Electrically Driven Liquid Film Flow Boiling: A Two-Phase Heat Transport Device Driven by EHD Mechanisms

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Acknowledgments

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Electrohydrodynamics

EHD: Interactions between electrical fields and flow fields

EHD Phenomenon

$$\boldsymbol{f}_e = \rho_e \boldsymbol{E} - \frac{1}{2}E^2 \nabla\varepsilon + \frac{1}{2}\nabla\left[E^2\left(\frac{\partial\varepsilon}{\partial\rho}\right)_T \rho\right]$$

Coulomb Force

- Acts on space charges

Dielectrophoretic Force

- Polarization force acts on gradients of electrical permittivity

Electrostriction Force

- Polarization force relevant for compressible fluids

Note: Coulomb force pumps the fluid (i.e., EHD pumping) while the di-electro-phoretic (DEP) force separates the vapor phase from the liquid phase.

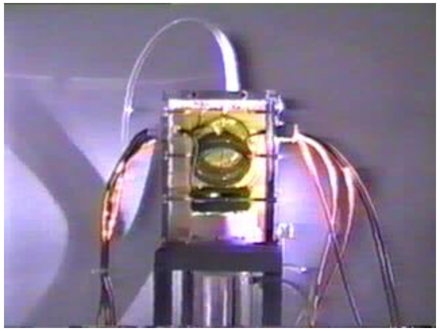
EHD Pumping

- Interaction of electric fields and free charges in a dielectric fluid
- Coulomb force main mechanism of this interaction
- Electric field and free charges required

Electric Charge Generation

- Direct injection; ion-drag pumping
- Induction; induction pumping
- Dissociation; conduction pumping

