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Ahmad Abu-Heiba

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OAK RIDGE NATIONAL LABORATORY
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Energy and Transportation Science Division

Evaluation of Prototype Membrane Based Air Conditioner

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ABSTRACT

A prototype cooling system that uses water as refrigerant was built and sent to Oak Ridge National Laboratory (ORNL) for laboratory performance evaluation. The prototype uses electrochemical compressor technology. The compressor consists of nanostructured polymer membranes that transfer water molecules isothermally. Performance evaluation at ORNL was aimed at characterizing the cooling performance of the prototype at different evaporating and condensing temperatures. Evaluation concluded that the compressor performed as expected, however, the integrated cooling system did not provide cooling.

1. SYSTEM DESCRIPTION

The system consists of an electrochemical water vapor compressor that is housed in a sealed vessel, heat exchanger that acts as a condenser for water vapor and an expansion device. Water charge resides at the bottom of the vessel and the whole system is under vacuum. The vessel is also charged with Hydrogen in 1:2 mole ratio to water vapor. The electrochemical compressor uses membranes made of nanostructured polymer materials to transport Hydrogen molecules across a permeable membrane. Electrochemical compression of hydrogen is accomplished by splitting hydrogen into protons and electrons in a reversible reaction (Figure 1.) This occurs on a platinum-catalyst-coated polymer electrolyte membrane to maximize efficiency. Under an externally-imposed voltage, the resulting protons migrate through the polymer electrolyte membrane that conducts positively-charged cations but blocks negatively-charged anions and electrons. The protons then recombine with electrons on the other side of the membrane to reform into hydrogen, but at a higher pressure. In this manner, hydrogen is pumped across the membrane and the pressure differential developed is proportional to the applied voltage. Water vapor molecules are dragged by the Hydrogen protons across the membrane, effectively compressing water vapor.

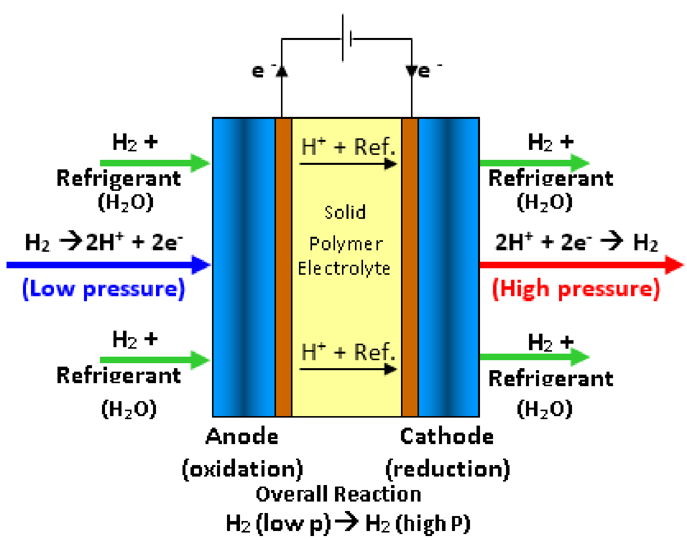

Figure 1. The ECC cell uses an external voltage to pump hydrogen and a refrigerant, in this case, water, across a solid polymer electrolyte membrane

A schematic of the system and its idealized thermodynamic cycle are shown in Figure 2. The discharged water vapor then exchanges heat with cooling water and condenses. The condensed water flows through a pressure control device and it expands. The temperature of the water drops as a result and this cold water is returned to and mixed with the water charge in the vessel. An electric heater is inserted into the vessel to heat the water charge to control its temperature.

