34th Thermal & Fluids Analysis Workshop (TFAWS)

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A Novel Way to Enhancing Heat Transfer for Thermal Management Via Electrostatic Resonance

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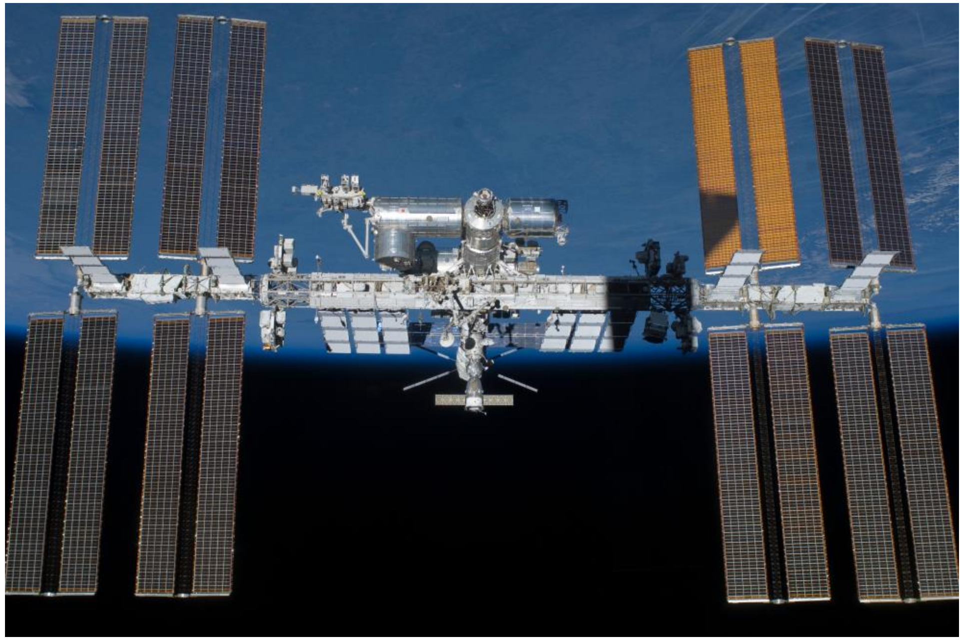
Motivation

Long term space exploration creates a need for effective thermal management systems



Challenges:

- Absence of gravity induced convection
- Extreme temperatures
- Limited resources

https://www.nasa.gov/mission_pages/station/main/index.html

Background

Active thermal management

- Regulate temperature with active control system and mechanical components
- Advantage: Allows more effective temperature control, adaptability, higher heat load and performance optimization
- Drawbacks: Complexity and cost from mechanical parts, power consumption and mechanical failures
- Examples: Heaters, fluid loops, thermoelectric coolers, and pumped fluid loop

Passive thermal management

- Regulate temperatures without the use of powered equipment
- Advantage: Does not require fans or pumps, generally lighter and use less space, and maintenance costs
- Drawbacks: Limited control, slower response times, limited scalability and inefficient in extreme environments
- Examples: Paint and coatings, heat pipes, deployable radiator, and thermal storage units

Resonant induced thermal management

- Combination of passive and active thermal management
- No moving components but needs power supply for electrostatic forcing
- Use resonant induced flow to increase heat transfer from parametric forcing
- The internal fluids are interchangeable which allows for variability when optimizing this system for specific purposes

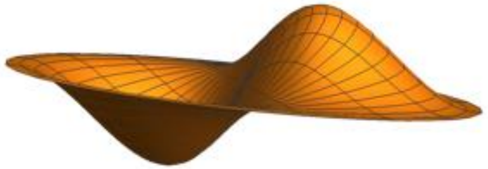
What Is Resonance?

Resonance occurs when the frequency of your forced oscillation matches the natural frequency of the system causing large deformation

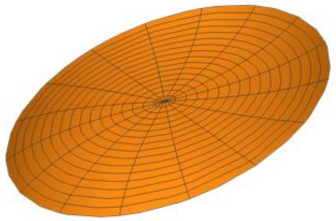
Natural frequency (the oscillating or sloshing yellow colored water in a glass) – Nevin Brosius

Dependent on Mode

(1,2)



(2,1)



(1,1)

Natural Frequency of Inviscid Fluid Layer

$$\omega_n^2 = \frac{(\cancelto{0}{\Delta \rho g k} + \gamma k^3)}{\rho \coth(kH)}$$

