Characterizing Mass and Heat Transfer over Stagnant Water

February 25, 2025

Group TR9
Taihar Tsengel, Alexander Tam,
Vincent Kwok, and Matthew Lokhonia

Mass and Heat Transfer Over Stagnant Liquids is Everywhere

Why understand MT and HT in a stagnant body of water?

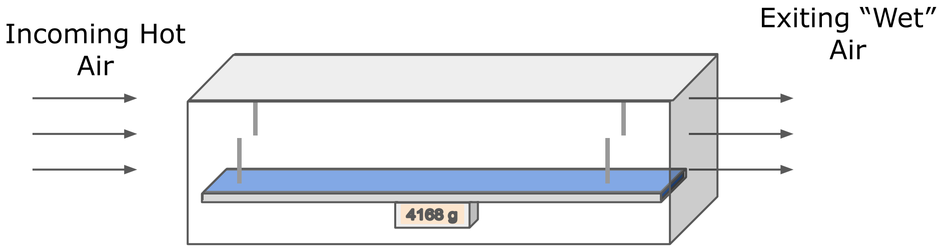
- Results can be extrapolated to other liquids and gases
  - O_2 stripping in beverages
  - O_2 removal from semiconductor manufacturing
  - Increasing humidity in HVAC systems

- Helps better understand MT and HT theory

Objectives

- Identify how mass transfer coefficient depends on air velocity
- Characterize the concentration and thermal boundary layers

Methods



$$K_{m,H2O} = \frac{N_{H2O}}{\Delta c_{H2O}}$$

Equation 1. Flux Relationship[1]

$$K_{m,H2O} = \frac{D_{H2O,air}}{\delta_c}$$

Equation 2. Film Theory Method[1]

$$Sh_L = 0.664 Re_L^{1/2} Sc^{1/3}$$

$$K_{M,H_2O} = \frac{0.664 D_{H_2O,air}}{L} Re_L^{1/2} \left(\frac{\nu_{\text{air}}}{D_{H_2O,air}} \right)^{1/3}$$

Equation 3. Reynold's Method using laminar flow[2]

Independent Variable
- Air Velocity v_∞

Constants
- Temperature
- RH% room

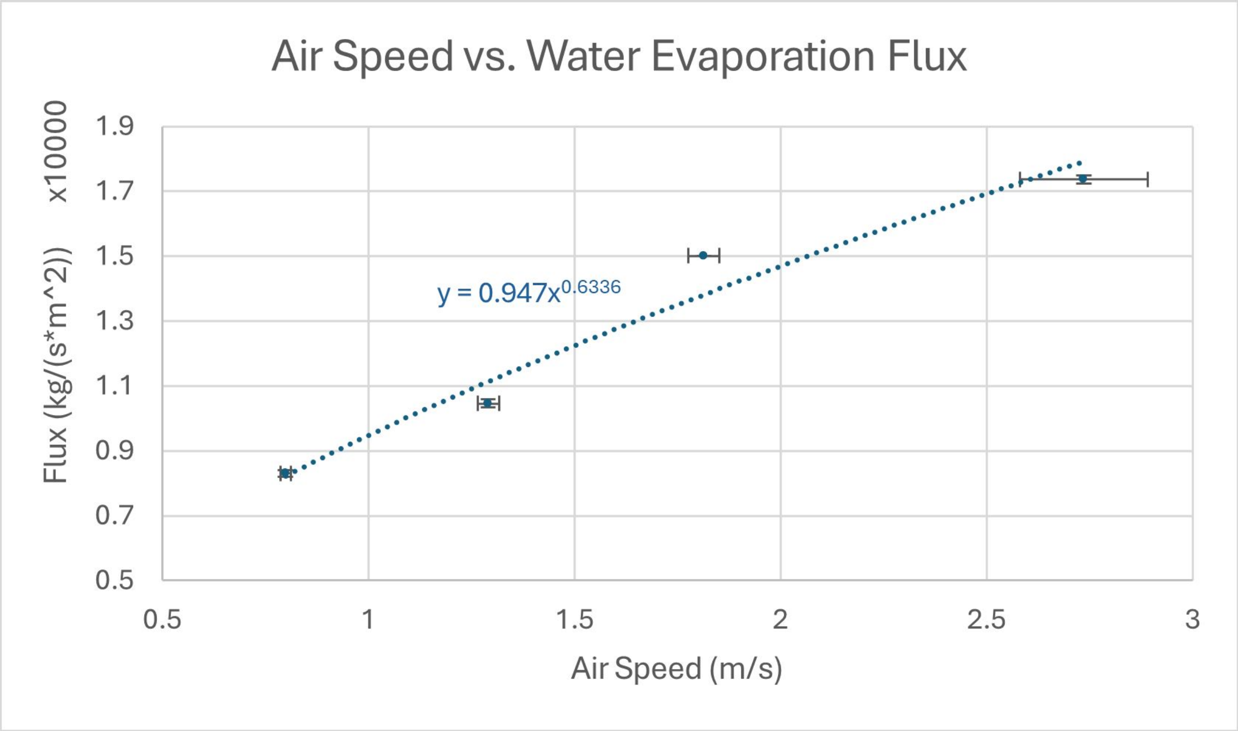
Measure
- RH% outlet air
- Mass of water + tray