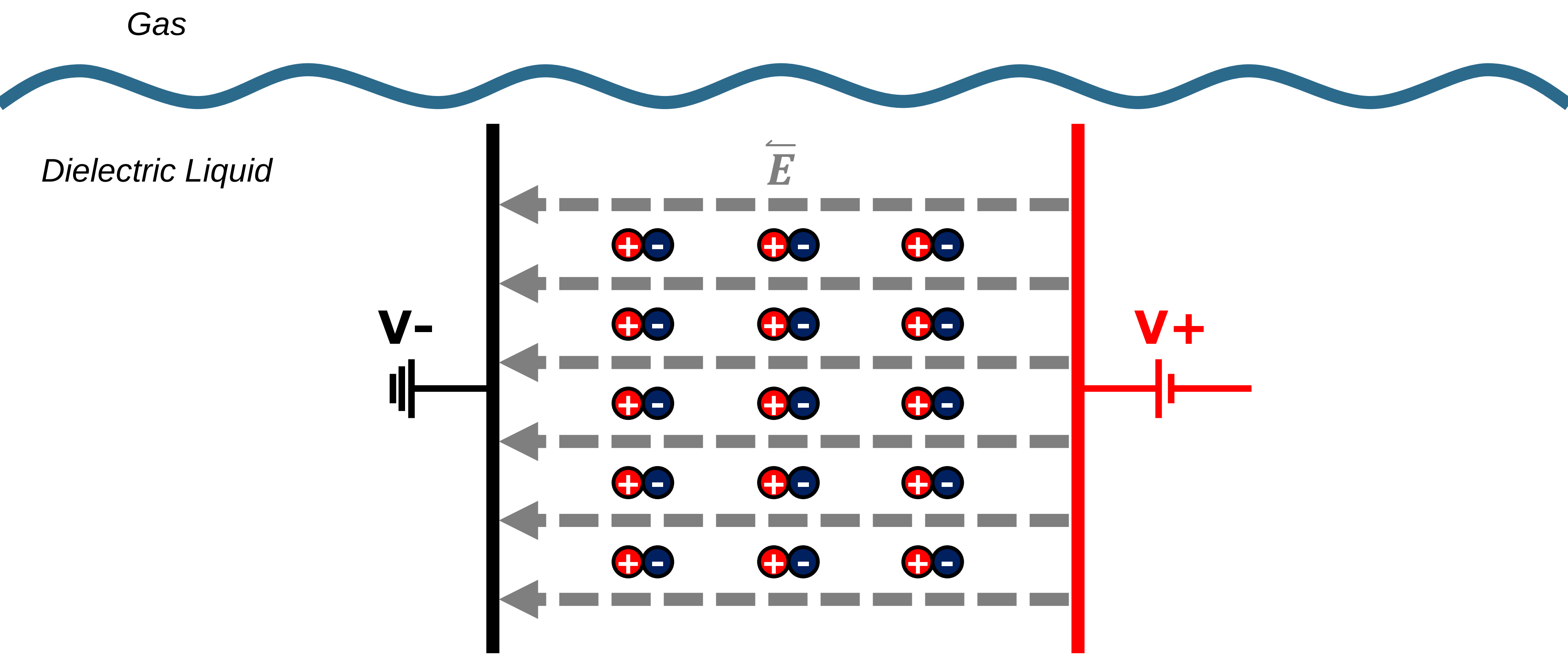
ion-drag pumping



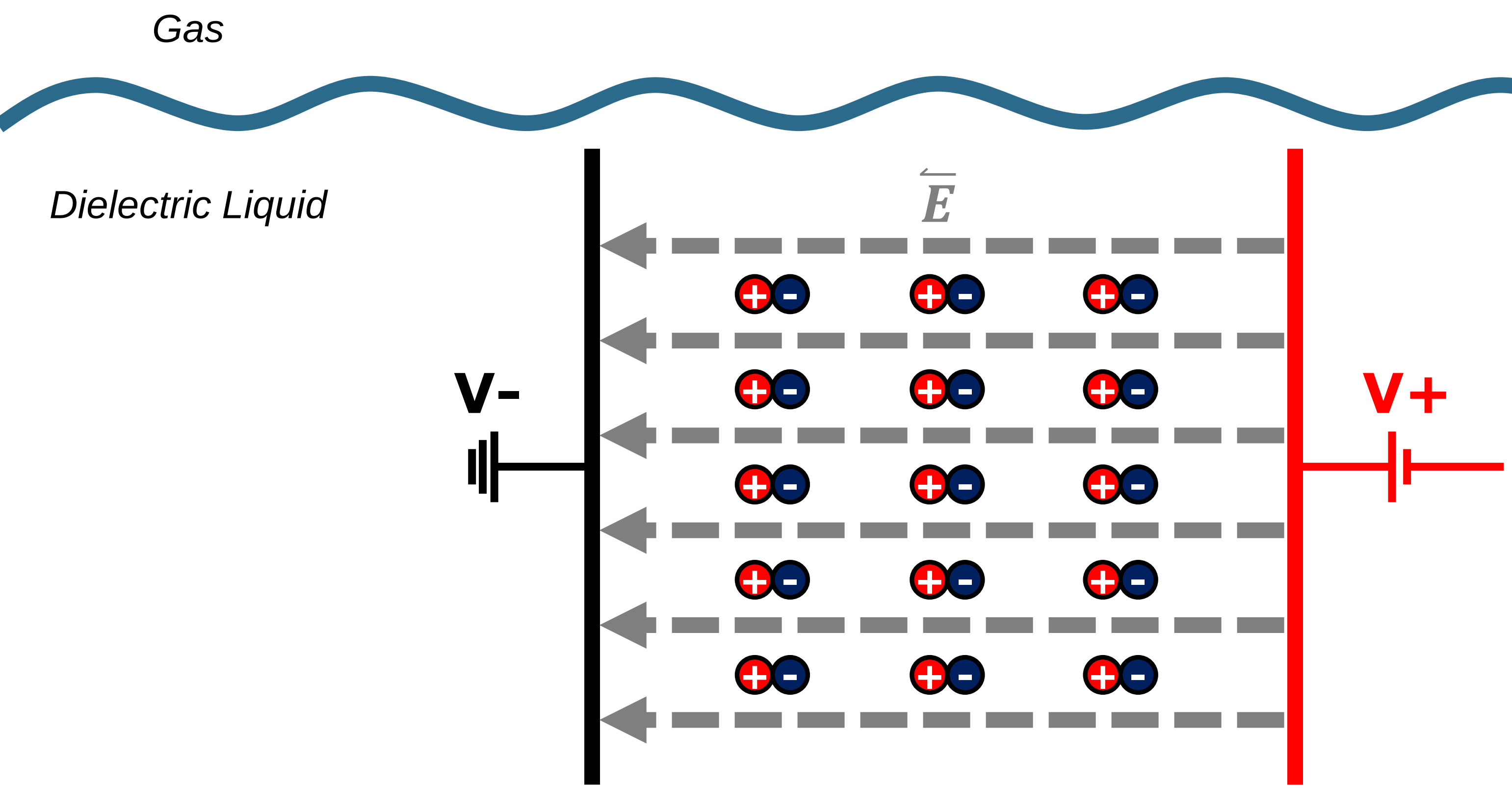
external condensation

induction pumping of external condensation

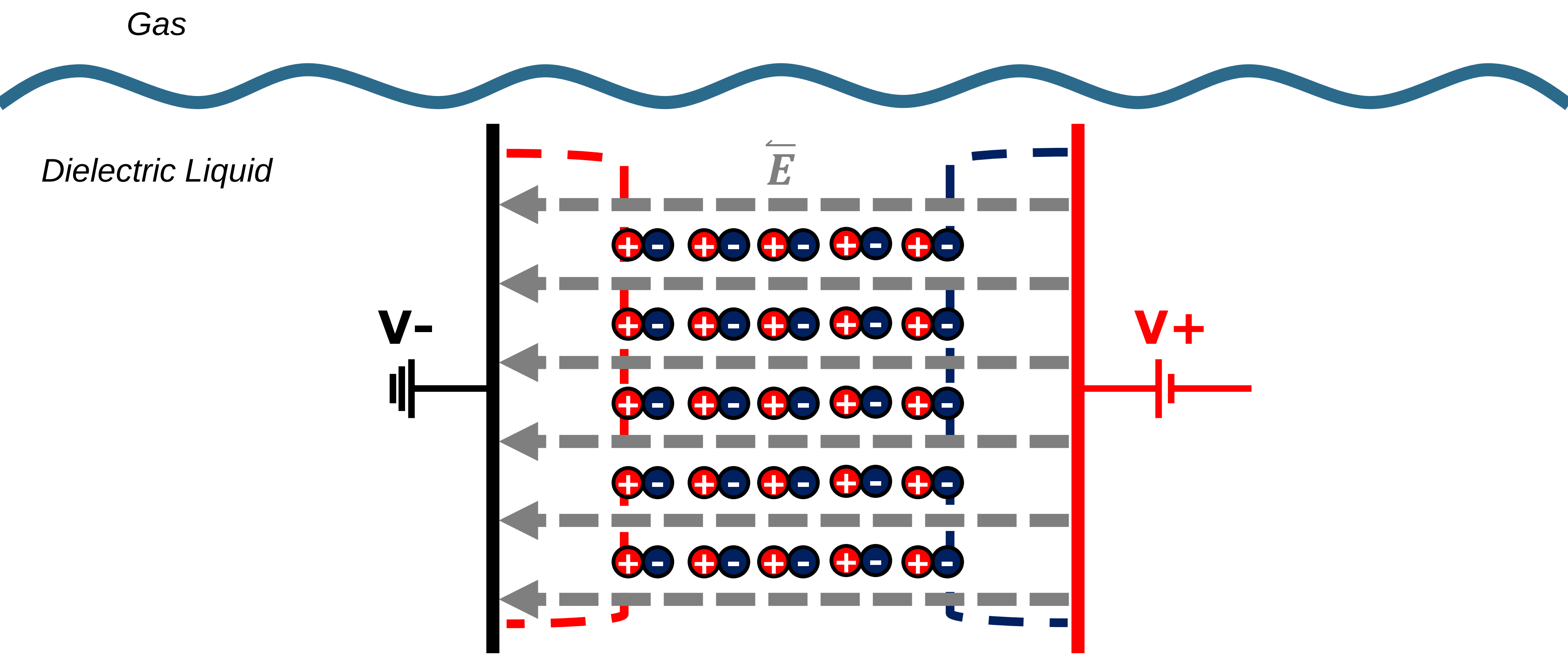
Illustration of EHD conduction pumping



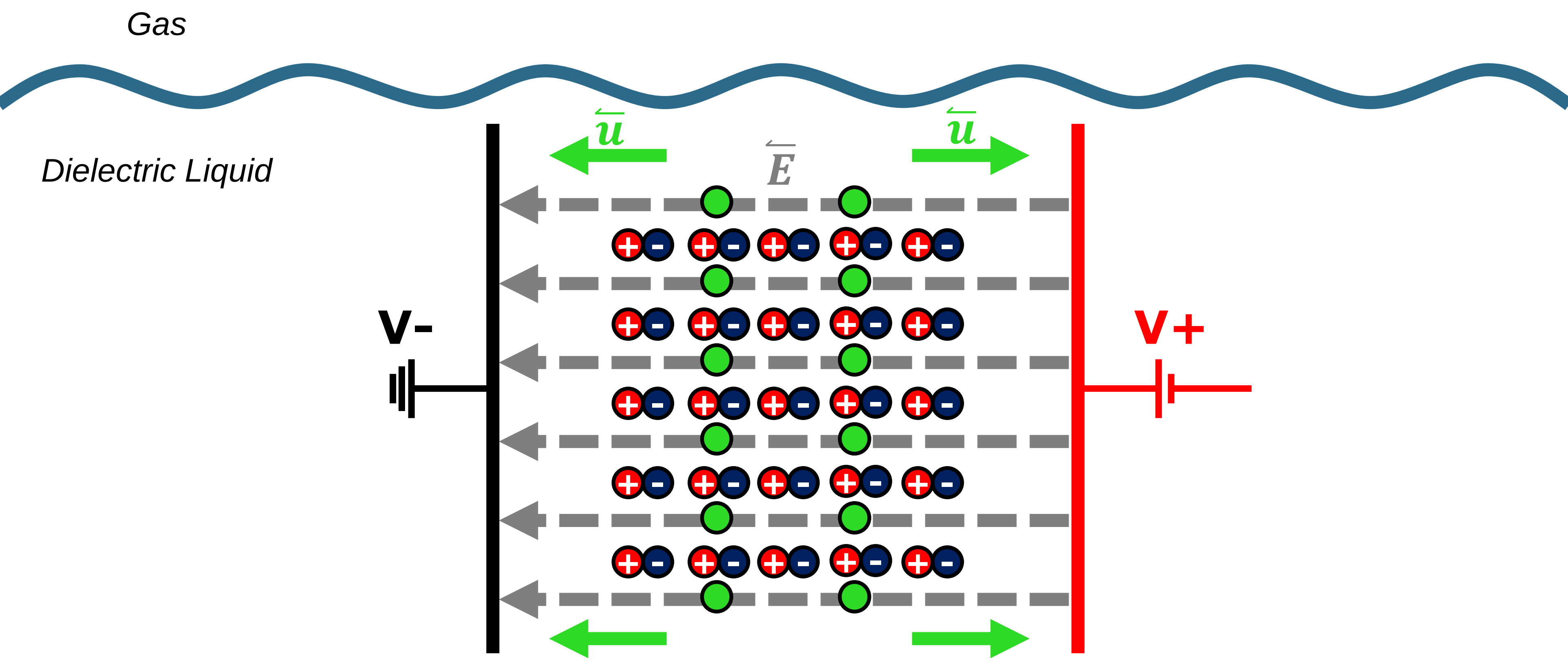
Consider an electrolytic solution containing **positive** and **negative** ionic species.



Ionic species will move along **electric field** lines based on their charge.

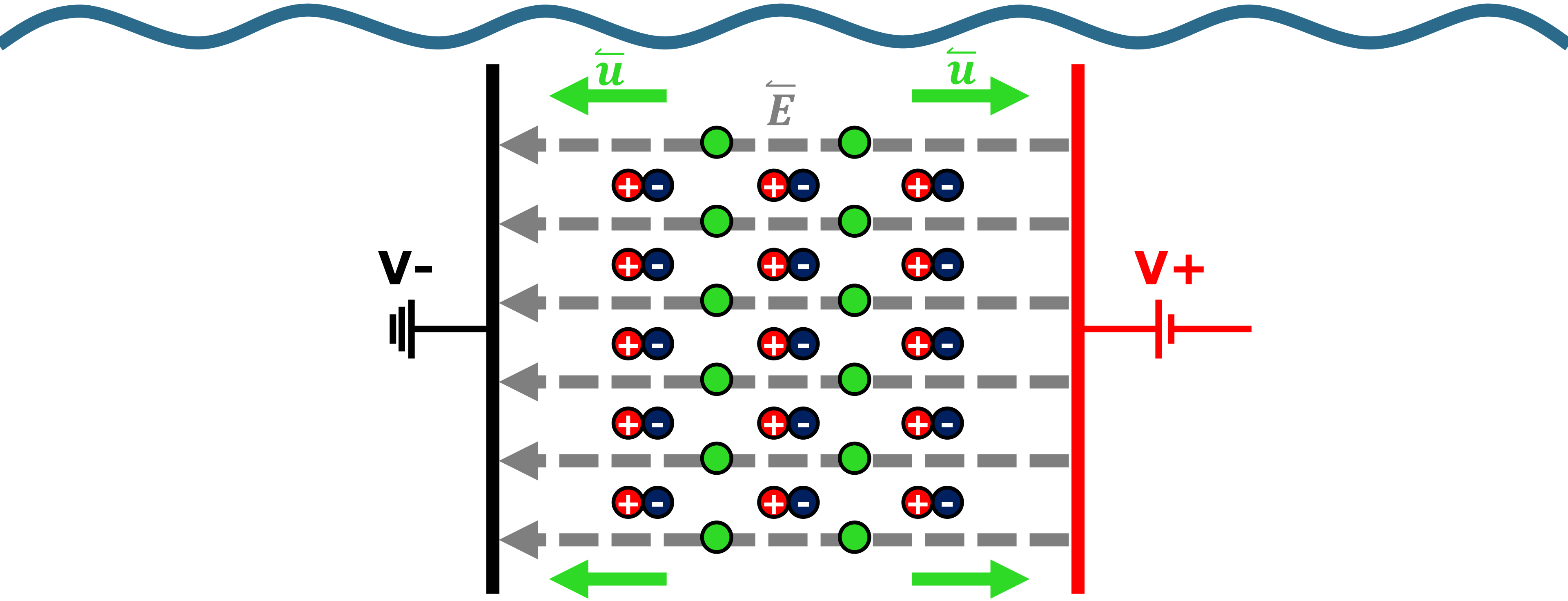


Subjected to strong enough electric fields, the dissociation rate increases, and regions of space charge will develop in the vicinity of the electrodes, known as **heterocharge layers.**

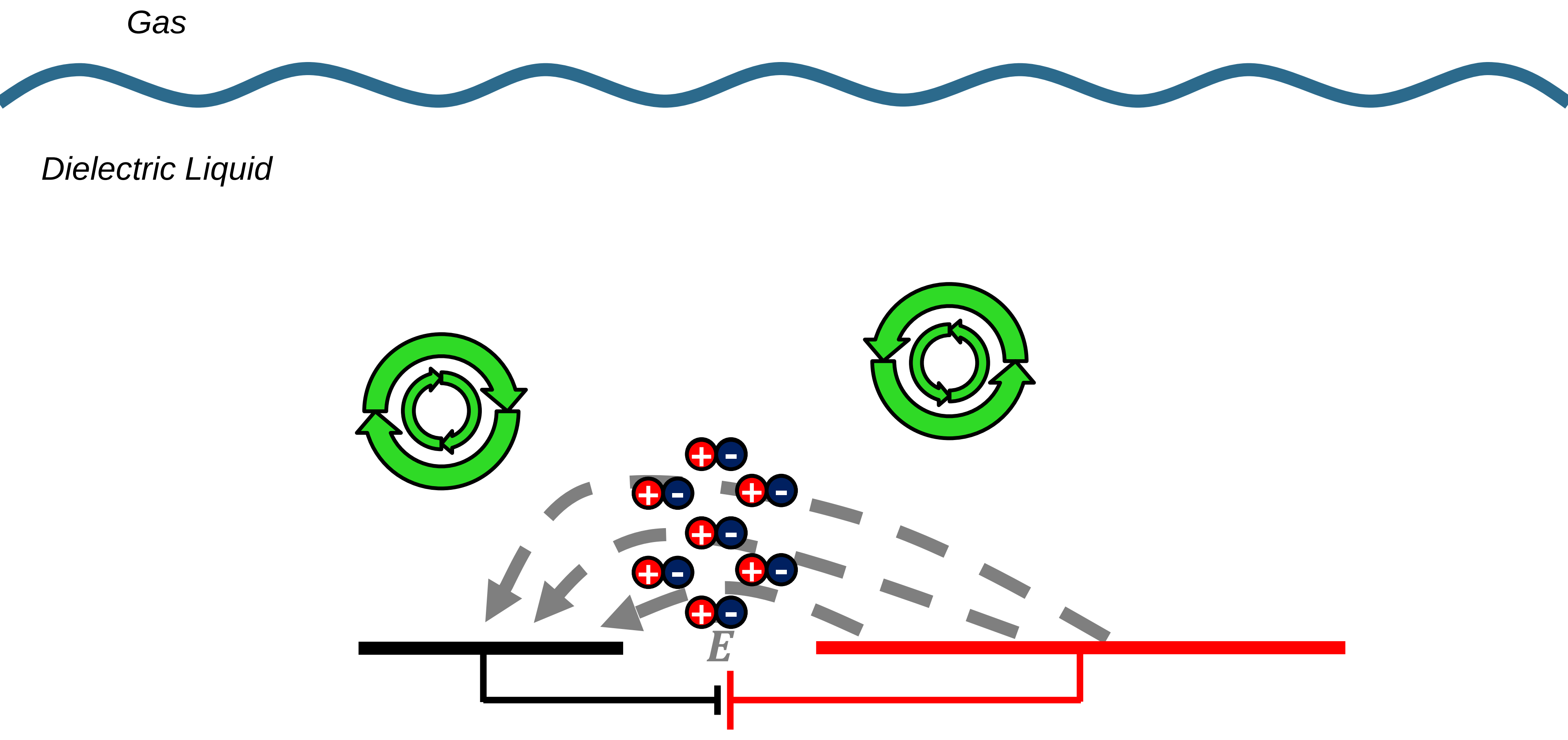


The motion of ions imparts shear forces on **neutral molecules** in the liquid, and bulk motion is generated.

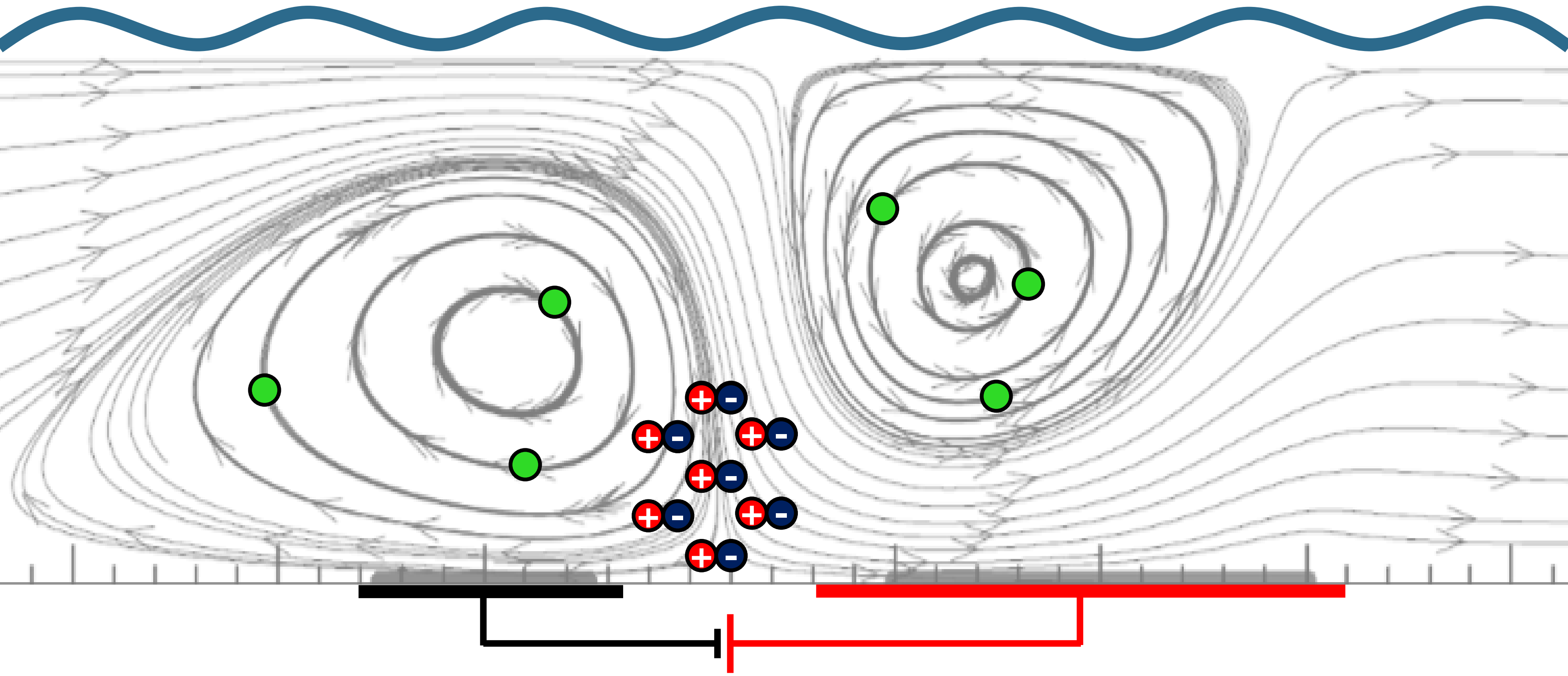
Now consider asymmetric electrodes, resulting in an asymmetric electric field.