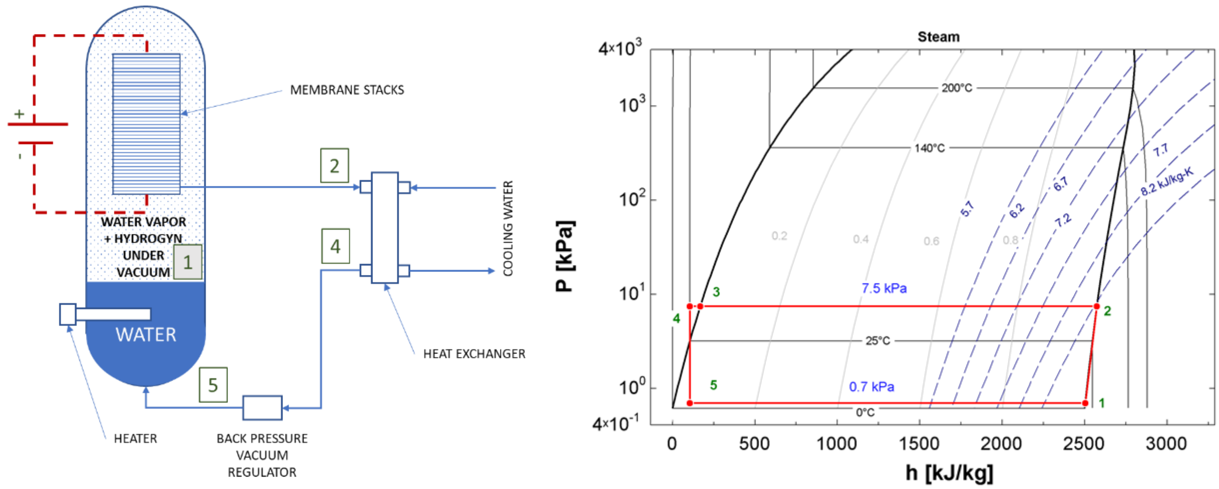

Figure 2. Left: schematic of the system. Right: Ideal thermodynamic cycle at design point. The numbers in square boxes on the schematic correspond to state points on the P-h diagram on the right

The electrochemical compressor consists of four stacks of membranes that are mounted on a wooden baseplate as shown in Figure 3. Mounted into the same baseplate are four circulation fans as shown in Figure 4. These fans are meant to increase water vapor access to the membranes if needed.

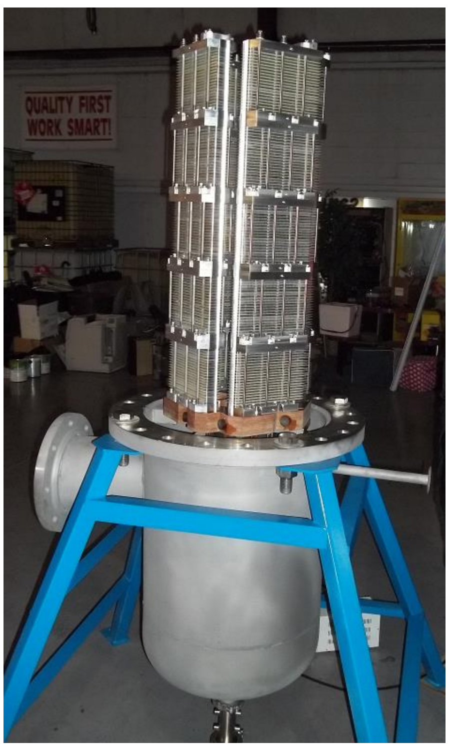

Figure 3. Membrane stacks mounted on a wooden baseplate. Only two stacks are shown in this photo

Figure 4. Circulation fans mounted into the baseplate. This photo was taken looking down. The fans push the flow upward (perpendicular to the paper and outward)

The design targets for the system is to produce 1.2 kW of cooling while rejecting 1.23 kW of heat to the cooling water in the condenser heat exchanger.

2. SYSTEM SET-UP

The prototype was delivered to ORNL by DAIS Analytics for testing to validate its performance and was assembled in-situ (Figure 5.) To prepare the system for running, the following steps are followed:

1. The system was evacuated to an absolute pressure of 154 Pascal.
2. The system was charged with distilled water. The total weight of the charge was weighed and recorded. It was 32 kg.
3. The system was then charged with Hydrogen to a pressure equal to 1.5 times the initial pressure to obtain a hydrogen to water vapor of 1 to 2.

