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Pervaporation Membrane for Refrigerator Vegetable Tray Applications

Jacob Zerby[a], Bamdad Bahar[a*], Anderson Bortoletto[b]

[a] *Xergy Inc. 299 A Cluckey Drive, Harrington, DE 19952*
[b] *Sub-Zero Group, Inc. 4717 Hammersley Road, Madison, WI 53711*

Abstract

Many vegetables produce moisture and need moisture for preservation. Higher relative humidity in the vegetable trays or crisper drawers helps to keep vegetables sturdy and fresh. However, cold surfaces can result in condensation and the presence of liquid water inside the unit. One disadvantage of using heat pumps in refrigerators, it the propensity to develop condensation inside vegetable trays. Approximately 1.3 billion tonnes of food is wasted per year around the world [1], leading to excess energy requirements and greenhouse gas emissions. It is important to control all aspects of spoilage, including food storage during refrigeration. One method to increase the storage time of vegetables is to control moisture inside these trays and reduce dehydration, while preventing condensation, or pooling of water. In this paper we describe a pervaporation method, utilizing advanced composite ionic membranes, to control the humidity levels of a sealed box. The system involves an ultra-thin, ultra-strong, ultra-high-water permeability ionic membrane, with a circulation system for enhanced pervaporation. The system improvements allow for a sealed box, Air Exchange Rate (AER) <0.5/hr, with a large reduction in membrane area and reduced dehydration of food illustrated by reduced fluctuations of the internal relative humidity. Membrane properties, chemistry selection and methods of operation for optimal design of a vegetable tray preservation system with heads of lettuce as the source of moisture. Real life, in-situ performance data is provided.

Keywords: Membrane; Humidity Control; Vegetable Tray; Refrigerator;

1. Main text

1.1. Introduction

During storage of vegetables in vegetable trays, water vapor is released from the vegetables and must be removed at a specified, preferably variable, rate to eliminate condensation and rotting of the produce. Currently, the main method for reducing condensation in a vegetable tray is through an opening that can be manually adjusted to let out water vapor as needed. This requires the customer to adjust the opening on the food being stored and is prone to user error. A smarter, more elegant solution with adaptive moisture transfer rates is required to meet the growing demands of food preservation.

The proposed pervaporative solution, portrayed in Figure 1, allows a pathway for high levels of moisture to diffuse to an environment with less moisture, while cutting off the transport of other gaseous species. Pervaporation through a membrane is the process of a liquid or gas-sorbing onto the feed side of a membrane, permeating through the membrane, and subsequently evaporating off at the permeate side of the membrane. The driving force across the membrane is the concentration gradient, with high humidity inside the tray transferring to the low humidity environment in the refrigerator. The dense membrane only allows the transport

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[*] Corresponding author. Tel.: 1-302-629-5768
E-mail address: bamdad.bahar@xergyinc.com

of polar species through, i.e. water, and acts as a barrier to nitrogen and oxygen. High moisture levels are desirable to maintain the freshness of the vegetable and extend the shelf life, whereas allowing too much water vapor to leave the tray causes the vegetable to dry out and be thrown away. There is a need to remove just enough moisture to prevent condensation, without drying out the vegetables.

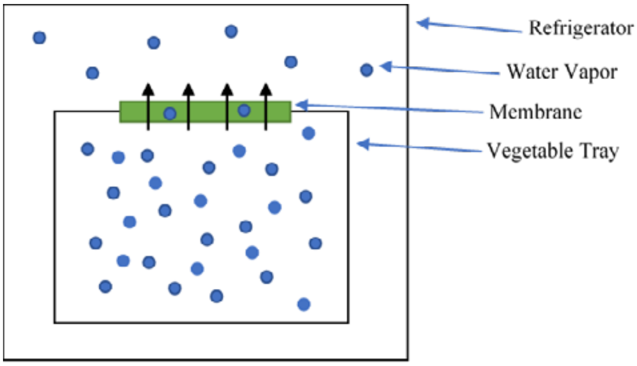

Fig. 1. Diagram of Pervaporative Solution for Humidity Control for Vegetable Trays

1.2. Testing

Initial testing and down selection of membranes was conducting at ambient conditions in the 20 L enclosure, depicted in Figure 2. The room was held around 50% RH and 20°C for all tests. An ultrasonic humidifier was placed in a water bath and plumbed to the box. An air compressor was hooked up to the humidification setup to increase the amount of water vapor entering the box. The humidification system was turned on until the humidity inside the box reached ~90% RH. The test ran until the box hit below 75% RH.

