SYSTEMS ASPECTS OF GHG MITIGATION: OPPORTUNITIES AND CHALLENGES

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INTRODUCTION

Carbon capture and storage (CCS) technologies are an essential component of the lowest cost pathways for limiting atmospheric CO_2 equivalent concentrations to 450 ppm.[1] There are three approaches to carbon capture: post-combustion capture, pre-combustion capture, and oxycombustion. All three approaches are technically viable, but the cost and energy penalties are currently high. To overcome these challenges requires the simultaneous, integrated development and optimization of transformational new technologies, materials and processes.[2] Process integration (PI) will be an essential part of such an approach for cost effectively reducing GHG emissions associated with the use of fossil energy in the power and industrial sectors.

POST-COMBUSTION CARBON CAPTURE

Post-combustion carbon capture (PCC) separates CO_2 from flue gas after combustion. Thus, this approach is applicable to the majority of power plants as well as industrial sources. A particular challenge is that the CO_2 in the flue gas stream is present at relatively low concentrations of 10-15%. A number of technologies are being developed for PCC, including thermal swing approaches using both solvents and solid sorbents. Since PCC is considered an add-on technology, heat integration is typically limited to the capture process itself, with a “crossflow heat exchanger” a central component of most solvent and sorbent systems. Many innovative approaches have been developed to reduce the overall energy penalty within a carbon capture process[3]; however, these narrow system boundaries limit the opportunities for process integration, which could result in improved efficiency.

Chen et al.[4] recently demonstrated the improvements possible when simultaneously considering process optimization and integration of a PCC system with a supercritical pulverized coal power plant. Four subsystems were considered: the boiler, steam cycle, carbon capture system and compression system. Steam for the capture process is obtained from the steam cycle; thus, heat integration results in higher net power efficiency. The net efficiency of the base power plant is 42.1% without CCS. Adding an optimized CCS system with no heat integration other than a crossflow heat exchanger between the adsorber and regeneration, the net efficiency drops to 31.0%. Heat integrating the resulting process across all four subsystems increases the efficiency to 32.7%; however, simultaneously optimizing the CCS system while performing process integration results in a net efficiency of 35.7%. In all cases, the target CO_2 removal ratio of 90% is satisfied. Net efficiency is among the most significant contributors to the ultimate cost of CCS, demonstrating the value of process integration across broad system boundaries while simultaneously optimizing the design of the CCS system. In this example, optimizing process parameters while simultaneously performing heat integration, enabled higher temperature differences between hot and cold streams resulting in smaller heat exchanger area requirements due to the larger heat transfer driving force even though the total heat recovery was increased.

PRE-COMBUSTION CARBON CAPTURE

Pre-combustion capture is applicable to integrated gasification combined cycle (IGCC) power systems, which also have the potential to manufacture other high-value energy commodities, including transportation fuels and petrochemicals. In this approach, the fuel is converted to a mixture of CO_2 and hydrogen via a water-gas shift reaction. Compared with PCC, the CO_2 is as higher pressure and concentration, reducing the energy required for the separation. Such processes are significantly more complex, increasing the opportunities for process integration, especially in hybrid polygeneration systems which produce electricity, fuels, and chemicals.[5]

OXYCOMBUSTION

Another approach is to separate the oxygen from nitrogen before combustion, resulting in a relatively pure stream of CO_2. The traditional approach is oxycombustion in which an air separation unit (ASU) is employed to create a pure oxygen stream. An oxycombustion power plant consists of five key subsystems: ASU, boiler, steam cycle, pollution controls and CO_2 polishing unit (CPU). Many researchers have identified approaches to increase efficiency and reduce costs of oxycombustion by heat integrating parts of the overall process and considering alternate ASU configurations. For example Fu et al. recently optimized just the compression train of the ASU while heat integrating with the steam cycle resulting in absolute efficiency improvements of 0.5–0.6% points.[6] However, to fully optimize and simultaneously integrate the entire oxycombustion process will require an equation-based optimization framework that uses detailed models.[7] Such a framework has been reported and preliminary results indicate substantial opportunities to balance trade-offs between subsystems, optimize oxygen purity and more effectively utilize waste heat by adjusting pressure ratios and temperatures in the steam cycle and compression systems. For example, using this framework, an energy-efficient ASU-CPU integrated system was recently proposed that reduces power consumption by 15% over a previously optimized ASU-CPU design, resulting in an absolute efficiency improvement of 1.3%.[8]

CHALLENGES AND FUTURE POTENTIAL

Applying PI in conjunction with GHG mitigation technologies will be essential for reducing the energy penalty, especially as more advanced energy conversion technology gets deployed and consideration of CCS expands beyond power production. The potential of PI's impact is directly proportional to the size of the system available for integration. Thus, as CCS technologies are applied to more complex systems, the potential for PI to play a significant role will increase. This may be most apparent in polygeneration systems or industrial systems in which the CCS technology can be integrated with other processes.

A significant challenge will be overcoming the barriers between technology developers to enable such integration possible. Different vendors are likely to provide different parts of the overall system (such as boiler, ASU and CCS technologies) making integration more challenging. Another challenge will be operational flexibility, which can be addressed by incorporating flexibility criteria during simultaneous process optimization and integration. While all these challenges can be overcome, they will require a concerted effort to develop the computational tools to show the potential savings and to address the technical barriers. The U.S. refining industry, which has long embraced PI, provides inspiration for the long term potential of PI to improve the efficiency of GHG mitigation technologies: it has a 50% lower fraction of "lost" process heat compared to the average across all U.S. manufacturing industries.[9] A similar reduction for integrated CCS technologies would significantly reduce the barriers to their widespread deployment.

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