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Low-Temperature Desorption: The Next Generation in Amine-based CO_2 Capture Technology

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Post-combustion CO_2 capture technology is currently one of the most mature and adaptable decarbonization technology for existing fossil fuel emission sources. Amine-based chemical absorption has been recognized as one of the most promising processes supporting the large-scale industrial demonstrations due to its advantages such as fast absorption rate, high CO_2 selectivity, and suitability for flue gas under low partial pressure conditions. However, it has been constrained by issues like high regeneration energy consumption and temperature, severe absorbent degradation, or high viscosity which significantly increase the carbon capture operating costs and limit the large-scale promotion. In recent years, academia and industry have conducted extensive research focusing on key areas such as absorbent iteration and energy integration, aiming at the goal of low-energy consumption and low-cost CO_2 capture. Although phased breakthrough has been realized including the development of dual-phase absorbents, water-lean absorbents, the long-term operational performance of absorbents developed in laboratories and the results of large-scale demonstrations still need to be tested for practical industry applications. Based on existing research results, we systematically reviewed the iterative path of absorbent development in terms of energy consumption, analyzed the diverse advantages of low-temperature desorption processes, and clarifies other technical issues beyond energy consumption for technology implementation, providing a reference for subsequent industrial development.

ITERATIONS OF CHEMICAL ABSORBENTS

Chemical absorbents have undergone three generations of iterative upgrades, continuously focusing on reducing energy consumption, controlling volatility, and stabilizing cycles to optimize performance.[1] The first generation of single-component absorbents includes organic amines, carbonates, ammonia, and amino acid salt systems. These absorbents are mature and widely adaptable, but they have problems including high regeneration energy consumption, strong volatility, and easy oxidation and degradation. The regeneration energy consumption remains at 3.0-4.0 GJ/t CO_2, and they are unable to simultaneously achieve high-efficiency CO_2 capture and low energy consumption operation, resulting in relatively poor overall economic performance.

The second-generation hybrid amine absorbent achieves an initial balance between performance and energy consumption by modifying a mix of highly active primary amine and low regeneration heat tertiary amines, reducing regeneration consumption to 2.5-3.5 GJ/t CO_2 and effectively improving the performance shortcomings of single absorbents. It is also the most widely used system in current industrial demonstrations. However, this system still primarily uses water as the main component, which results in high latent heat loss due to evaporation, abrupt changes in solution viscosity, and volatility of components, leaving very limited room for further reduction in energy consumption.

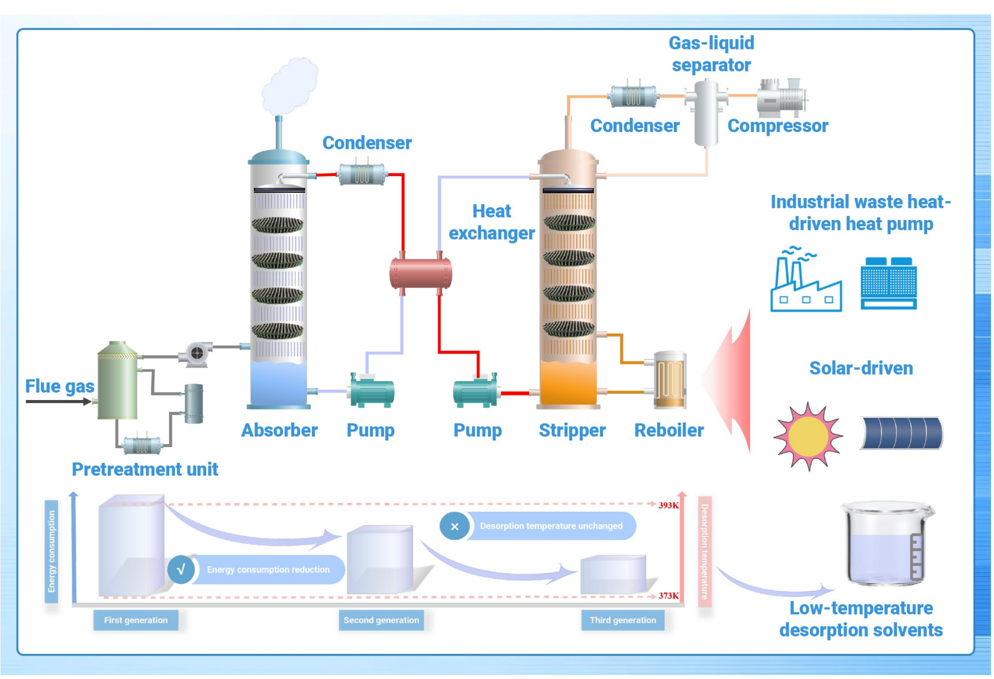

Figure 1. Iterations of absorbents and prospects

The third-generation low-water absorption agents include new systems such as amino biphasic, homogeneous low-water solvents, and ionic liquids. Relying on organic solvents to replace water and phase-splitting regeneration mechanisms, they significantly reduce solvent evaporation losses, effectively suppress volatilization, and can lower regeneration energy consumption to below 2.5 GJ/t.

However, these absorbers generally face issues such as viscosity exceeding 100 mPa·s after absorption, hindered mass transfer, and complex degradation pathways, making large-scale application difficult.[2] Overall, the iteration of third-generation absorbers has achieved significant optimization in energy consumption and volatility, but it has still not solved the multi-feature coordination challenge of high loading, low energy consumption, low viscosity, and low degradation. Additionally, the overall desorption temperature is relatively high, and there is still a considerable gap from stable large-scale industrial application.

