Automation technology for lower carbon capture costs

The high cost of carbon capture as a result of relatively limited energy efficiency presents challenges for its widespread adoption by the cement industry. Advanced automation can improve the energy efficiency of carbon capture, increasing its viability within cement production.

■ by **Seth Harris**, Emerson, USA, and **Gerardo Muñoz**, AspenTech, USA

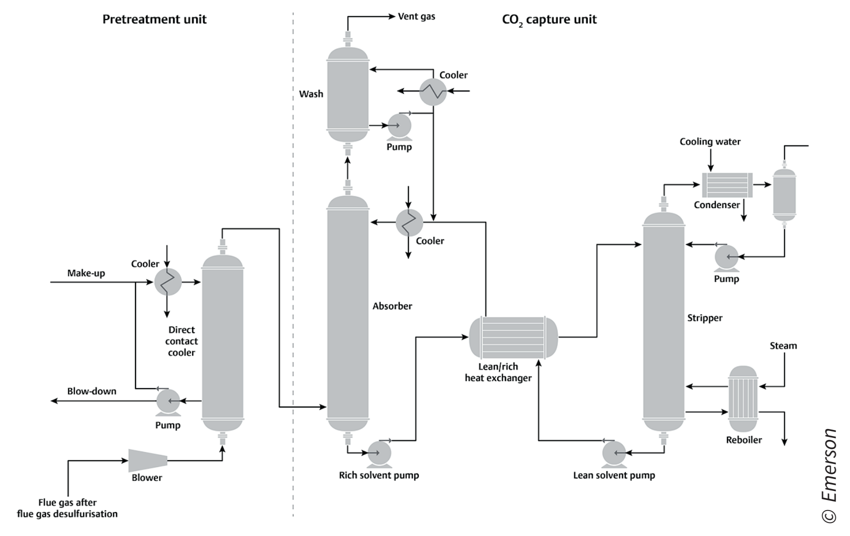
Carbon capture is a vital technology to reduce the carbon footprint of the hard-to-abate cement industry. A significant share, up to 70 per cent, of CO_2 emissions in this sector arises from the chemical process of calcining calcium carbonate, a process challenging to address through conventional methods. Adoption by leading companies, ongoing capex investment and long-term growth projections all point to the viability of carbon capture and storage (CCS) technology at a commercial scale. In the cement sector, this includes implementing technologies that improve production efficiency by feeding CO_2 back into the kiln, utilising carbon mineralisation methods to facilitate the injection of captured CO_2 into fresh concrete and using CO_2 to reduce the limestone ratio, which helps to lower processing and energy consumption.

Solving key challenges

To drive meaningful change, widespread adoption of CO_2 capture and utilisation at cement plants is imperative. However, there are still several key challenges that must be addressed. First among these is lowering the operational costs involved, especially those associated with the energy-intensive capture process. The most common capture method is through absorption, which involves a solvent such as monoethanolamide that binds to CO_2 from flue gas. While the solvent remains in a liquid state, the subsequent release and vaporisation of CO_2 is achieved through heating.

An alternative method, pressure swing adsorption, exposes the solvent to lower pressure, causing dissolved CO_2 to separate and recharge the solvent, generating a high-purity CO_2 stream.

Carbon capture through absorption involves a solvent binding to CO_2 from flue gas. While the solvent remains in a liquid state, the subsequent release and vaporisation of CO_2 is achieved through heating



© Emerson

Chemical reactions involved in absorption and solvent regeneration require large amounts of energy from reboilers and fired heaters. The collection, cooling and pre-treatment of flue gas also demands a significant amount of energy. According to the International Energy Agency (IEA), most carbon capture processes today consume anywhere between 10-40 per cent of the energy generated for the entire production process. This ratio, called the energy penalty, determines the efficiency of a given carbon capture system.

The energy penalty, quantified as the cost per tonne of captured CO_2, depends on a number of factors, including: the capture rate, capture method (amine absorption, adsorption, membrane, etc), filtration media efficiency, energy source used for filtration media regeneration (eg, natural gas boiler, waste heat, coal-fired power, renewables), and the concentration of the CO_2 in the collected flue gas. Across different industry sectors the cost ranges between US$15-120/t of captured carbon, depending on the emissions source, according to the IEA.

Regulatory factors and carbon costs on the open market further influence the energy penalty, with Canada and the EU taxing emitted tonnes at a certain rate, ultimately driving investment. The USA has implemented incentive systems based on tax credits to support industries with emissions, such as cement production, with the common goal of maximising CO_2 concentration while minimising energy use.

Streamlining engineering and process design

It is important that the industry continues to improve the performance of current capture methods, develops more energy efficient capture technologies and uses renewable sources to power capture systems. Operational efficiency gains begin with design considerations, where engineers strategically select materials, operating conditions, process configurations, and equipment to establish cost integrity, ensuring project feasibility and maximising return on investment. Flaws or inadequate equipment selection during this phase can result in inefficiencies and permanent energy losses. Simultaneously, efforts to improve heat integration, reduce pressure drop, and enhance heat recovery contribute significantly to lowering a facility's energy, capital, and operating costs.