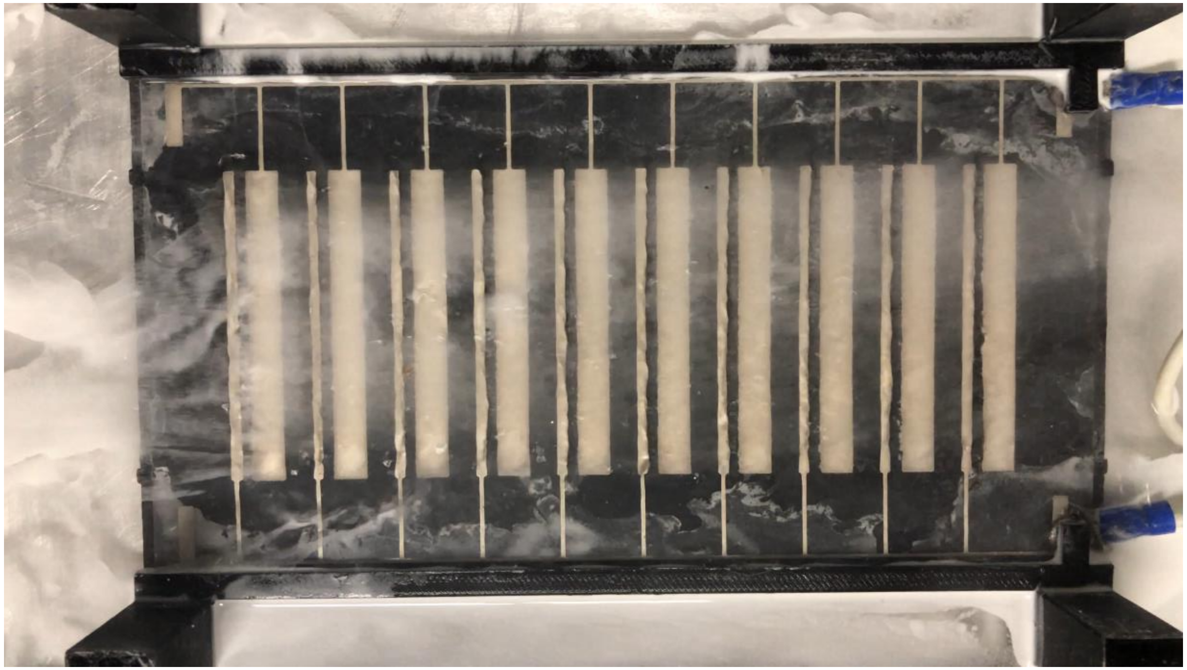
The asymmetric electric field results in a net Coulomb Force in one direction, and **vortices** are formed near the electrodes.



The generated flow field in a liquid film, from Yazdani and Yagoobi, 2009.



EHD Conduction Pumping of Liquid Film



EHD Conduction Pumping – Theoretical Model

- Initial work by Atten and Yagoobi for static pressure generation via EHD conduction mechanism
- In EHD conduction, charge carriers are not produced by injection, but by dissociation of molecules/impurities within fluid:

$$AB \leftrightarrow A^{+}B^{-}$$

Theoretical Model (cont.)

- Equations that govern charge density:

$$\frac{\partial p_{eq}}{\partial t} + \nabla \cdot \boldsymbol{\Gamma}_{+} = k_D c - k_R p_{eq} n_{eq} \quad (3)$$

$$\frac{\partial n_{eq}}{\partial t} + \nabla \cdot \boldsymbol{\Gamma}_{-} = k_D c - k_R p_{eq} n_{eq} \quad (4)$$

$$\boldsymbol{\Gamma}_{+} = b_{+} p_{eq} \boldsymbol{E} + p_{eq} \boldsymbol{u} - D_{+} \nabla p_{eq} \quad (5)$$

$$\boldsymbol{\Gamma}_{-} = -b_{-} n_{eq} \boldsymbol{E} + n_{eq} \boldsymbol{u} - D_{-} \nabla n_{eq} \quad (6)$$

- Electric field vector:

$$\nabla \cdot \boldsymbol{E} = \frac{\rho_e}{\varepsilon} = \frac{p_{eq} - n_{eq}}{\varepsilon} \quad (7)$$

$$\boldsymbol{E} = -\nabla \phi \quad (8)$$

Theoretical Model (cont.)

- Electric body force density:

$$\boldsymbol{f}_e = \rho_e \boldsymbol{E} - \frac{1}{2} E^2 \nabla \varepsilon + \frac{1}{2} \nabla \left[E^2 \left(\frac{\partial \varepsilon}{\partial \rho} \right)_T \rho \right] \qquad (9)$$

- Continuity equation:

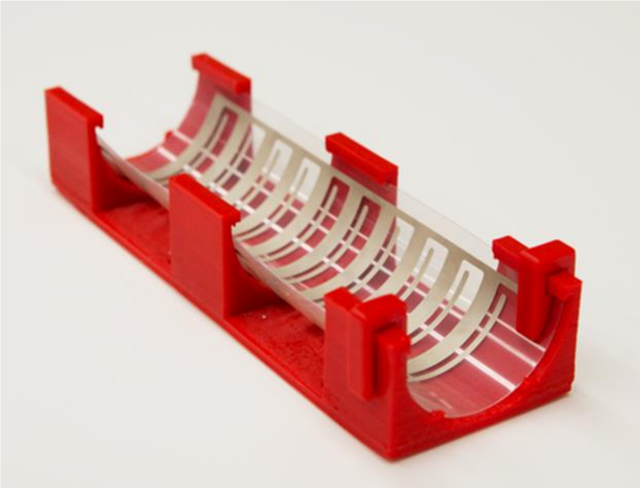
$$\nabla \cdot \boldsymbol{u} = 0 \qquad (10)$$

- Momentum equation:

$$\rho (\boldsymbol{u} \cdot \nabla) \boldsymbol{u} = -\nabla P + \mu \nabla^2 \boldsymbol{u} + \rho \boldsymbol{g} + \rho_e \boldsymbol{E} \qquad (11)$$

EHD Advantages

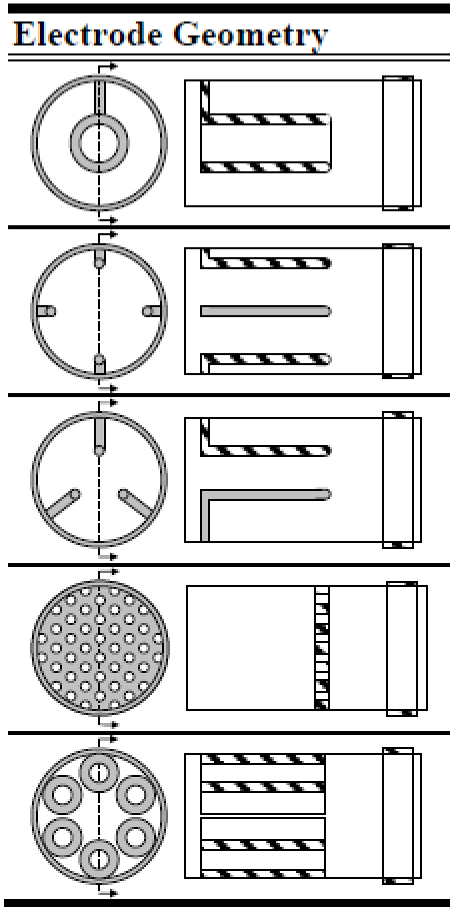
- applicable from macro to micro scales
- simple design
- light weight
- non-mechanical, no rotating machinery
- rapid and easy control of performance
- low power consumption
- low acoustic noise
- smart/active system
- effective flow distribution control
- intelligent mixing
- *flexible*

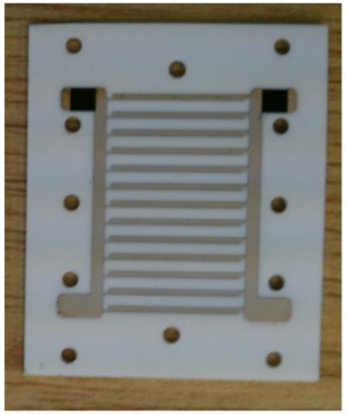


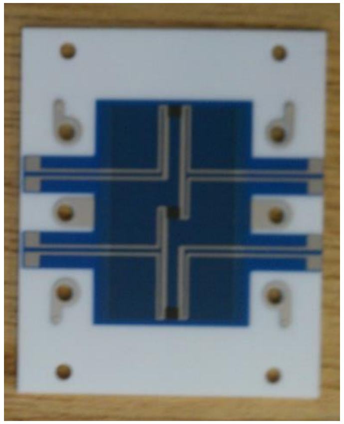
EHD Constraints

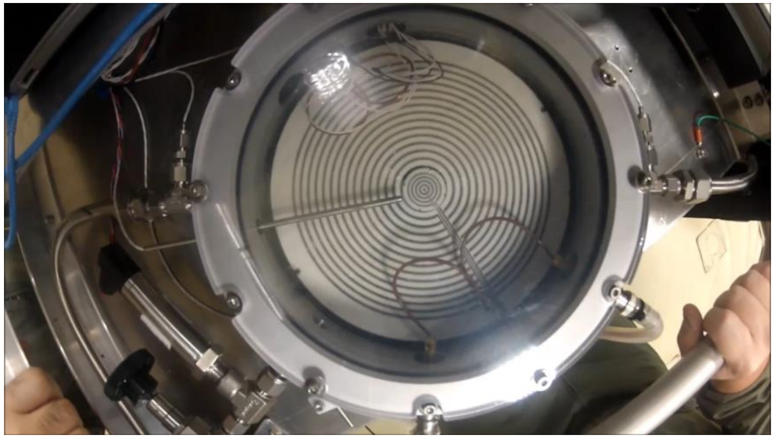
- high voltage/electric field
- electric field interference
- electrically conductive fluids
- low pumping efficiency

