Team 11: Pool Evaporation

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Mechanical Science & Engineering
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Presentation Overview

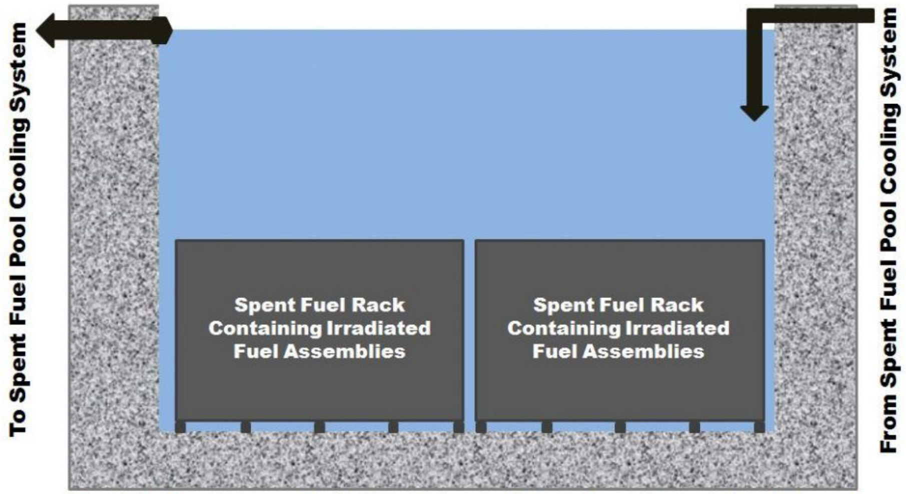
- Introduction
- Goals
- Problem
- Experimental Setup
- Literature Review and Theory on Pool Evaporation
- Time Planning and Deliverable
- Budget

Introduction

- Sponsor: Sargent & Lundy
- Task: Predict evaporation rates of pool in different configurations
- Application: Nuclear reactor spent fuel pool
- Little literature available

Problem

- Spent Fuel Pool: Deep pools of water used to cool spent fuel
- Why is it important to control water level?
- Fukushima disaster

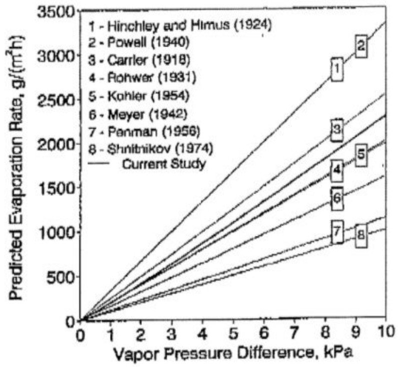


Spent fuel pools are about 45 feet deep with reinforced concrete walls and floors. Metal racks sitting on feet a few inches off the floors hold irradiated (spent) fuel assemblies. Water from the pool is circulated through the spent fuel pool cooling system to remove the decay heat produced by unstable radioactive byproducts in the irradiated fuel.

Objectives and Deliverables

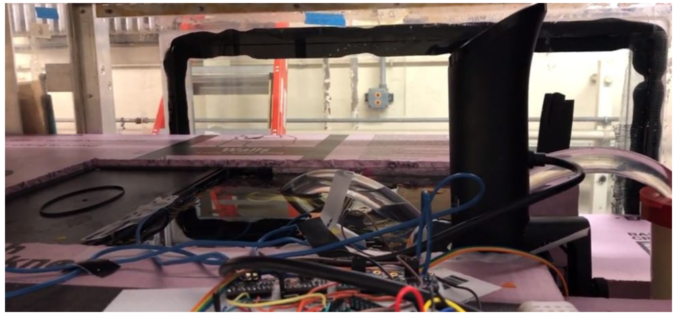
Analytical Model

- Derive model for forced and natural convection of a pool taking into account:
    - Environmental Conditions
    - Airflow Speed
    - Water Temperature



