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TECHNICAL ARTICLE

Research on the Application of Hollow Fiber Membrane Reactor for CO2 Absorption Based on Amino Acid Salt Solution in Carbon Capture Energy Tower

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ABSTRACT

This paper addresses the current situation of high energy consumption and high costs in DACC factories. It proposes to use the existing closed cooling towers in civilian buildings as the target for the transformation of carbon capture energy towers, resulting in a significant reduction in equipment investment in the transformation plan. The combined membrane absorption technology of liquid absorption and membrane separation is adopted to carry out multi-functional transformation of the closed cooling towers. On the basis of retaining the original heat exchange coils, an internal cooling carbon capture module is added, transforming the cooling tower used for air conditioning from a single cooling water heat dissipation function to a device integrating carbon capture, cooling tower, and heat source tower functions. Inside the carbon capture energy tower, the hollow fiber membrane contactor is embedded in a modular form, with air flowing in the shell side, while amino acid salt solutions flow inside the hollow fiber membrane filaments. To achieve better absorption effect and lower regeneration temperature, the absorbent adopts an amino acid salt solution system, and membrane distillation technology is used to achieve low-temperature regeneration at 70-80 °C. CO2 passes through the pores with diameters of several tens of nanometers in the hollow fiber membrane, significantly shortening the chemical absorption reaction rate and greatly improving the carbon capture efficiency, reducing the energy consumption of electricity and heat from the traditional 3.0 GJ/t CO2 to around 1.8 GJ/t CO2. By setting a capillary heat exchanger inside the hollow fiber contactor to remove the heat from the absorption reaction, the purpose of providing heat for the air conditioning end devices in winter is achieved.

KEYWORDS Amino Acid Salt Solution, Direct Air Carbon Capture, Energy Tower, Hollow Fiber Membrane Reactor (Contactor), Membrane Distillation

1. Introduction

We know that industrial enterprises, public and residential buildings, and various transportation vehicles in megacities and super-large cities are all sources of carbon dioxide emissions, with a quantity far exceeding that of small cities, county towns, towns, and even rural areas. Traditional CCUS technologies (Zhao 2021) are effective for concentrated carbon emission sources in industry, while the air conditioning cooling and heating systems of buildings are relatively scattered and have the characteristics of distributed energy use. Therefore, from the perspective of energy characteristics, direct air carbon capture technology (DACC technology) has more advantages. However, huge carbon capture devices rely on a large amount of air flowing through the capture

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device, and the power consumption of the fan for driving is also huge (Zeman 2007). Unlike laying a large area of photovoltaic panels for power generation, although the carbon capture efficiency is higher than the photoelectric conversion efficiency of the panels, the former uses free solar energy, while the latter can use wind power to drive the fan, but using precious "green electricity" for high-energy-consuming carbon capture is highly questionable in terms of its own rationality.

If the carbon capture function is integrated into the air conditioning system of civil buildings, such as cooling towers or large volume air handling units, so that traditional air conditioning equipment can simultaneously possess the additional function of carbon capture while meeting its own functional requirements, it is a creative and good idea.

According to the data from the "2024 China Urban and Rural Construction Carbon Emission Research Report (2024 Edition)", in 2022, the carbon emissions from building operations across the country reached 2.31 billion tons of carbon dioxide, accounting for approximately 21.7% of the total national carbon emissions. Since all the carbon emissions in this part can be traced back to the operation of the building, if all the emissions in this part are eliminated by the building-integrated DAC tower, it would be equivalent to an air volume of approximately 2.94×10^{14} cubic meters (estimated by AI). If each device operates for 4,000 hours per year and can process 50,000 to 100,000 cubic meters of air per hour, then the number of devices required would be approximately 735,000 to 1,470,000 units. And this number is smaller than the current stock of civil/industrial cooling towers in our country.

The annual operating hours of a cooling tower are often related to factors such as the climate zone it is located in and the application scenario. Most cooling towers are used for less than 4,000 hours a year, meaning their annual utilization rate is less than 50%, and the equipment is idle for the rest of the time. During periods when cooling is not required, the cooling towers are operated to capture CO_2, enabling the users of the cooling towers to achieve negative emission capabilities. This means that whether it is to balance the carbon emissions of the users themselves or to use the captured CO_2 in the carbon trading market, it will bring higher returns to the users/investors.

This plan not only enables the reduction of deployment costs by leveraging existing infrastructure, but also further compresses the unit carbon capture energy consumption and investment through large-scale application. Combined with the peak-valley regulation demand of the power grid, the equipment can operate efficiently during periods of surplus electricity, thereby enhancing the overall utilization efficiency of the energy system. With the advancement of materials and technologies, the stability of the absorbent circulation and the heat consumption for regeneration will continue to be optimized, leading to a steady decrease in operating costs. The centralized regional process layout can also achieve unified collection and resource utilization of carbon dioxide, forming a low-carbon circular economy demonstration path.