Calculate
- Water flux
- Boundary layer thicknesses

Find Mass Transfer Coefficient

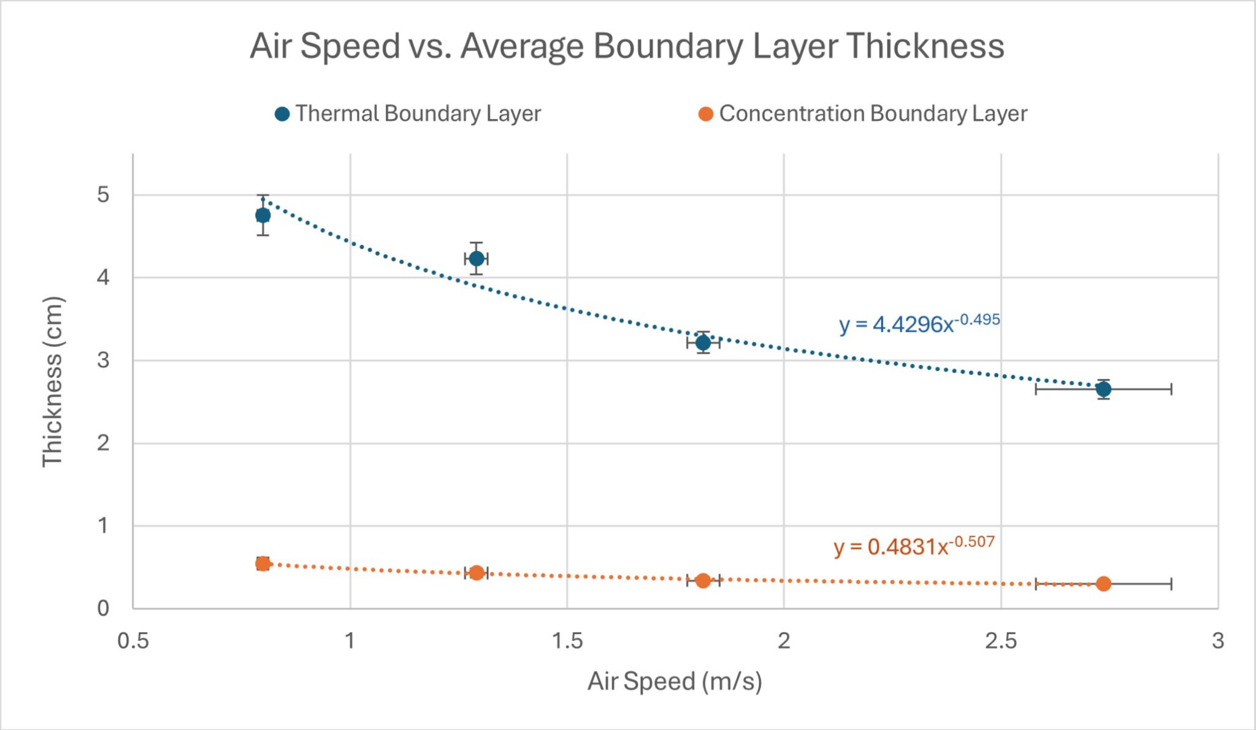
(1) Behesti-Pour, A. Katz. Mass Transfer (MT)_Revised_2024.docx; University of California, Berkeley: Berkeley, California, 2024.
(2) Incropera, F. P., DeWitt, D. P., Bergman, T. L., & Lavine, A. S. (2007). *Fundamentals of momentum, heat, and mass transfer* (5th ed., p. 528). John Wiley & Sons.

