Electromagnetic Process Heating for Efficiency and Electrification

William Grieco ▪ **Paul Yelvington** ▪ RAPID Manufacturing Institute™

The reactor and process streams of almost all continuous-flow, heterogeneous catalyzed processes require heating or cooling. Catalytic packed-bed and fluidized-bed reactors typically use energy-intensive indirect heating via fuel combustion or conventional heating via conduction, convection, and radiation from hot fluegas. These approaches have limited efficiency due to inherently poor heat and mass transfer in the reactor.

Indirect heat transfer through surfaces, such as reactor walls and embedded tubes, suffers from scaling problems. At larger scales, the surface-to-volume ratio diminishes, making it difficult to maintain a uniform reactor temperature. Transported-bed reactors, which introduce heat by recirculating a heat carrier, have additional complexities related to disengaging, reheating, and reintroducing the carrier. Poor conduction across reactor cross-sections often produces temperature gradients that reduce volumetric reactivity, process selectivity, catalyst lifetime, and process stability.

Chemical engineering practices focus on increasing space velocity or lowering catalyst loading to mitigate poor heat and mass transfer. This yields energy and economic inefficiencies, including lower per-pass conversions and higher separation and recycle costs. These approaches also drive high capital intensities that typically favor large, centralized plants and limit the opportunities to use small, remote, or intermittent sources of raw materials and energy. Traditional fixed- and fluidized-bed approaches are historically proven and refined, but for the reasons discussed, they have limited potential for future improvement.

Selective heating is a new approach that could minimize wasted energy and dramatically change the energy and carbon footprints of industrial chemical processes.

Electromagnetic (EM) radiation is a process heating method that provides precise heating of heterogeneous catalysts and other reaction substrates for organic reactions or materials processing. Microwave and radio-frequency (RF) heating are two different types of energetic stimulation. Microwaves can be used to selectively heat dielectric catalysts or catalyst supports, and inductive RF heating can be used to heat conductive catalyst supports or reactor internals. Both offer precise control of reaction site temperatures and the opportunity to decouple reaction surface and bulk fluid temperatures. EM-enhanced thermocatalytic reactions promise significant advantages, including:

- precise volumetric heating, which proportionally scales up and down over a range of productivities, lowering barriers to process scale-up and reducing the associated capital risk for deploying new or updated process technologies
- quick on and off
- higher turndown ratios than traditional bulk heating approaches, allowing reactors to operate over a wider range of production capacities
- semi-independent control of temperature at reactive sites and in bulk process fluids, which can improve selectivity and conversion, minimize byproduct formation, and reduce catalyst fouling and degradation
- small footprints for modular distributed systems.

Microwave and RF reactors have historically been limited to lab-scale and pilot-scale systems. The first production-scale microwave-enhanced chemical plant was commissioned by Microwave Chemical Co., Ltd. (Osaka, Japan) to produce roughly 10 m.t./day of esters from waste. Nevertheless, significant challenges remain in the commercialization of EM-enhanced reaction systems, including:

- precise and robust local temperature measurement
- understanding of the design and selection of susceptors (*i.e.,* material that converts electromagnetic energy to heat) and multiscale EM reactor modeling
- design of EM hardware for continuous processes, rather than small-scale batch processes.

The RAPID Manufacturing Institute sponsors two projects that focus on solving these problems. Researchers at West Virginia Univ., in partnership with the Univ. of Pittsburgh, Shell, and the National Energy Technology Laboratory, are demonstrating the continuous lab-scale upgrading of natural gas to value-added aromatics. Experiments show higher conversions at lower bulk temperatures than in conventional thermal reactor systems. Similarly, researchers at the Univ. of Delaware, in collaboration with Raytheon and Rutgers Univ., are developing and testing reactor equipment along with modeling and simulation tools to better understand microwave-assisted reaction chemistry.

Not only can EM-enhanced thermocatalytic reactors be used alone to improve energy efficiency and yield, these process intensification (PI) platform technologies can also be used in load-following or hybrid modes when low-cost, renewable solar and wind assets are available to provide power. Given that EM energetics can be turned on and off quickly with limited transients and respond well to production turndowns, these technologies are well suited for intermittent solar and wind resources. EM-enhanced modular reactors could also serve as storage systems for time-shifting solar- and wind-generated electricity.

Modular EM reaction systems could be deployed to upgrade natural gas or valorize waste biomass near sources of raw materials. Additional research and development is needed for this vision of a partially electrified CPI to become a reality. CEP