Δρ : Density difference between fluid and passive gas

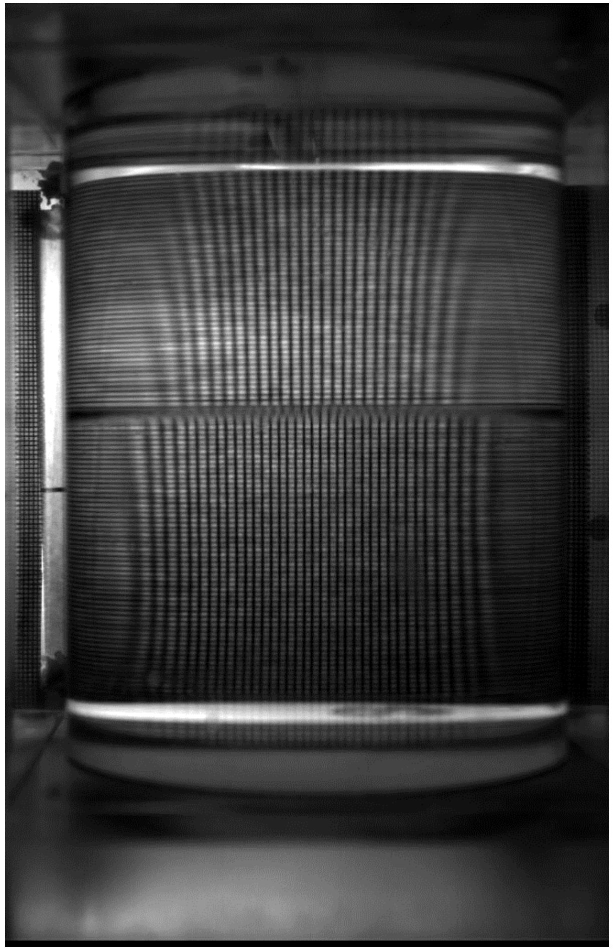
γ : Surface tension

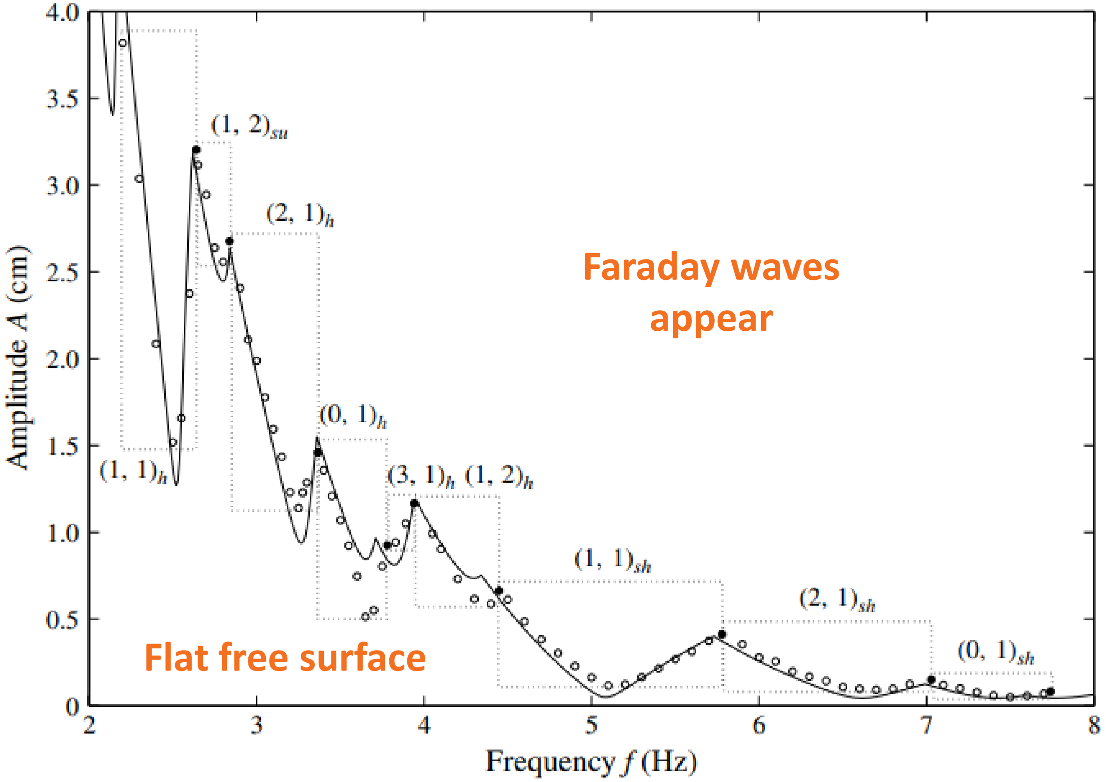
k : Wave number of pattern

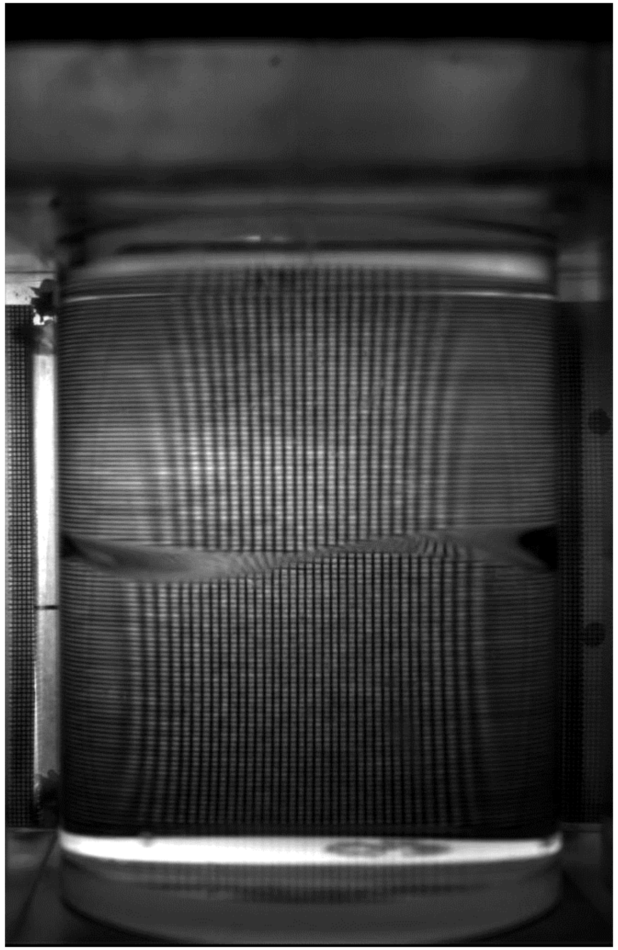
H : Height of the fluid layer

ρ : Density of fluid

Faraday Instability



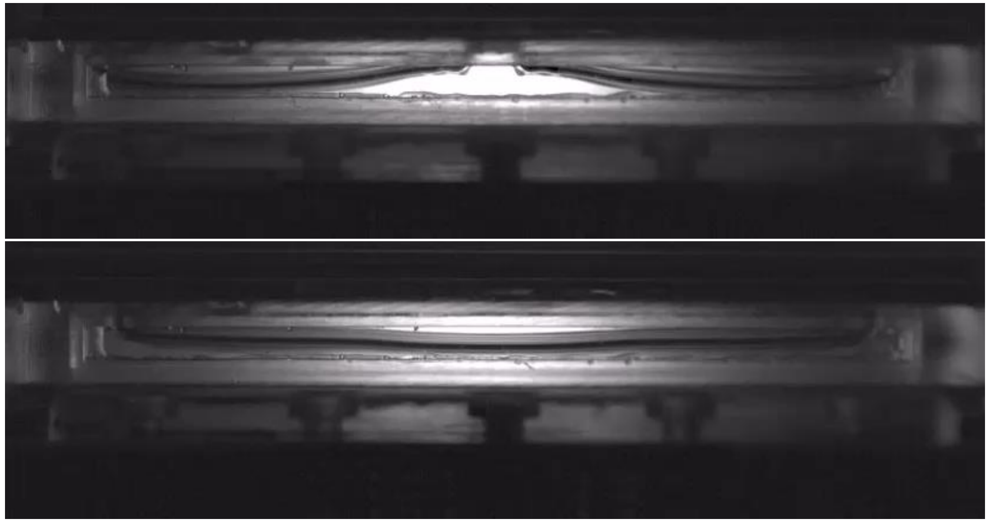




Resonance between natural frequency and induced external frequency

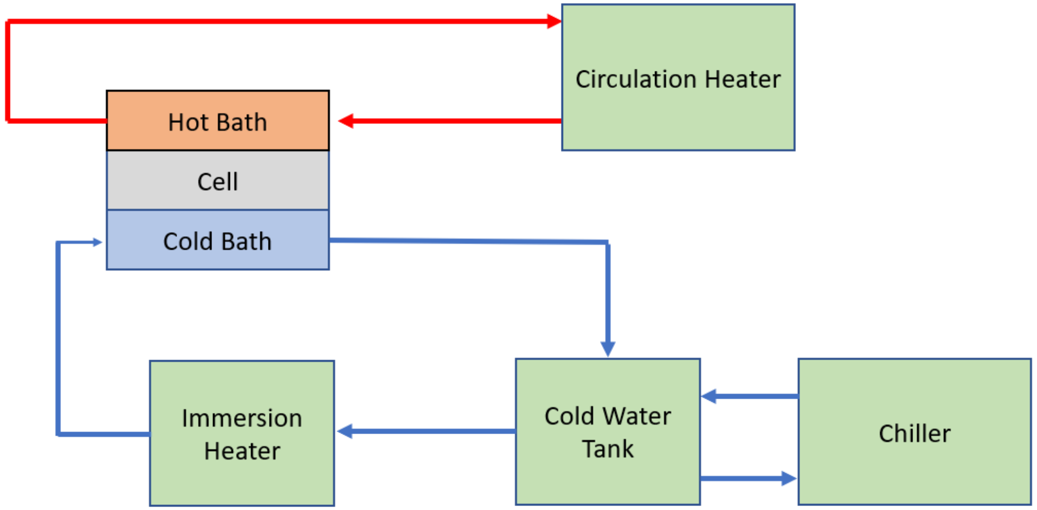
Batson et.al. The Faraday Threshold In Small Cylinders And The Sidewall Non-ideality, JFM

