

Lab #3 — Mass Transfer in a Package Film

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FABE 3130 — SP 2017

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Monday/Wednesday 7:05 - 8:25pm Lecture

Tuesday 10:45 - 12:35am Lab

Summary of Key Results

The experimental measurements taken throughout this laboratory, including weight change, surface area, film thickness, temperature, and relative humidity, had a significant influence on both the flux of water vapor and the experimental permeability value. Primarily, weight change and surface area directly influenced the mass flux of water vapor to roughly the same extent. Film thickness, temperature, and relative humidity directly influenced the permeability value, with film thickness contributing the least. Moreover, the mass flux of water vapor is proportional to the permeability, therefore any influence on mass flux proportionately impacted permeability. Specifically, the potential errors for each of the experimental measurements were shown to have a significant impact on each of their values and consequently on the overall outcomes of the experiment.

Introduction

This lab explored the concept of mass transfer via analysis of water vapor transmission through a polymer package film during a specified period of time. The amount of water vapor transmission, along with the package surface area and vapor pressure gradient, was then utilized to estimate the permeability of the package film.

Experimental Procedures

A zip-lock plastic bag was provided; the dimensions of the bag, including height and width, were measured. The thickness of the package film was measured using calipers. Approximately 25 g of a dry absorbing material was placed in the bag, and the exact mass (weight) was recorded. The bag and its contents were then placed in a controlled temperature and relative humidity chamber on March 28 at 3:35PM. The relative humidity and dry bulb temperature of the chamber were maintained at 69.1% and 103.8 °F, respectively. The package was kept in the controlled chamber for approximately 7 days; it was removed from the chamber on April 4 at 10:10AM, and the final weight of the bag and its contents were then measured and recorded.

Data and Results

The table below contains the raw data that was measured and recorded during the laboratory session as well as data and results calculated for analysis.

$Length_{bag}$	0.165 m
$Width_{bag}$	0.149 m
A_{bag} (surface area)	0.04917 m^2
$Time_{initial}$	March 28, 3:35PM
$Time_{final}$	April 4, 10:10AM
Δt	585300 s
$Mass_{initial}$	27.3469 g
$Mass_{final}$	27.6361 g
$Mass_{water}$	0.2892 g
N_A (mass flux)	$1.0049 \times 10^{-5} \text{ kg/m}^2 \cdot \text{s}$
$Thickness_{film}$ (Δz)	0.00004 m
$Temp_{chamber}$	39.89 °C
$RH_{chamber}$	69.10%
p_{A1} (vapor pressure outside package)	5.076 kPa
p_{A2} (vapor pressure inside package)	0 kPa
P (permeability)	$1.7749 \times 10^{-9} \text{ kg} \cdot \text{m/m}^2 \cdot \text{kPa} \cdot \text{s}$

Analysis of Data

The following expression describes water vapor transmission through the package film based on the relationship between mass flux and vapor pressure gradient:

$$N_A = \left[\frac{D_{AB} \times S \times A}{22.414} \right] \left[\frac{(p_{A1} - p_{A2})}{(\Delta z)} \right] = \frac{\text{Mass}_{\text{water}}}{A_{\text{bag}} \times \Delta t}$$

The properties represented by each of the variables and their corresponding values are calculated, explained, and utilized throughout this lab report when applicable.

In order to compute the mass flux, N_A , it was necessary to first determine the surface area of the package, A_{bag} , the amount of time the package was inside the chamber, Δt , and the weight of the water transmitted through the package film, $\text{Mass}_{\text{water}}$. The surface area of the package, A_{bag} , was determined by multiplying the length of the bag by the width of the bag and then multiplying by 2 to account for both sides of the bag:

$$A_{\text{bag}} = 2 \times (\text{Length}_{\text{bag}} \times \text{Width}_{\text{bag}}) = 2(0.165 \text{ m})(0.149 \text{ m}) = 0.04917 \text{ m}^2$$