Advanced performance engineering software

Advanced performance engineering software plays a pivotal role in evaluating the economic feasibility of proposed capture processes well before implementation. These tools, equipped with comprehensive property databanks and algorithms accurately model complex chemical and thermodynamic systems, enable engineers to predict reliability issues, identify inefficiencies, estimate energy requirements, assess risk and proactively address problems.

Adjusting variables such as solvent type, concentration, temperature, pressure and flow conditions can significantly reduce energy requirements. For instance, proper design considerations for amine regeneration applied to coal combustion flue gas can improve efficiency from 5.5 to 3.0GJ/t of CO_2 captured for advanced amines, translating to reduced steam costs and a lower energy penalty.

Digital twin technology

While engineering models are beneficial in the early stages, digital twin technology allows engineers to further streamline the design and operation of capture systems by leveraging analytical computer models to improve energy efficiency and reduce costs, both before and after a system is brought online. A digital twin, a software-based virtual replica of assets, simulates the operation of a system, predicts maintenance requirements, and identifies areas for improvement. Carbon capture digital twins can simulate gas and liquid stream flow through the capture system, allowing engineers to identify optimal conditions for capturing CO_2 with minimal energy consumption and obtain guidance for optimal operations as flue gas compositions change with the use of different fuels in the kiln. Digital twin technology also facilitates real-time monitoring and performance comparison, enabling quick detection of deviations or abnormalities indicating energy waste. Beyond design and simulation, digital twin simulation proves invaluable for training personnel, offering a better understanding of system operation and optimisation under various conditions. This is particularly crucial for the safe start-up of new CCS units.

Increasing efficiency of heat transfer

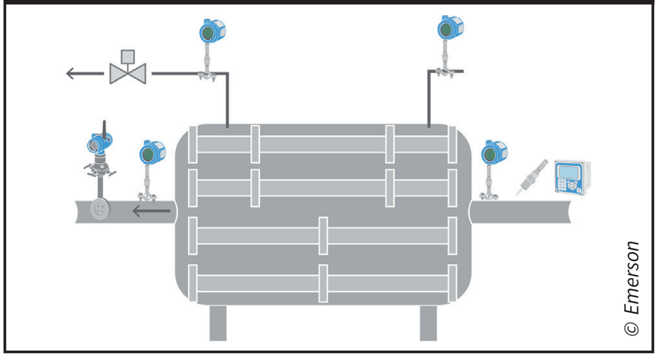
Efficient heat generation and transfer equipment are central to the cost integrity of any facility engaged in carbon capture. Boilers, pumps, compressors, cooler units and heat exchangers play a vital role in transferring heat between hot flue gas and cool solvent or other filtration media, facilitating chemical reactions in the capture process. Plate-and-frame heat exchangers, comprising thin plates stacked and separated by gaskets, are among the most efficient designs, often achieving efficiency levels of 90 per cent. Shell-and-tube heat exchangers, consisting of tubes within a larger shell, are also common. Both designs optimise thermal energy transfer by directing solvent and flue gas along the correct paths at optimal flow rates.

However, heat exchangers are susceptible to fouling, corrosion and other maintenance issues that can impact efficiency. Impurities such as ash and solid particulates in flue gas can persistently foul heat exchanger tubing, reducing available area for heat transfer and necessitating more energy for media regeneration. CO_2, when combined with water or other contaminants, is corrosive, further degrading exchanger steel surfaces. The efficiency of a heat exchanger depends on various factors, including the opening temperature of the heat pipe, fluid flow rate, tube angles and spacing. Mismanagement of these factors can lead to wasted energy, increased maintenance costs, and heightened safety risks.

Continuous monitoring and management of heat transfer equipment are crucial for minimising the energy penalty of a capture system. In the past, traditional wired instrumentation faced limitations, especially in physically remote settings. However, advancements in wireless technology have made it reliable and cost-effective. High-accuracy sensors, deployed using wireless technology, can improve data collection for heat transfer optimisation. Real-time measurement of differential pressure, flow, and temperature using a single self-diagnostic wireless device further enhances accuracy.

While aggregating more data on heat exchanger performance and steam generation is valuable, translating this information into operational decisions is crucial. Integration of smart field devices and wireless networking, coupled with pre-configured analytical software, allows assigning an overall performance rating for each unit. When deviations from baseline occur, the software alerts operators to assets needing attention before negatively