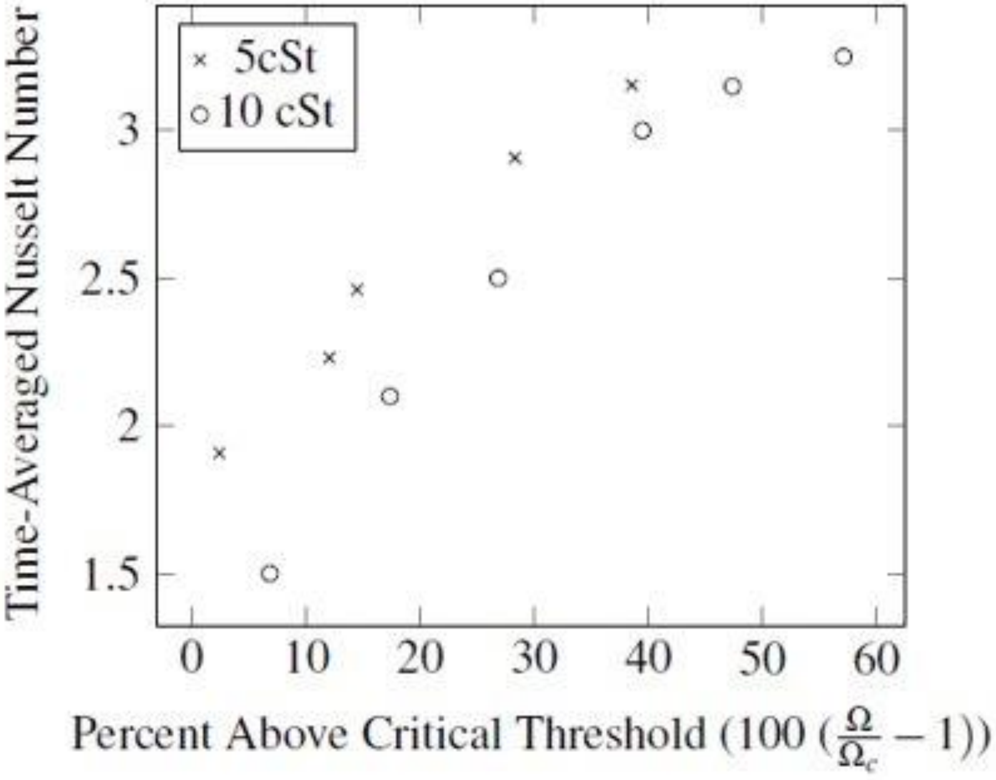
Mechanically Forced Heat Transfer



5 cSt

10 cSt



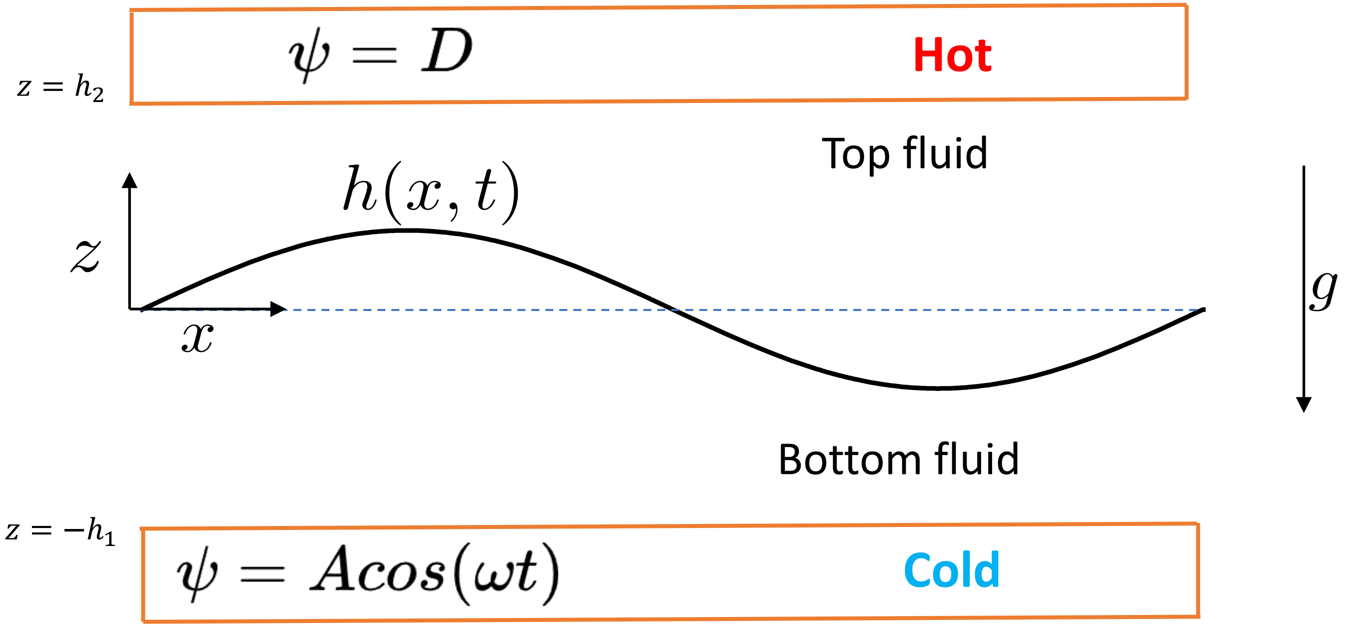


$$Nu = \frac{convective\ heat\ transfer}{conductive\ heat\ transfer}$$

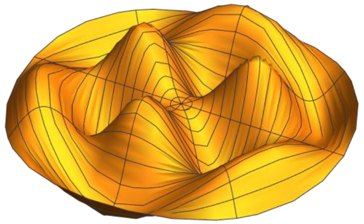
Ω : *Acceleration*

Ω_c : *Critical Acceleration*

Electrostatic Faraday Instability



(3,2) mode (water and 1.5 cst Si-oil)