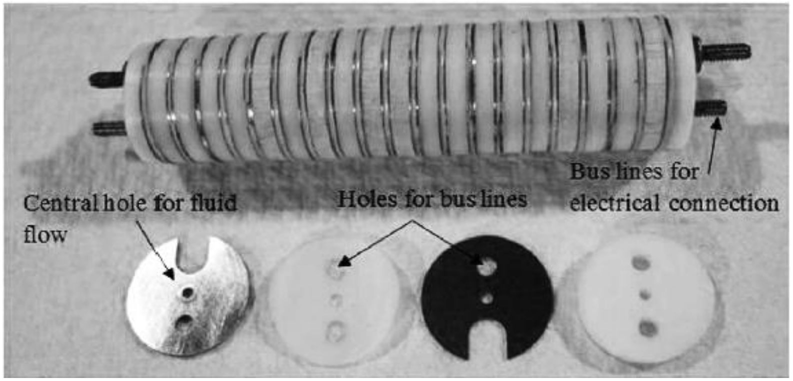
Examples EHD Conduction Pumps





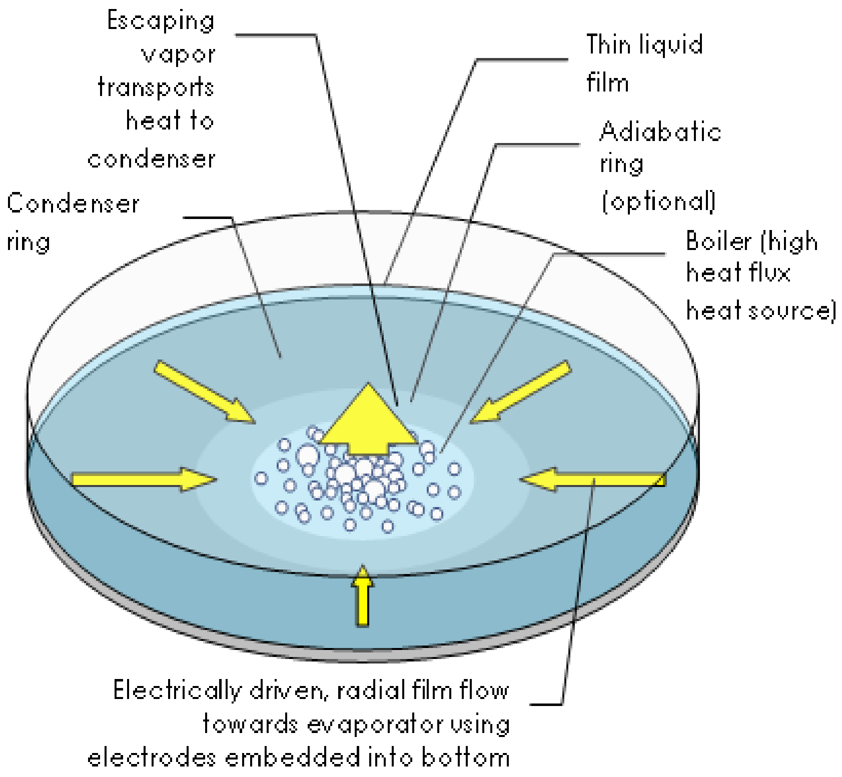






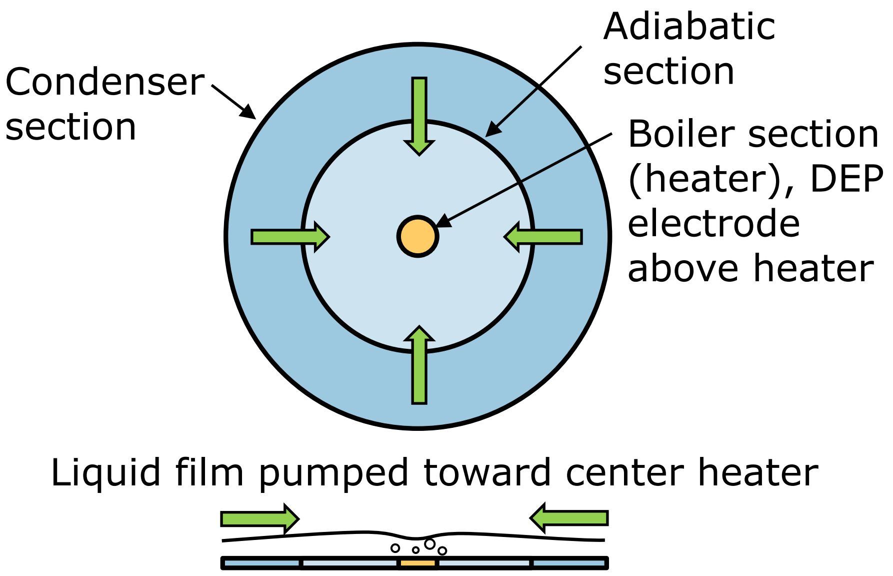
A Two-Phase Heat Transport Device Driven by EHD - Concept

- Different from well-known pool boiling
- Liquid-vapor interface is only a short distance away from heater (1-3 mm)
- Complex liquid-vapor phase change phenomenon in presence and absence of electrical field and gravity



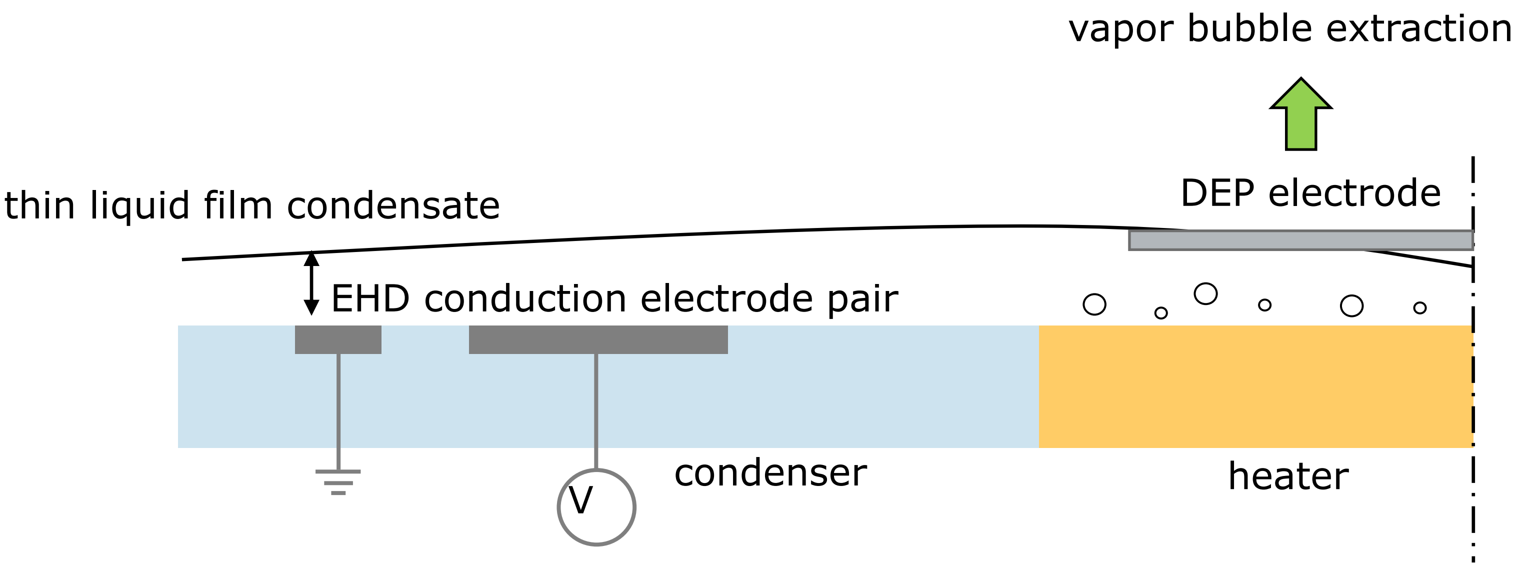
Concept (cont.)

- Electrodes lithographically printed onto condenser surface
- Applied voltage to electrode generates intense electrical field
- Electrical body force generates pumping within dielectric liquid film
- DEP electrode extracts bubbles away from heater surface



Concept (cont.)

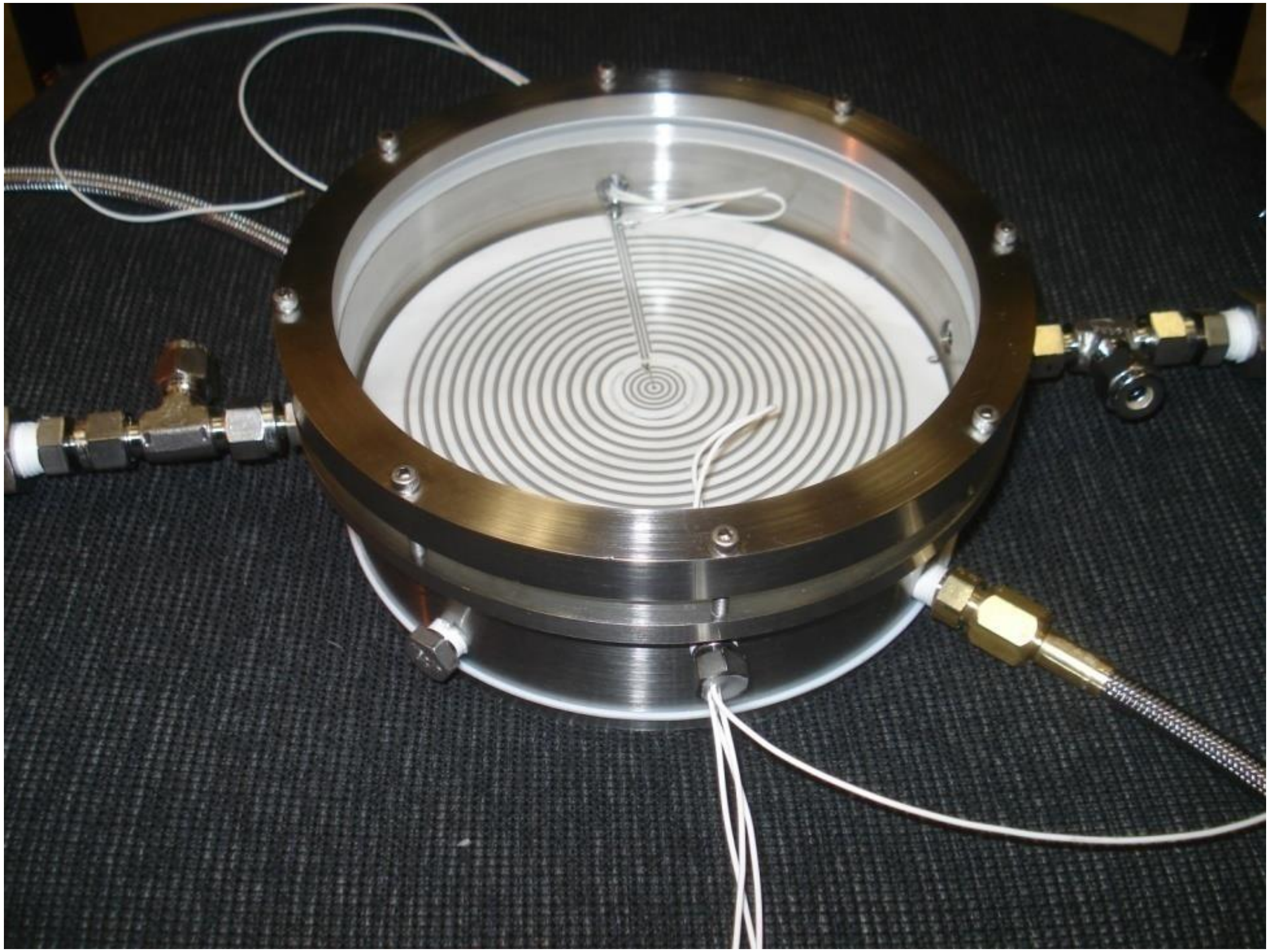
- One of the few techniques to pump liquid film
- Design of electrodes based on theoretical and numerical understanding



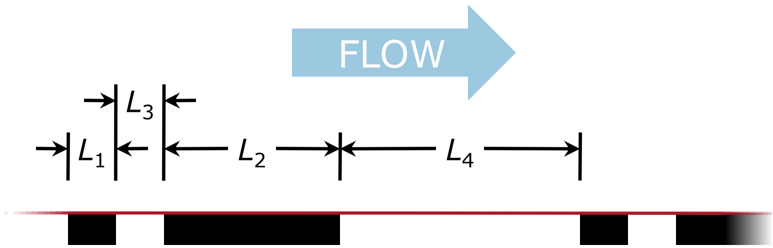
Objectives

1. Provide fundamental understanding of the electrically driven (based on EHD conduction phenomenon) liquid film flow in the presence of phase change (liquid to vapor), in the absence of gravity
2. Provide phenomenological foundation for the development of electric field based two-phase thermal management systems leveraging EHD engineering advantages to develop systems of arbitrary mass flow requirements and geometries.