Evaporation Rate of Water Increases with v_∞



Suggests that Mass Transfer Coefficient Increases with Air Speed

Boundary Layer Thickness decreases with v_∞



Thermal Boundary Layer much larger than Concentration Boundary Layer

Boundary Layer Thickness scales with approximately $v^{-0.5}$

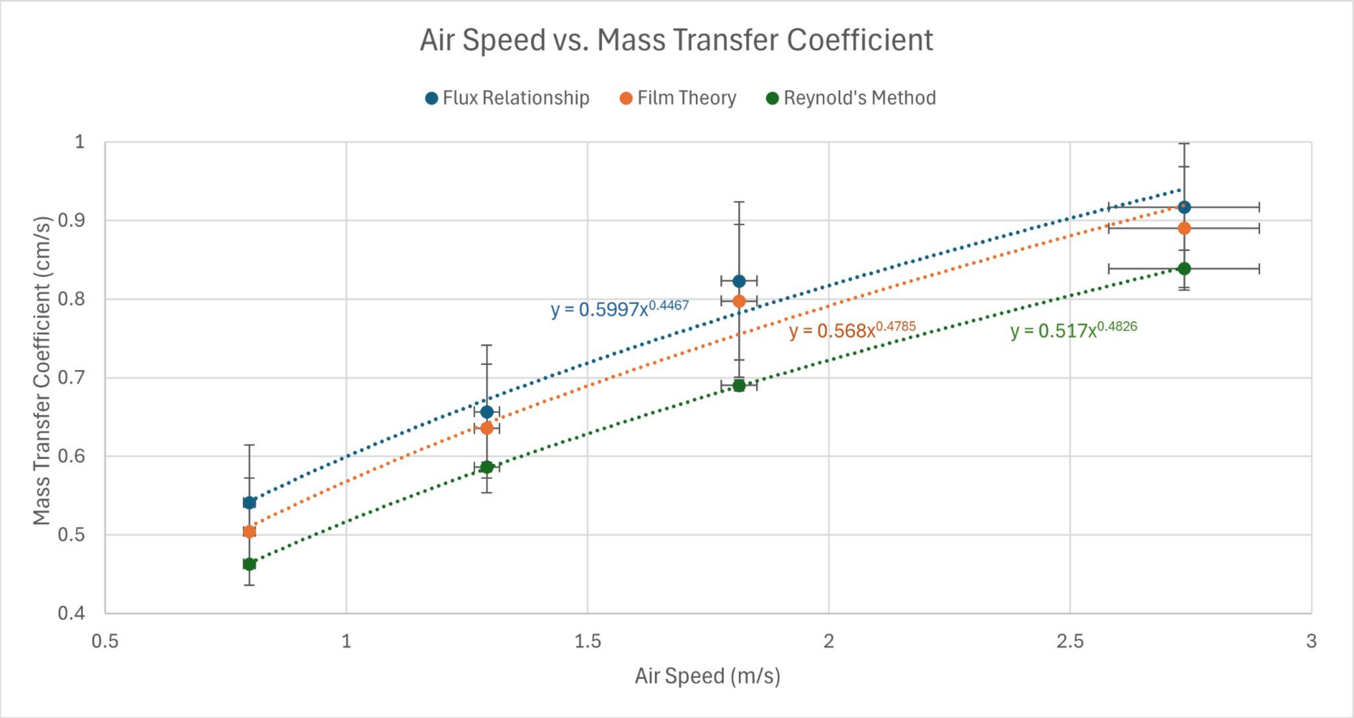
Expectation: $\delta_T, \delta_C \propto v^{-0.5}$

Thermal Boundary Layer: $\delta_T = 4.43v^{-0.50\pm0.07}$

Concentration Boundary Layer: $\delta_C = 0.48v^{-0.51\pm0.05}$

Wind Speed (m/s)	δ_T (m)	δ_C (m)
2.74 ± 0.16	0.0265 ± 0.0011	0.0030 ± 0.0003
1.81 ± 0.04	0.0321 ± 0.0013	0.0034 ± 0.0004
1.29 ± 0.03	0.0423 ± 0.0019	0.0043 ± 0.0006
0.799 ± 0.012	0.048 ± 0.002	0.0053 ± 0.0007

Mass Transfer Coefficient increases with v_∞



Reynold's method has lowest margin of error due to many velocity samples

Mass Transfer Coefficient scales with approximately $v^{0.5}$

Expectation: $K_m \propto v^{0.5}$

Flux Relationship: $K_m = 0.60v^{0.45\pm0.05}$

Film Theory: $K_m = 0.57v^{0.48\pm0.05}$

Reynold's Method: $K_m = 0.517v^{0.483\pm0.003}$

Wind Speed (m/s)	Flux Relationship K_m (m/s)	Film Theory K_m (m/s)	Reynold's Method K_m (m/s)
2.74 ± 0.16	0.0092 ± 0.0008	0.0089 ± 0.0008	0.0084 ± 0.0002
1.81 ± 0.04	0.0082 ± 0.0010	0.0080 ± 0.0010	0.00690 ± 0.00007
1.29 ± 0.03	0.0066 ± 0.0008	0.0064 ± 0.0008	0.00586 ± 0.00006
0.799 ± 0.012	0.0054 ± 0.0007	0.0052 ± 0.0007	0.00463 ± 0.00004