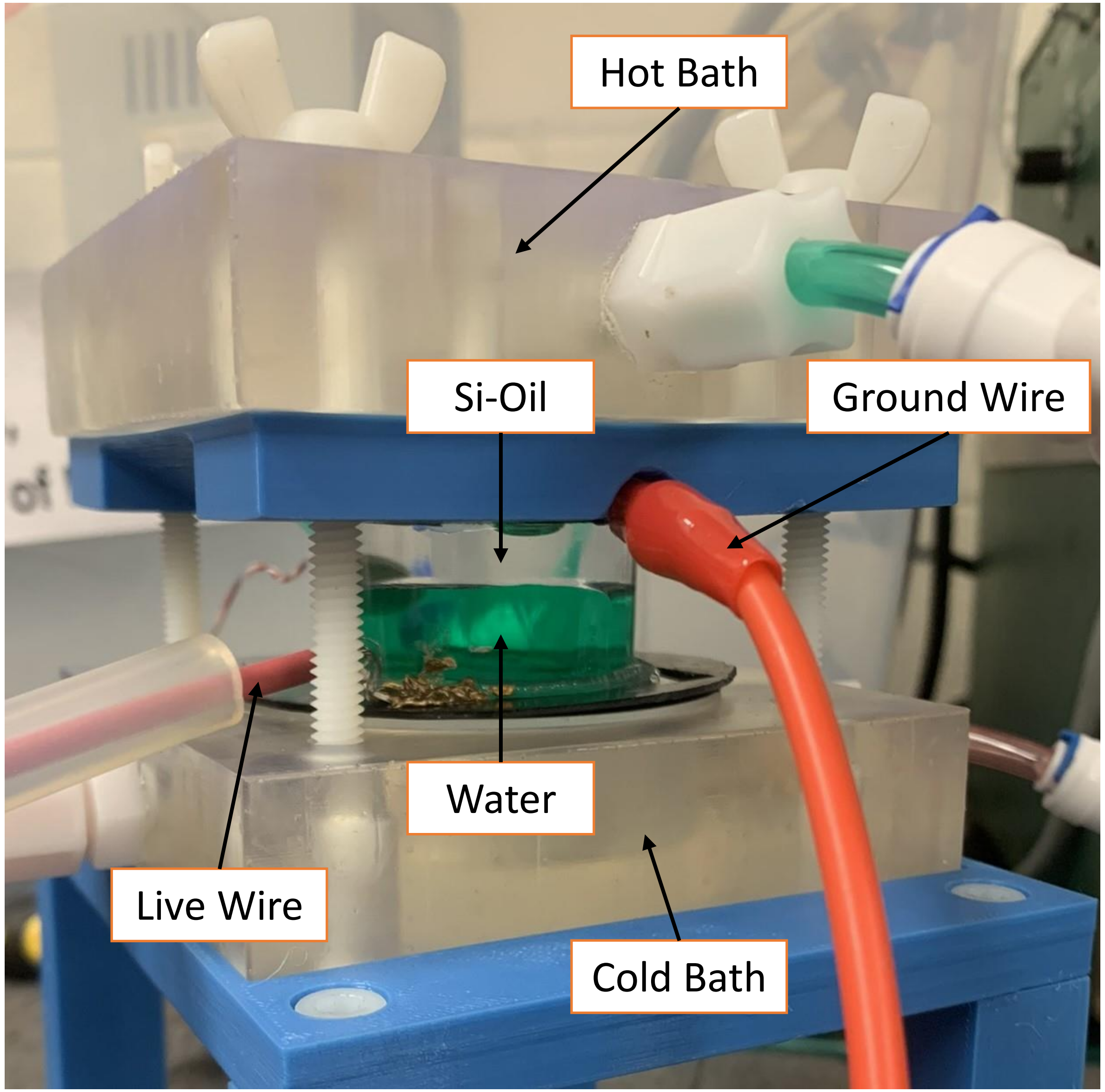


Natural Frequency

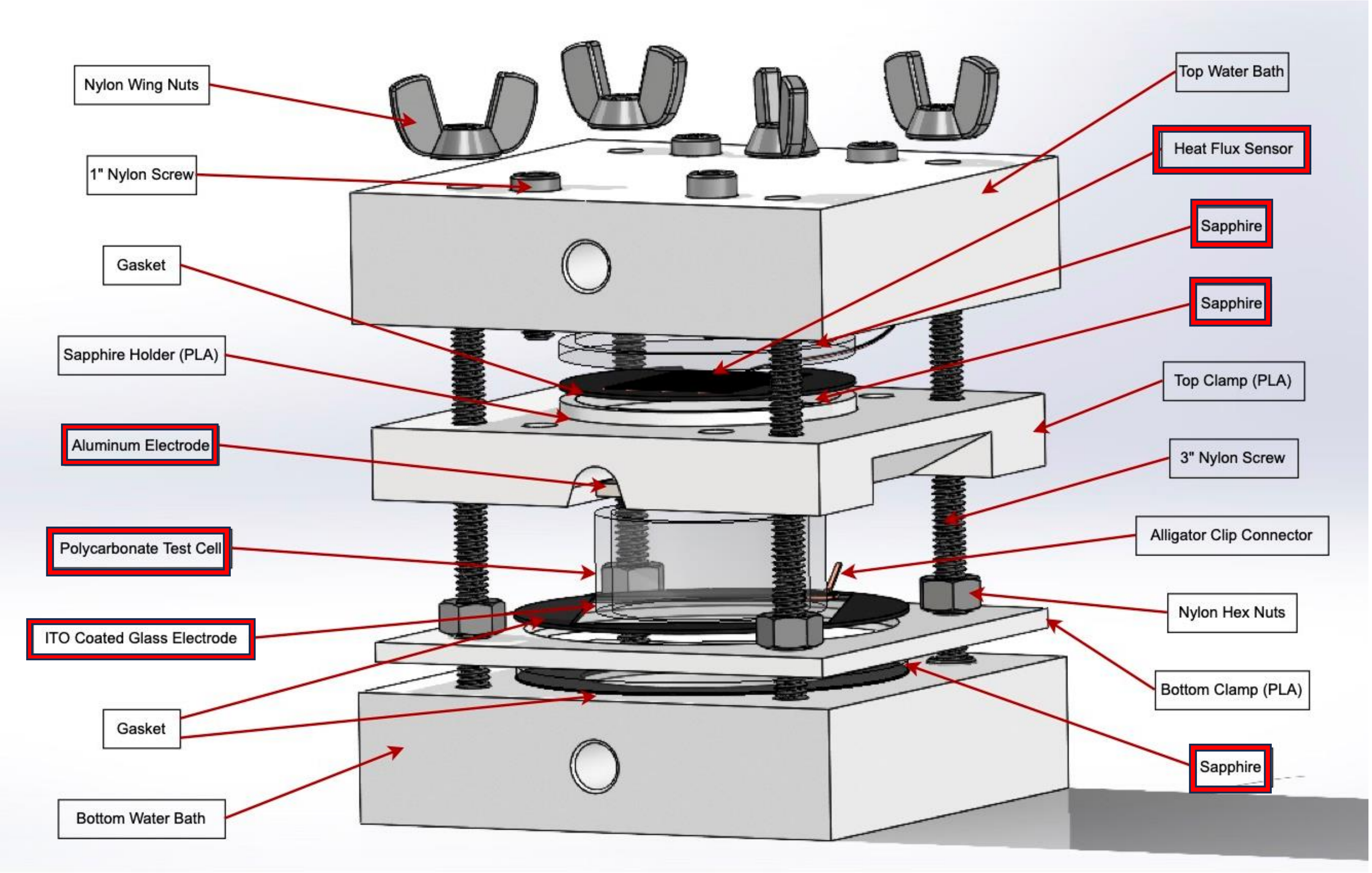
$$\omega_n^2 = \frac{\left(\Delta\rho g k + \gamma k^3 - \boxed{\frac{\epsilon_2 \epsilon_0 coth(kh_2)}{h_2^2} D^2 k^2}\right)}{\rho_2 coth(kh_2) + \rho_1 coth(kh_1)}$$