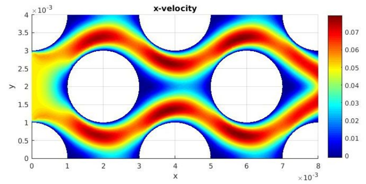
Experiment

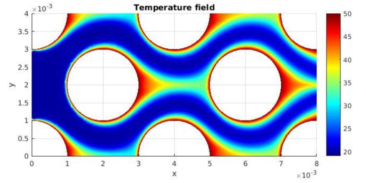
- Develop experiment controlling airflow
- Record surrounding conditions and observe effects on evaporation rate
- Use experimental data to verify performance of analytical model



CFD Model

- Use analytical model to create a Computational Fluid Dynamics Model showing the interaction between the pool surface and ambient





Project Progress

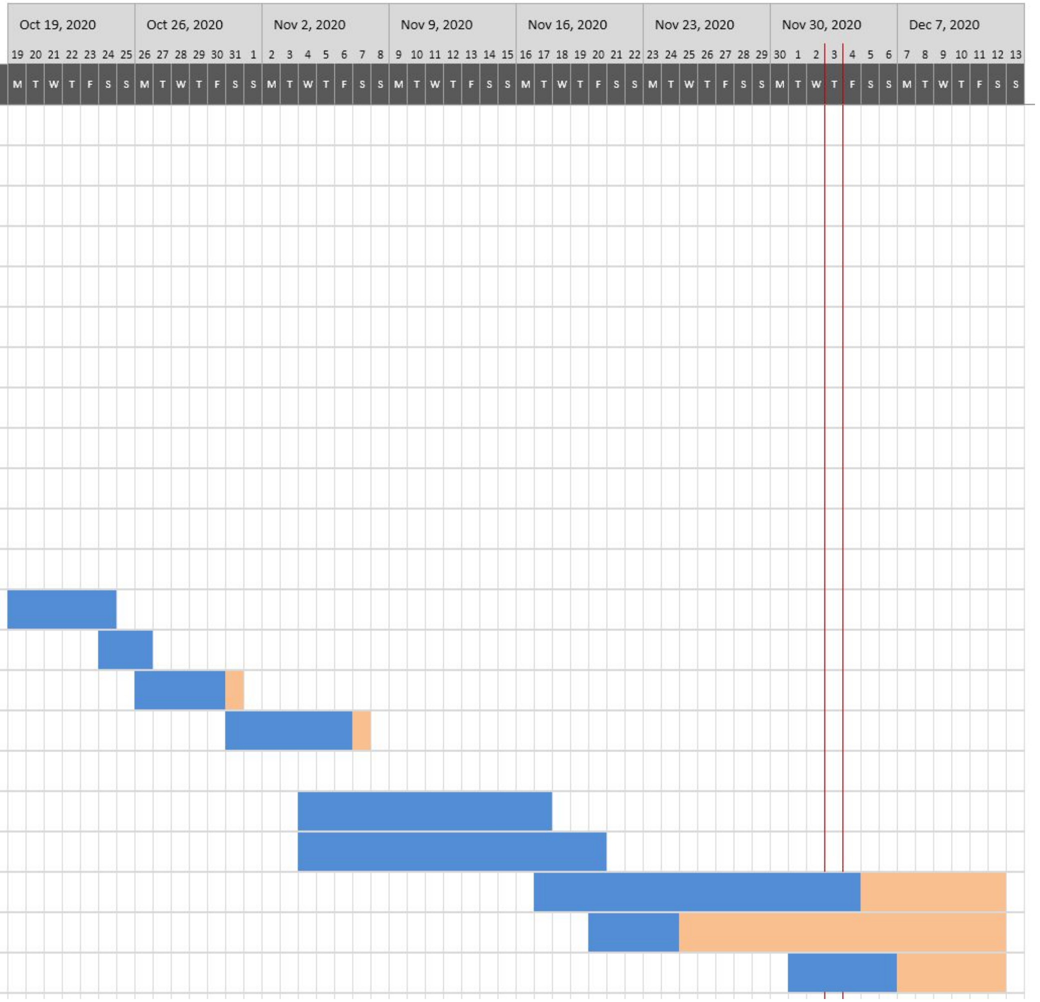
ME 470

Pool Evaporation Sponsored by Sargent & Lundy

Project Start: Fri, 9/11/2020

Display Week: 7

TASK	ASSIGNED TO	PROGRESS	START	END
Research and Ideation				
Pugh Matrix for Experimental Design	Rodrigo, Mitch	100%	9/11/20	9/18/20
Pugh Matrix for Simulations	Kevin, Juyi	100%	9/11/20	9/18/20
Experimental Design	Rodrigo, Mitch	100%	9/18/20	9/22/20
Bill of Materials	Rodrigo, Mitch	100%	9/22/20	9/27/20
Preliminary Analytical Model	Kevin, Juyi	100%	9/12/20	9/18/20
Proposal Paper	All	100%	9/11/20	9/14/20
Proposal Presentation	All	100%	9/11/20	9/17/20