From this, it can be concluded that embedding the carbon capture module into civilian/commercial cooling towers is a completely technologically and economically feasible solution. The carbon capture module we chose here is the hollow fiber membrane contactor, which is used for gas separation and purification. This is one of the hot research areas in China and abroad over the past 30 years.The influence of spatial structure on the process separation and mass transfer of the hollow fiber membrane contactor was analyzed and explored from three aspects: the flow mode of the system, the shell-side baffle, and the filling density of the membrane module (Sun 2008). A solar-assisted carbon capture system based on hollow fiber membrane contactors was designed, and technical and economic research as well as environmental assessment studies were conducted on it.In this system, polypropylene membrane was selected as the material for preparing the membrane contactors (Mu 2024). An improved polypropylene hollow fiber membrane contactor was designed, and its CO_2 absorption and desorption capabilities for seven different absorption liquids were compared (Cui 2012). A CFD simulation study on hollow fiber membrane contactors was conducted (Yang 2008). MATLAB was applied in the study of the mass transfer model for the separation of CO_2 gas by hollow fiber membranes (Li 2006). HFMC technology was applied to control the CO_2

concentration in buildings, and a hollow fiber membrane circulation absorption/desorption system was proposed and verified. By using a cross-flow membrane module composed of porous hydrophobic PTFE (polytetrafluoroethylene) hollow fiber membranes, the indoor CO_2 concentration can be effectively maintained at a comfortable and healthy level of around 1000 ppm (Xu 2024). A hydrophobic polypropylene hollow fiber membrane contactor as the absorption device and MEA as the absorption liquid will be used to absorb low-concentration CO_2 in the air, the influence of different operating factors on the membrane absorption effect will be investigated, and a mass transfer model based on the membrane absorption principle will be established (Changjin 2010). Research on the spontaneous wetting of membranes was conducted, and a reasonable and applicable method to delay membrane wetting was discovered. That method is to add inorganic salts/alkalis to the DEA solution to increase the surface tension of the solution. The adsorption phenomenon at the solid-liquid interface can be disturbed by the anions and cations in the inorganic salts/alkalis, and thereby the occurrence of membrane wetting is delayed (Lu 2020). Four single absorbents (ethanolamine (MEA), ethylenediamine (EDA), diethanolamine (DEA), and piperazine (PZ)), as well as two-component and three-component mixed absorbents prepared from these single absorbents, were selected to study their absorption characteristics in the carbon removal system of hollow fiber membranes, and the optimal ratios and optimal operating parameters for each mixed absorbent were obtained (Qu 2016).Based on the theory of gas-liquid mass transfer and focusing on the removal of gases, the influence of the solution on the membrane in the membrane absorption process was taken as the main line, and research on the influence of different types of absorbent solutions on the membrane structure and the mass transfer process was conducted (Zhang 2011).

From the above, it can be seen that the improvement of carbon capture efficiency depends on factors such as the selection of the absorbent, the selection of membrane materials, and the gas-liquid flow mode of the membrane contactor.However, in the aforementioned literature, the average pore diameters of the membranes in the membrane contactors were all below the nanometer level, which directly affected the rate of chemical absorption reactions and consequently reduced the carbon capture efficiency.

2. Hollow fiber membrane contactor（HFMC）

2.1. The mechanism of chemical decarbonization reactions

The absorbents commonly used for HFMC mainly include alkaline solutions (sodium hydroxide solution, sodium carbonate solution, potassium hydroxide, etc.), amine solutions (ethanolamine, ethylenediamine, dimethylamine), ionic liquids, etc (Fattah *et al.* 2023). However, these types of absorbents have many limitations. For instance, amine solutions are volatile and highly toxic, while ionic liquids are difficult to degrade and impose a significant environmental burden, etc (Goff and Rochelle 2006). Compared with traditional amine solutions, amino acid salt solutions are regarded as potential carbon dioxide absorbers due to their lower evaporation rate and fewer degradation problems (Zhang *et al.* 2018). AASs, as a kind of green and harmless alkaline salt solution, has the potential to become the best absorbent. The amino acid salts are non-toxic and harmless, and their regeneration temperature is much lower than that of amine solutions (Deng 2014). They react very rapidly with CO_2, especially being suitable for the capture of low-pressure CO_2, which means that smaller absorption tower equipment can be used, reducing the investment cost. By developing new amino acid salts and combining them with other solvents to solve the problem of high viscosity. In summary, choosing amino acid salt solutions is more suitable for carbon capture from the atmosphere.

2.2. The working principle of membrane contactors

The gas-liquid hollow fiber membrane contactor is a gas separation device composed of porous hollow fiber membrane tube bundles. The fiber membrane tube bundle is encapsulated within the housing, providing a large number of contact interfaces for the gas and liquid. During operation, gas flows through the outer surface of the fiber, and gas molecules penetrate into the membrane through the membrane pores. The liquid flows within the membrane and comes into contact with the permeated gas molecules, achieving selective absorption of the gas molecules (Eskandari *et al.* 2022).