Experimental Work – Test Cell



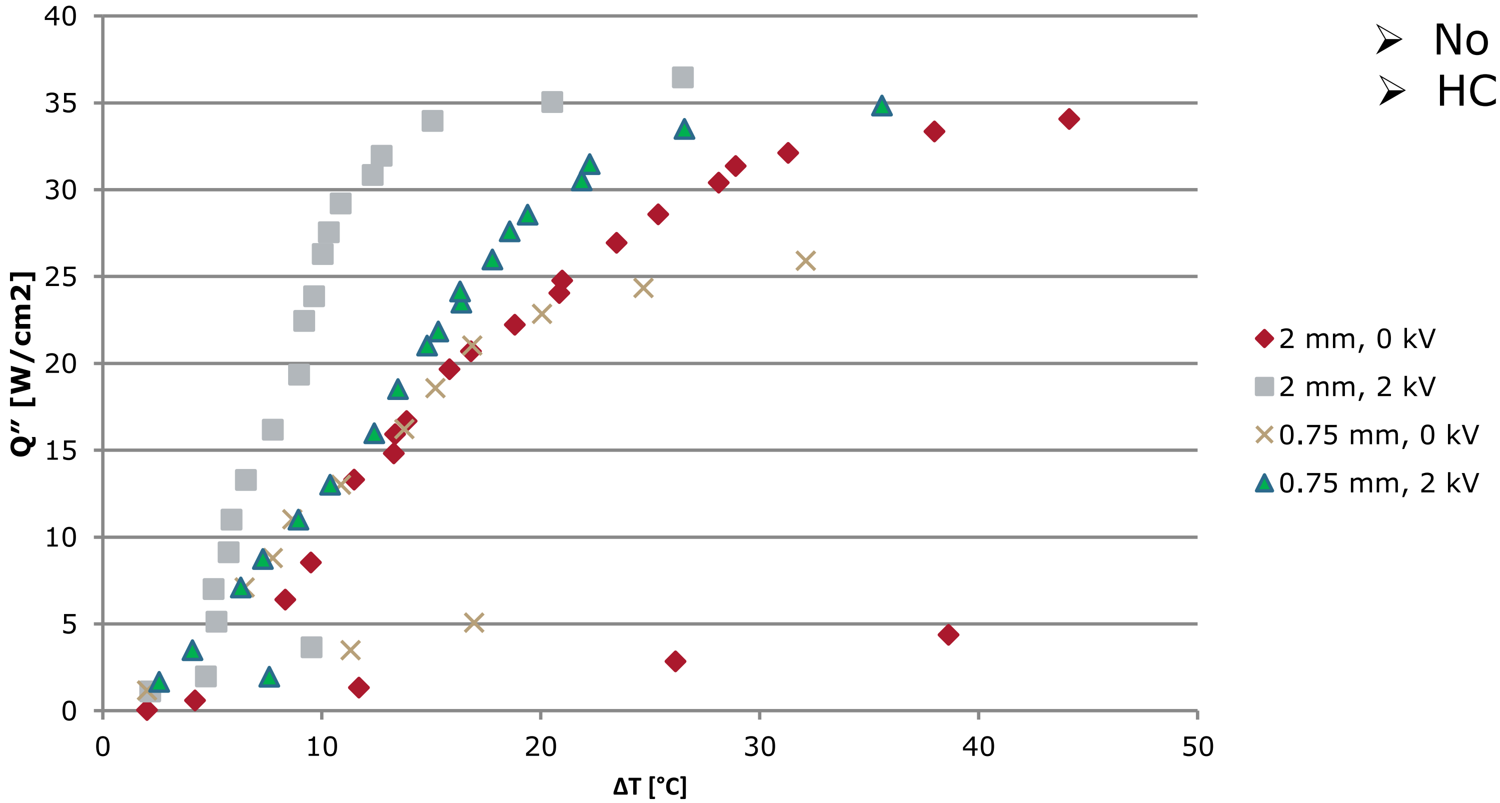
EHD Conduction Pump Design



Dimension	Outer (Condenser)
L_1	508 µm
L_2	1.52 mm
L_3	508 µm
L_4	2.54 mm
m	7

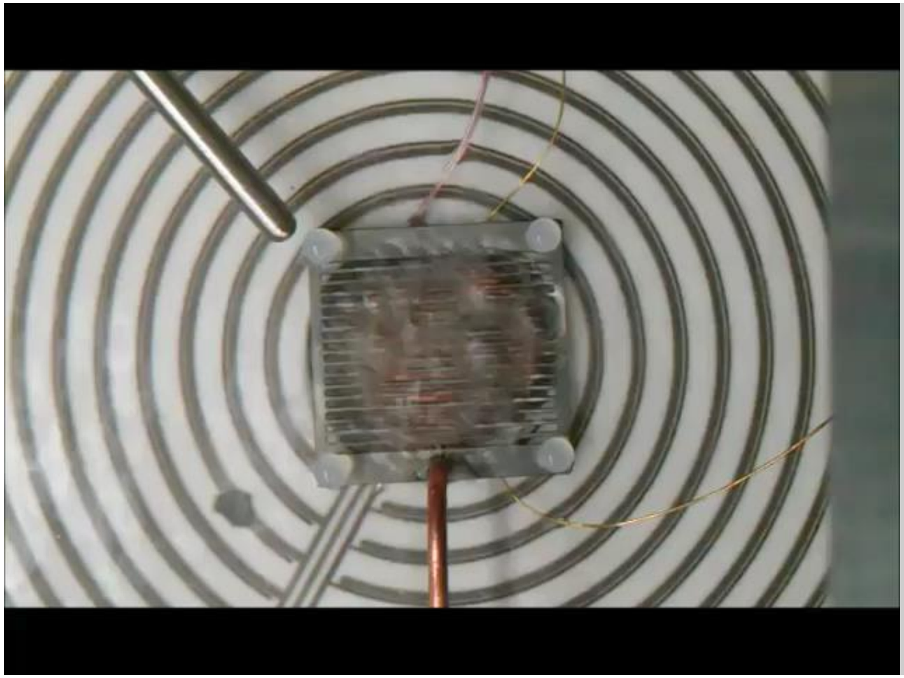
Experimental Results

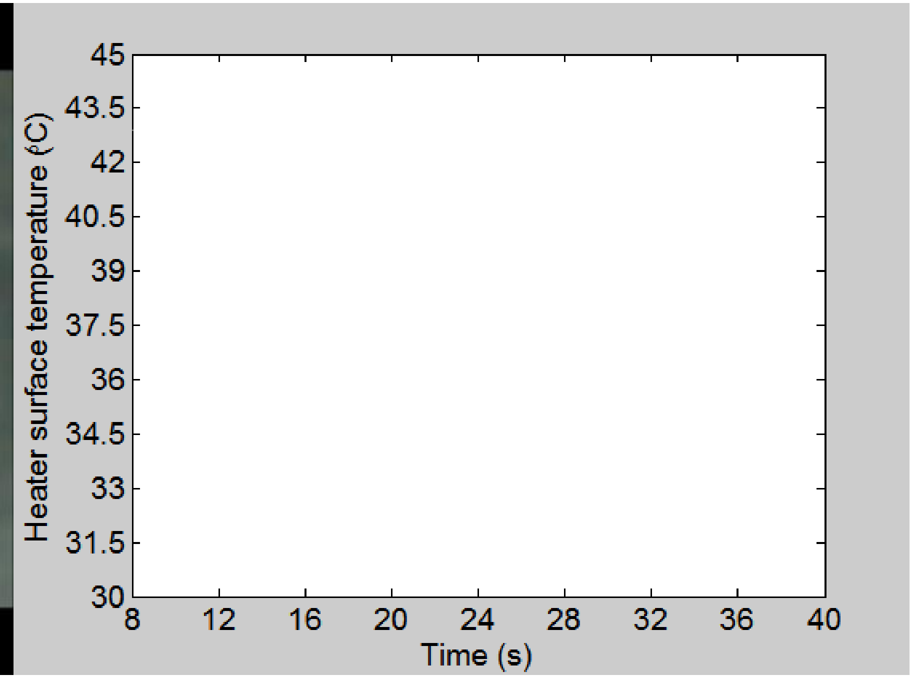
- Liquid film boiling results: Influence of applied EHD voltage and liquid film thickness



- No DEP
- HCFC123

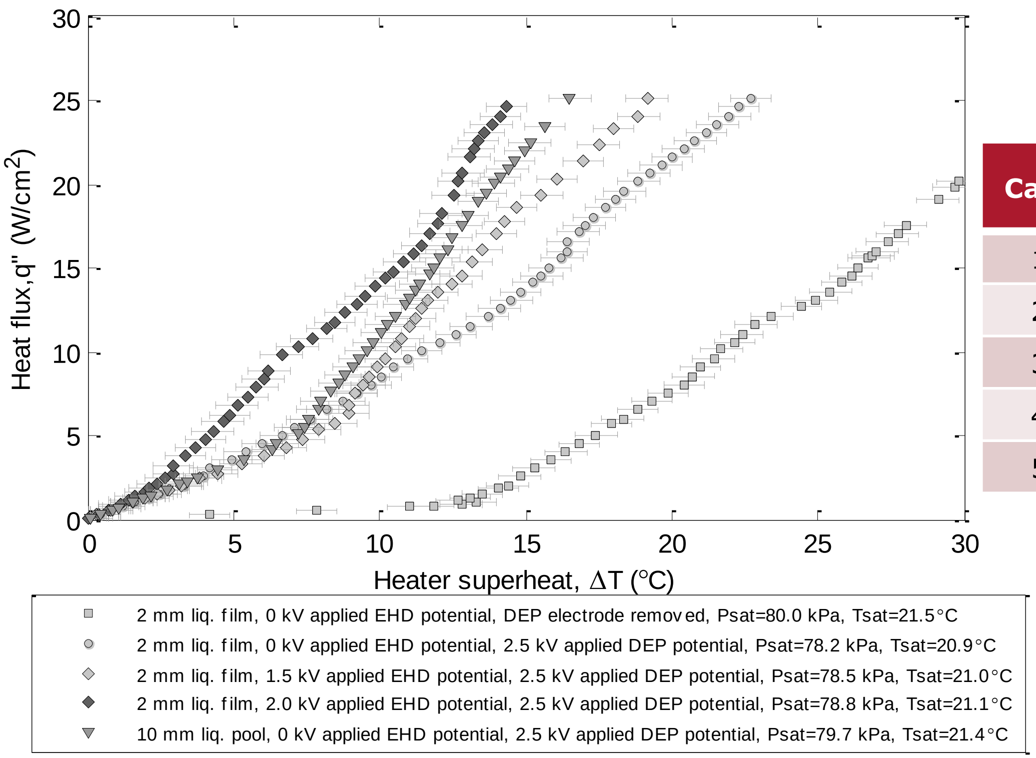
Effect of DEP Extraction Force on Heater Surface Temperature





- HCFC-123, 2.0 mm liquid film, P_{sat} = 78.2 kPa, T_{sat} = 20.9°C
- Heat flux, q”: 10.0 W/cm^2
- 0 kV applied EHD potential
- 2.5 kV applied DEP potential

Select Experimental Results

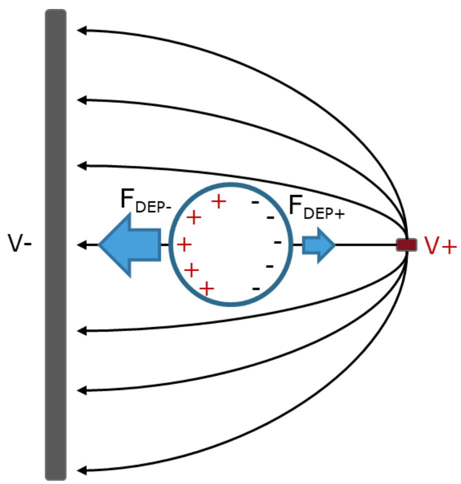


- HCFC 123
- w and wo DEP

Case	ΔT (°C)	Corresponding heat flux (W/cm^2)	Comparison to case 1
1	14.1	1.83	--
2		12.6	589%
3		17.1	834%
4		24.1	**1217%**
5		20.4	1015%

Dielectrophoretic (DEP) Vapor Extraction

$$F_{DEP} = 2\pi R_0^3 \frac{\varepsilon_l(\varepsilon_v - \varepsilon_l)}{\varepsilon_v + 2\varepsilon_l} \nabla E^2$$



Diverging Electric Field

$\mathbf{F_{DEP+}} \neq \mathbf{F_{DEP-}}$

DEP Effect Demonstration

Multiscale Heat Transfer Laboratory

Heat Flux: 10 W/cm^2

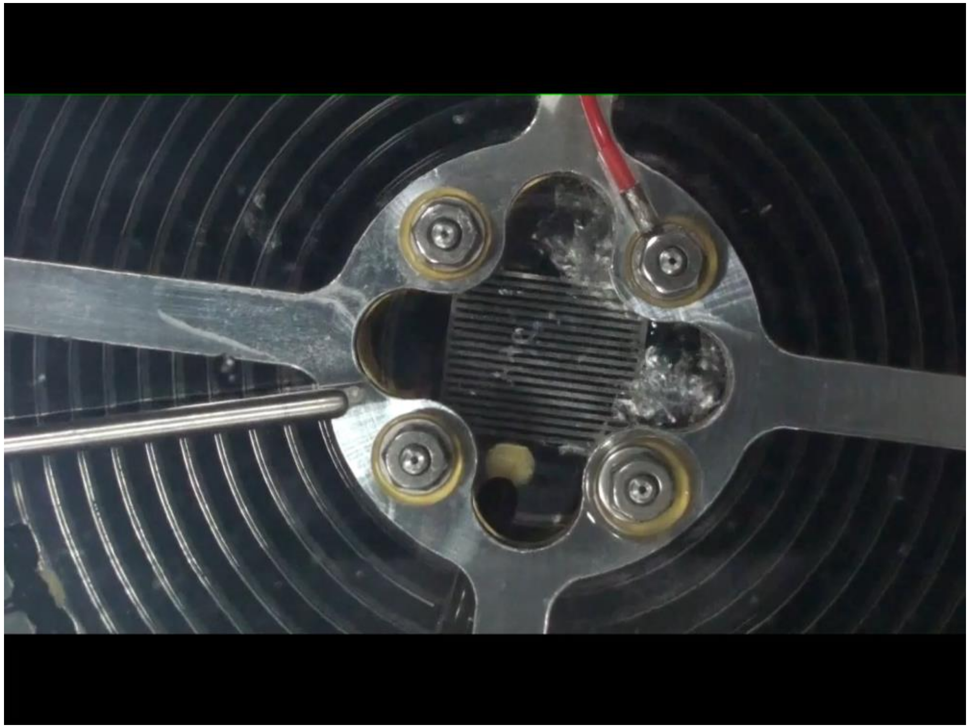
DEP Voltage: 0-2kV

Working Fluid: HFE-7100

Mar. 22, 2021

Sustaining Boiling in Microgravity

- HFE 7100
- W EHD and DEP



Effect of Non-Condensable Gas on Phase Change

- Condensation is impeded in two ways:
  - Partial pressure of vapor is lowered, so dew point of the vapor decreases.
  - Higher gas concentration impedes diffusion of vapor molecules to the liquid surface.
- Thermocapillary flows induced in boiling, which inhibits bubble detachment.
- Increasing system pressure decreases bubble size.

