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High-Rate Production of Nanomaterials using Modulated Induction Thermal Plasmas and its Optimization by Machine Learning

Yasunori Tanaka[1]
[1] Faculty of Electrical, Information and Communication Eng., Kanazawa University
e-mail(speaker): tanaka@ec.t.kanazawa-u.ac.jp

Nanoparticles/nanopowders have garnered significant attention across various fields, including electronics, biomedical, energy, and environmental applications, owing to their unique physical and/or chemical properties. As the demand for these materials increases and their applications become more widespread, the development of efficient mass production methods has become crucial. In this regard, we have devised a novel approach for nanoparticle synthesis using a combination of pulse-modulated induction thermal plasma (PMITP) and time-controlled feeding of feedstock (TCFF), which we refer to as the "PMITP+TCFF method." The PMITP sustains a thermal plasma field through coil current modulation in a rectangular waveform, resulting in periodic variations between higher-temperature and lower-temperature plasma states. The TCFF complements this process by synchronously and intermittently supplying feedstock, further enhancing the synthesis efficiency [1]. At 20 kW power, the PMITP +TCFF method achieves exceptional production rates, yielding 400 g/h of Al^{3+}-doped TiO_2 nanopowder, 720 g/h of Fe^{3+}-doped TiO_2 nanopowder, and 180 g/h of Si nanoparticles/nanowires, among other examples [2,3].

Building on these advancements, the authors have further developed the "Tandem-MITP+TCFF method" to achieve even higher production rates for nanoparticles/nanomaterials [4]. The tandem-MITP involves two independent coils arranged in a single plasma torch to generate a long axial thermal plasma field. The upper coil ensures the robustness and stability of the thermal plasma, while the lower coil sustains a significantly modulated thermal plasma state. Utilizing this approach, we have successfully synthesized a large quantity of nanoparticles at production rates exceeding several hundred g/min in experimental settings [4].

The Tandem-MITP+TCFF approach demonstrates a promising avenue for the high-rate production of nanoparticles and nanomaterials. These innovations hold immense potential for meeting the escalating demand and promoting the widespread utilization of these materials in diverse applications. The efficient mass production of nanoparticles is a crucial step towards harnessing their full potential in shaping future technologies and addressing various global challenges.

However, in Tandem-MITP+TCFF method, there are a large number of parameters that should be controlled, and it is not easy to optimize them. On the other hand, the authors have developed a numerical thermofluid model for the thermal plasma field, the behavior of raw material particles including heating, melting, and evaporation, and nanoparticle production and transport in the Tandem-MITP + TCFF method [5]. Using this model, we have investigated the effects of the controlled parameters on nanoparticle production. We also studied the optimization of operating conditions for the main control parameters of nanoparticle production using the Tandem-MITP + TCFF method by applying a numerical fluid dynamics model and machine learning techniques. In this study, the sequential approximate multi-objective optimization method (SAMOO) with radial basis function-neural network (RBF-ANN) was used [6], and the modulation conditions that generate "a larger amount" of Si nanoparticles with smaller diameter with fewer trial calculations were examined [7]. In this study, the amplitude modulation of the upper and lower coil currents were both set to be square waves (PM) with a period of 15 ms, and the following nine control parameters were used as control parameters with limited ranges: upper input power time averaged 10-20 kW, duty ratio DF_{upper} of the upper coil current, modulation degree SCL_{upper}, and lower coil currents DF_{lower} and SCL_{lower} were set independently to 0-100%. The feedstock was fed intermittently, and the DF_{feed} of the feedstock feed was also varied from 0-100% with a delay phase time of t_{feed}^{delay}=0-15 ms. The downstream cooling gas (QG) was also introduced intermittently, with feed DF_{QG} = 0-100%, delay phase time t_{QG} = 0-15 ms, and flow rate QQG = 0-100 L/min.

One optimal condition obtained is as follows: $P_{upperin}$ =12 kW, SCL_{upper}= 99%, DF_{lower}= 72%, SCL_{lower}= 28%, DF_{feed}^{valve}= 43%, t_{feed}^{delay}= 6.5 ms, Q_{QG}=95 slpm, DF_{QG}^{valve}=61%, and t_{QG}^{delay}= 13 ms. The upper coil current is unmodulated, while the lower coil current is highly modulated, resulting in large fluctuations in the temperature and fluid fields. In this modulated plasma, the material is introduced into the hot thermal plasma by feeding the material in the latter half of the on-time period, and steady evaporation is obtained in accordance with the movement of the material. Efficient cooling is achieved by introducing cooling gas in cycles at the timing when the evaporated vapor reaches the downstream.

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