The core structure of the membrane contactor (shown in Figure 1) is simple. Gas flows through the outer shell, while the absorbent flows within the membrane filaments. The membrane pores do not have selectivity for molecules. Due to the hydrophobic material of the membrane filaments, the absorption liquid will not enter the membrane filaments (shown in Figure 2), and the gas and liquid phases will not come into direct contact. We chose the porous polytetrafluoroethylene (PTFE) membrane because it can provide a stable and efficient gas-liquid mass transfer interface, with high hydrophobicity, excellent chemical stability, high mass transfer efficiency, good operational flexibility, and compact equipment. It has excellent compatibility with absorbents such as amines, inorganic salts, and ionic liquids. The maximum working pressure can exceed 1.5 Mpa, and the pore size can be stably maintained at 0.01-0.05 µm. It can operate continuously for 8-10 years. Even when it gets wet, it can be restored to its original state through technical means. In terms of cost, it is only about 40% of the similar products from abroad. The inner core is composed of sponge-like polymer material, which allows liquid to flow through in a seepage manner. The outer layer is covered with a PTFE nano-scale (20-60nm) hydrophobic membrane structure. The capillary grid is embedded as the second channel into the core structure. The structure where different media circulate separately in the tube and within the loose material can achieve the "internal cooling" dual-media separate circulation heat and mass exchange function, promptly removing the heat generated during the absorption process.

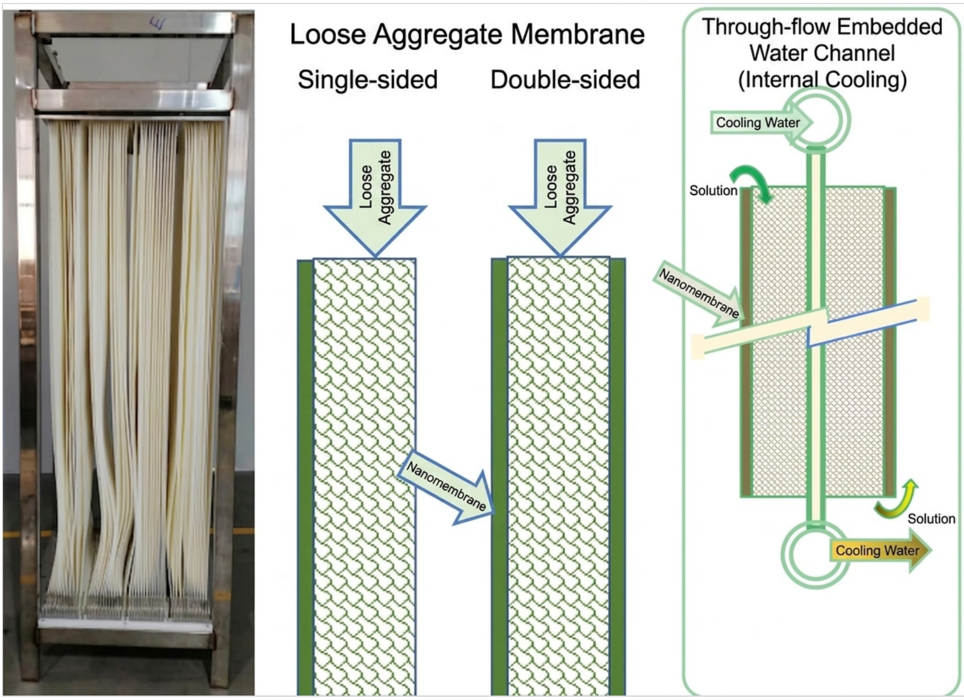

Figure 1. Physical photo and schematic diagram of the core structure.

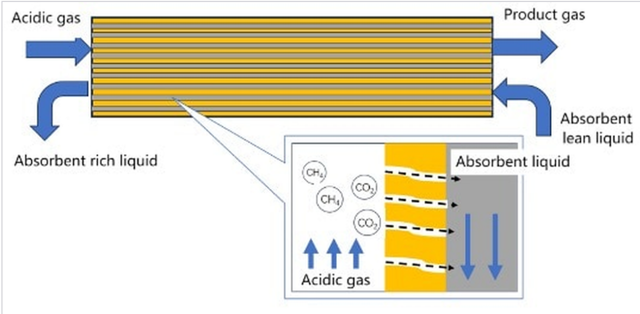

Figure 2. Schematic diagram of the absorption process of membrane contactors.

Compared with the traditional packed tower reactor, the specific surface area of the traditional packed tower is 100-250 m^2/m^3, while that of the hollow fiber membrane contactor is usually 1500-3000 m^2/m^3. The higher specific surface area makes the membrane contactor occupy less space, have a lower equipment height, and also result in less equipment weight. Better operational flexibility. The hollow fiber membrane contactor separates the gas from the absorbent by the membrane filament wall. Therefore, the gas-liquid phase flow rate can be controlled separately during operation without any gas-liquid ratio limit. At the same time, it can avoid bubbling, liquid flooding, and mist entrainment, etc. In terms of installation, the liquid in a traditional packed tower relies on gravity. Therefore, a very small tilt of the packed tower will lead to a decrease in the removal efficiency. Relatively speaking, membrane contactors rely on gas pressure to complete separation. They can be skid-mounted or installed horizontally without affecting the decarbonization efficiency.