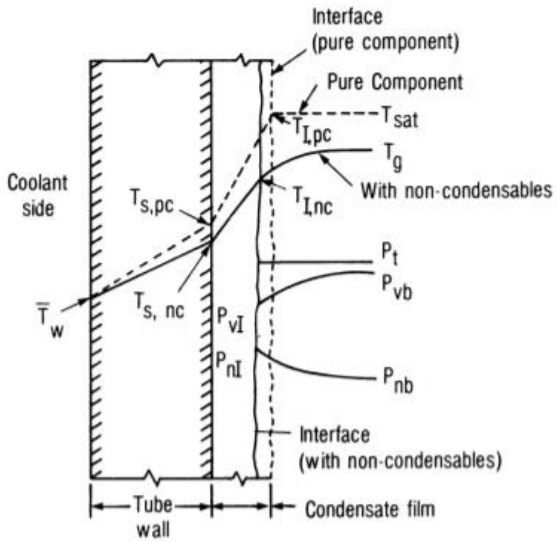
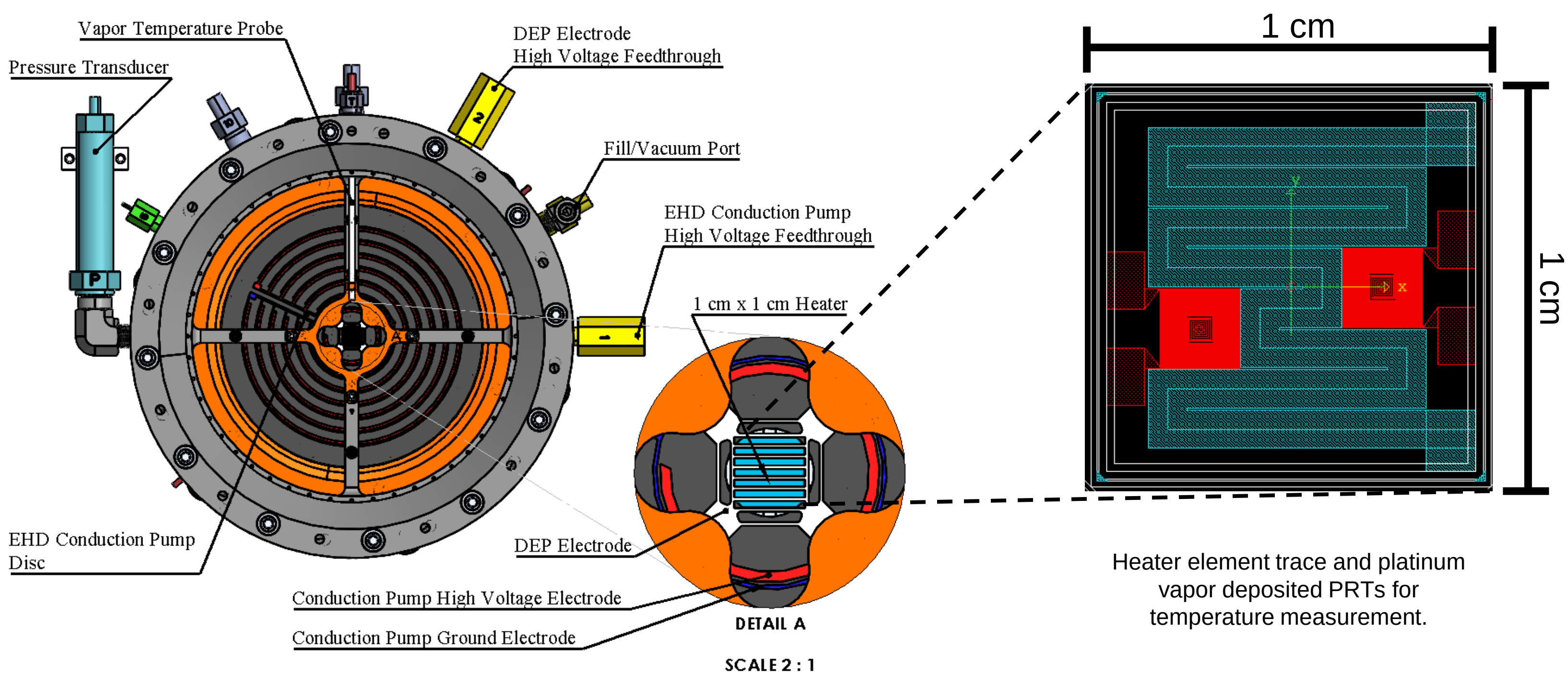


FIGURE 8. Boundary Layer Temperature and Pressure Distributions [6].

Jensen (1988)

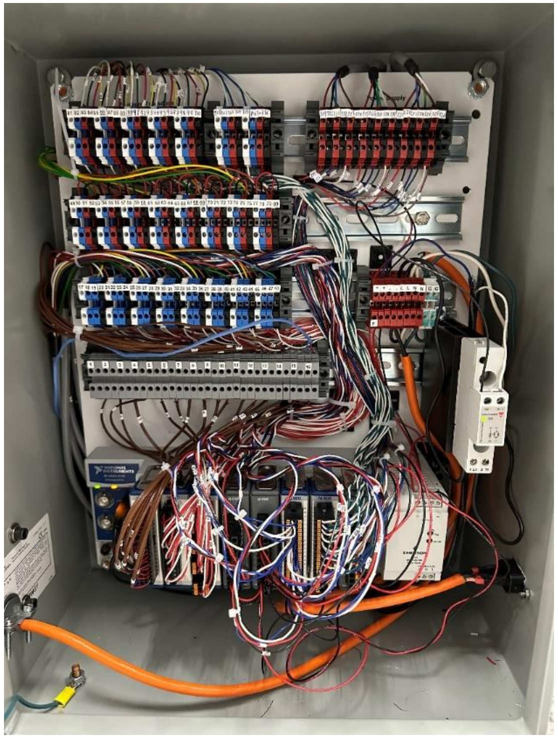
Experiment Chamber Design

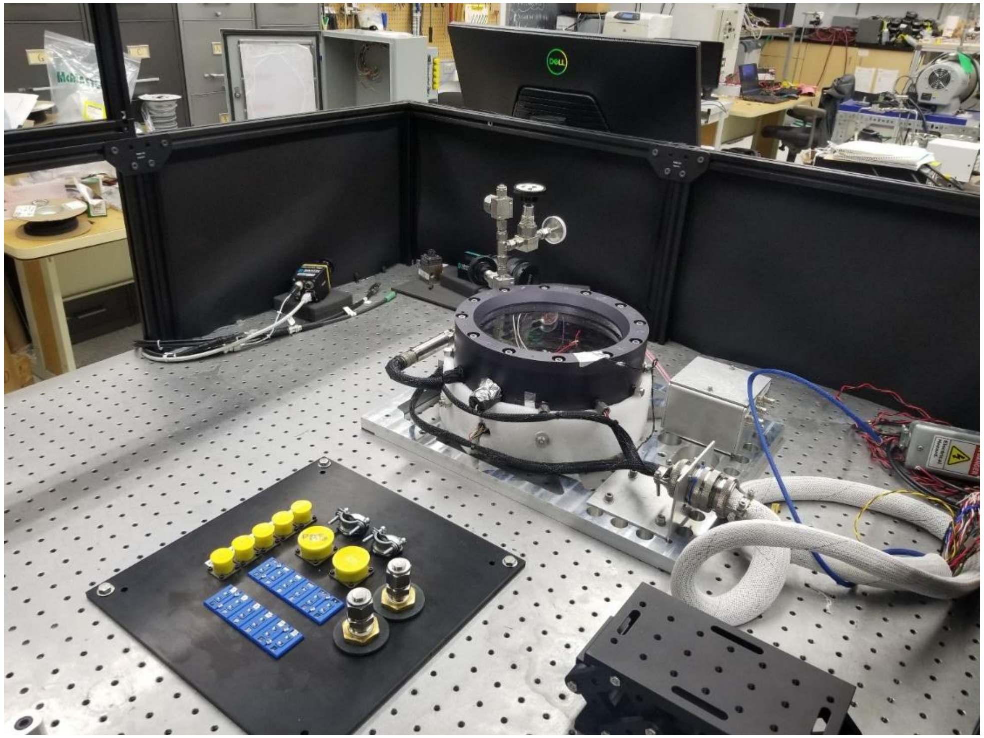
Working Fluid: HFE-7100
2 mm Liquid Film (55 g)



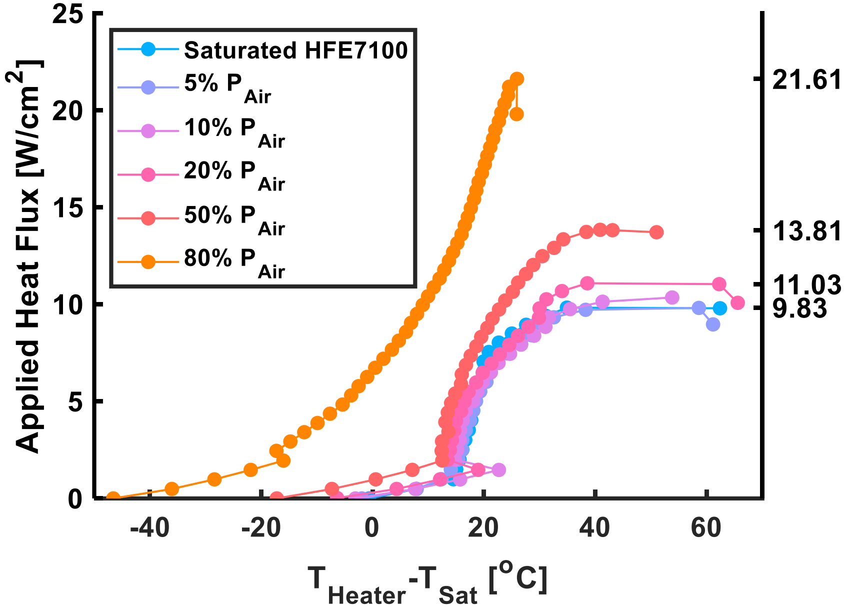
Heater element trace and platinum vapor deposited PRTs for temperature measurement.

