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Highly-Controlled Thermofluid Fields in Tandem Modulated Induction Thermal Plasmas for High-Rate Nanoparticle Synthesis

Yasunori Tanaka[1]

[1] Faculty of Electrical, Information and Communication Eng., Kanazawa University

e-mail: tanaka@ec.t.kanazawa-u.ac.jp

Nanoparticles exhibit distinctive size-dependent physical and chemical properties that render them indispensable in a broad spectrum of advanced applications, including electronics, energy systems, catalysis, and environmental technologies. The industrial realization of nanomaterials demands synthesis methods that deliver both high throughput and precise control over particle attributes. In our prior work, we introduced the pulse-modulated induction thermal plasma (PMITP) system in conjunction with time-controlled feedstock feeding (TCFF) [1–3], achieving high production rates for ion-doped TiO_2 and silicon nanoparticles. However, challenges remain in maintaining thermal plasma stability and achieving spatial control, particularly under conditions of high feedstock loading.

To overcome this issue, we developed an advanced technique—tandem modulated induction thermal plasma with time-controlled feedstock feeding (tandem-PMITP+TCFF) [4,5]. This configuration features two axially aligned induction coils encompassing a single plasma torch: the upper coil supplies steady electromagnetic heating, while the lower coil is driven with large-amplitude rectangular modulation. The TCFF scheme allows synchronized, intermittent feedstock feeding during the defined thermal modulation phases, thereby enhancing vaporization efficiency and nanoparticle formation control.

A salient advantage of the tandem-PMITP+TCFF system lies in its ability to manipulate the thermofluid field both spatially and temporally, facilitating the formation of customized vapor-phase and aerosol environments. Numerical simulations incorporating magnetohydrodynamic effects, energy transport, and particle kinetics indicate that the modulation waveform critically governs the cooling behavior of vaporized feedstock and the resulting nucleation dynamics. In addition, extensive optimization of the tandem-PMITP+TCFF method has been conducted, focusing on key operational parameters such as coil current amplitude ratios, modulation waveform duty factor, and feedstock injection timing, etc[6,7]. The system's flexibility offers high-resolution control over particle size distributions and synthesis rates under a wide range of plasma conditions. Simulation outputs demonstrate strong correlation with experimental results, validating the reliability and versatility of the tandem configuration.

Furthermore, we developed the tandem-AMITP+ TCFF system, which incorporates arbitrary waveform modulation for coil currents—including rectangular, sawtooth, and triangular forms. These waveform types enable even finer spatiotemporal regulation of thermal plasma conditions, which, in turn, influences the mean diameters of synthesized nanoparticles and nanowires. Numerical simulations corroborate the distinct effects of waveform shape: rectangular and sawtooth waveforms facilitate rapid cooling and vapor supersaturation, whereas triangular waveforms promote gradual thermal transitions conducive to particle growth via coagulation. Experimental validation using silicon feedstock confirms these insights. Specifically, sawtooth waveform modulation leads to rapid vapor quenching and yields nanoparticles predominantly under 100 nm, while triangular modulation fosters slower cooling, resulting in enhanced coagulation and the formation of larger particles. These trends are quantitatively substantiated through aerosol density assessments and particle size distribution analyses.

To exert greater control over downstream thermofluid behavior, we introduced a modified reactor design featuring multi-flange configurations along the inner reactor wall. These flanges adjust the entrainment gas flow entering the plasma jet. Computational simulations reveal that single- and double-flange geometries generate strong vortex structures, which enhance convective cooling and induce localized supersaturation critical for nucleation. Experimentally, the double-flange design significantly increases aerosol density and particle yield while simultaneously decreasing the mean particle size.

In summary, the tandem-MITP+TCFF system represents a robust and adaptable platform for high-rate nanoparticle synthesis with fine precision. By leveraging waveform engineering, spatiotemporal modulation of the thermal field, and downstream flow control, this methodology opens new frontiers in plasma-assisted nanomanufacturing and offers a scalable solution for the production of functionally tailored nanomaterials.

References

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