Δρ : Density difference between fluid 1 and 2
γ : Surface tension
k : Wave number of pattern
h_i : Height of the fluid layer
ρ_i : Density of fluid
ε_2 : Permittivity of fluid
ε_0 : Permittivity of free space
D: Constant voltage

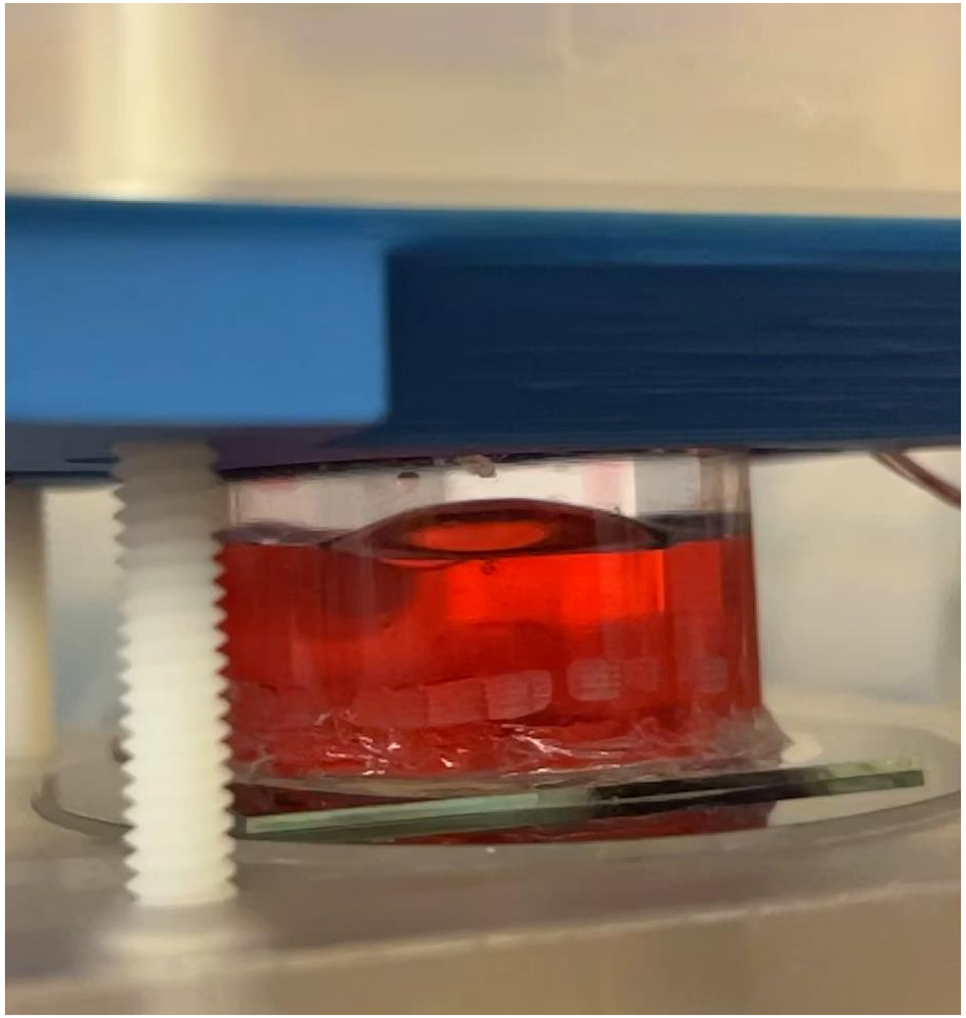
Electrostatic Experimental Design



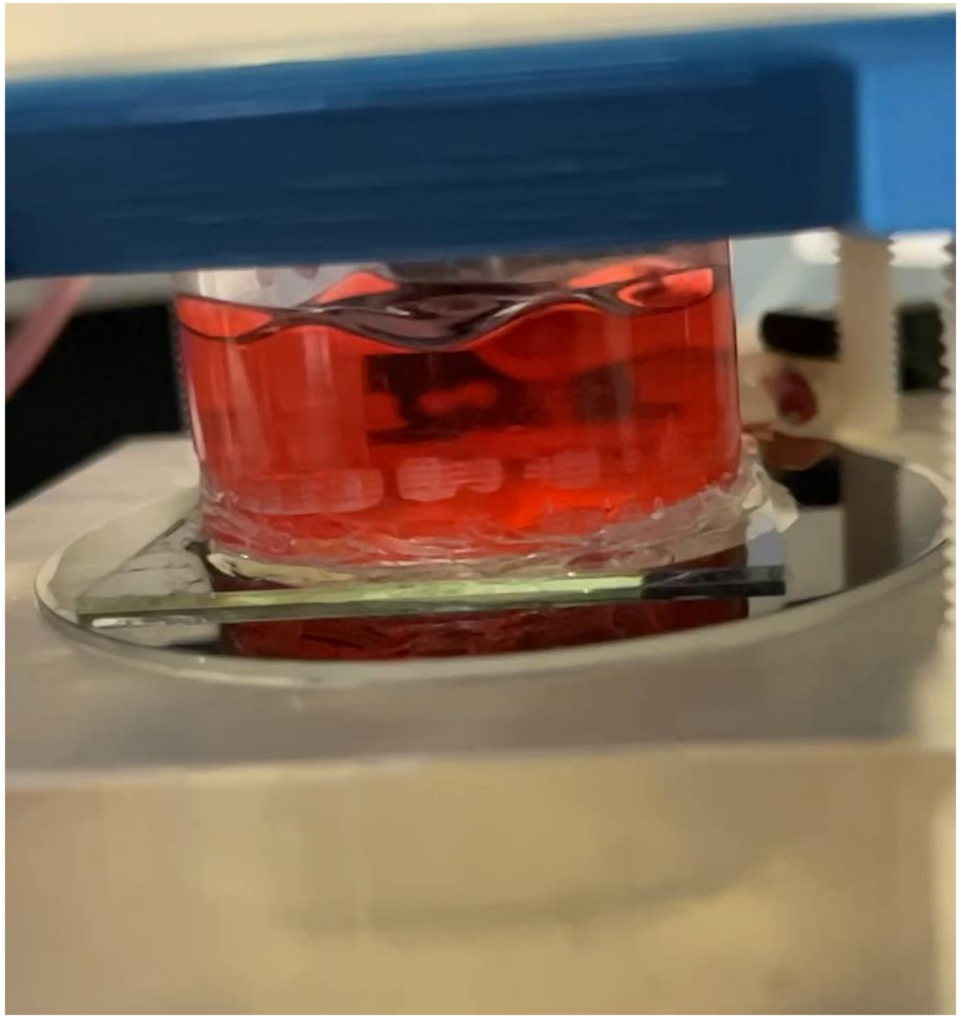
