidized Bed Granulator with an Acoustic Emission Sensor. *Powder Technol.* **2000**, *113*, 88–96.
- (20) Wang, H.; Yang, W. Scale-up of an electrical capacitance tomography sensor for imaging pharmaceutical fluidized beds and validation by computational fluid dynamics. *Meas. Sci. Technol.* **2011**, *22*, 104015.
- (21) Rennebaum, H. S.; Müller, C. R.; Penn, A. Vertical Tubes in Bubbling Fluidized Beds: A Magnetic Resonance Imaging Study of Particle and Bubble Behavior. *Powder Technol.* **2025**, *457*, 120870.
- (22) Zhu, X.; Xu, Y.; Tu, Q.; Che, H.; Wang, H. Advanced Measurement Techniques for Gas-Solids Fluidized Beds in the Power and Energy Industry - A Review. *Measurement: Energy* **2024**, *4*, 100030.
- (23) Rieck, C.; Hoffmann, T.; Bück, A.; Peglow, M.; Tsotsas, E. Influence of Drying Conditions on Layer Porosity in Fluidized Bed Spray Granulation. *Powder Technol.* **2015**, *272*, 120–131.
- (24) Orth, M.; Kieckhefen, P.; Pietsch, S.; Heinrich, S. Correlating Granule Surface Structure Morphology and Process Conditions in Fluidized Bed Layering Spray Granulation. *KONA Powder Part. J.* **2022**, *39*, 230–239.
- (25) Sherazi, H. H. R.; Zorbas, D.; O'Flynn, B. A Comprehensive Survey on RF Energy Harvesting: Applications and Performance Determinants. *Sensors* **2022**, *22*, 2990.
- (26) Leong, W. Y. Energy harvesting techniques for self-powered industrial IoT sensor nodes In *2025 IEEE Symposium on Industrial Electronics & Applications (ISIEA)*; IEEE: Kuala Lumpur, Malaysia, 2025; pp 1–6.
- (27) Routray, S. K.; et al. Energy Harvesting Microcontrollers for IoT In *2025 3rd International Conference on Self Sustainable Artificial Intelligence Systems (ICSSAS)*; IEEE: Erode, India, 2025; pp 388–393.
- (28) Pullwitt, S.; Kulau, U.; Hartung, R.; Wolf, L. C. A feasibility study on energy harvesting from soil temperature differences In *Proceedings of the 7th International Workshop on Real-World Embedded Wireless Systems and Networks*; ACM: Shenzhen China, 2018; pp 1–6.
- (29) Pinuela, M.; Mitcheson, P. D.; Lucyszyn, S. Ambient RF Energy Harvesting in Urban and Semi-Urban Environments. *IEEE Trans. Microwave Theory Tech.* **2013**, *61*, 2715–2726.
- (30) Graham, A. M.; Daskalakis, S. N.; Fusco, V.; Tentzeris, M. M.; Asimonis, S. D. A Highly Efficient, Scalable, Tetra-Band Metamaterial-Based Ambient RF Energy Harvester. *IEEE Trans. Microwave Theory Tech.* **2025**, *73*, 6787–6798.
- (31) Boshkovska, E.; Ng, D. W. K.; Zlatanov, N.; Koelpin, A.; Schober, R. Robust Resource Allocation for MIMO Wireless Powered Communication Networks Based on a Non-Linear EH Model. *IEEE Trans. Commun.* **2017**, *65*, 1984–1999.
- (32) Mouapi, A. Radiofrequency Energy Harvesting Systems for Internet of Things Applications: A Comprehensive Overview of Design Issues. *Sensors* **2022**, *22*, 8088.
- (33) Lu, X.; Wang, P.; Niyato, D.; Kim, D. I.; Han, Z. Wireless Networks With RF Energy Harvesting: A Contemporary Survey. *IEEE Commun. Surv. Tutor.* **2015**, *17*, 757–789.
- (34) Bi, S.; Ho, C. K.; Zhang, R. Wireless powered communication: opportunities and challenges. *IEEE Commun. Mag.* **2015**, *53*, 117–125.
- (35) Chabalko, M. J.; Sample, A. P. Three-Dimensional Charging via Multimode Resonant Cavity Enabled Wireless Power Transfer. *IEEE Trans. Power Electron.* **2015**, *30*, 6163–6173.
- (36) Yue, Z.; Zhang, Q.; Yang, Z.; Bian, R.; Zhao, D.; Wang, B.-Z. Wall-Meshed Cavity Resonator-Based Wireless Power Transfer Without Blocking Wireless Communications With Outside World. *IEEE Trans. Ind. Electron.* **2022**, *69*, 7481.
- (37) Tamura, M.; Ide, A. Cavity-Resonance-Enabled Wireless Power Transfer System With Compensation for Frequency Fluctuations Caused by Equipment Installation and Its Operation. *IEEE J. Microw.* **2026**, *6*, 91–99.
- (38) Le, T.; Mayaram, K.; Fiez, T. Efficient Far-Field Radio Frequency Energy Harvesting for Passively Powered Sensor Networks. *IEEE J. Solid-State Circuits* **2008**, *43*, 1287–1302.
