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Electrochemical inerting (oxygen control) for food preservation

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Abstract

One of the primary applications for heat pumps is for refrigeration as part of the food chain. Despite widescale adoption, approximately 1.3 billion tons of food is wasted per year around the world [1], leading to excess energy requirements and greenhouse gas emissions. An alternate approach to food preservation is to decrease the oxygen levels in a container to deter spoilage. Decreasing the oxygen levels by merely 3% improves the shelf life of meats and other foods from several days to upwards of weeks. In this paper we describe a solid-state method of oxygen control based on an electrolysis cell, a derivative technology of fuel cells. This technology is quiet, requires no maintenance, and takes up very little space in a refrigerator, making it superior to current pressure/membrane swing adsorption (PSA/MSA) systems employing compressors. This low energy system can be used in conjunction with heat pumps for refrigeration, and in some cases replace heat pumps completely. This paper provides real life, in situ operational data.

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1. Introduction

Creating an inert environment through electrochemical means is a disruptive method for food preservation that can reduce, and in some cases replace, the energy footprint required by heat pump technology to maintain reduced temperatures in a refrigerator.

Currently, inerting systems utilize PSA systems in which a gas stream is fed to a reactor bed by means of a compressor. Certain gas molecules preferentially absorb onto the reactor bed, while others pass through unreacted. The system then undergoes a pressure swing, or change in pressure, to remove the reacted molecules and regenerate the reactor bed. Because there is a regeneration phase the system operates in batch mode, typically requiring multiple beds out of phase This method is very noisy, due to the use of a compressor, bulky, due to the batch method of operation, and energy intensive. The purpose for developing an alternative method of oxygen removal is to reduce the noise, size, and energy requirement of the traditional PSA system.

Several years have been devoted to the development of these systems to assist standard refrigeration in the preservation of food. As depicted in Figure 1, 5 Generations of systems have been manufactured and implemented, each with increases in performance and decreases in cost from the previous generation [2].

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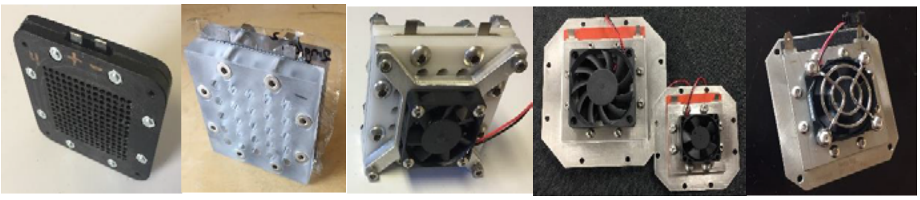

Fig. 1. The 5 generations of oxygen control devices

For an electrochemical inerting system, half of the electrochemical cell operates like the anode of a proton exchange membrane (PEM) water electrolyzer (PEMWE), and the other half of the cell operates like the cathode of a PEM fuel cell (PEMFC). Below, Figure 2 details the operation of all three systems.

The PEM is coated with catalyst on both the anode and cathodes, and then sandwiched by gas diffusion layers (GDL) to assist in electrical conductivity and gas/liquid diffusion to and from the membrane. In PEMWE, water is introduced at the anode side of the system and broken down to oxygen and protons. The protons transport across the membrane to the cathode and react to form hydrogen. In PEMFC, hydrogen is introduced at the anode and reacted to form protons. The protons transport across the membrane and react with oxygen at the cathode to form water and energy.

The PEM inerting system takes moisture out of the air and reacts that moisture at the anode to generate protons and oxygen. The protons transport across the PEM to the cathode and react with oxygen to reform water. The formation of water depletes oxygen in the environment making it rich with nitrogen. The additional water can back diffuse across the PEM or be removed via another dehumidification technology.

Table 1. PEM water electrolysis technology reaction pathways

PEMWE	PEMFC
$Anode: H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^-, E^0 = 1.23V$ $Cathode: 2H^+ + 2e^- \rightarrow H_2, E^0 = 0.00V$ $Total: H_2O \rightarrow \frac{1}{2}O_2 + H_2, E^{0,total} = 1.23V$	$Anode: H_2 \rightarrow 2H^+ + 2e^-, E^0 = 0.00V$ $Cathode: 2H^+ + \frac{1}{2}O_2 + 2e^- \rightarrow H_2O, E^0 = -1.23V$ $Total: H_2 + \frac{1}{2}O_2 \rightarrow H_2O, E^{0,total} = -1.23V$
PEM Inerting	
$Anode: H_2O \rightarrow 2H^+ + \frac{1}{2}O_2 + 2e^-, E^0 = 1.23V$ $Cathode: 2H^+ + \frac{1}{2}O_2 + 2e^- \rightarrow H_2O, E^0 = -1.23V$ $Total: Oxygen\ Depletion, E^{0,total} = 0.00V$	