As can be seen from Figure 2, the gas-liquid exchange mode of the membrane contactor adopts the cross-flow pattern. Since the gas and liquid phases flow in opposite directions along the membrane medium and simultaneously undergo mass transfer, this mode can provide the maximum average concentration driving force.

2.3. The mass transfer process and the improvement of mass transfer efficiency in membrane reactors

The mass transfer process mainly consists of three parts: the diffusion of gas and absorbent, the diffusion on the membrane filament surface, and the diffusion within the membrane. The resistance includes the gas phase boundary layer resistance, membrane resistance, and liquid phase boundary layer resistance. Figure 3 shows the distribution of mass transfer resistance within the membrane reactor and the diffusion paths of each part. By optimizing the pore size and surface wettability of the membrane material, the membrane resistance can be significantly reduced; using a turbulence booster or increasing the flow rate can effectively reduce the thickness of the gas-liquid two-phase boundary layer, thereby improving the overall mass transfer coefficient. In addition, choosing hollow fiber membranes with a high specific surface area helps to increase the effective contact area, further enhancing the mass transfer effect. In the figure, H represents the Henry coefficient; k_L, k_M, and k_G are the mass transfer coefficients for the liquid phase, membrane phase, and gas phase, respectively.

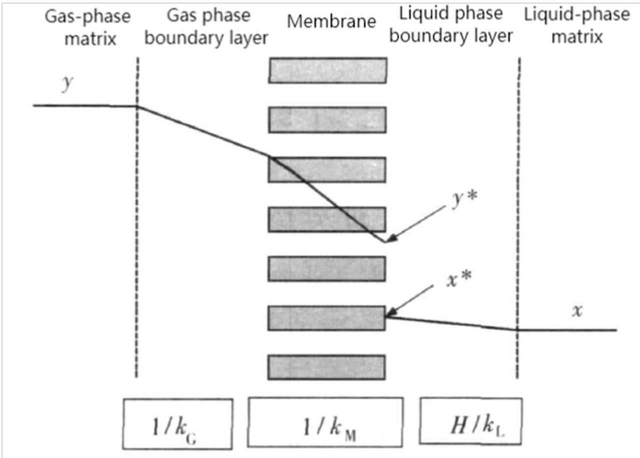

Figure 3. Schematic diagram of mass transfer in hollow fiber membrane contactor.

2.4. The innovation of the carbon capture module in the renovation of air conditioning cooling towers

1. Convert the heat exchangers in the traditional closed cooling towers into corrosion-resistant plastic capillary heat exchangers;
2. Replace the traditional water distributor with a hollow fiber contactor based on nano-sized PTFE membranes;
3. The system covers the functions of summer cooling, winter heating (through chemical absorption reaction heat), and carbon capture, replacing the single cooling function, to achieve the year-round use of the energy tower;
4. For the overall addition of carbon capture function for regional building complexes, the idea of building a regional carbon process energy treatment station was proposed for the first time in China.

3. Carbon capture energy tower

3.1. The similarities and differences between the functions of civil cooling towers/heat source towers and carbon capture functions

Both cooling towers and air capture devices require driving a large amount of ambient air to flow through the equipment. However, the heat and mass exchange (heat, water vapor) between the cooling tower and the air is to use the air as a heat sink, so as to release the heat in the cooling system into the environment. However, the air capture device only focuses on mass exchange with the ambient air, using air as the carbon source, with the aim of stripping as much of the low-concentration CO_2 from the air as possible. At this point, heat exchange is not within the scope of consideration of the air capture, and the reaction heat that accompanies it dissipates naturally.After the dual-carbon target was proposed, it is necessary to integrate the functions of cooling, heating and carbon capture, enhancing the carbon reduction capacity of urban building complexes. Therefore, for large public buildings, the multi-functional transformation of cooling towers is imperative.

Adding chemicals to the water circulation of cooling towers is to maintain water quality and prevent malfunctions caused by water quality issues. The air capture device needs to be equipped with an amino acid salt solution of appropriate concentration, so that the CO_2 in the ambient air can come into contact with the alkaline amino acid salt solution at a low temperature (below 35 °C) as much as possible, causing an exothermic reaction and generating unstable salt compounds, thereby achieving the purpose of capturing CO_2. The sediment/residue formed by adding chemicals in the water circulation of the cooling tower to protect water quality needs to be separated from the water system and discharged as harmful substances, and there is no need for recycling and regeneration. The air capture device, on the other hand, requires that some of the products be directly heated and regenerated inside the tower, undergoing reversible thermal decomposition reactions to release CO_2 and be reduced to an amino acid salt solution.

The above analysis indicates that the cooling tower function and the carbon capture function are not contradictory, but rather highly correlated and complementary. Considering the modification of the cooling tower to incorporate the function of an air capture device, it should be highly reasonable. Table 1 lists the situations under three usage functions. The integration of the functions requires the modification of the cooling tower. Compared to the purely CO_2-gathering equipment investment of the DACC technology, modifying the cooling tower accordingly can ensure the operation quality of the cooling tower while rationally utilizing and processing the CO_2 compounds, thereby achieving a much higher technical and economic return than the DACC technology, which is undoubtedly a more reasonable solution.

Table 1. Sub-item Function Table of Carbon Capture energy Tower.