Tests were conducted with and without a fan system to quantify the enhancement to pervaporation.

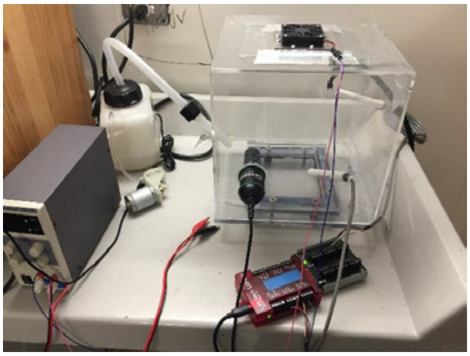

Fig. 2. Membrane Testing Enclosure

1.3. Results and Discussion

The slope of the change in absolute humidity over time was calculated between the range of 85-75% RH and multiplied by the volume of the box, giving the estimated flux rate of the membrane with a box RH of 80% and a room RH of 50%. The following equation was used to calculate the permeance of the membrane:

$$Permeance = \frac{Flux}{(Active\ Area) * (VP_{box} - VP_{ambient})}$$

where the Active Area is the open area of the membrane, VP_{box} is the vapor pressure inside the box (at ~80% RH and ~20°C), and $VP_{ambient}$ is the ambient vapor pressure. Note that the testing methods differ from the ASTM E96; the test method was modified to more closely resemble the actual in application use of the membrane [2]. Instead of maintaining a constant RH in the test chamber, as in the ASTM method, the chamber was charged with an initial 80% RH, which was then allowed to decrease over the period of the test. This batch-like test is reflective of the actual vegetable tray application.

The permeance of the membranes increased with decreasing thickness as expected, as there is less material for the moisture to permeate through. While small changes where not found to have a statistically significant effect on the permeance, as in the range of thickness of membranes B in Figure 3, the permeance of membranes significantly increases with large decreases in thickness, as in membrane A. The best two performing membranes, A and C, are derived from fluorinated ionomers, while membrane B is a non-fluorinated ionomer.

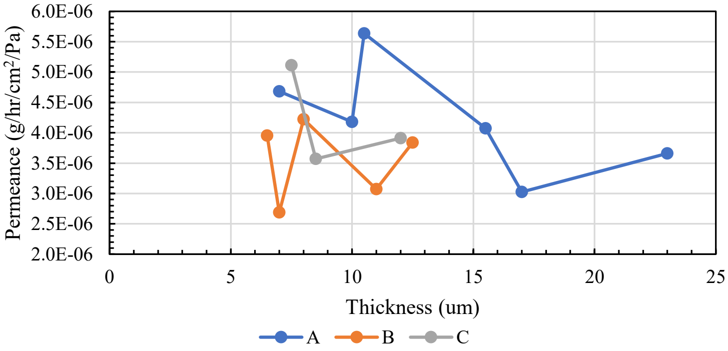

Fig. 3. Permeance of membranes without fan systems

The same test was carried out to analyses various fan systems. As depicted in Figure 4, using a single fan on the inside or outside of the membrane led to a minimal increase in moisture removal rate. However, using a fan on both sides improved the pervaporation by 25x. This suggests that the rate limiting steps are the sorption onto the membrane surface and evaporation from the permeate side, and that they are around the same magnitude and must be addressed simultaneously, as seen in Figure 5. Having such a large increase in performance from the fan system allows for a smarter humidity control system to be used. The fan speeds can be adjusted to adjust the moisture transfer rate based on a sensor in the enclosure; the slower the fan the slower the moisture transfer rate. Employing the fan system is essentially employing a “switch”. By sizing the membrane appropriately, the membrane acts as a poor transmitter of moisture when the fans are off, or a moisture barrier, and rapidly removes humidity when the fans are on the and the membrane is “switched” on.