Modeling				
Analytical Model		100%	9/18/20	9/25/20
CFD Model		0%	9/18/20	10/2/20
Experiment				
Experiment Construction		100%	9/26/20	10/24/20
Experiment Testing		100%	10/24/20	10/26/20
Data Analysis		90%	10/26/20	10/31/20
Model Revision		90%	10/31/20	11/7/20
Final Report				
Prepare Poster		100%	11/4/20	11/17/20
Prepare Trade Show		100%	11/4/20	11/20/20
Prepare Video		60%	11/17/20	12/17/20
Prepare Final Report		20%	11/20/20	12/17/20
Assemble Project Files		40%	12/1/20	12/17/20



Experimental Parameters

- Physical model creation to gather data
- Experimental setup variables
- Temperature: 25 - 90°C
- Air flow velocity: 0 - 3m/s
- Must measure:
  - Air speed
  - Humidity
  - Air temperature
  - Water temperature
- Must remain in $1500 budget

Variable	Symbol	Unit
Water Temperature	T_w	°C
Water Vapor Pressure	P_w	°C
Partial Pressure of water in Air	P_a	MPa
Flow speed	V	m/s
Distance between Water Surface And Top of Tank	d_{step}	m
Lead-up Distance	d_{LU}	m
Length of Water Tank	L	m
Evaporation rate / mass flux	J / m’’	$kg/m^2/h$