- (39) Stoopman, M.; Keyrouz, S.; Visser, H. J.; Philips, K.; Serdijn, W. A. Co-Design of a CMOS Rectifier and Small Loop Antenna for Highly Sensitive RF Energy Harvesters. *IEEE J. Solid-State Circuits* **2014**, *49*, 622–634.
- (40) Harada, S.; Kobayashi, Y.; Sawano, T.; Noguchi, E. Direct measurement of fluid force on a particle in liquid by telemetry system. *Int. J. Multiphase Flow* **2011**, *37*, 898–905.

- (41) Izadi, Y.; Beiranvand, R. A Comprehensive Review of Battery and Supercapacitor Cells Voltage-Equalizer Circuits. *IEEE Trans. Power Electron.* **2023**, *38*, 15671–15692.
- (42) Pozar, D. M. *Microwave Engineering*, 4ed.; John Wiley & Sons, Inc: Hoboken, NJ, 2012.
- (43) Liebe, H. J. An Updated Model for Millimeter Wave Propagation in Moist Air. *Radio Sci.* **1985**, *20*, 1069–1089.
- (44) Gutierrez-Cano, J. D.; Plaza-Gonzalez, P.; Canos, A. J.; Garcia-Banos, B.; Catala-Civera, J. M.; Penaranda-Foix, F. L. A New Stand-Alone Microwave Instrument for Measuring the Complex Permittivity of Materials at Microwave Frequencies. *IEEE Trans. Instrum. Meas.* **2020**, *69*, 3595–3605.
- (45) Dang, K.; Wei, K.; Hao, Y.; Zhang, J.; Zhou, H.; Huang, S.; Zhang, T.; Bian, Z.; Zhang, Y.; Wang, X.; Zhao, S. A 5.8-GHz High-Power and High-Efficiency Rectifier Circuit With Lateral GaN Schottky Diode for Wireless Power Transfer. *IEEE Trans. Power Electron.* **2020**, *35*, 2247–2252.
- (46) Dehghani, S.; Mirabbasi, S.; Johnson, T. A 5.8-GHz Bidirectional and Reconfigurable RF Energy Harvesting Circuit With Rectifier and Oscillator Modes. *IEEE Solid-State Circuits Lett.* **2018**, *1*, 66–69.
- (47) Mohamed, N.; Eltresy, N. A.; Elnaghi, B. E.; Magdy, A.; Abdallah, E. A. Wideband circularly polarized leaky wave rectenna. *Sci. Rep.* **2026**, *16*, 4119.
- (48) He, H.; Dan, Z.; He, Z.; Liu, C. Compact High-Efficiency All-Polarization Rectenna for Wireless Power Transmission. *IEEE Antenn. Wireless Propag. Lett.* **2025**, *24*, 706–710.
- (49) Deng, X.; Yang, P.; Chen, S.; Ren, W. Design of a 2.4 & 5.8 GHz Efficient Circularly Polarized Rectenna for Wireless Power Transfer Applications. *Electronics* **2023**, *12*, 2645.
- (50) Shi, Y.; Fan, Y.; Li, Y.; Yang, L.; Wang, M. An Efficient Broadband Slotted Rectenna for Wireless Power Transfer at LTE Band. *IEEE Trans. Antennas Propag.* **2019**, *67*, 814–822.
- (51) Reed, R.; Lohrabi Pour, F.; Ha, D. S. An efficient 2.4 GHz differential rectenna for radio frequency energy harvesting In *Proceedings of the IEEE 63rd International Midwest Symposium on Circuits and Systems (MWSCAS)*; Springfield, MA, USA, 2020; pp 208–212 .
- (52) Wang, S. C.; Li, M. J.; Tong, M. S. A High-Performance Rectenna for Wireless Power Transfer in CubeSats. *IEEE Antenn. Wireless Propag. Lett.* **2020**, *19*, 2197–2200.
- (53) Assimonis, S. D.; Fusco, V.; Georgiadis, A.; Samaras, T. Efficient and sensitive electrically small rectenna for ultra-low power RF energy harvesting. *Sci. Rep.* **2018**, *8*, 14642.
- (54) Pietsch, S.; Kieckhefen, P.; Heinrich, S.; Müller, M.; Schönherr, M.; Kleine Jäger, F. CFD-DEM modelling of circulation frequencies and residence times in a prismatic spouted bed. *Chem. Eng. Res. Des.* **2018**, *132*, 1105–1116.
- (55) Mathur, K. B.; Epstein, N. *Spouted Beds*; Academic Press: New York, 1974.
- (56) STTS22H | Product STMICROELECTRONICS Datasheet; Datasheet STTS22H | Product; STMICROELECTRONICS.
- (57) LSM6DSM | Product STMICROELECTRONICS Datasheet; Datasheet LSM6DSM | Product; STMICROELECTRONICS.
- (58) LPS22DF | Product STMICROELECTRONICS Datasheet; Datasheet LPS22DF | Product; STMICROELECTRONICS.

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