Electrostatic Experimental Design



Electrostatic Resonance Videos

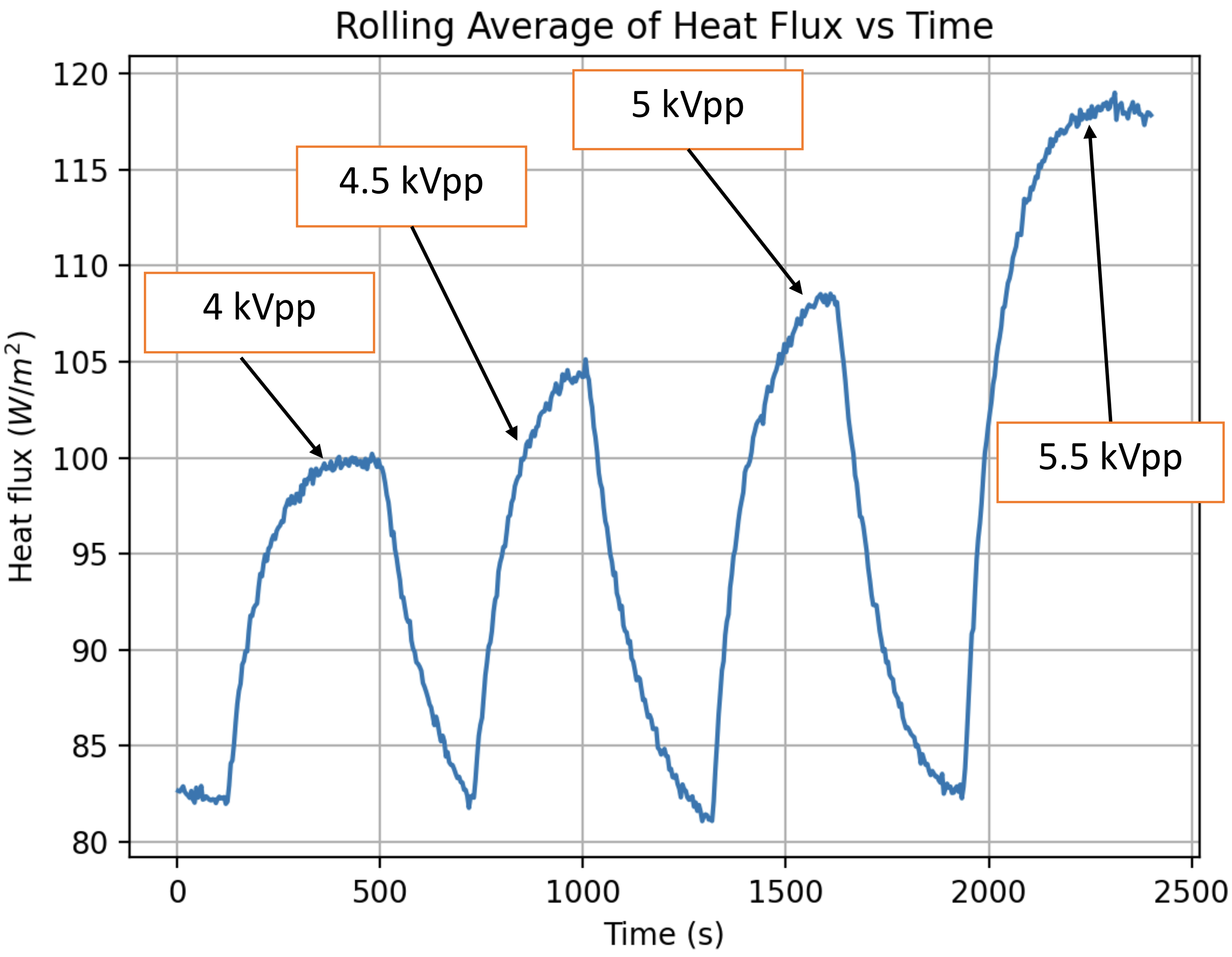


(1,2) waveform at 3 Hz and 5.5 kVpp



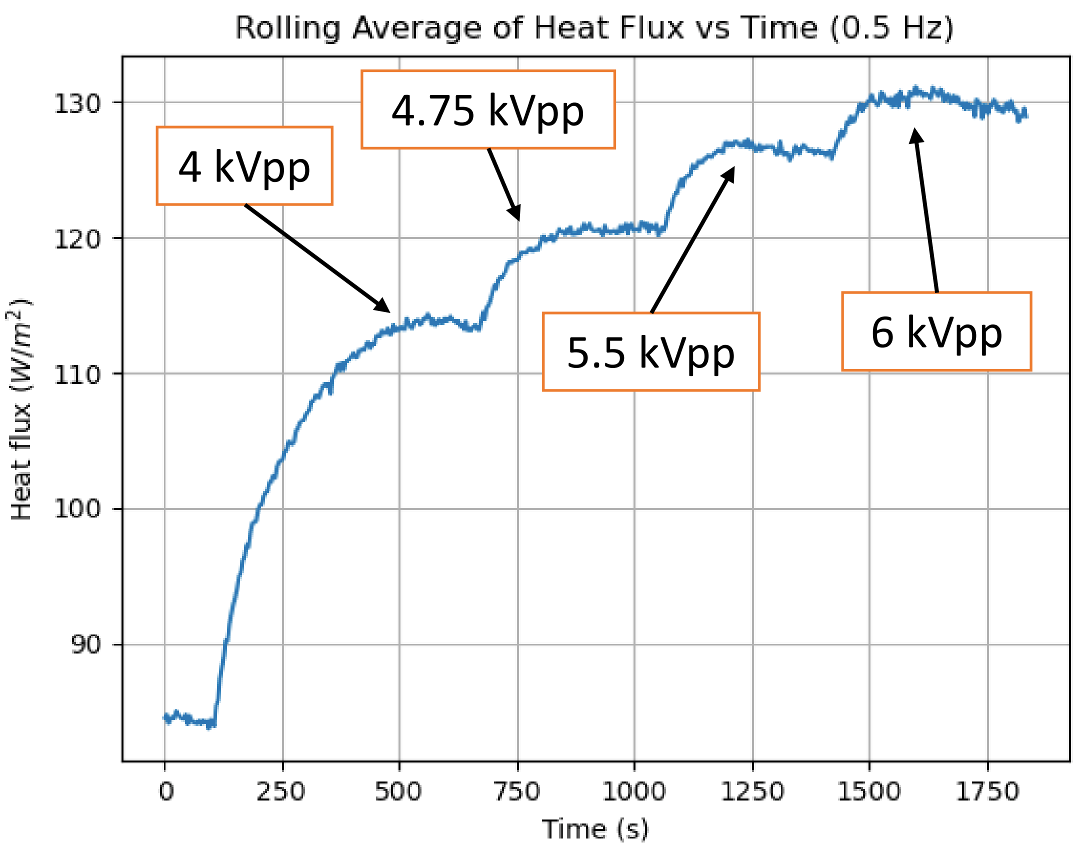
(6,1) waveform at 7 Hz and 6 kVpp

Results

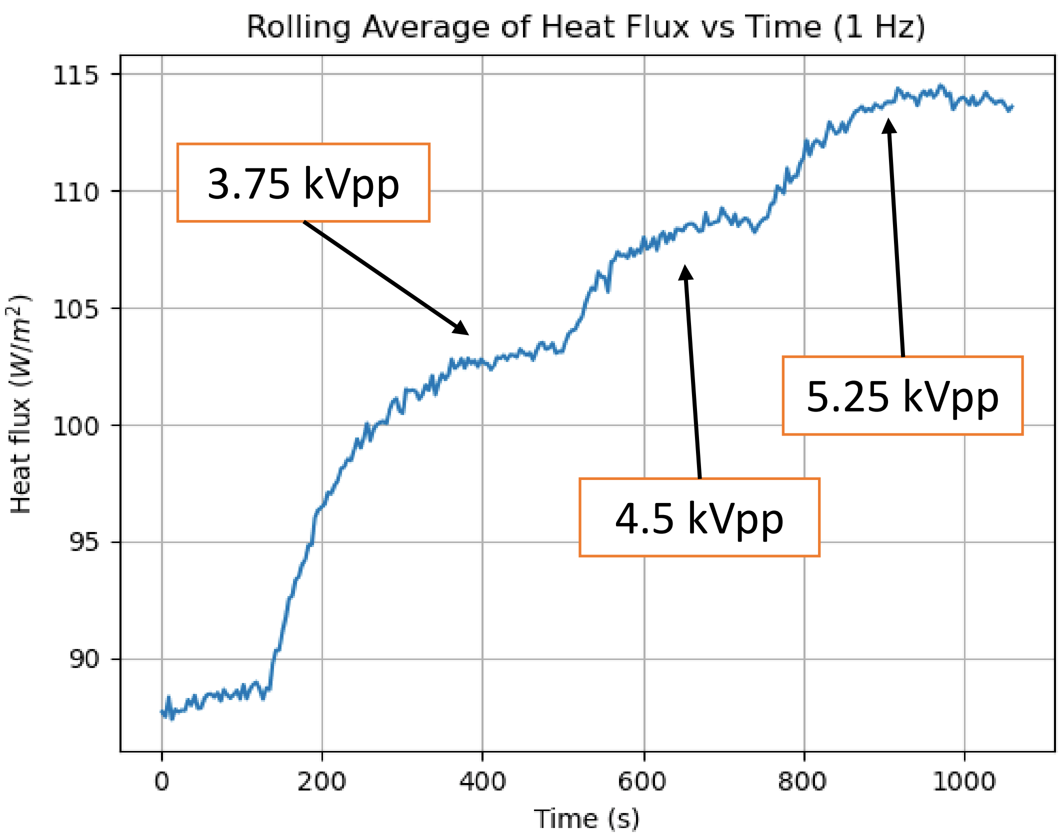


Rolling Average of Heat Flux vs Time