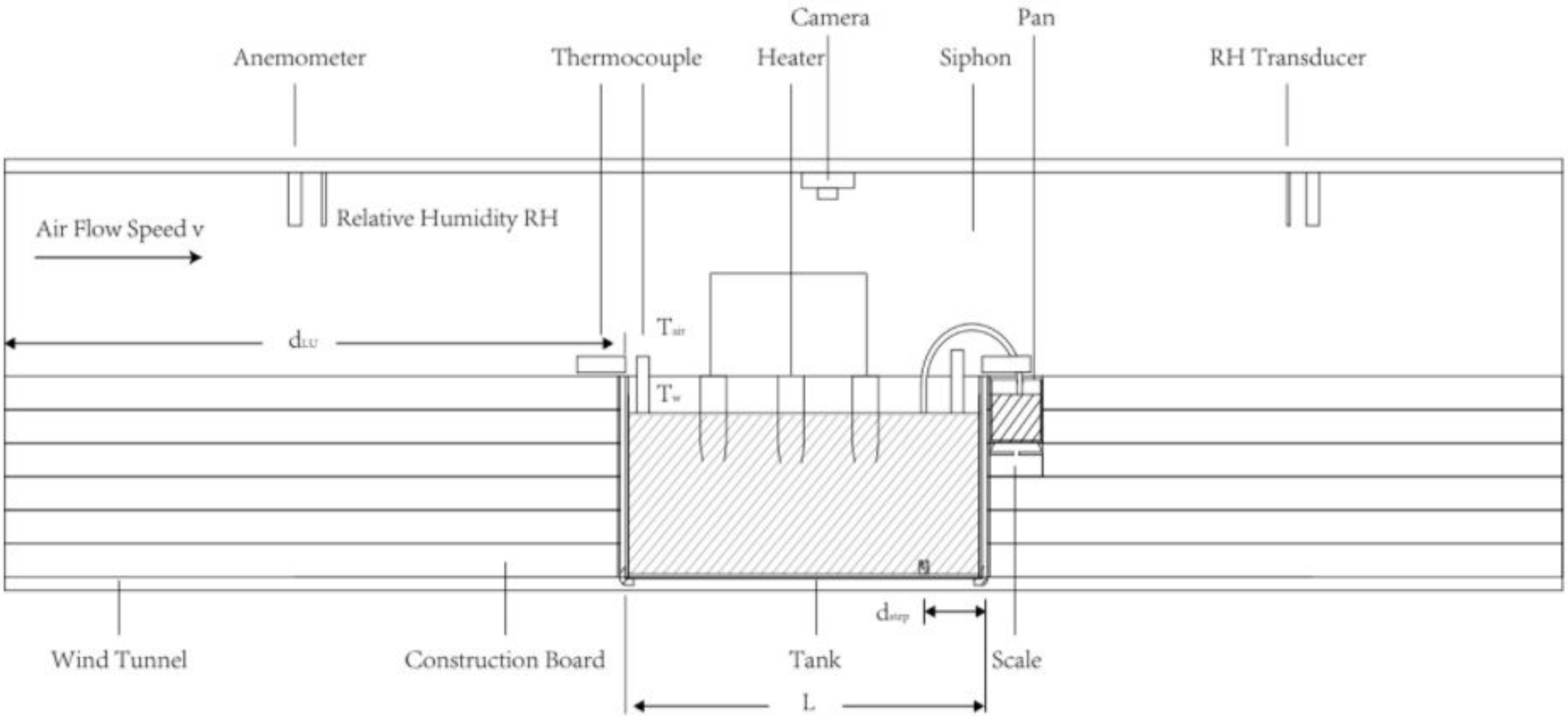
Variables to Consider

Variable	Symbol	Unit
Water Temperature	T_w	K
Water Vapor Pressure	P_w	K
Partial Pressure of water in Air	P_a	MPa
Flow speed	V	m/s
Distance between Water and Wind Tunnel Floor	d	m
Lead-up Distance	d_{LU}	m
Length of Water Tank	L	m
Evaporation rate / mass flux	J / m''	$kg/m^2/h$

Physical Model

- Experimental Design using University wind tunnel
- 5-gallon tank with a weight pan connected via siphon
- Construction Board to extend tank surface
- Arduino Circuit to measure:
  - Air Temperature
  - Relative Humidity (DHT22)
  - Water Temperature (Thermocouple)
- Water heated with submersible heater, temperature varied 25^{0}C - 90 ^{0}C
- Wind speed varied 0-3m/s, 3 hours of experiment time