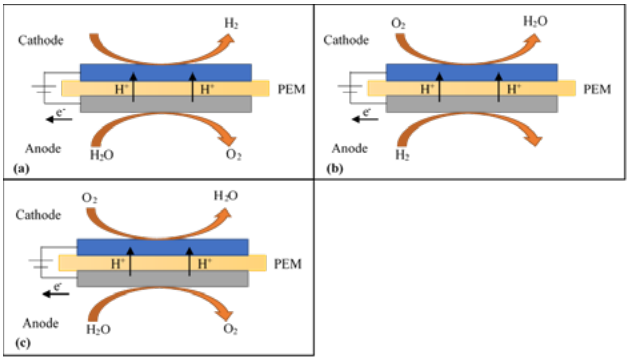

Fig. 2. Operation of (a) a PEMWE for hydrogen generation, (b) a PEMFC for power generation, and (c) a PEM inerting system for oxygen removal

2. Testing and Results

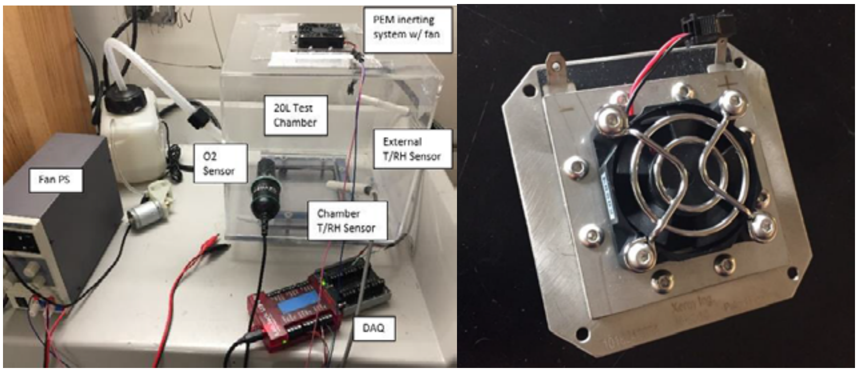

Fig. 3. Oxygen control chamber test set up (left); Sample oxygen cell (right)

The oxygen control chamber test was set up as depicted in Figure 3. Single cell membrane electrode assemblies (MEAs) were sandwiched between current collectors and housings to conduct performance testing. Several membranes were then tested to characterize the performance and determine feasibility of an air-based oxygen depletion system, including commercially produced perfluorosulfonic acid/PTFE copolymer membranes and in-house developed composite membranes. Testing was carried out in a 20 L container, while monitoring cell performance (voltage and current), temperature, humidity, and chamber oxygen levels. All cells were equipped with fans to improve mass flow of moisture to the membrane surface. The room RH was maintained between 45-55% and the room temperature was maintained between 22-23C. A constant 2 V was applied to each cell to carry out inerting.

Three composites of varying thickness (<50 µm) and ionomer composition were assembled into housings and testing against commercially produced 50.8 µm (212) and 127 µm (115) membranes. All systems achieved 75% efficiency for oxygen removal. The composite membranes all gave equivalent performance of around 1 g/hr. while NR212 and N115 achieved oxygen removal rates of 0.58 g/hr. and 0.23 g/hr. respectively. Composites A and B had the highest levels of back diffusion, leading to the lowest humidity increase of all the systems during the inerting process. This is desirable as an environment below 100% RH is preferred for food preservation. The difference in moisture addition to the box for the various membranes highlights the ability to adjust the internal conditions of the chamber through membrane customization.

The results of this testing (Figure 4) shows a power consumption of approximately 10.7 W (membrane - 4.75A @ 2V, fan – 12V @ 0.1A) for the membrane system used in testing. It took approximately 0.64 hours to drop the oxygen from 20.8% to 17.8%, giving the energy consumption of the system to be approximately 6.8 Wh or 9.5 Wh/g-O_2. This system would typically cycle three times a day, for three hours each cycle, putting its average daily energy consumption at about 61 Wh/day. Large-scale PSA systems, the energy consumption is around 500 kWh/tonne-O_2 (0.0005 Wh/g-O_2) [3]. Figure 5 provides an image of a refrigerator equipped with a commercial PSA-type oxygen control system now available in China. While the electrochemical system requires water vapor to operate, the bulk humidity in empty refrigerators is sufficient. Refrigerators to tend to have a bulk relative humidity in the range of 20%-50%, and only increase as food is added.