The system at this point was ready to be powered (electric power applied to membranes) and run.

Figure 5. Left: the vessel containing the membrane stacks is being assembled. Right: final assembly showing the vessel, condenser heat exchanger and cooling water flow controller

The following measurements, shown in Figure 6, were recorded;

1. Pressure inside the vessel.
2. Discharge pressure.
3. Pressure at the compressed water vapor and Hydrogen outlet of the condenser heat exchanger.
4. Discharge temperature.
5. Temperature of water vapor inside the vessel.
6. Temperature of the liquid water inside the vessel.
7. Temperature of the compressed water vapor and Hydrogen at the outlet of the condenser heat exchanger.
8. Temperature of the cooling water at the inlet to the condenser heat exchanger.
9. Temperature of the cooling water at the outlet of the condenser heat exchanger.
10. Volumetric flow rate of the cooling water.
11. Voltage and current supply to the membranes.
12. Electric power supply to the electric heater.

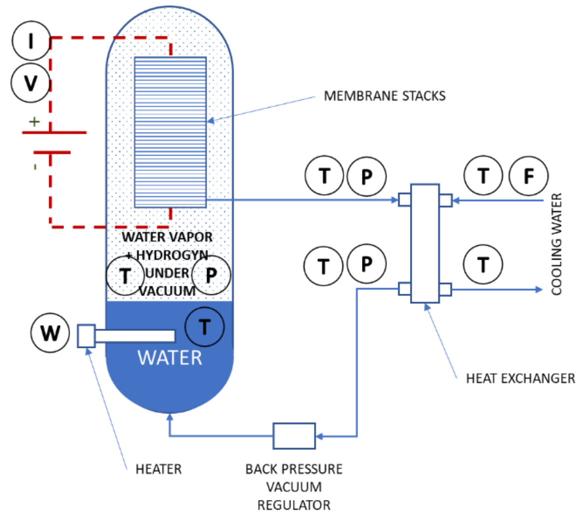

Figure 6. Schematic of the system showing the location of measurement points.

The vessel and the piping were thermally insulated to minimize heat gain from the ambient.

3. SYSTEM TESTING

The goal of this test was to compare the laboratory performance of the system against the design targets. Testing started in May 2017. First test was conducted at power supply of 6.2 Volt across each stack. The circulating fans and the electric hater were turned off. As shown in Figure 7, the temperature of the liquid water inside the vessel decreased with time although at a slow rate. The cooling power provided by the circulating water vapor was approximately 50 Watts as calculated from the time trend of the temperature of the liquid water charge in the vessel. This cooling power was provided by the cooling water, as calculated from the cooling water flow rate and its temperature difference across the condenser, and there was no heat pumping effect. The electrochemical compressor moved water vapor across a pressure ratio of 2.