Physical Model



Physical Model

Kevin’s Presentation

Experiment

Variable	Symbol	Unit
Water Temperature	T_w	°C
Water Vapor Pressure	P_w	°C
Partial Pressure of water in Air	P_a	MPa
Flow speed	V	m/s
Distance between Water Surface And Top of Tank	d_{step}	m
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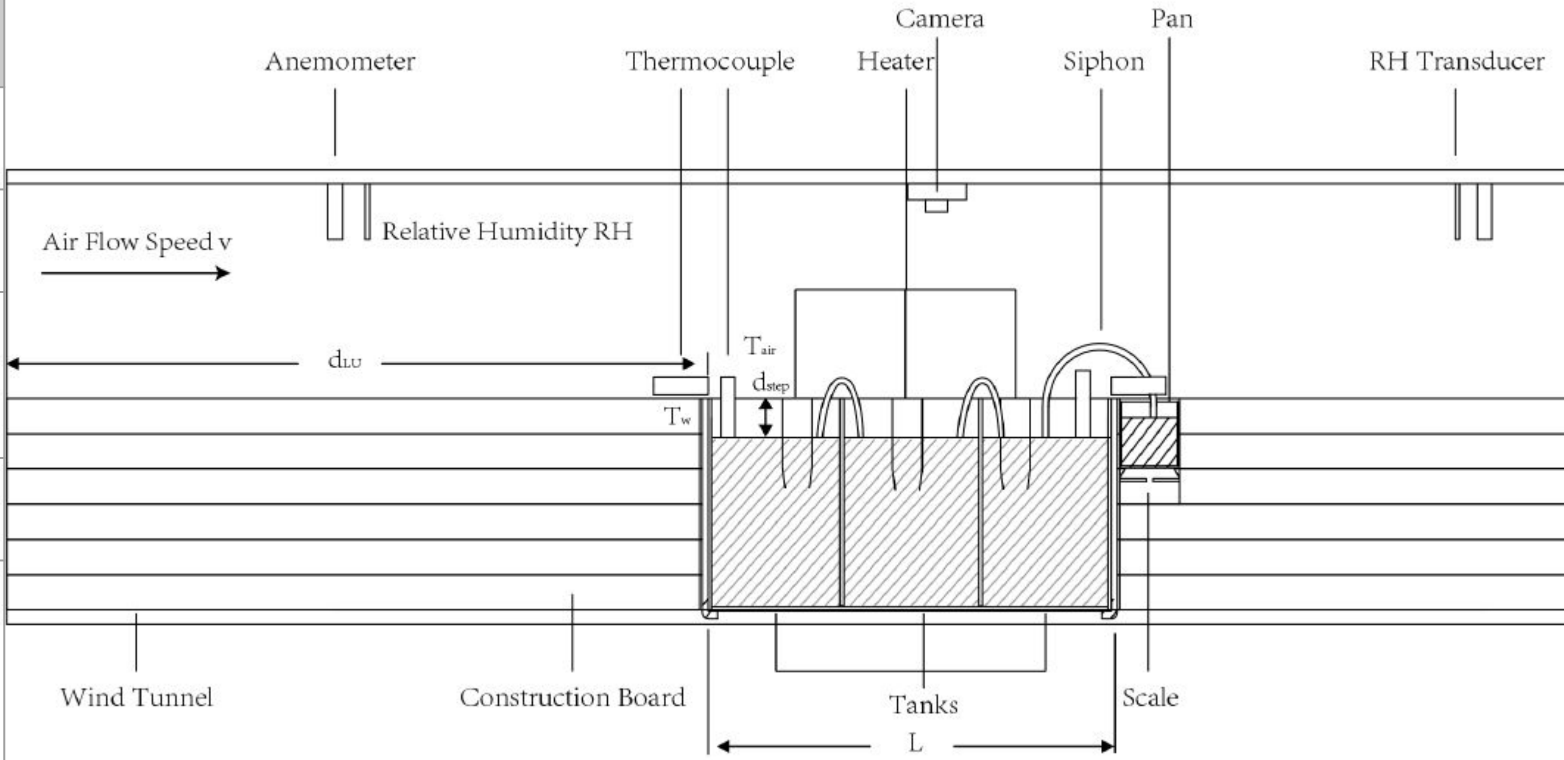
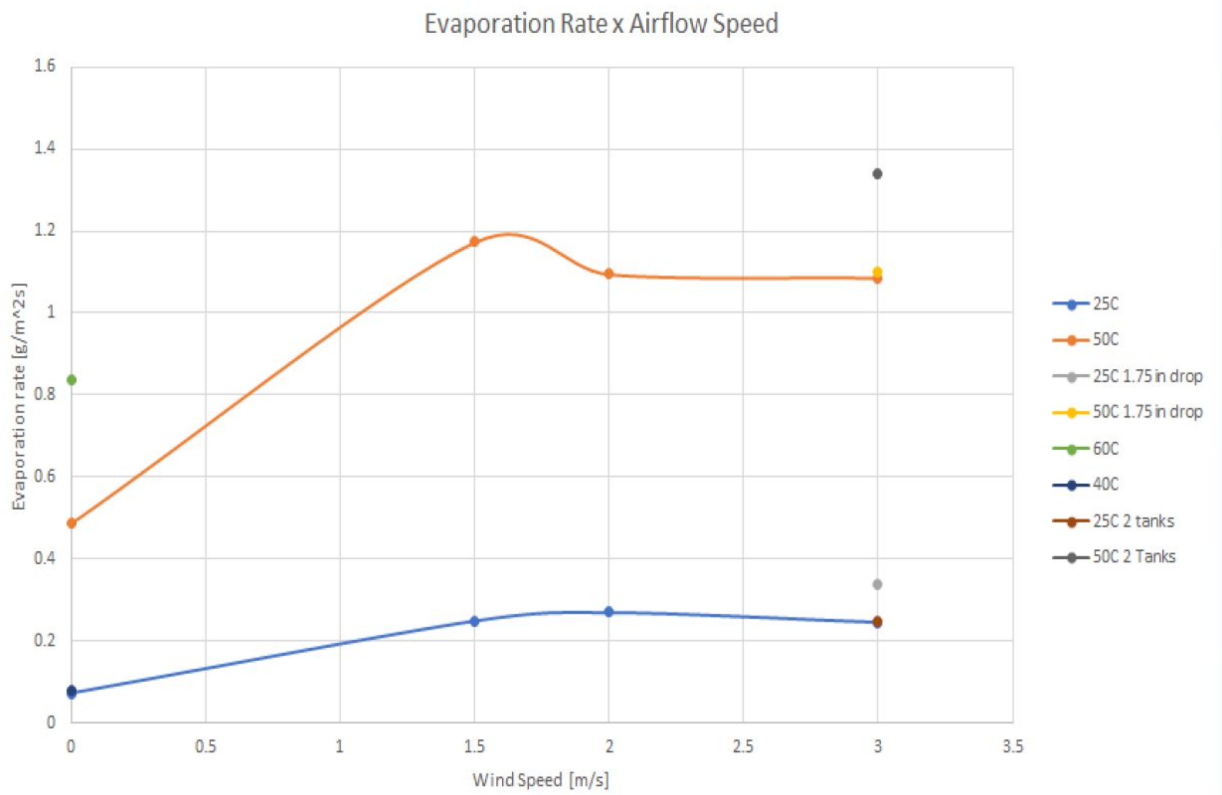
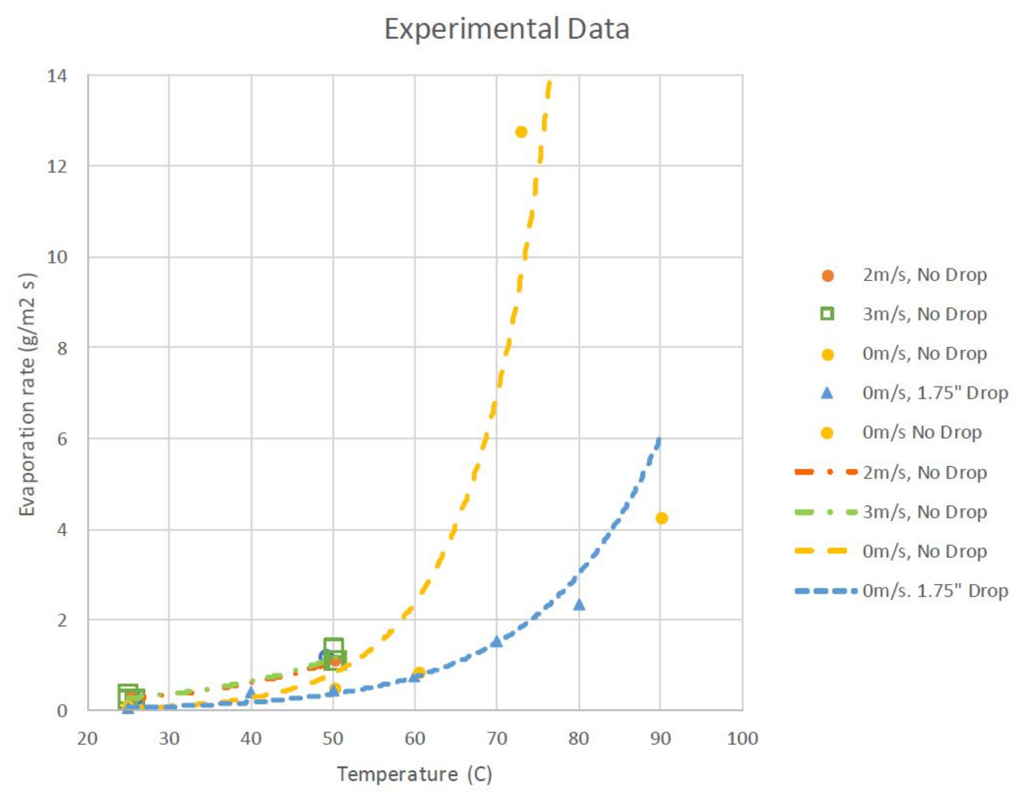