Comparison project	**Sub-function of the carbon capture energy tower**		
	Carbon Capture	**Cooling Tower**	**Heat Source Tower**
Application period	All periods of the year	Summer (cooling)	Winter (heating)
Working principle	Air and liquid undergo heat and mass exchange in the reaction (contact) vessel		
Properties of the solution	Amino acid salt solution	Water	Ethylene glycol solution
Air exchange output	Liquid absorption (membrane absorption)	evaporation cooling	condensation heat release
Cold and heat dissipation method	Capillary network heat exchanger	heat exchange	heat exchange
Water quality control	Null	Add chemical agents (for water quality control)	Add antifreeze
Regeneration process	Heating	Null	Null
Output of the water system	CO_2 gas	Impurities after water quality treatment	Diluted antifreeze

The built-in capillary heat exchangers and membrane contactors are arranged vertically and crosswise in the energy tower, ensuring that during the carbon capture process in winter and transitional seasons, the water in the capillary heat exchangers can fully absorb the heat from the reaction heat, thereby effectively providing hot water for the air conditioning system. If the heat is insufficient, supplementary heat sources can be set up for auxiliary heating. During the cooling season in summer, the water in the capillary heat exchangers undergoes enthalpy exchange with the air in the energy tower, causing the water to cool and completing the water circulation of the conventional cooling water.

All the places that use cooling towers are energy-consuming areas. Adding carbon capture function to cooling towers is an additional service, which can partially or completely offset the carbon emissions of the system. This fully complies with the technical and economic goals of carbon neutrality.

3.2. Technical measures for transforming cooling towers into carbon capture energy towers

Cooling towers are widely used industrial and civil equipment, and are extremely popular in almost all manufacturing industries, data centers, as well as numerous commercial and civil air conditioning systems that employ water-cooled chillers. According to data from the Research Institute of Coordinated Industry, the total demand for cooling towers in China is expected to be approximately 1.46 million units in 2025, with a market size of 7.86 billion yuan. Civil cooling towers (mainly for large central air conditioning systems, data centers, etc.) accounted for 44.2% of the market total in 2022. Even if we estimate conservatively at a 40% proportion, the annual demand in 2025 would be approximately 584,000 units. According to incomplete statistics, the approximate number of industrial/commercial cooling towers currently in operation in China ranges from several million to several tens of millions (as shown in Figure 4).

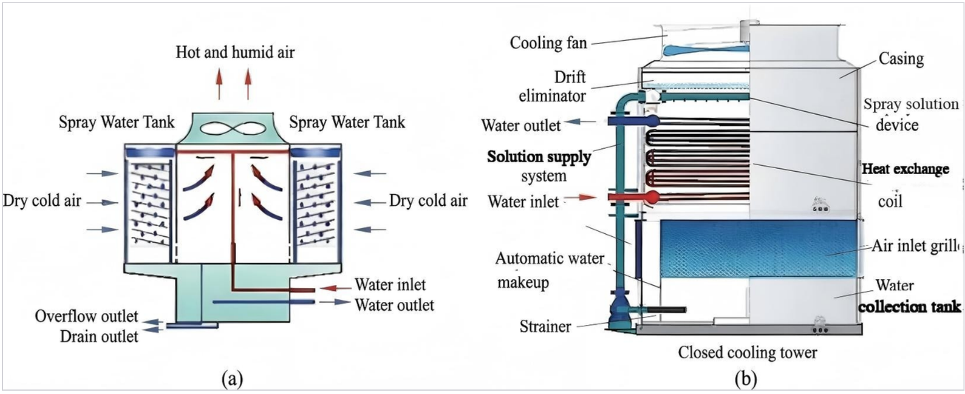

Figure 4. (a) Open cooling tower and (b) Closed cooling tower (with carbon capture function).

The key focus of the multi-functionalization renovation of existing civil cooling towers is the closed cooling towers (on the right side of Figure 4). The main renovation technical measures include two types. The first is the dual-loop design, which suggests adopting a mode that combines the closed cooling tower with external spray absorption liquid. The inner loop is for clean cooling water, providing cooling for the air conditioning main unit; the outer loop is for carbon capture absorption liquid, which is sprayed out through the spray tower and comes into contact with the air. These two loops exchange heat through a plate heat exchanger. This not only protects the air conditioning main unit from contamination but also facilitates independent management of the absorption liquid. However, this method requires attention to the compatibility of materials, that is, the fillers, water collection trays, and pipes need to be replaced with materials that are resistant to alkali (such as resistant to sodium hydroxide solution corrosion) and chloride ion corrosion (such as stainless steel, specific plastics). The second is to install a membrane contactor inside the cooling tower, using membrane separation technology to capture carbon dioxide. The carbon capture reaction module is connected in parallel with the existing cooling water circulation heat exchange module, with separate inlet and outlet pipes, and the internal flowing solution and water are present, without the water distribution device. The solvent regeneration module is set as an external process module and not placed inside the tower. In this way, the absorption solution circulates internally in the membrane fibers, thereby reducing the corrosion requirements for the components of the cooling tower. The upgraded control strategy requires upgrading, that is, integrating sensors such as pH value, conductivity, and solution concentration to achieve intelligent switching and optimized operation between the carbon capture mode and the pure cooling mode. Further speaking, the conventional cooling water heat exchange tubes can be transformed into plastic capillary network heat exchangers and placed inside the membrane contactor, arranged in a cross pattern. In winter, the reaction heat generated during the carbon capture process can be taken away and supplied to the air conditioning end, truly achieving the year-round uninterrupted operation of the energy tower, as shown in Figure 5.