4 kVpp
4.5 kVpp
5 kVpp
5.5 kVpp
Heat flux (W/m^2)
120
115
110
105
100
95
90
85
80
0
500
1000
1500
2000
2500
Time (s)

Results



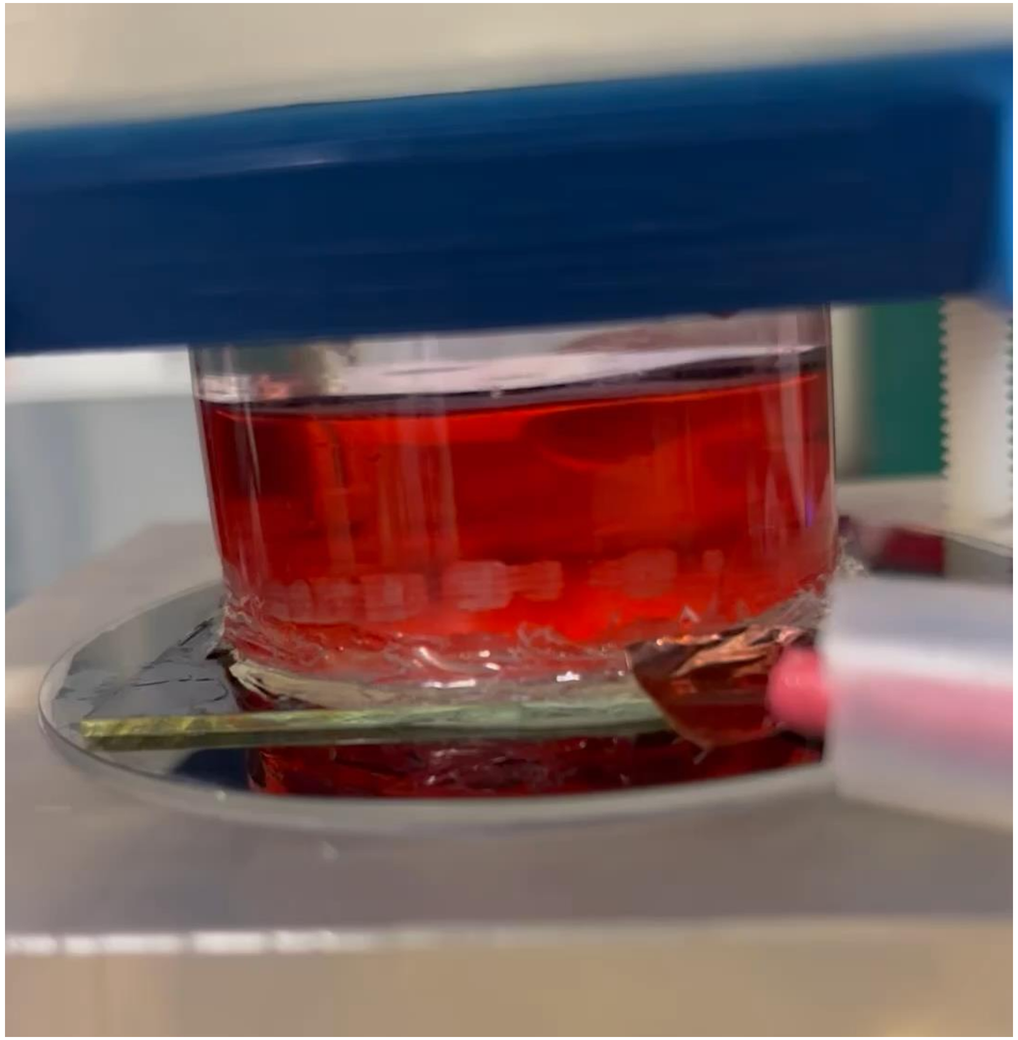
Rolling Average of Heat Flux vs Time (0.5 Hz)
Heat flux (W/m^2)
Time (s)
0
250
500
750
1000
1250
1500
1750
90
100
110
120
130
4 kVpp
4.75 kVpp
5.5 kVpp
6 kVpp