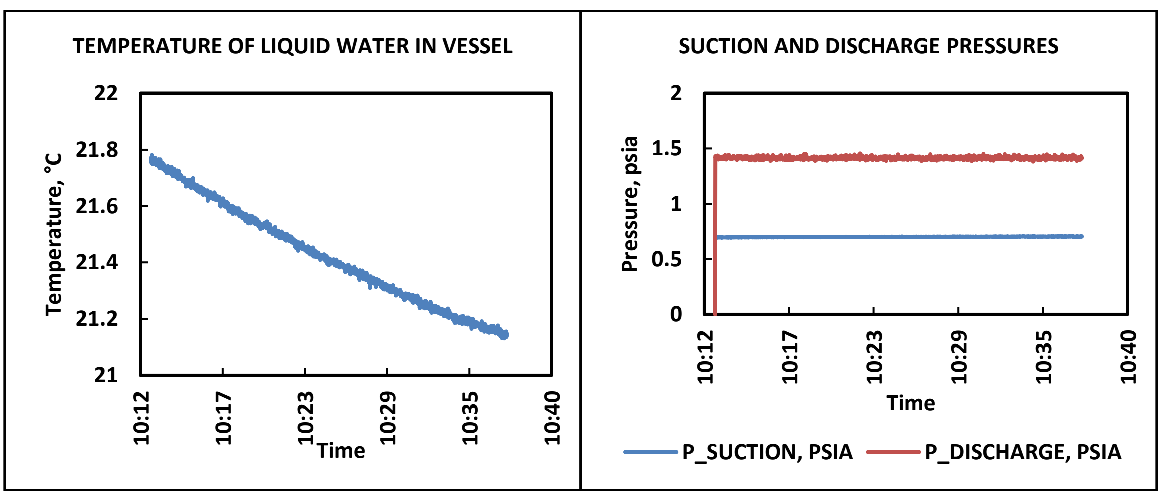

Figure 7. Left: temperature trend of the liquid water inside the vessel. Right: discharge and suction pressure across the electrochemical compressor

The voltage was then raised to 10 Volts across each stack to see if the higher voltage would result in more cooling. The circulating fans were kept off and the heater was turned on. The temperature trend of the liquid water in the vessel and the suction and the discharge pressure during this test are shown in Figure

8. The calculated cooling power from the temperature trend of the liquid water was also 50 Watts. Increasing the supply voltage from 6.2 V to 10 V did not result in more cooling power. The discharge pressure responded to the increase in voltage and increases from 1.41 psia to 1.58 psia which was the saturation limit of the pressure transducer. This transducer was replaced later on with another one with higher measuring range.

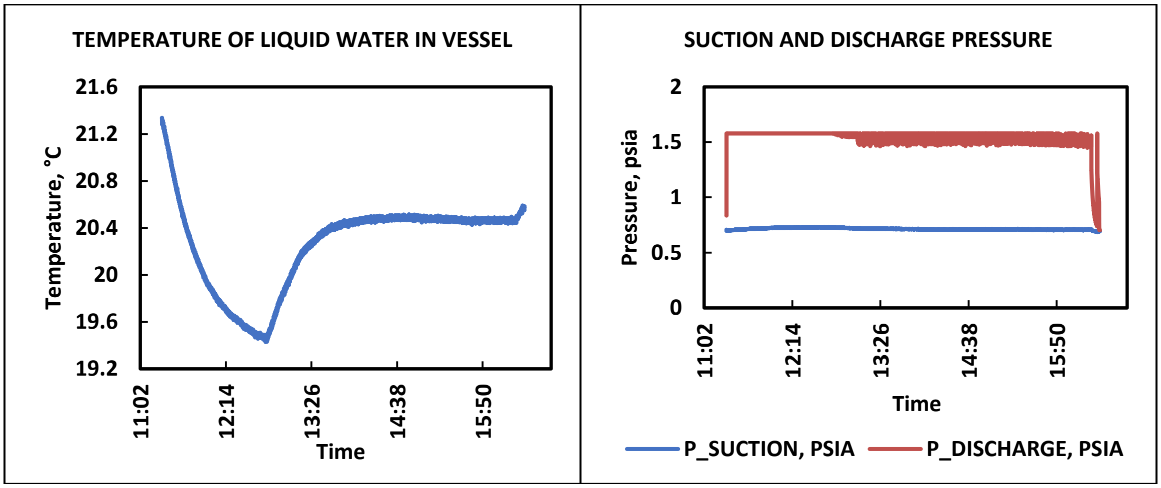

Figure 8. Left: temperature trend of the liquid water inside the vessel. Right: discharge and suction pressure across the electrochemical compressor. The heater was turned on after approximately 20 minutes, causing the liquid water temperature to increase

Several other tests were conducted at different settings of the back-pressure regulator. None resulted in improved performance and no cooling capacity due to heat pumping was observed. The project team then decided to take troubleshooting actions to identify the root cause of the poor performance. In June 2017, troubleshooting started by verifying the performance of the electrochemical cells comprising the compressor. This was done by applying voltage to each stack and measuring the resulting passing current. The resulting Voltage-Current curves are shown in Figure 9. These values were then compared to the manufacturer's specified characteristics of the cells. The comparison showed that the cells performed as expected and within specifications.