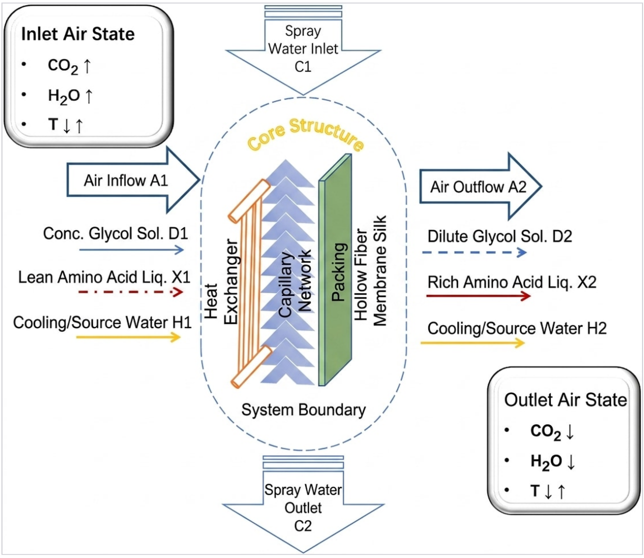

Figure 5. Physical model of the carbon capture energy tower.

For the original air conditioning cooling tower, the application method after its carbon capture function is added is as follows:

- During peak hours (design load), the carbon capture function is not activated to avoid the heat from the carbon capture reaction affecting the cooling capacity of the equipment;
- During off-peak hours (partial load), the backup cooling tower's carbon capture function can be activated for carbon capture;
- During non-cooling periods (transition seasons), it can be 100% used for carbon capture;
- During heating periods (winter), the carbon capture function can be utilized simultaneously. The heat generated during the carbon capture process can be used for heating, replacing the original winter heating scheme, significantly improving the equipment's efficiency and reducing winter heating energy consumption.

3.3. The functional combination of the carbon capture energy tower

In the physical model shown in Figure 5, the inflow and outflow of each medium do not occur simultaneously. The air flow system is its main influencing factor. Ethylene glycol solution and amino acid salt solution are selected based on the chosen function. Cooling water/heat source water is the function of cooling tower/heat source tower. In the internal heat exchange (closed system/internal cooling type) equipment scheme, the cooling water/heat source water has its own independent circulation. However, in the external heat exchange equipment scheme, this circulation does not exist but is combined in the ethylene glycol solution circulation or amino acid salt solution circulation system in the form of liquid-liquid heat exchange.

Based on the cooling tower, through different combination methods, the following several functional combinations can be formed:

1. Traditional cooling tower functions: Air circulation + spray water circulation. It is further divided into open/closed cooling tower functions:

- Open tower: Directly obtain cooling capacity from the spray circulating water;

- Closed tower: The cooling capacity is obtained through the circulating water in the capillary tube network heat exchanger.

2. Heat source tower function: Air circulation (without spray water) + ethylene glycol solution circulation, which is further divided into internal/external exchange heat.

- Internal heat exchange: Heat is obtained through the circulation of heat source water in the capillary heat exchanger.
- External displacement heat is obtained through plate heat exchangers in the circulation path of ethylene glycol solution.

3. Cooling tower + wet recovery (dehumidification) function. This function is suitable for using evaporative cooling technology to provide cooling capacity, but due to the scarcity of water resources, it is required.

Recover moisture as much as possible: A module + ionic liquid absorption liquid circulation.

4. Cooling tower + carbon capture function, this function enables users to obtain carbon capture capability with less investment: A module + amino acid salt solution circulation ring.
5. Pure carbon capture function: Under the D module configuration, if the cooling tower does not need to operate (in winter), this module can be run: Air Circulation + Amino acid salt solution.
6. Simple dehumidification function: In the dry low-temperature zone, this module can be used to collect moisture from the air: air circulation + ionic liquid absorption liquid.
7. If two sets of diaphragms are adopted, multiple combination functions can be formed:

- Cooling tower + wet recovery + carbon capture: The amino acid salt solution and ionic liquid absorption liquid each have a circulation and membrane group.
- Heat source tower + carbon capture: The same as above, but the cooling tower function is idle during operation.

4. The closed-loop large circulation system of the energy tower

Taking the traditional liquid absorption method for carbon capture as an example, NaOH is reused through an increased chemical reaction process for carbon capture. However, $CaCl_2$ needs to be specifically designed in combination with the operation of the solution-integrated air conditioning system to ensure the regeneration of $CaCl_2$ and the $CaCl_2$ demand of the solution-integrated air conditioning system. As shown in Figure 6.

