Advanced materials processed with energy efficiency in mind

What's appropriate in development may be a detriment in full-scale production

By Tom Mroz and Robert Blackmon

Energy-efficiency considerations, when scaling advanced-materials processing, directly impact product commercial viability. During advanced-material development, process designs rarely focus on efficiency, however, but rather on the material's technical value. Energy efficiency is usually considered later, when product cost becomes a concern. These costs can equal 1/5 or more of unit cost. The initial process route developed can be in fact a hindrance to efficiency when scaling to industrial levels.

Further, in high-temperature processes (2000 to 3000 C), which are notorious energy wasters, high-temperature reaction generation involves a tremendous energy investment; containment of these energized states, and loss prevention from the reactor, is a constant battle.

A critical path to achieving energy efficiency presents itself when scaling production from thimbles to tons per year. But going from bench-scale process inception to large-scale production is challenging. The common research laboratory tends to use small-scale bench equipment, typically used in periodic or batch mode. Materials are processed at a scale easily handled by a few researchers. Time and energy required for the material process are not indicative of a mature, well-integrated production environment.

Often, a recipe conforms to constraints inherent to the development process, with resident times, ramp rates and hold times determined in inefficient batch-scale equipment. Decoupling a mature process from these recipe constraints, while maintaining desired characteristics, is an obstacle to achieving commercial production. Basic recipe inputs — time, temperature, ramp rate and interface velocities for gas-solid interactions — must often be redefined to facilitate continuous processing.

As such, scaling thermal processes is rarely a simple matter of linear extrapolation. At experimental scales, conversion rates of many solid-solid and solid-gas reactions are primarily a function of setpoint temperature, overall atmospheric chemistry and reactant size. In small test furnaces, temperatures track this control profile very well. If the sample load is relatively small, it also may track with this desired profile. At the same time, removing product gases and replenishing with fresh gas is simplified by the furnace's small internal volume and ratio of sample to furnace volume. Under these conditions, product uniformity is rarely a significant concern.

When scaling to larger loads, abilities to heat or cool the material mass and to introduce or remove gases from the solids play an increasingly important role in reaction efficiency. Often these become the primary variables controlling conversion rate, and therefore process throughput and efficiency. These variables create process limitations that extend total processing time and total energy use.

Therefore, energy-efficiency wise, batch processes are at a significant disadvantage. Requirements to heat and then cool product loads, reaction containers, structural components and refractories are especially inefficient. For higher temperatures and faster heating and cooling rates, equipment also may be water cooled, improving equipment functionality, but decreasing energy efficiency.

Efficient thermal processes apply heating and cooling to the most minimal load possible. In an ideal situation, this means processing reactants continuously, without need for material containment. Material boats or component trays transported on a carrier or car — such as a pusher, roller hearth or mesh belt conveyor — allow for significant material production, but ancillary material must also go through the temperature cycle. In some cases, material containers move through the furnace on rails or by other means. This eliminates temperature treatment of support materials and is more efficient.

With a wide variety of design and construction material options available for conveyance furnaces, the most efficient designs recover heat or re-circulate hot containers within the furnace heating zone, restricting heating and cooling requirements almost exclusively to the process material. In more advanced designs, opportunities for recovering heat from product carriers can minimize system efficiency impact. In some cases, it's even possible to engineer material flows so that exiting material is directly cooled by association with cool, incoming reactants, which are concurrently preheated. This is not common and can be difficult to achieve.

To gain even more energy efficiency, eliminating containerized material conveyance is a must. The most obvious way to do this is a rotary furnace. As the reactant bed moves through the tube, it is constantly stirred by tube rotation. Stirring action enhances thermal transfer to the bed, improves product gas removal and increases solid/gas exchange when furnace gas is also a reactant. Given these enhancements, product material often exhibits improved uniformity compared to static bed-processed materials. Additionally, because only reactant powder is heated and cooled, thermal efficiency is significantly improved.

Vertical furnaces offer a reasonable alternative to rotary-tube furnaces when material movement in a rotary furnace is unsatisfactory, or where other features — such as very short or long lead times, significant interaction with reaction atmospheres or completely contact-free reactions — are required. Energy use is primarily related to product heating and supporting necessary reactions. Interaction with furnace walls is minimal. This type furnace can be invaluable in combination processes, such as for spray pyrolysis coupled with calcining.

Unfortunately, many thermal processes involve powders or aggregated mixtures, and therefore require containers or constructs for material transport.

Achieving improved energy efficiency in bulk materials processing is still in its early stages. However, Harper has demonstrated equipment designs that deliver benefits for select processes. It continues to examine additional opportunities to expand this concept to a wider range of materials.

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