Experimental Data trends





- Increasing water temperature increases evaporation rate
- Shielding the water surface from the wind by lowering the height of the water has no effect
- Increasing length of tank has no effect
- Increasing flow rate from 0 to 1 m/s increased evaporation rate
- However, increasing flow rate from 1.5 m/s to 3 m/s had little effect on evaporation.
- Increasing flow rate increases evaporation rate because it wicks away airborne water particles

Juyi Zhang Presentation

Literature Review

- Pauken MT, et al. “Novel method for measuring water evaporation into still air”. In the 1993 Winter Meeting of ASHRAE Transactions. Part 1, Chicago, IL, USA, 01/23-27/93 1993 (pp. 297-300).
  - Empirical formula
- Raimundo et al. “Wind tunnel measurements and numerical simulations of water evaporation in forced convection airflow”. International Journal of Thermal Sciences. July 2014
  - CFD Simulation
  - Comparison of different empirical models
- M. Quinn Brewster, “Evaporation of water at high mass-transfer rates by natural convection air flow with application to spent-fuel pools”, International Journal of Heat and Mass Transfer, 2017
  - Established model
  - Comparison on the result of different theoretical model

Empirical Formula

- Generalized formula for evaporation into calm air (1)

$$J = C\left(p_w - p_a\right)^b$$

$$J = K\left(C_w - C_a\right)^k$$

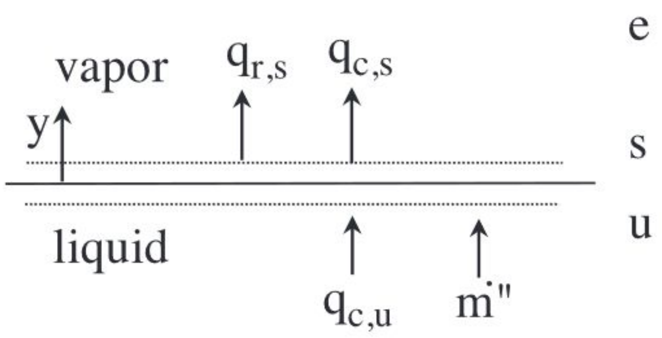
- For forced convection, there are roughly a polynomial relationship between the velocity and the constant in equation

$$C = A + Bv + Cv^2$$

- The model is derived from experimental data
  - Each experiment can have different condition.
  - The factor is constantly changing in different literature
- such model does not meet our high standard of generalizability and accuracy

Theoretical Model

- Settled on Spalding Model
- Primary Model to study
- Developed from Professor Brewster's work
- Generalizable and Accurate



$$q_{c,u} + \dot{m}'' h_u = \dot{m}'' h_s + q_{r,s} + q_{c,s} + j_{i,s} h_{i,s}$$

$$\dot{m}'' = -\rho D_{1,2} \frac{\partial m_1}{\partial y}\Big|_s + \dot{m}'' m_{1,s}$$

$$q_{c,u} - q_{r,s} + \dot{m}'' h_u = -\rho\alpha \frac{\partial h}{\partial y}\Big|_s + \dot{m}'' h_s$$

$$m'' = g_m B_m \text{ where } B_m = \frac{m_{1,s} - m_{1,e}}{1 - m_{1,s}} \text{ and } g_m = \frac{-\rho D_{12}}{m_{1,s} - m_{1,e}} \frac{\partial m_1}{\partial y}\Big|_s$$

$$g_m^* = \frac{\rho D_{12}}{L} Sh \qquad Sh = 0.14 Ra_m^{1/3}$$

$$Ra_m = Gr \cdot Sc = \frac{g(\rho_s - \rho_e)L^3}{\rho \nu^2} \cdot \frac{\nu}{D_{12}}$$

$$g/g^* = 1.8 * ln(1 + B_m)/B_m$$

[1] image from M. Q. Brewster,"Evaporation of water at high mass-transfer rates by naturalconvection air flow with application to spent-fuel pools,"International Journal of Heat and Mass Transfer, 2017.

Next Steps

- CFD Model
- Analytical Model with existing equations
- Order Materials and construct experiment
- Collect and analyze data
- Review Analytical and CFD Model