Electrochemical Membrane Technologies for use in Energy Systems

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This article concerns the electrochemical compressor, which is a mass transport device capable of compressing gases via a chemical process, rather than a mechanical process. Solid-state pumping for a variety of working fluids is attainable through electrochemical processes in membranes. Similar principles that work to generate electricity in fuel cells may also have practical applications in heat pumping and air conditioning, as they can be exploited to reliably transfer selected gases from reservoirs of low concentration to those of high concentration. In this article, we present two such technologies: electrochemical ammonia compression and electrochemical dehumidification, as well as some of their potential uses. We present empirical findings, which detail the performance of these technologies as well as strategies to use these technologies most effectively.

Introduction

In virtually all commercial heat pumps and refrigeration units around the world, a mechanical compressor is responsible for supplying the work needed for useful heating and cooling. However, there may be an alternative that does not rely on moving parts. The electrochemical compressor (EC) is a mass transport device capable of compressing gases via a chemical process, rather than a mechanical one. The EC uses the same ion exchange membranes found in hydrogen fuel cells, but the EC consumes electricity without creating any net chemical changes in the working fluid while fuel cells consume gas to generate electrical potential.

The electrochemical hydrogen compression phenomenon has been known for decades and commercial hydrogen EC devices are available for purchase today. However, recent experiments have demonstrated that electrochemical compression is possible with a variety of working fluids, including, but not limited to, gaseous ammonia and water vapor [1]. In this article, two applications for the EC are presented: electrochemical ammonia compression and electrochemical dehumidification.

The current project work aims to demonstrate the steady-state compression of ammonia vapor at practical pressure ratios with efficiencies that rival those of conventional mechanical compressors. The ammonia EC is being investigated for its potential use in vapor compression heat pump cycles as well as in energy storage applications. Furthermore, electrochemical water transport could be applied to air conditioning applications as a means of separate sensible and latent cooling.

The electrochemical compression device

The EC device consists of three main components: the gas distribution channels, the electrodes, and the membrane. The gas distribution channels, shown in Figure 1, supply the working fluid to the electrodes, which are made of a porous, electrically conductive material. The electrochemical reactions occur in the membrane electrode assembly (MEA), which is the assembly of both electrodes and the ion exchange membrane. An external voltage is supplied across the two electrodes. Under the external voltage, the working fluid reacts with a carrier gas to form an ion. The ion is then able to traverse across the membrane, which is impermeable to electrons. When the ion reaches the opposite electrode, the ion then reforms into its constituent molecules. This process is able to push ions across the membrane even in the presence of an opposing concentration gradient, which is how we are able to get useful compression out of this phenomenon. A diagram of the EC cell is provided in Figure 1.

Although a single cell does not provide a practical amount of compression work, several compression cells may be stacked together to increase either the pressure lift or the mass flow rate of the working fluid. Combining two compressors in series increases the total pressure ratio and combining two compressors in parallel increa-

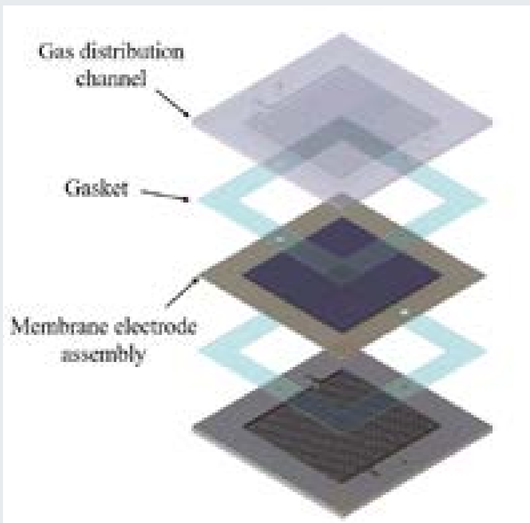

Fig. 1: Exploded diagram of an electrochemical compressor cell.

ses the total flow rate. Because the ammonia EC has demonstrated the required pressure ratio in a single stage, we do not need to combine cells in series. Instead, the current research looks to create several parallel connections.

Electrochemical ammonia compression

Ammonia, which is one of the most commonly produced chemicals in the world, is one of the oldest known refrigerants and has negligible ozone depletion and global warming potentials. Additionally, provided carbon-neutral raw materials and process energy are used for the manufacture of the ammonia, liquid ammonia can be used as carbon-neutral fuel for ammonia fuel cells and ammonia-driven internal combustion engines. Such energy storage applications require high pressure storage of ammonia; therefore, an efficient ammonia compressor becomes necessary for both refrigeration and energy storage applications.