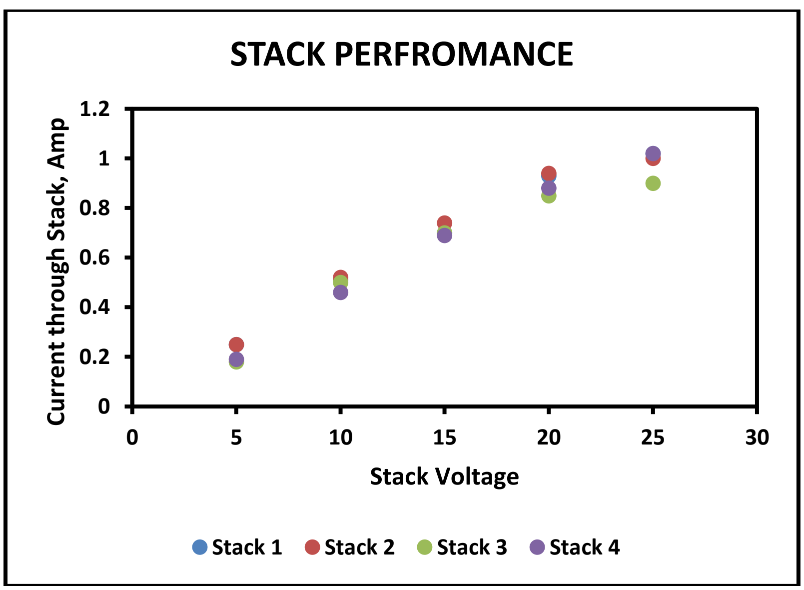

Figure 9. Voltage – current characteristics of individual stacks

The other conceivable reason for the poor performance were:

1. the membranes not having enough water, or
2. the resistance to the flow of the water vapor + Hydrogen mixture is too high.

Additional tests were planned to test both hypotheses. The test plan was to run the electrochemical compressor for extended lengths of time (overnight) to observe the trend of the current consumption. Current consumption is an indication of the flow of water vapor across the membranes. The test plan was executed in August. The recorded current consumption trend is shown in Figure 10.