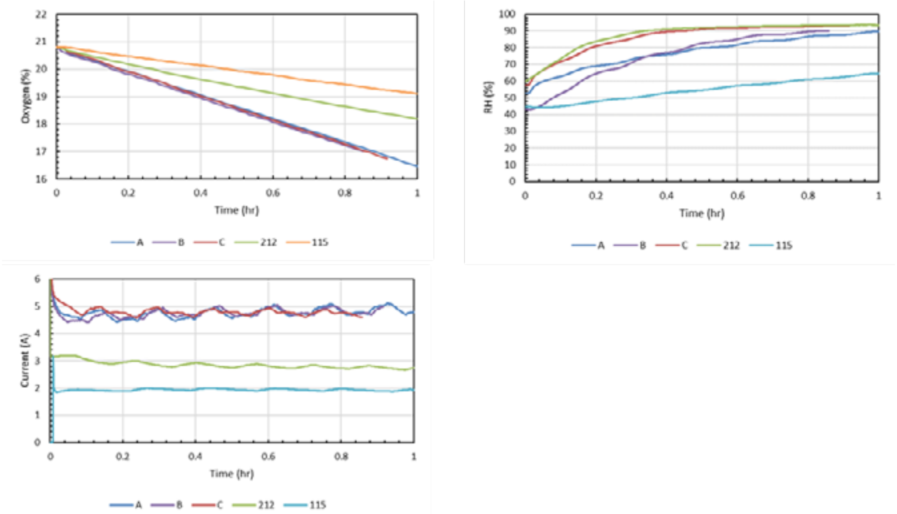

Fig. 4. Test results (in clockwise order, starting with the top left), Oxygen control results; Relative humidity change during oxygen control; Current draw during testing.

Fig. 5. Commercial Refrigerator with PSA type Oxygen control system

The fan system of the electrochemical system emits a faint noise of 20 dBa and is the only component significantly contributing to the noise of the system. As seen in Figure 6, this noise is quieter than a bedroom at night. Micro-compressors in PSA-type systems have noise levels upwards of 65 dBa [4]. This is as loud as normal conversation. In fact, 60 dBa is the threshold of possible permanent damage, thus this noise level is not appropriate for consumers [5].

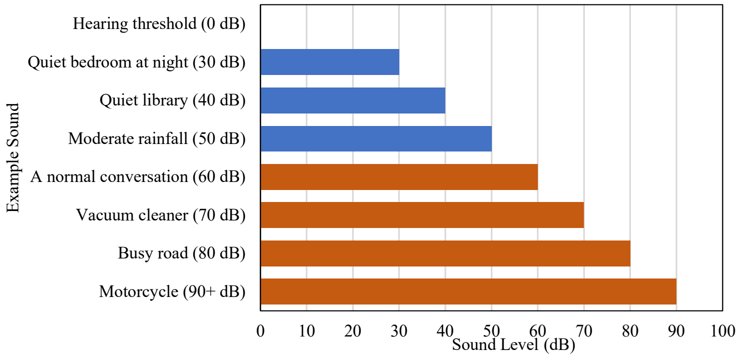

Fig. 6. Decibel levels of common sounds (sound levels at which long-term exposure can lead to hearing damage in orange) [4]

3. Conclusion

An electrochemical inerting system provides a much simpler, sleek, less complex, and lower noise alternative to PSA systems. The largest downside to the novel system is the greater energy consumption. Despite this increased energy consumption, the daily energy consumption of the system is still minimal; its daily power consumption is less than 4% of a typical 2 kWh/day refrigerator [6]. This system still has the potential for further development, exploring new membranes and decreasing the catalyst loading to improve its efficiency and decrease the system cost.

Thin composite membranes achieve the oxygen depletion rates in an electrochemical device, which is required for food preservation, whereas conventional free-standing membranes in the same devices do not [3]. This is a unique aspect of this technology and has resulted in dramatic performance improvements in food preservation applications.

4. Nomenclature

Table 2. Acronyms and abbreviations, defined

Term	Definition	Term	Definition
GDL	Gas Diffusion Layers	PEMWE	Proton Exchange Membrane Water Electrolyzer
MEA	Membrane Electrode Assembly	PSA	Pressure Swing Adsorption
PEM	Proton Exchange Membrane	PTFE	Polytetrafluoroethylene
PEMFC	Proton Exchange Membrane Fuel Cell	RH	Relative Humidity

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