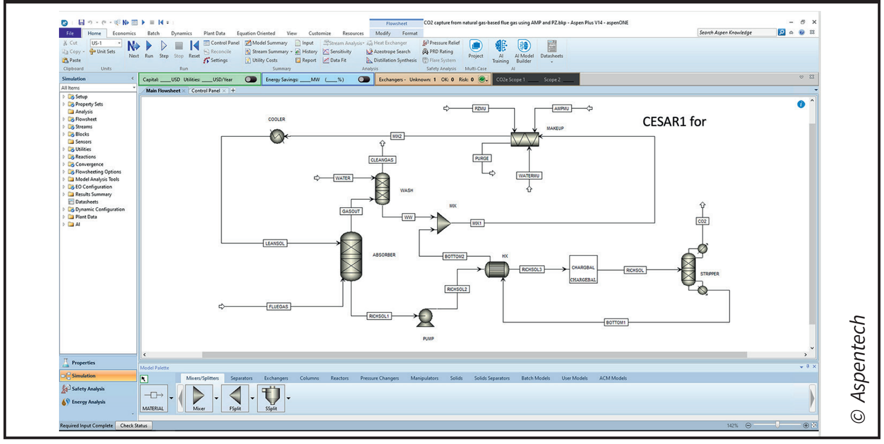
Wireless measurement devices help improve management of heat transfer equipment, crucial for minimising the energy penalty of a capture system


© Emerson

Continuous gas analysis provides real-time data on chemical composition and CO_2 concentration, enabling heat used for solvent regeneration to be regulated


© Emerson

AspenTech's process simulation software, Aspen Plus®, plays an important role during technical and economic feasibility of carbon capture processes for hard-to-abate industries like the cement industry



© Aspentech

impacting energy costs.

Optimising performance extends beyond heat exchangers to boilers, pumps, compressors, and critical equipment. Advanced adaptive process control software enhances capture system efficiency across multiple variables by allowing equipment to run closer to operational and safety constraints, minimising energy use. Variable frequency drive motors enable precise control of rotating assets, while energy management information systems consolidate energy performance across many complex assets enabling operators to prioritise activities for the biggest impact. Pre-configured analytical software tailored for multi-fuel boilers using off gases, waste fuels and biomass further reduces a system's carbon footprint while increasing steam production capacity and stability.

Balancing capture rate vs energy use

The objective of all carbon capture units is to isolate as much pure CO_2 as possible with the least energy consumption. Achieving the ideal balance between capture rate and energy cost is where automation holds significant potential. A comprehensive evaluation of factors and a systematic, multi-dimensional approach is required. Rigorous process simulation techniques play a crucial role, aiding operators in understanding the behaviour and performance of their capture system.

Analytical models, utilising physics and chemistry correlations, accurately predict interactions between different components in the CO_2 absorption or adsorption process and solvent regeneration process, along with resulting energy requirements. By simulating different operational scenarios and parameters, the impact of varying capture rates on energy consumption and vice versa can be assessed without real-world experimentation. Techno-economic analysis evaluates the viability of a proposed capture system and its integration with the production facility, by assessing risks, estimating capital and operational costs, including energy consumption and evaluating potential revenue streams from utilisation of captured CO_2.

Process simulation, examining regeneration temperatures, pressures, chemical compositions and other variables can minimise energy requirements while maintaining a satisfactory capture rate. Techniques like design of experiments, sensitivity analysis and numerical optimisation algorithms find optimal operating conditions that vary depending on application scale, geographical location and policy incentives. Site-specific evaluations, considering industry-specific factors, help tailor capture systems to meet specific needs and objectives.

Integrated control systems are pivotal for managing capture rates and energy consumption in carbon capture systems. By continuously monitoring operating conditions, performance metrics and relevant parameters, such as temperature, pressure, flow rate, and composition, control systems optimise the capture process in real time. They regulate parameters such as adsorbent bed temperature, adsorption pressure, or solvent flow rate to ensure the CO_2 capture rate remains within the desired range. This control scheme helps maintain high capture efficiency, minimise energy consumption, and optimise system performance. Real-time optimisation ensures energy-intensive steps occur under the most efficient conditions.

When the carbon capture system is integrated with the existing production process, this requires coordination with the rest of the facility. Advanced process control (APC) software facilitates this integration, optimising energy usage and load distribution, ensuring efficient resource utilisation and maximising overall system efficiency. The value of APC extends to new facilities, particularly within the adsorber/absorber unit, leveraging advanced machine learning algorithms to optimise performance.

Advanced measurement technology such as density meters and gas analysers can also contribute significantly to maintaining the ideal capture-to-energy balance. Density meters provide crucial information about capturing agent concentration, aiding in controlling solvent regeneration and optimising energy consumption. Continuous gas analysers offer real-time data on chemical composition and CO_2 concentration, enabling the control system to regulate heat used for solvent regeneration. These analysers simplify regulatory reporting, aiding operators in making better operational decisions and achieving the desired capture-energy balance. Monitoring the chemical composition of complex fluids, density meters, and gas analysers play a vital role in troubleshooting, throughput and safety. Analysing historical data and patterns helps operators identify new opportunities for efficiency, develop better predictive models, and recommend operational adjustments. This data-driven optimisation approach continuously improves capture rates and energy consumption, enhancing the economic viability of carbon capture systems.

Conclusion

Automation, advanced engineering tools, and innovative process design are integral to overcoming challenges and achieving cost-effective carbon capture in the cement industry. Streamlining engineering and process design, enhancing heat transfer efficiency, and balancing capture rates with energy use are key strategies. By harnessing digital twin technology, wireless sensors, and advanced process control, the cement industry can significantly reduce the energy penalty associated with carbon capture, contributing to a more sustainable and environmentally friendly future. ■