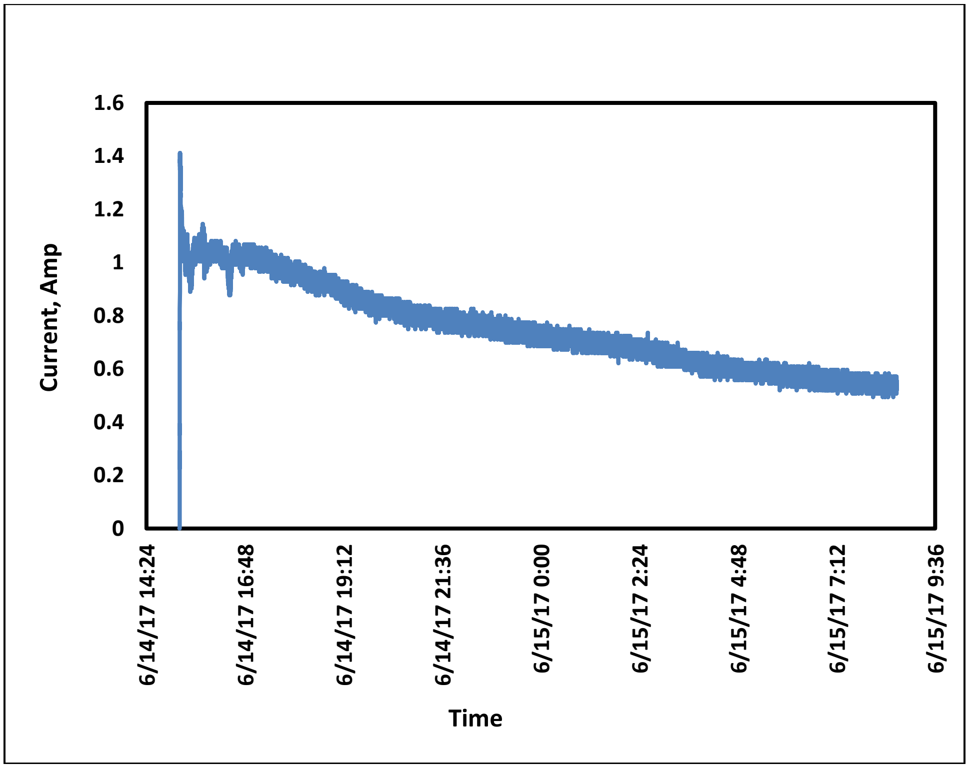

Figure 10. Current flow during overnight run. notice that it decreases

The current decay suggested that the reason for the poor performance is that there is not enough water vapor available to the membranes.

To resolve the issue of the starvation of the membranes of water vapor, the manufacturer suggested covering the gaps between the stacks, highlighted in Figure 11, and the area formed by the stacks at the top to form a closed plenum to the fans. This plenum would confine the discharge of the fans and forces it to flow through the cells of the compressor.

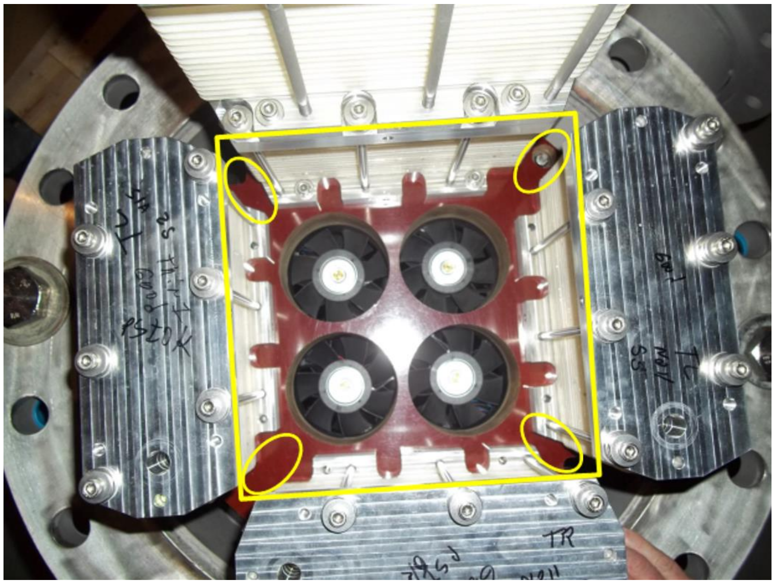

Figure 11. The ovals highlight the vertical gaps to be sealed. The area contained by the square will be covered.

Vertical gaps between stacks were sealed by insulated rubber tubes and a polycarbonate plate was fabricated and placed on top of the stacks to cover the top of the plenum as shown in Figure 12.

Figure 12. Left: transparent polycarbonate plate used to cover the top of the plenum formed by the stacks. Right: showing the placement of one of the insulating tubes to block the vertical gaps between stacks.

The system was run with the fans on at different supply voltages and back pressures, but no cooling capacity was produced.

4. CONCLUSION

The system was tested as shipped but produced no cooling capacity. After several rounds of troubleshooting, modifications were made to improve water vapor availability to the membranes of the electrochemical compressor. The modifications were not effective, and the system still did not produce cooling capacity. Troubleshooting revealed that the electrochemical compressor performed as expected. The inability of the system to produce cooling capacity was most likely due to the system level integration.