The amount of time the package was inside the chamber, Δt , was found by determining the amount of time between the start date (when the package was placed in the chamber), $\text{Time}_{\text{initial}}$ of March 28 at 3:35PM and the end date (when the package was taken out of the chamber), $\text{Time}_{\text{final}}$ of April 4 at 10:10AM. First, the number of whole days was found to be 6, accounting for the time between March 28 at 3:35PM and April 3 at 3:35PM. Converting 6 days to seconds:

$$6 \text{ days} \left(\frac{24 \text{ hours}}{1 \text{ day}} \right) \left(\frac{60 \text{ minutes}}{1 \text{ hour}} \right) \left(\frac{60 \text{ seconds}}{1 \text{ minute}} \right) = 518400 \text{ seconds}$$

Next, the number of whole hours was found to be 18, accounting for the time between April 3 at 3:35PM and April 4 at 9:35AM. Converting 18 hours to seconds:

$$18 \text{ hours} \left(\frac{60 \text{ minutes}}{1 \text{ hour}} \right) \left(\frac{60 \text{ seconds}}{1 \text{ minute}} \right) = 64800 \text{ seconds}$$

Finally, the number of whole minutes was determined to be 35, accounting for the time between April 4 at 9:35AM and 10:10AM. Converting 35 minutes to seconds:

$$35 \text{ minutes} \left(\frac{60 \text{ seconds}}{1 \text{ minute}} \right) = 2100 \text{ seconds}$$

Adding the number of whole days, hours, and minutes, all converted to seconds, gives a total time, t , of:

$$\Delta t = 518400 \text{ seconds} + 64800 \text{ seconds} + 2100 \text{ seconds} = 585300 \text{ seconds}$$

The weight of the water transmitted through the package film, $\text{Mass}_{\text{water}}$, was found by subtracting the initial weight of the package, $\text{Mass}_{\text{initial}}$, from the final weight of the package, $\text{Mass}_{\text{final}}$:

$$\text{Mass}_{\text{water}} = \text{Mass}_{\text{final}} - \text{Mass}_{\text{initial}} = 27.6361 \text{ g} - 27.3469 \text{ g} = 0.2892 \text{ g}$$

The mass flux, N_A , can then be computed from the relationship between the surface area of the package, A_{bag} of 0.04917 m^2 , the amount of time the package was in the chamber, Δt of 585300 seconds, and the weight of the water transmitted through the package film, $\text{Mass}_{\text{water}}$ of 0.2892 g:

$$N_A = \frac{\text{Mass}_{\text{water}}}{A_{\text{bag}} \Delta t} = \frac{0.2892 \text{ g} \left(\frac{1 \text{ kg}}{1000 \text{ g}} \right)}{(0.04917 \text{ m}^2)(585300 \text{ seconds})} = 1.0049 \times 10^{-5} \frac{\text{kg}}{\text{m}^2 \cdot \text{s}}$$

In order to determine Permeability (P), it was necessary to first determine the vapor pressure difference. The vapor pressure difference is equal to the difference between the vapor pressure outside the package, p_{A1} , and the vapor pressure inside the package, p_{A2} . The vapor pressure outside the package, p_{A1} , was calculated using the conditions of the air within the chamber, namely relative humidity, RH, of 69.1%, and dry-bulb temperature, $\text{Temp}_{\text{chamber}}$, of 103.8°F . Since the desired units of pressure, kPa, are metric, the temperature was first converted to Celsius:

$$(103.8^\circ\text{F} - 32) \times \left(\frac{5}{9} \right) = 39.89^\circ\text{C}$$

Next, the saturation pressure at 39.89°C was retrieved from Table A-9 (Properties of Saturated Water) by using linear interpolation:

$$5.628 \text{ kPa} + \left(\frac{39.89 - 35}{40 - 35}^\circ\text{C} \right) (7.384 - 5.628 \text{ kPa}) = 7.345 \text{ kPa}$$