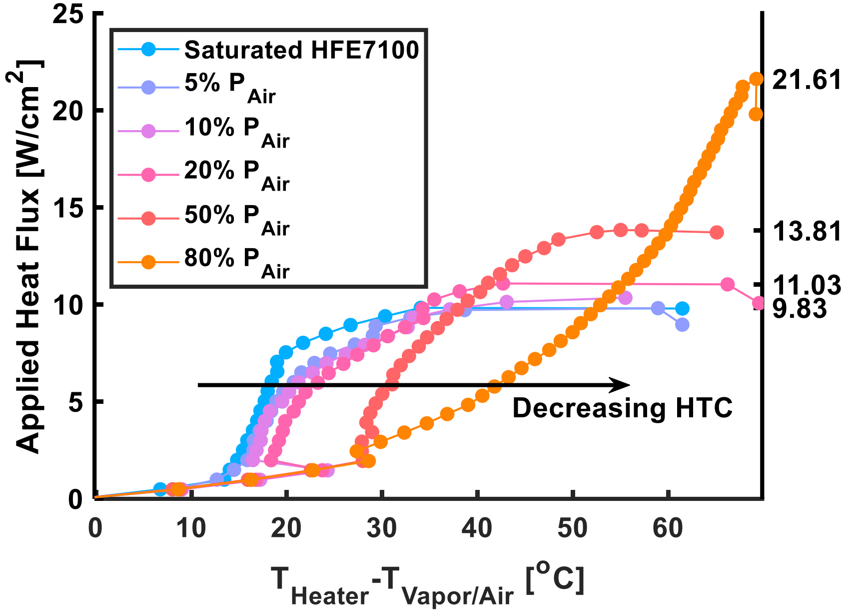
Testbed





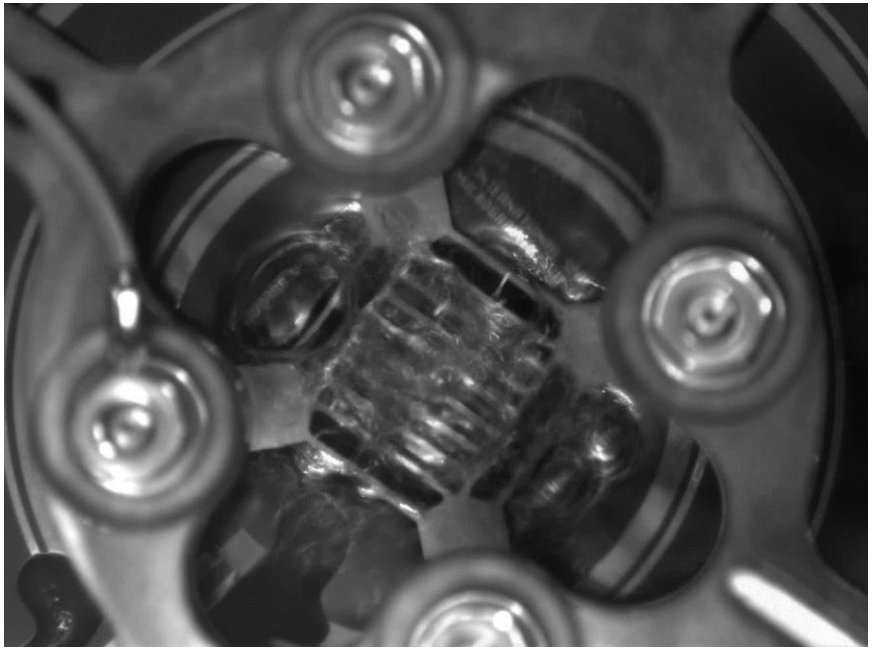
Effect of P_{Air} – Without EHD and DEP



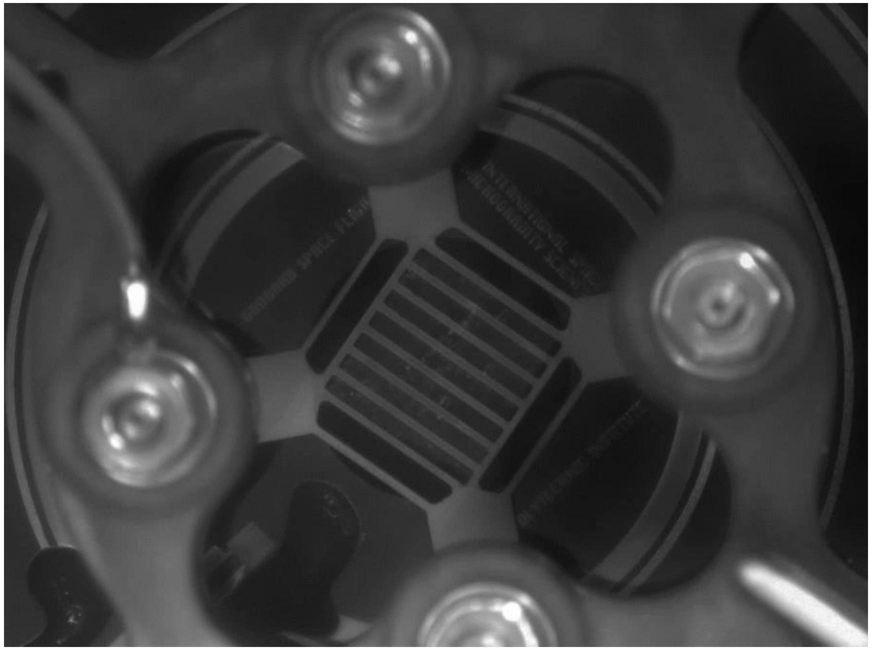


Boiling Behavior, Saturated vs 50% P_{Air}

- wo EHD and DEP

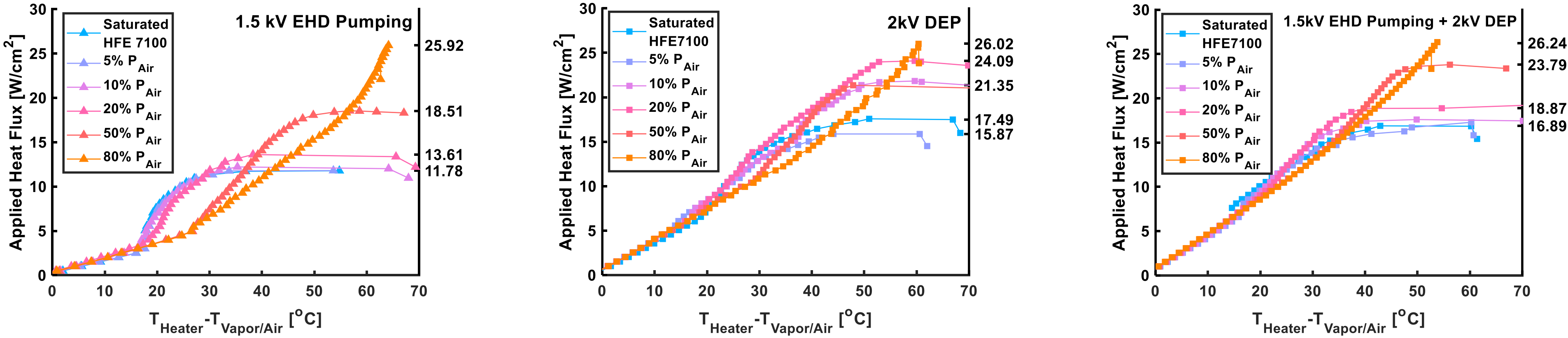


Saturated HFE-7100
1.5 W/cm^2

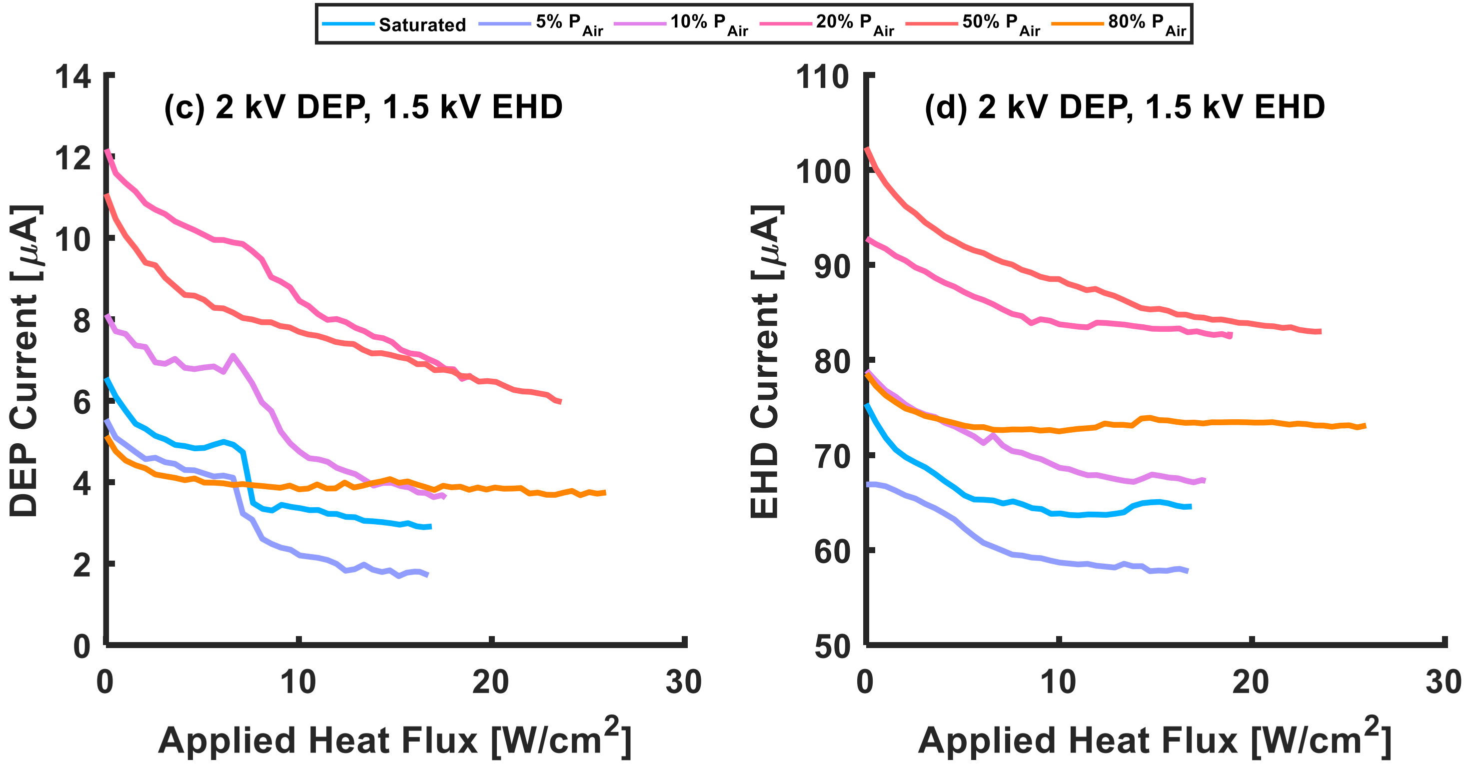


50% P_{Air}
2 W/cm^2

Effect of P_{Air} – With EHD & DEP



Electric Current Behavior



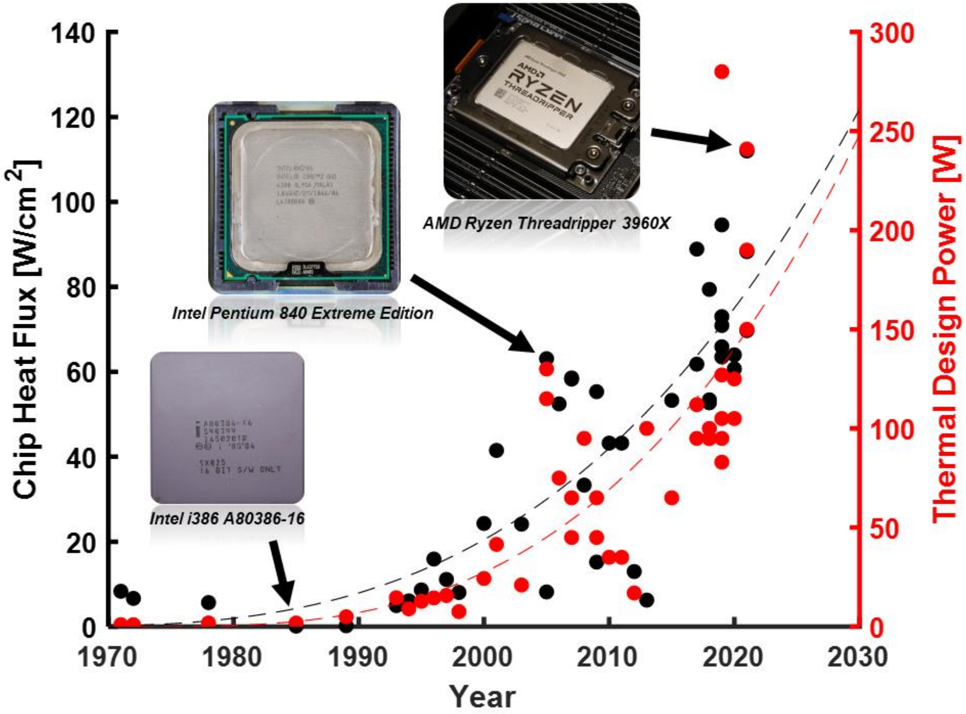
Non-condensable Gas - Summary

- The effect of non-condensable gas on the performance of electrically driven liquid film flow boiling was measured.
- EHD and DEP were found to provide significant heat transfer enhancements that were largely independent of air concentration.
- The effect of water vapor introduced into the system affected the measured current of the EHD and DEP.
- Further numerical study of this multiphase system is warranted to fundamentally understand the impact of EHD.
- This work will be published in ASME Journal of Heat and Mass Transfer.