Rolling Average of Heat Flux vs Time (1 Hz)
Heat flux (W/m^2)
Time (s)
0
200
400
600
800
1000
90
95
100
105
110
115
3.75 kVpp
4.5 kVpp
5.25 kVpp

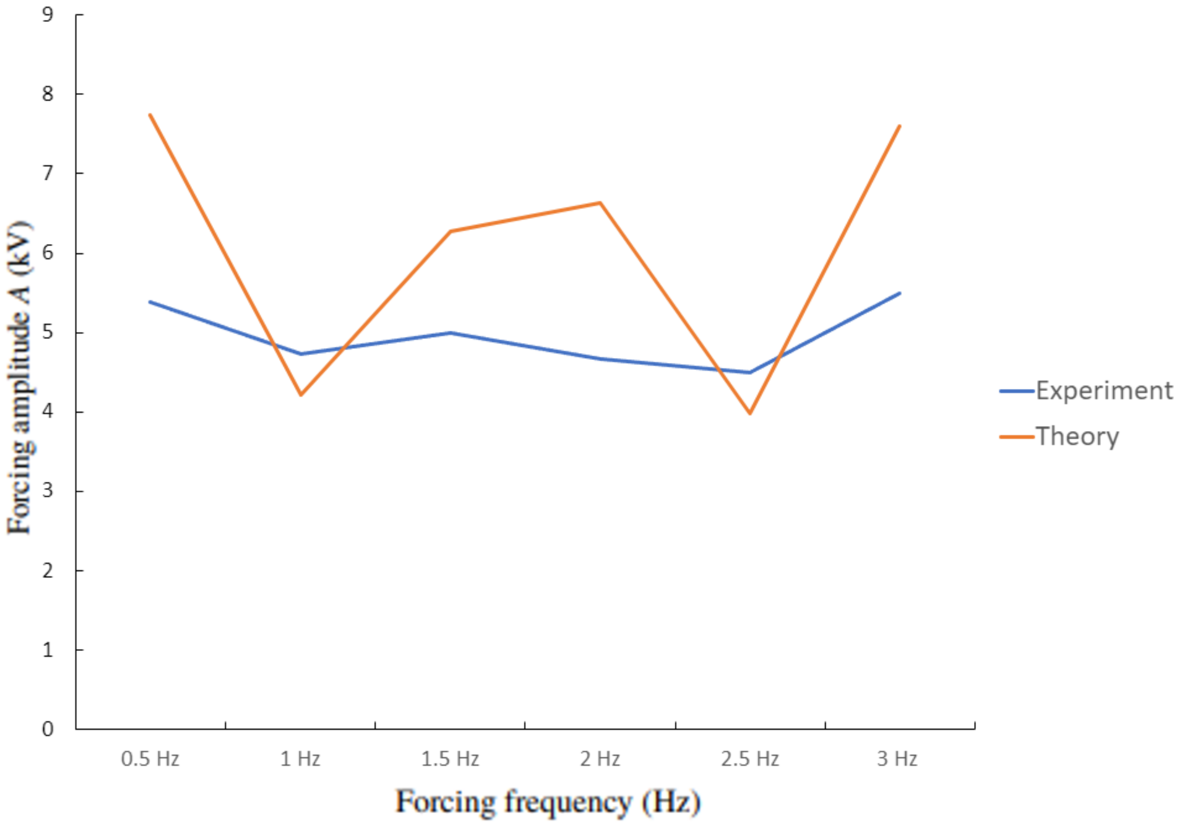
Experimental Issues

- Meniscus waves from wall effects caused by the small geometry of the cell

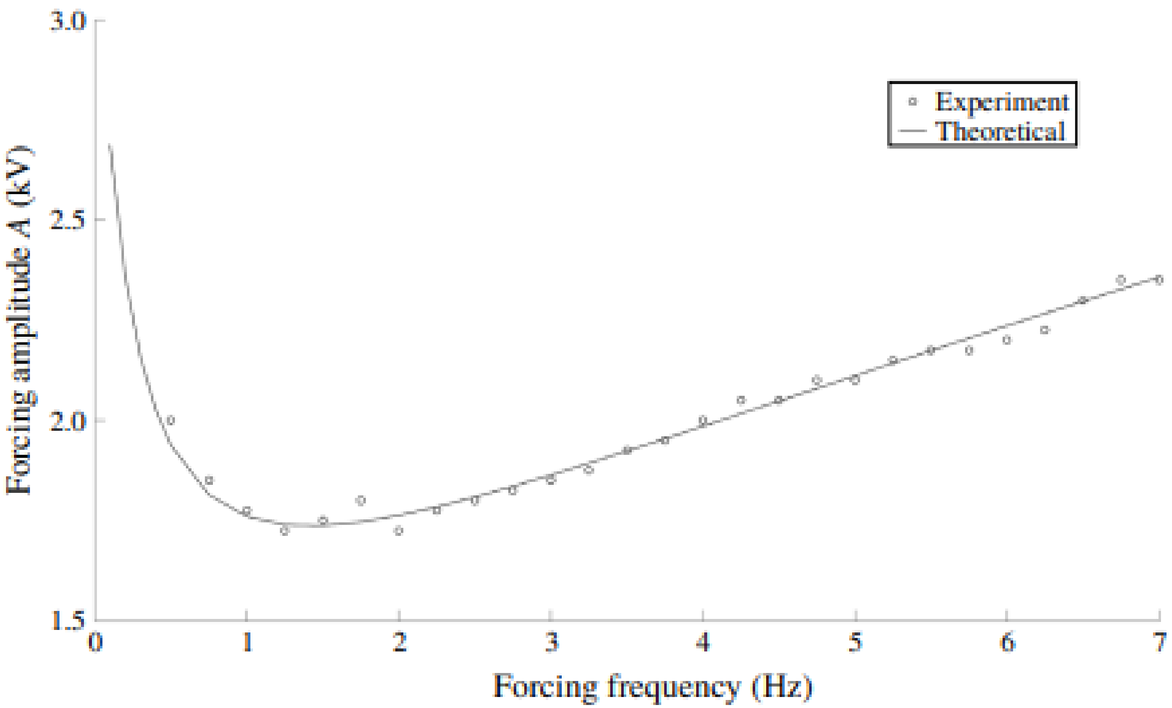


Experimental Issues

- Deviation from perfect conductor theory



Cell width: 1.5 in
Water height: 17.1 mm
Si-Oil height: 5.7mm



Cell width: 5 in
Water height: 33 mm
Si-Oil height: 5.1 mm

Future Plans

- Larger cell to minimize the influence of meniscus waves
- Test different types of fluid
  - Liquid metals
  - Phase change fluids
  - Heat transfer fluids
- Create theory that couples electrostatic Faraday equations with energy equations

Conclusion

- Preliminary research shows that heat flux can be increased through resonance in a fluid system
  - Over 50% increase for some trials
- Data trends show that the lower frequencies have a higher percentage increase of heat flux than its higher counterparts
  - Possibly due to penetration depth of waves
- Changes need to be made to cell design to minimize variability

Questions?