Multiplying this pressure by the relative humidity within the chamber:

$$(7.345 \text{ kPa})(0.691) = 5.076 \text{ kPa}$$

gave the vapor pressure outside the package, $p_{A1} = 5.076 \text{ kPa}$. The vapor pressure inside the package, p_{A2} , was assumed to be 0 kPa, indicating that there was no vapor pressure inside the sealed bag. The vapor pressure difference was then calculated:

$$(p_{A1} - p_{A2}) = 5.076 \text{ kPa} - 0 \text{ kPa} = 5.076 \text{ kPa}$$

The relationship between the vapor pressure difference, $p_{A1} - p_{A2}$ of 5.076 kPa, the mass flux, N_A of $1.0049 \times 10^{-5} \frac{\text{kg}}{\text{m}^2 \cdot \text{s}}$, the surface area, A_{bag} of 0.04917 m^2 , and the film thickness, Δz of 0.00004 m can then be used to determine the permeability, P:

$$\begin{aligned} D_{AB}S = P &= \frac{N_A \times 22.414 \times \Delta z}{(p_{A1} - p_{A2})} = \frac{\left(1.0049 \times 10^{-5} \frac{\text{kg}}{\text{m}^2 \cdot \text{s}} \right) \times 22.414 \times (0.00004 \text{ m})}{(5.076 \text{ kPa} - 0 \text{ kPa})} \\ &= 1.7749 \times 10^{-9} \frac{\text{kg} \cdot \text{m}}{\text{m}^2 \cdot \text{kPa} \cdot \text{s}} \end{aligned}$$

Discussion of Results

The following table provides a presentation of key results used throughout the discussion of experimental outcomes.

Temp _{chamber}	39.89 °C
RH _{chamber}	69.10%
A _{bag} (surface area)	0.04917 m ²
Mass _{water}	0.2892 g
N _A (mass flux)	1.0049 x 10 ⁻⁵ kg/m ² ·s
Thickness _{film} (Δz)	0.00004 m
P (permeability)	1.7749 x 10 ⁻⁹ kg·m/m ² ·kPa·s

- 1. The influence of each experimental measurement (weight change, surface area, film thickness, temperature, relative humidity) on the flux of water vapor and the experimental permeability (P) value. Discuss the influence of potential measurement errors on the outcomes.**

The weight of water transmitted through the package film was taken to be the change in weight of the package and its contents, found by subtracting the initial weight of the bag from the final weight of the bag. One potential cause of error in measurement could have been the result of simple user error, specifically in operating the scale incorrectly or failing to be meticulous enough. Additionally, all of the mass that was accumulated was considered to be water. This assumption does not necessarily account for any additional particulates or contaminants that may have accompanied the water and contributed to the increase in mass. These potential measurement errors—corresponding to the value determined to be the weight of water transmitted through the package film—would have a direct influence on the mass flux of water vapor. Mass flux of water vapor was computed using only this value, the experimentally measured surface area of the bag, and the time change, thus accuracy of this value would have been essential in achieving the outcome expected for the value of N_A. Consequently, the value of the permeability would be erroneous since mass flux of water vapor is used directly in its calculation.

The surface area was found using the experimental measurements of length and width of the bag. These measurements corresponded precisely to the dimensions given on the box, so it is reasonable to assume they were relatively accurate. Nevertheless, the exact dimensions could very slightly depend on the precision of manufacturing, and therefore could've marginally skewed the surface area they were used to calculate. Additionally, when calculating the surface area, the bag was considered to be two completely flat planes rather than the three-dimensional object that it realistically is. Potential measurement errors relating to the surface area value would have an influence on the mass flux of water vapor and in turn the permeability similarly to

those relating to the value used as the mass of water transmitted through the package film, as both are used directly in the calculation.

The film thickness of the bag was measured entirely experimentally using calipers. As such, aside from potential errors in calibration of the caliper itself, there was considerable risk of user error due to the compressibility of the plastic film material. In order to obtain a precise measurement, just the right amount of force is required to be exerted on the calipers. This potential measurement error would have no influence on the mass flux of water vapor. Furthermore, though the value of film thickness, Δz , is used directly in the calculation of permeability, its magnitude is very small compared to other values used in the computation, and therefore any error in its value would have an almost negligible effect on the permeability.