Technology Applications

Thermal Management of Electronics

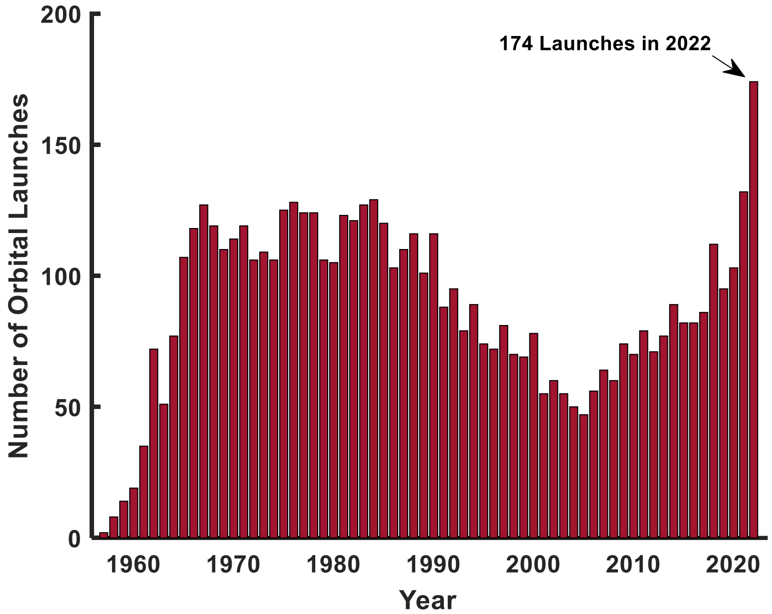
Thermal Management of Electronics

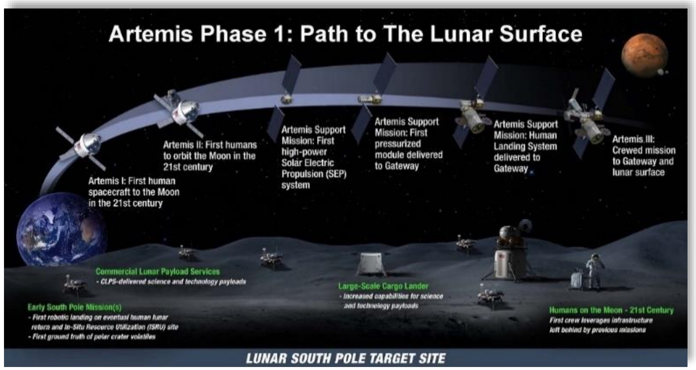


Thermal demands of consumer CPUs, data from cpuworld.com.

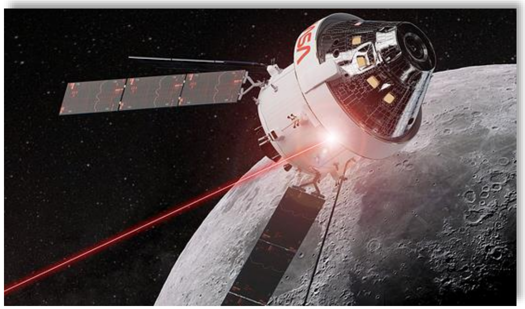
Frontier supercomputer, ORNL (Wikimedia Commons).

Electronics in Space

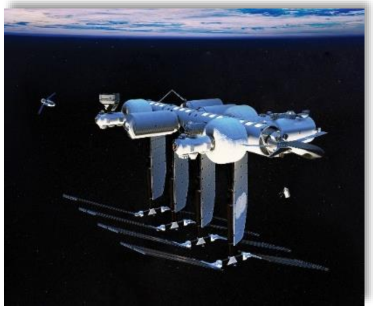




Artemis mission plan By NASA - nasa.gov, public domain



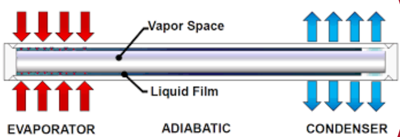
Laser Communications Terminal for Artemis II
NASA GSFC, MIT Lincoln Lab, Lockheed Martin
https://www.nasa.gov/feature/goddard/2022/the-future-of-laser-communications



Orbital Reef
Blue Origin & Sierra Space

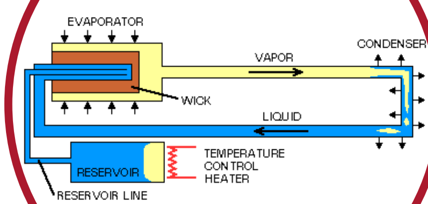
Heat Transport and Thermal Management in Microgravity

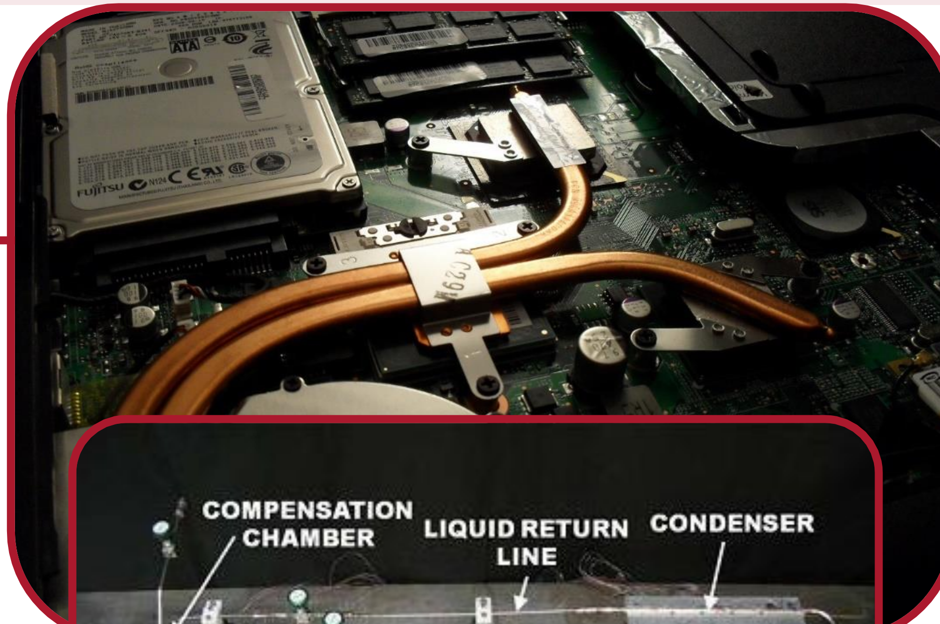
Heat Pipes

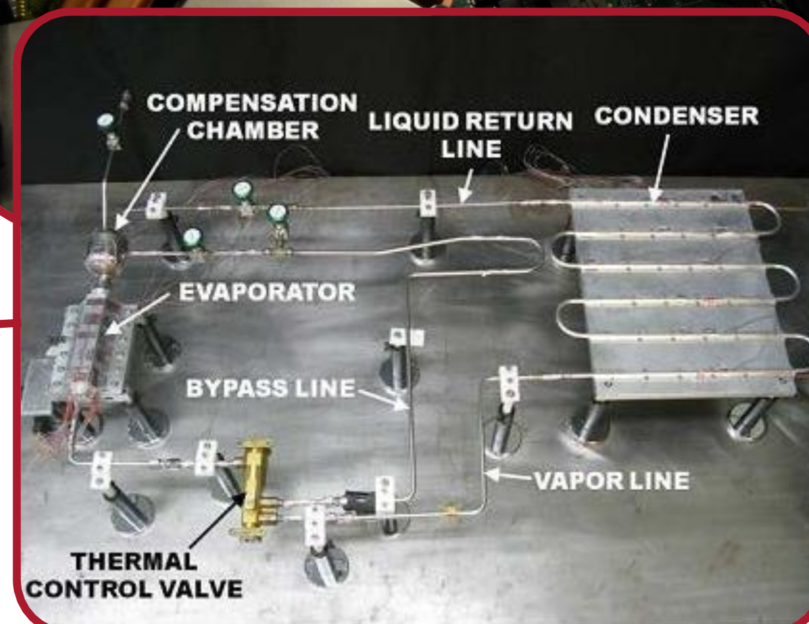


Passive Systems

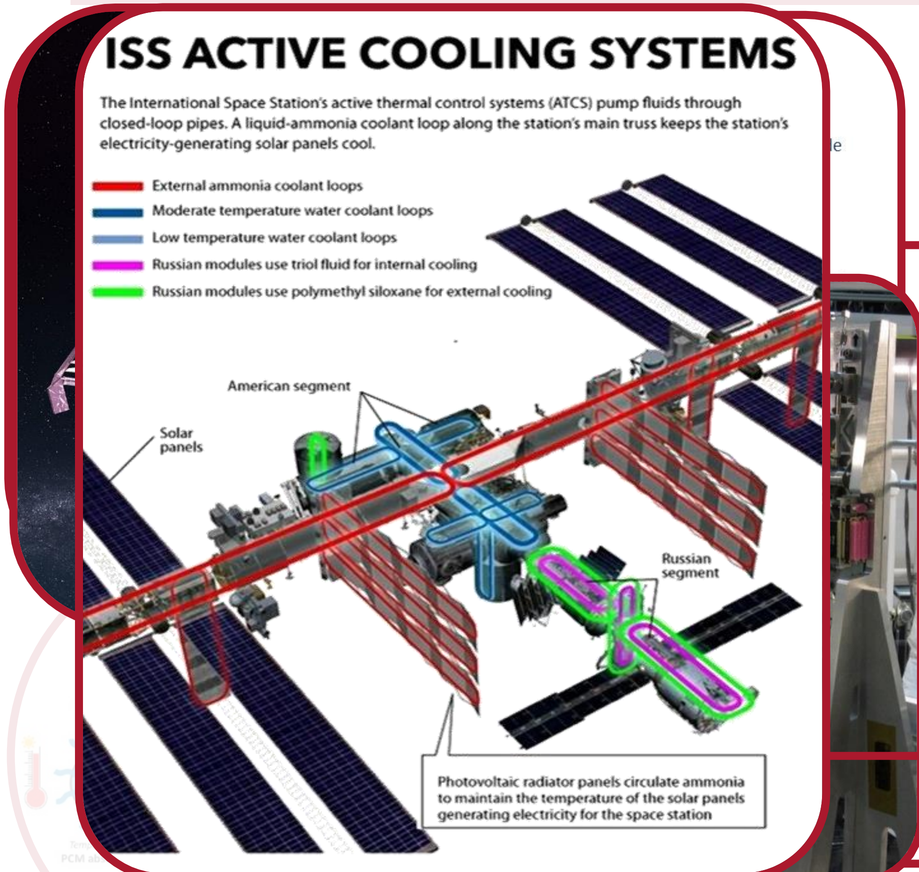
Capillary Pumped Loops







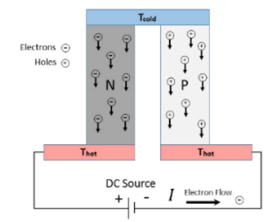
Heat Transport and Thermal Management in Microgravity



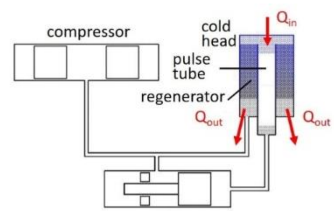
Credit: Karl Tate, SPACE.com

Active Systems

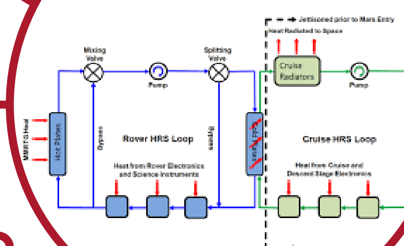
Thermoelectric Coolers



Pulse Tube Coolers



Mechanically Pumped Loops



…ansport Distance

Limited Temperature Range

Moving Parts Prone to Fail

Summary

- A fundamental study to understand the interactions between electric field and flow field, in the presence and absence of phase change, with and without the gravity.
- An applied study to develop heat transport devices for space and terrestrial applications.

Thank you!

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