Conclusions

1) **Flux Increases with Air Speed**

2) **Thermal BL larger in size than Concentration BL**

3) **BL thickness scales with $v^{-0.5}$**

4) **Mass Transfer Coefficient scales according to $K_m \propto v^{0.5}$**

Appendix A: Mass Flux Values

Wind Speed (m/s)	Mass Flux (kg H_2O/m^2*s)
2.74 ± 0.16	0.0001737 ± 0.0000013
1.81 ± 0.04	0.0001502 ± 0.0000000
1.29 ± 0.03	0.0001046 ± 0.0000013
0.799 ± 0.012	0.0000830 ± 0.0000011

Appendix B: Temperature and Concentrations Gradient Calculations

$$(dT/dz)_0 = \frac{N_{A0}\Delta H_{va}}{k}$$

p

$$(dC_A/dz)_0 = \frac{N_{A0}(x_{A0}-1)}{D_{AB}}$$

Where,

N_{A0} = Flux of water

k = Thermal conductivity of water

x_{A0} = Interface water mole fraction

Appendix C: Temperature and Concentrations Gradient Values

Wind Speed (m/s)	$(dT/dz)_0$ (K/m)	$(dC_A/dz)_0$ (kg/m^4)
2.74 ± 0.16	702 ± 5	-6.34 ± 0.05
1.81 ± 0.04	605 ± 0	-5.382 ± 0.006
1.29 ± 0.03	420 ± 5	-3.70 ± 0.04
0.799 ± 0.012	333 ± 5	-2.92 ± 0.04

Appendix D: Concentration Calculations

$$P_{water} = (RH/100)*P_{sat,water}$$

$$C_{bulk} = \frac{P_{water}}{R*T_{Air}}$$

$$C_{interface} = x_{A0} \frac{P}{R*T_{interface}}$$

Where,

RH = Relative Humidity

x_{A0} = Interface water mole fraction

Appendix E: Temperature and Concentration Boundary Layer Thickness Calculations

$$\delta_T = \frac{\Delta T}{(dT/dz)_0}$$

$$\delta_C = \frac{\Delta C_A}{(dC_A/dz)_0}$$

Where,

$\Delta T = T_{bulk} - T_{interface}$

$\Delta C_A = C_{bulk} - C_{interface}$

Appendix F: Temperature and Concentration Boundary Layer Thickness Values

Wind Speed (m/s)	δ_T (m)	δ_C (m)
2.74 ± 0.16	0.0265 ± 0.0011	0.0030 ± 0.0003
1.81 ± 0.04	0.0321 ± 0.0013	0.0034 ± 0.0004
1.29 ± 0.03	0.0423 ± 0.0019	0.0043 ± 0.0006
0.799 ± 0.012	0.048 ± 0.002	0.0053 ± 0.0007

Appendix G: Mass Transfer Coefficient Values

Wind Speed (m/s)	Flux Relationship K_m (m/s)	Film Theory K_m (m/s)	Reynold's Method K_m (m/s)
2.74 ± 0.16	0.0092 ± 0.0008	0.0089 ± 0.0008	0.0084 ± 0.0002
1.81 ± 0.04	0.0082 ± 0.0010	0.0080 ± 0.0010	0.00690 ± 0.00007
1.29 ± 0.03	0.0066 ± 0.0008	0.0064 ± 0.0008	0.00586 ± 0.00006
0.799 ± 0.012	0.0054 ± 0.0007	0.0052 ± 0.0007	0.00463 ± 0.00004

Appendix H: Equation Variable Definitions

Variable	Definition	Unit
$K_{m,H2O}$	Mass Transfer Coefficient	m/s
N_{H2O}	Mass Flux of Water	kg/(s*m^2)
Δc_{H2O}	Concentration Gradient (Surface - Bulk)	kg/m^3
$D_{H2O,air}$	Diffusivity of water into air	m^2/s
δ_c	Concentration boundary layer thickness	m
L	Length of plate	m
ν_{air}	Kinematic viscosity of air	m^2/s