The experimental measurements of temperature and relative humidity can be considered collectively, since their values were used solely in determining the vapor pressure difference, specifically the vapor pressure outside the package. The temperature was used to obtain a saturation pressure from a table containing properties of saturated water at specific temperatures; it was then multiplied by relative humidity to obtain the vapor pressure outside the package. Because the vapor pressure difference has a direct and significant impact on the permeability, any experimental errors contributing to its computation would also impact the degree of accuracy of the outcome. Primarily, the values of temperature and relative humidity used were assumed to have remained constant throughout the entire week, which is rather unrealistic.

2. The permeability (P) is expected to be in the range from 10^{-10} to 10^{-8} kg m/m² s kPa. Discuss the reasons for differences between the experimental values and the expected outcomes.

The permeability calculated, $1.7749 \times 10^{-9} \frac{\text{kg} \cdot \text{m}}{\text{m}^2 \cdot \text{kPa} \cdot \text{s}}$, was in fact within the expected range from 10^{-10} to $10^{-8} \frac{\text{kg} \cdot \text{m}}{\text{m}^2 \cdot \text{kPa} \cdot \text{s}}$. There are a variety of reasons, nonetheless, for differences that could have occurred between the experimental values and the expected outcomes. One such explanation could be that the permeability of the plastic bag may change due to shifts in location or atmosphere as time passes. Additionally, the relative humidity and temperature inside the chamber could have fluctuated slightly if it were opened and closed for samples from other laboratories. Further discrepancies between the experimental values and expected outcomes would most likely be due to experimental measurement errors as discussed in the previous question.

3. Discuss the relationships among the mass diffusivity (D), solubility (S) and Permeability (P). If $S = 10 \text{ kg/m}^3 \text{ kPa}$, estimate the magnitude of mass diffusivity (D).

There is a directly proportional relationship between the permeability (P) of a material and the material's mass diffusivity (D_{AB}) and solubility (S). The solubility relates the concentration within the film to the partial pressure, while the mass diffusivity represents the process by which matter is transported. Permeability is equal to the product of mass diffusivity and solubility:

$$D_{AB} \times S = P$$

Therefore, if $S = 10 \frac{\text{kg}}{\text{m}^3 \cdot \text{kPa}}$, with $P = 1.7749 \times 10^{-9} \frac{\text{kg} \cdot \text{m}}{\text{m}^2 \cdot \text{kPa} \cdot \text{s}}$, rearranging the above formula, the magnitude of D_{AB} would be calculated to be:

$$D_{AB} = \frac{P}{S} = \frac{1.7749 \times 10^{-9} \frac{\text{kg} \cdot \text{m}}{\text{m}^2 \cdot \text{kPa} \cdot \text{s}}}{10 \frac{\text{kg}}{\text{m}^3 \cdot \text{kPa}}} = 1.7749 \times 10^{-10} \frac{\text{m}^2}{\text{s}}$$

Conclusions

The experimental measurements, including weight change, surface area, film thickness, temperature, and relative humidity, had a significant influence on the flux of water vapor and the experimental permeability value. Likewise, the potential measurement errors associated with each value also largely impacted the overall outcomes of the experiment. Differences were observed between the experimental values and expected outcomes, specifically in the case of permeability, also principally due to error in experimental measurements. The permeability depends directly on the solubility and mass diffusivity, and can be represented via their product.

References

Çengel, Yunus A. and Ghajar, Afshin J. Appendix 1 Table A-9 of *Heat and Mass Transfer: Fundamentals and Applications*, 5th Edition. New York: McGraw-Hill Education.

Fischer, Joel. (MOCON Lab Manager, Producer). (2010). *High Temperature Permeation Testing* [Webinar Series]. Retrieved from <https://www.slideshare.net/guywray/high-temp-webinar>