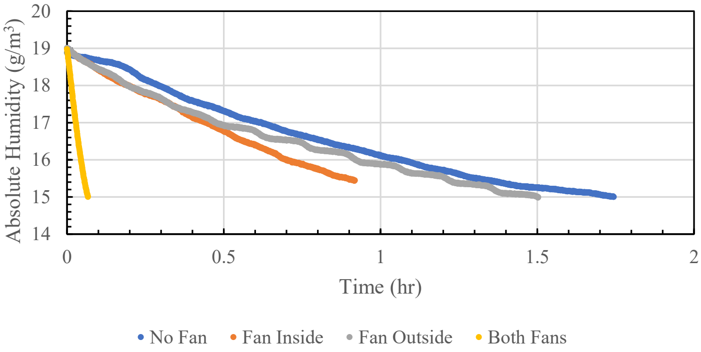

Fig. 4. Results of Fan Configuration Testing

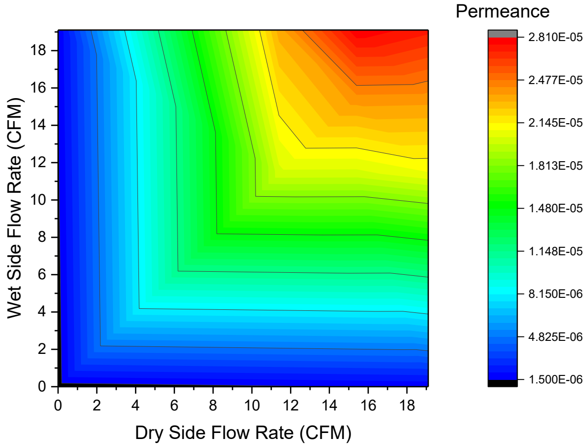

Fig. 5. Results of Flow Rate Analysis

All membranes tested were composite structures, with a base polymer imbibed into a porous support layer. The composite structure allowed for membranes almost 5 µm thick to be evaluated, allowing for high moisture permeance, without sacrificing on the mechanical properties of the membrane. In Table 1, the various support structure-polymer architectures were analyzed, and several (containing Support 1 and 2) were found to have enough mechanical strength for use in a vegetable tray.

Table 1. Mechanical strength of various combinations of base polymer and support material

Architecture	Support 1 – Chemistry 1	Support 1 – Chemistry 2	Support 2 – Chemistry 1	Support 2 – Chemistry 2	Support 3 – Chemistry 2	Support 4 – Chemistry 1
Force (N)	24.76	12.48	6.11	5.57	3.60	1.16
Ultimate Tensile Strength (MPa)	247.6	124.8	58.2	50.6	36.0	11.6

Figures 6 illustrate prototype membrane systems for humidity control for a vegetable tray inside a refrigerator.

Fig. 6. Vegetable Tray with Prototype Membrane System and a fan system (left) and without a fan system (right) Installed for Testing

2. Conclusions

The high permeability and tensile strength of the tested membranes shows strong potential for their application in vegetable trays and crisper drawers. During in-refrigerator application testing, the bulk refrigerated space was found to cycle between 20% and 50% RH. Without a pervaporative membrane the loaded vegetable tray tended have a very high relative humidity, condensing and pooling water. In application, the pervaporative membrane was able to maintain the optimal RH of over 90% without condensation. This system does not have a significant power requirement. The fan system draws 12 V at 0.1 A and the remainder of the system does not draw any power. The fan system can be set to a timer or humidity sensor as a method of controlling the humidity of the tray. Even if the fans ran 24 hours a day, would increase the total daily energy consumption of a typical refrigerator by less than 2%. In the future, thinner membranes and new materials can continued to be explored for higher performance, strength, and permeability.

Acknowledgements

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[4] US Patent Applications: 20190192806, 20190100844

Appendix: The Food and Agriculture Organization of the United Nations' suggested storage conditions for selected produce

Table 2. Storage requirements of humidity sensitive produce [3]

Produce	Storage Temperature (°C)	Relative Humidity (%)
Asparagus	0-2	95
Green Beans	5-7	90-95
Carrots	0	90-95
Cauliflowers	0	90-95
Cucumbers	7-10	90-95
Cabbage	0	90-95
Peppers	7-10	90-95
Ceuregettes	0-10	90-95