Fluidized Bed Scale Up for Sustainability Challenges

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Highlights

- Fluidized beds remain at the forefront of the present time-critical sustainability challenges.
- Reviews how scale-up tools have evolved over the years and the promising new tools.
- Addresses some of the barriers of these tools in the design and scale-up of fluidized beds.
- Discusses what can be done to circumvent these barriers to accelerate today's scale-up efforts.

1. Introduction

The persistent interest today in using the fluidized bed to tackle time-critical sustainability challenges (e.g., carbon capture by particulate sorbents, methane-to-hydrogen, plastic-to-chemicals, etc.) is not surprising, considering the proven efficacy of such unit operations over 100 years in wide-ranging applications.

With today's urgent climate-change-related processes and the need for sustainability and circularity, expediting the commercialization of these new concepts is all the more critical. Carbon-zero goals have been set for as soon as 2025, so the timeline is akin to the same urgency during World War II that drove the operation of 35 commercial fluidized catalyst cracking unit (FCCU) within five years from conception [1]. We need to move faster without compromising today's and tomorrow's energy conservation, safety, waste reduction, and emissions reduction objectives.

2. Discussion

Historical Tools (< 1990)

The scale-up of this era is driven by expensive (time-wise and cost-wise) experiments. It was highlighted in 1985 that, although the oil and chemical industries have successfully transformed chemistry concepts into commercial technology and products, chemical plants processing solids have been underperforming with respect to that designed for the past two decades [2]. This deficiency was attributed to the focus of industrial research and development (R&D) on chemistry rather than physics. In particular, the lack of focus on fluidization hydrodynamics significantly diminished the scale-up ratio at each step [1]. Specifically, when plug-flow reactors (PFRs) and continuous stirred tank reactors (CSTRs) scaled at 1,000 – 10,000 times, fluid catalytic cracking (FCC) reactors and fluid coking scaled at roughly 20-150 and 40 times, respectively, from pilot- to commercial scales in 1940 - 1950s. At that point, no multiphase reactor model is adequate to either enhance existing units or scale up new ones, which is tied to the poor understanding of the macro-scale structures that impact inter-phase contact, and thus unsurety of heat and mass transfer, and pressure and temperature effects [3].

Yesterday's Tools (1990 - 2005)

Towards improving predictive capability, this era brought about efforts directed at first-principles understanding underpinning the governing equations that describe the various fluidization phenomena, particularly with respect to bridging the microscale phenomena to the macroscale challenges in practical applications. The overarching goal has been to achieve a fully specified model that runs efficiently. As an example, the convention was homogeneous grids, which may not be as accurate. Specifically, each set of equations describes a grid whose size is chosen based on the resolution targeted. It is now well-known that sub-grids can be used to resolve small meso-scale structures (i.e., bubbles and clusters), which are constantly evolving. However, sub-grid models were not available yet in 2000 [3], and thus, smaller grids have to be used throughout the system to factor in the smaller structures. Coupled with energy and species balances, the magnitude of the task is not trivial and thus not commonly carried out back then.

Today's Tools (2005 - 2020)
As models improved and confidence in model predictions grew, the possibility of quickening the scale-up of fluidized bed processes became a reality. The general embracing of commercial software by around 2005 was due to significant improvements to hardware that made possible simulations of commercial units for the simulations of commercial fluidized bed reactors.
Commercial codes have been shown to be accurate within the confines of the code's capabilities. Indeed, both well-established engineering companies [4, 5] as well as start-ups [6] have embraced such commercial tools. It should be noted that these codes are limited when other factors such as shape, interparticle forces, agglomeration, clustering, attrition, and particle growth or shrinkage come into play. Capturing these effects requires adaptations to the constitutive equations involving the drag and the collisional stresses, along with numerical operations with spatial (and temporal) resolution.

Tomorrow's Tools (> 2020)
Tomorrow's tools for scale-up will rely heavily on artificial intelligence (AI). As artificial intelligence (especially machine learning and deep learning) proliferates in nearly all disciplines of science and technology, AI is expected to lead significant changes of the research and development of gas-solid fluidization, specifically in data analysis, generative equipment design, flow sheet synthesis, modeling, and even risk analysis.

4. Conclusions

The scaling up fluidized beds has been purposefully pursued for more than 100 years. Yet, over that time, scale-up tools have not significantly changed.

With today's urgent climate-neutral processes and the need to speedily move to sustainable resources, expediting the commercialization of these fluidized beds is all the more crucial. Given a century of commercial fluidized beds, tools that mitigate risk and accelerate development are inevitably available. The problem is that such tools are often neglected, inadequately implemented, ineffectively resourced and/or poorly understood. This effort addresses some of the barriers of these tools in the design and scale-up of fluidized beds, as well as what can be done to circumvent these barriers.

References

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Keywords
fluidization; scale-up; sustainability; data-driven model