ADVANTAGES OF LOW-TEMPERATURE DESORPTION

Although energy consumption has been significantly reduced after multiple generations of absorber improvements, the regeneration temperature of the absorbent remains around 110-130 °C. Reducing the solvent water content can decrease the consumption of latent heat of evaporation, but it also leads to increased viscosity and weakens the mass transfer performance of the absorbent. If the regeneration temperature can be lowered below 100 °C while maintaining high regeneration efficiency, it would be possible to avoid water evaporation, prevent latent heat consumption, and resolve the high viscosity issue of third-generation low-water absorbents, achieving both low energy consumption and high mass transfer performance. It will offer advantages with renewable heat integration including solar energy without concentration, waste heat-driven heat pump (shown in Figure 1).

In terms of system integration advantages, low-temperature regeneration conditions can adapt to low-grade heat sources commonly found in power plants and the chemical industry, such as industrial waste heat and low-temperature solar energy, replacing the traditional high-cost, high-energy-consumption high-pressure steam heating mode and significantly reducing the external high-grade energy input to the system.[3,4] In typical power plant decarbonization scenarios, when the regeneration temperature is 120 °C, steam needs to be extracted from the intermediate stage of the turbine. However, the superheated steam does not match the regeneration temperature, requiring throttling and cooling before supplying heat to regenerate the absorbent, resulting in additional capture energy consumption. When the regeneration temperature is reduced to 90 °C, it can better match other extraction points, and the lower regeneration energy consumption can reduce the steam extraction, thereby mitigating efficiency losses caused by the turbine operating off its rated condition. For non-power decarbonization scenarios, due to the lack of sufficient industrial waste heat to meet decarbonization demands, additional gas boilers or solar thermal collection are needed to meet the energy demands of high-temperature regeneration. However, when the regeneration temperature is reduced to below 90 °C or even lower, heating can be combined with a heat pump; low-temperature heat pumps often have higher COPs, and when utilizing solar heating, additional concentrating equipment can be avoided. Therefore, the development of low-temperature regenerated absorbents facilitates the deep integration of carbon capture devices with existing industrial production systems, adapts to retrofit scenarios of existing industrial equipment, and, by combining industrial waste heat and renewable solar energy, achieves cascade utilization of system heat, significantly enhancing the flexibility and universality of technology implementation.

In terms of absorbent protection and lifespan advantages, prolonged high-temperature operation can cause thermal degradation of the absorbent, leading to deterioration of capture performance. Under conventional high-temperature regeneration conditions, amine-based absorbents are prone to thermal and oxidative degradation and combined with the erosion from impurities such as SO_2 and NO_x in flue gas, this results in continuous loss of active components of the absorbent and decline in capture performance. Meanwhile, degradation products can exacerbate equipment corrosion. Low-temperature regeneration conditions can effectively suppress high-temperature side reactions of absorbent decomposition, reduce the rate of oxidative degradation, greatly improve the cyclic stability and service life of the absorbent, reduce costs for solvent replenishment, chemical replacement, and equipment anti-corrosion operation and maintenance, and ensure the long-term stable operation of the carbon capture system.

PROSPECTS AND RECOMMENDATIONS FOR FUTURE DEVELOPMENT

The traditional research paradigm for absorbents relies on experience, developing through testing and screening, which makes it difficult to break out of the dilemma of trade-offs among multiple performance indicators. In the future, an intelligent-driven research paradigm should be explored, constructing a multidimensional database covering molecular descriptors, thermodynamic parameters, viscosity, and degradation performance, and then training surrogate models that can predict reaction enthalpy, absorption capacity, and thermal stability. Combined with multi-objective optimization algorithms, this would enable the automatic search for optimal molecules in the high dimensional space of high load, low energy consumption, low viscosity, and low degradation.

When the desorption temperature drops below 100 °C, industrial low-grade heat sources such as power plant condenser circulating water residual heat, low-temperature waste heat from chemical processes, sensible heat from steelmaking slag, and low-temperature flue gas from cement kiln tails, as well as renewable energies such as solar heat and geothermal energy, can all become the main heat sources for regeneration. By constructing a plant-wide energy cascade optimization model with heat-electricity-carbon linkage, it is possible to achieve the temporal matching and complementary scheduling of multi-grade heat sources; designing a heat storage buffer system to smooth the intermittency of renewable energy and the fluctuations of industrial waste heat, ensuring continuous and stable operation of carbon capture devices under all operating conditions. On this basis, by embedding deep reinforcement learning algorithms, the absorbent circulation flow, heat pump compressor load, and desorption temperature setpoints can be dynamically optimized under multivariable conditions such as flue gas flow fluctuations, changes in waste heat supply, and electricity price peaks and valleys, ensuring that the system always operates at the optimal balance point of energy efficiency and carbon emissions throughout the full operational life cycle.

Performance evaluation under laboratory conditions is often based on idealized flue gas composition and steady-state operating parameters, making it difficult to reflect the complexity of industrial sites. In the future, it is necessary to establish pilot and demonstration units on typical emission sources such as coal-fired power plants, cement kilns, and steel mills, and carry out long-term continuous operation tests. During long-term testing, attentions can be focused on the decay curve of absorbent capacity and accumulation rules of degradation products, the activity retention rate and composition evolution of absorbents, and stability under variable loads. For the absorbent, it is necessary to develop real-time monitoring technology for degradation products based on online spectroscopy or electrochemical sensors, matched with bypass purification modules such as electrodialysis and ion exchange, to achieve continuous regeneration without stopping the operation, maintaining the active component concentration always within the process window.

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DECLARATION OF INTERESTS

The authors declare no competing interests.