The ammonia EC depends on a series of electrochemical half-reactions. In the first half-reaction, the ammonia reacts with hydrogen, which acts as a carrier gas, to form ammonium ions, according to equation (1), below. The ions then pass from the anode to the cathode via the cation exchange membrane, after which the second half-reaction occurs. In the second half-reaction, the ammonium ions react to reform ammonia and hydrogen gases at an elevated pressure, according to equation (2). This process is illustrated in Figure 2.

$2NH_3 + H_2 \rightarrow 2NH_4^+ + 2e^-$ (1)
$2NH_4^+ + 2e^- \rightarrow 2NH_3 + H_2$ (2)

We tested the ammonia EC under a variety of different pressure ratios and observed the power consumption for each. For stoichiometric inlet conditions at room temperature, while humidifying the inlet gas stream to around 40% relative humidity, the best observed EC performance is summarized in Figure 3. In the figure, the compressor power consumption per gram per second of fluid flow is plotted against the pressure ratio. The ammonia EC curve was generated based on the governing electrochemical laws for the EC and the observed losses in the cell during the test condition showing the best performance. The ammonia EC curve has the same slope as the curve of ideal isothermal compression because, in the observed experiment, the EC power consumption was too small to give rise to any increase in temperature. Thus, the small-scale compression processes are said to be isothermal.

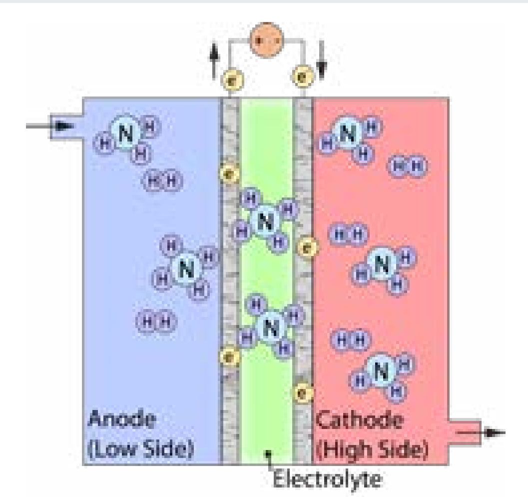

Fig. 2: Diagram of electrochemical transport of ammonia with hydrogen acting as a carrier gas.

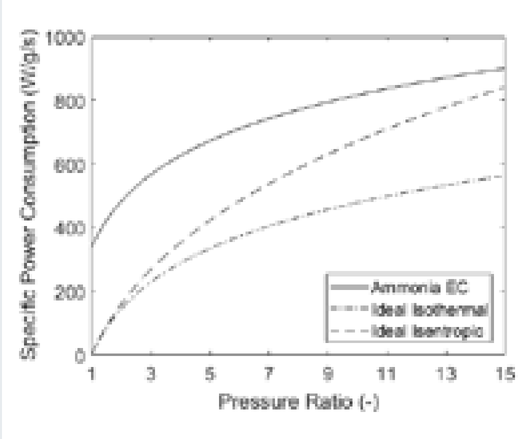

Fig. 3: Specific power consumption of an ammonia EC under a range of pressure ratios.

Electrochemical dehumidification

Another area of interest deals with electrochemical transport of water vapor for dehumidification applications. Currently, the most common methods for dehumidification involve water vapor condensation or desiccant absorption. Because it does not rely on either of these technologies, the electrochemical process provides an interesting alternative. In previous research efforts into electrochemical membrane dehumidification, researchers observed that the dehumidification performance may be limited by poor mass transfer [2]. However, in this novel approach to membrane water transport, a high voltage field, causing an electrohydrodynamic (EHD) effect, may increase the rate of water vapor transport through the membrane. This effect, which is used in food processing to dry perishable foodstuffs, increases mass transfer rates by destabilizing fluid boundary layers and increasing the partial pressure of water near the membrane surface.

Unlike the ammonia EC, the electrochemical dehumidifier relies on the transfer of negatively charge ions, so it uses an anion exchange membrane to complete the process. The dehumidification principle is that oxygen along with water vapor is electrochemically reduced to form hydroxide in the cathode through reaction in equation (3), below. Subsequently, the hydroxide is oxidized back to oxygen and water on the anode side, as explained by equation (4).