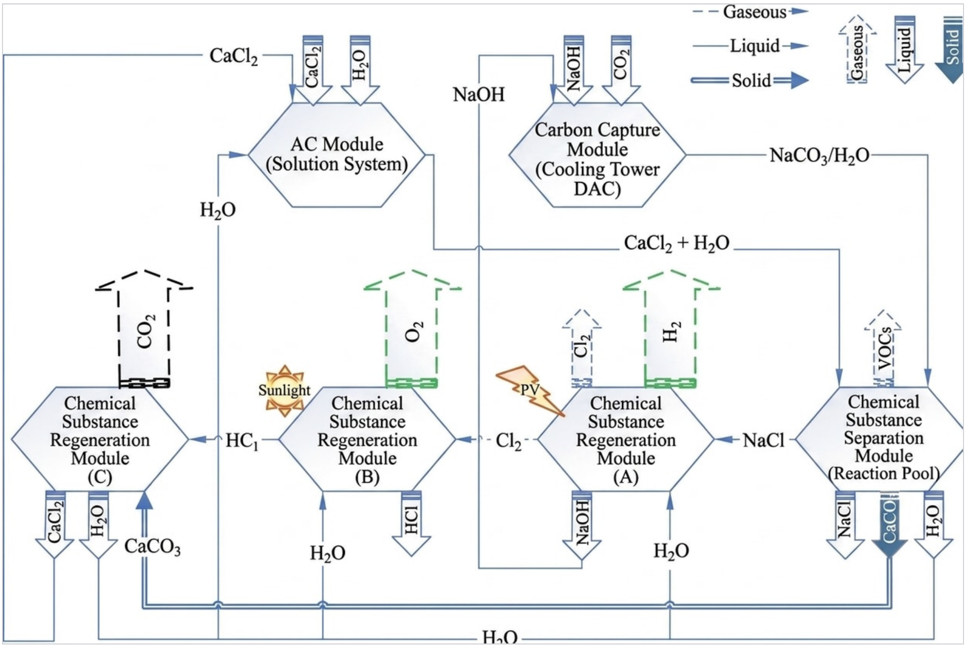

Figure 6. Shows the principle of the solution integrated system that includes all DACs and the large cycle of material regeneration.

It is possible to further choose to use solar energy (PV) to electrolyze NaCl to obtain NaOH, Cl_2 (chlorine) and H_2 (hydrogen) again. This step belongs to solar energy utilization, decomposing NaCl to obtain green hydrogen. Cl_2 can be again exposed to light to obtain HCl (hydrochloric acid) and O_2 (oxygen), which belongs to the utilization of solar energy to prepare oxygen (photosynthesis). HCl and $CaCO_3$ can be combined again to obtain $CaCl_2$ and CO_2 (carbon dioxide). At this point, the obtained $CaCl_2$ is reintroduced into the above-mentioned solution system for recycling, while CO_2 is a pure element that can be reused (in food, chemical, agricultural, etc.). Or it can be deeply buried for oil displacement.

This traditional process flow consists of four major modules, namely the air conditioning module, the carbon capture module, the regeneration module and the separation module. It reflects the entire process of carbon capture, utilization and storage. Although the absorption and desorption of CO_2 processes mentioned in this article are different from the traditional ones, the process combined with the solution integrated system is consistent.

5. Case Study on Annual Carbon Capture Capacity Calculation of Membrane Contactors

Based on the application period of carbon capture in the energy tower mentioned above, it can be concluded that it is appropriate to carry out carbon capture throughout the year (except for the cooling season) to avoid the impact of heat and cold balance. According to the macroscopic calculation of carbon capture volume in the typical southern regions of China (including hot summer and cold winter areas as well as hot summer and warm winter areas), this region has at least 5500 hours per year suitable for carbon capture. Since the application scenarios of cooling towers are mostly civil public buildings such as offices and commercial buildings without considering residential air conditioning (currently most adopt air-source heat pumps for cooling), the conservative calculation of single unit cooling capacity is 50kW per unit.

Using amino acid salt solution as the absorbent and employing membrane distillation technology to achieve low-temperature regeneration at 70-80 °C, the total desorption heat is calculated at 1.8 GJ/t CO_2. During winter operation, the absorbed reaction heat is recovered and used for building heating, equivalent to the DAC process providing free heat while capturing carbon. This can offset part of the operating costs. However, in the calculation of carbon capture volume, the recovery of reaction heat does not affect the CO_2 capture rate because the absorption reaction is spontaneous. The heat release is removed to facilitate the maintenance of low-temperature absorption conditions (increasing the equilibrium conversion rate). The carbon capture volume of the carbon capture energy tower can be calculated based on the circulating air volume required per 1 kW of heat load. Assuming the outdoor air CO_2 content is 0.04%, the carbon capture efficiency is set at 80%, and the outdoor air temperature is 20 °C. The calculation process is as follows:

The mass flow rate of CO_2 corresponding to each kW of net heat is

$$m_{CO_2} = \frac{1kW}{1.8GJ/t} = \frac{1kJ/s}{1800kJ/kg} = 0.0005556kg/s = 0.5556g/s = 2kg/h \tag{1}$$

The volume content of CO_2 in outdoor air is 0.04%, the average molecular weight of air is 29, the molecular weight of CO_2 is 44, and the mass fraction is:

$$w_{CO_2} = \frac{0.04}{100} \times \frac{44}{29} = 0.0004 \times 1.517 = 0.0006068 \tag{2}$$

The mass of CO_2 that can be captured per cubic meter of air is

$$1.204 \times 0.0006068 = 0.0007307kg/m^3 = 0.7307g/m^3 \tag{3}$$

Carbon capture efficiency

$$\eta_{capture} = 0.8,\ is\, 0.7307 \times 0.8 = 0.5846g/m^3 \tag{4}$$

The required volumetric flow rate of air is

$$V_{air} = \frac{0.5556g/s}{0.5846g/m^3} = 0.9504m^3/s = 3421m^3/h \bullet kW \tag{5}$$

If calculated based on 5500 hours per year, the total annual carbon capture volume (per kW of net heat) would be

$$M_{CO_2} = 2kg/h \times 5500h/a = 11000kg/a = 11t/a \bullet kW \tag{6}$$

The revenue from carbon trading (calculated based on the average EU carbon trading price of 74€/ton in 2025) is

$$I = 11 \times 74 = 814€/a \bullet kW \tag{7}$$

Based on the technical solution using a closed cooling tower, the heat source is the condensation waste heat generated by the air conditioner's cooling process. Suppose the cooling capacity of a single commercial air conditioner is 50 kW , and it's energy efficiency ratio (COP) is 3.0 (typical value), then

The condensation heat = Cooling capacity × (1 + 1/COP) = 50 × (1 + 1/3) ≈ 66.7 kW. Assuming that all the condensation heat can be used for DAC desorption (with the heat exchange efficiency assumed to be 100%)

Then the annual capture amount of a single air conditioner is

$$M_{CO_2,per\ unit} = 11t/a{\bullet}kW \times 66.7kW = 733.7t/a \tag{8}$$

Assuming that there are 4 million cooling towers suitable for multi-functional renovation in public buildings (based on the reasonable inference that the annual demand for cooling towers has been above 1 million in recent years and that the proportion of civilian cooling towers is over 40%) then the total carbon capture potential would be

$$M_{total} = \frac{733.7t}{a}{\bullet}unit \times 400Ten\ thousand\ units = 2.93Billion\ t/a \tag{9}$$

The above calculations undoubtedly demonstrate that the technical solution of upgrading and replacing the existing large number of cooling towers with energy towers with carbon capture capabilities is feasible. Moreover, integrating the central air conditioning sector into the development track of distributed carbon reduction will surely contribute to achieving the dual carbon goals. More importantly, under the leadership of new quality productive forces, direct air carbon capture technology provides a new technical solution for the HVAC system and the construction sector to achieve the "net zero carbon" goal (Wang 2024).

6. Conclusion

The analysis in this article is based on the problem that the currently operating civilian cooling towers are only used in summer and remain idle for most of the year, as well as the fact that building air conditioning equipment generally lacks carbon capture capabilities. It attempts to find technical improvement approaches to solve these two major problems, providing operational ideas for achieving the dual carbon goals. Based on the above explanations, the following conclusions can be drawn.

1. In response to the carbon neutrality goal of urban building complexes, it is proposed for the first time to transform the air conditioning cooling towers into multi-functional ones, so that the transformed energy towers can have three functions: cooling, heating, and carbon capture, ensuring continuous operation throughout the year and improving the efficiency of equipment utilization.
2. On the basis of the existing heat exchange tubes in traditional closed cooling towers, it is proposed for the first time to add an internal cooling type hollow fiber membrane contactor to achieve automatic switching between cooling and carbon capture. In winter, it can effectively utilize the existing heat exchange tubes (with internal ethylene glycol antifreeze) combined with plate heat exchangers to achieve external heat exchange, or effectively utilize the capillary heat exchanger inside the membrane contactor to achieve internal heat exchange.
3. To reduce the regeneration temperature of the liquid absorbent, amino acid salt solutions of nanoscale hollow membrane filaments are used for CO_2 absorption, combined with membrane distillation low-temperature regeneration, so that the consumption of electrical and thermal energy is reduced from the traditional 3.0 GJ/t CO_2 to around 1.8 GJ/t CO_2.
4. In areas where the carbon capture function needs to be increased in building complexes, regional carbon capture process stations can be established, which can be combined with existing energy stations to achieve comprehensive processing of energy utilization, completely solving the problem of low-carbon or zero-carbon in urban building complexes.

Declarations

Author contributions. Zhaochuan Hou: Investigation, Formal analysis, Data curation, Writing – original draft. **Liqing Yang**: Resources, Technical support, Data provision. **Yang Zhu**: Review, Suggestions for manuscript improvement. **Heinz-axel Guo**: Review, Suggestions for manuscript improvement.

Conflicts of interest. The authors have no competing interests to declare.

Data availability. The data mentioned in the text are all derived from the references cited or are reasonably inferred based on reliable reports available online. The data used in the case calculations are all consistent with the logical deduction process.

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