$2H_2O + O_2 + 4e^- \rightarrow 4OH^-$ (3)
$4OH^- \rightarrow 2H_2O + O_2 + 4e^-$ (4)

The molar ratio of water vapor to oxygen is fixed to 2 and is independent of the dehumidification ratio ensuring a steady rate of dehumidification under any operating conditions. To increase water transfer through the membrane, we use a high voltage source, generating an EHD force, which helps to push water vapor in main air stream towards the membrane, as well as en-

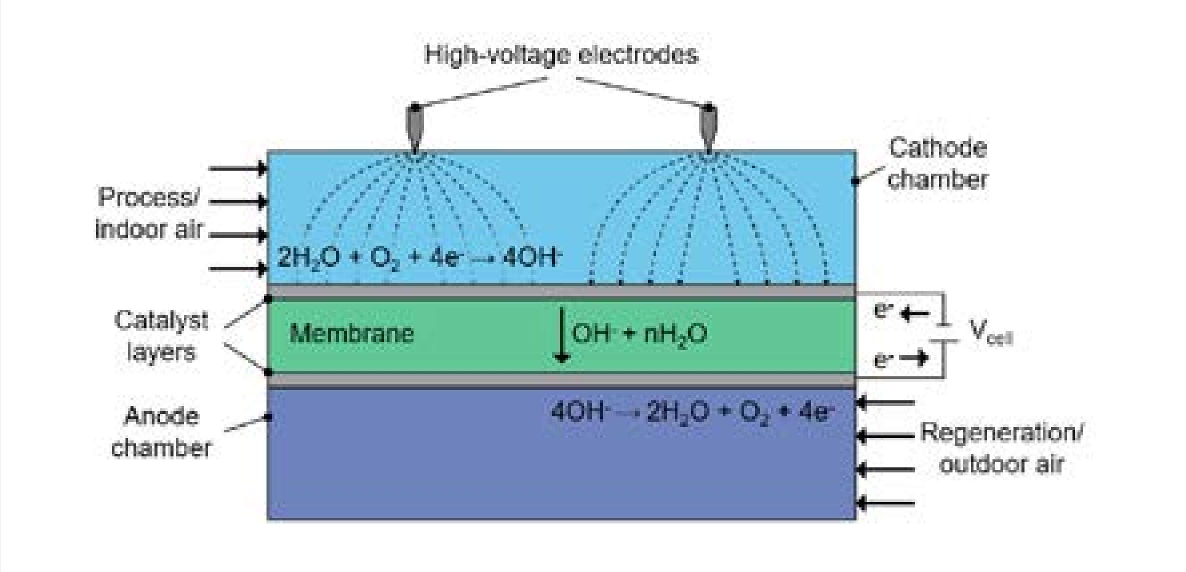

Fig. 4: Diagram of the electrochemical dehumidification process integrated with a high-voltage field, generating an electrohydrodynamic force.

courage effective mass transfer of water vapor. Figure 4 shows this process.

There are several possible modes of water transport in the membrane. Principally, there is electrolytic water transport, which is the water transfer governed by the electrochemical reactions. There is also diffusive water transport, which is the movement of water due to a concentration gradient. Lastly, there is electroosmotic transport, which is the phenomenon of water transfer through the membrane due to dipole interactions with the negatively charge hydroxide ion. The goal of this research is to develop a method for electrochemical dehumidification that maintains a stable rate of electrolytic transport, while maximizing the electroosmotic transfer and minimizing parasitic drag of water molecules.

The fundamental advantage of this method of water removal is that it does not rely on condensation. While vapor compression dehumidifiers must cool the water vapor below the dew point to condensate water vapor and separate out the liquid water, there is no net phase change in the EC dehumidification process. Therefore, the only energy consumption comes from the energy requirement for the electrolytic process. In the ongoing research efforts, we will conduct experiments to determine the rate of water transport in the anion exchange membrane under practical operating conditions. Additionally, we will investigate the benefits of the EHD component and determine the effectiveness of the electrochemical dehumidifier as compared to the current state-of-the-art in conventional dehumidification.

Conclusions

Both electrochemical compressor (EC) technologies are intended for use in energy systems. The ammonia EC could be used to drive a heat pump or refrigeration cycle using ammonia as the refrigerant. Additionally, the ammonia EC is being investigated for use in energy storage technology. Experimentation revealed that steady-state ammonia compression is attainable under a range of pressure ratios with reasonable energy consumption. Moreover, it is possible to separate ammonia from a dilute stream using the EC. While challenges persist in the integration of the EC into practical energy systems, this technology exhibits potential, especially in applications requiring high pressure ratios, for example liquid storage of ammonia for use as carbon-neutral fuel, provided carbon-neutral raw materials and process energy are used for the manufacture of the ammonia.

The water EC could be used as a dehumidifier to reduce latent cooling load in air conditioning applications. The electrohydrodynamic (EHD) component could help increase the rates of water transfer and decrease the parasitic diffusive losses in the membrane.

References

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