# Performance comparison between co-current and counter-flow ACC tubes

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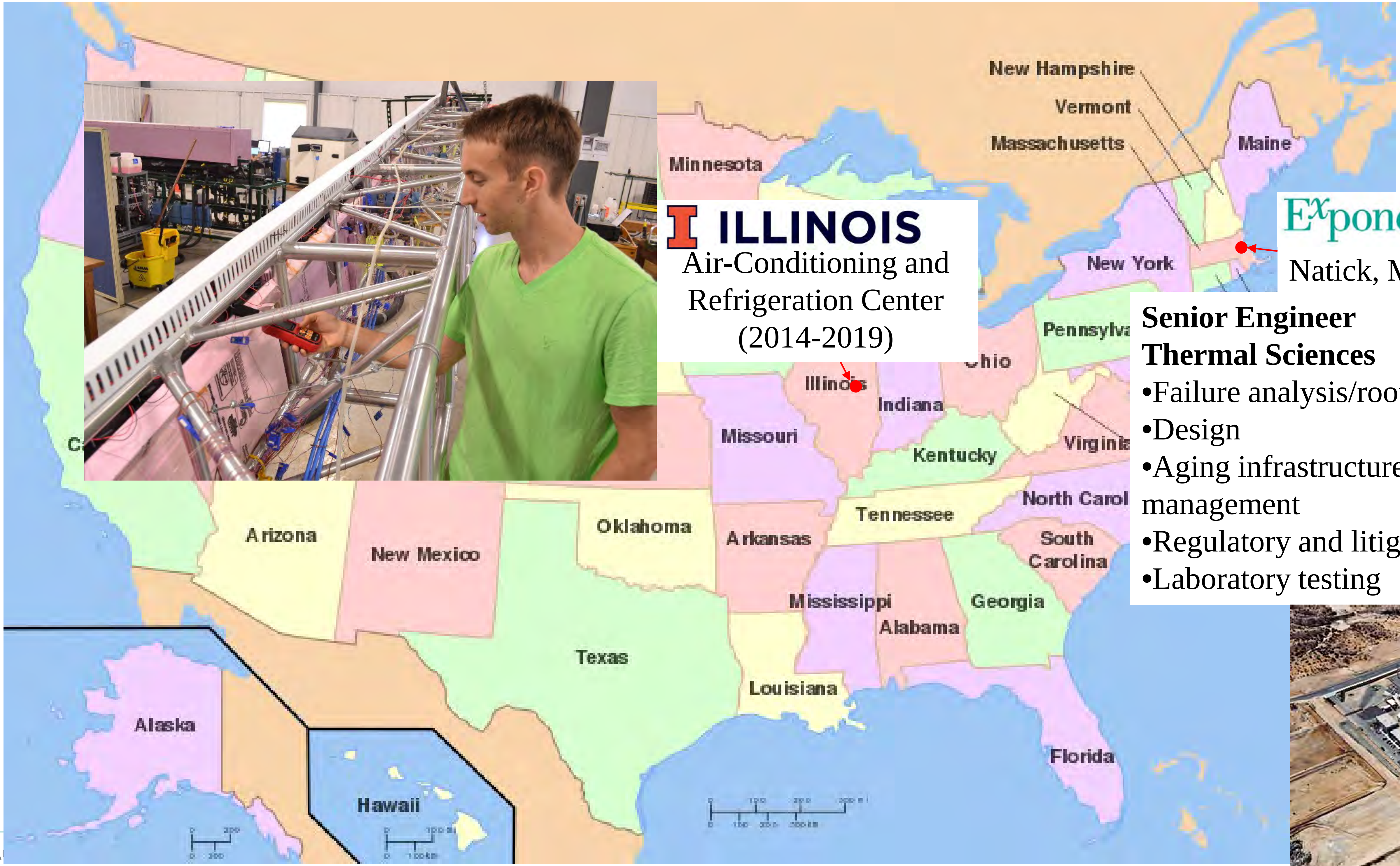
# Outline

- Background and motivation
- Visualization of liquid flow
  - Co-current
  - Counter-flow
- Cooling performance
  - Co-Current
  - Counter-Flow
    - Effect of Flooding
- Pressure drop
- Summary

# Introduction




ILLINOIS
Air-Conditioning and Refrigeration Center (2014-2019)

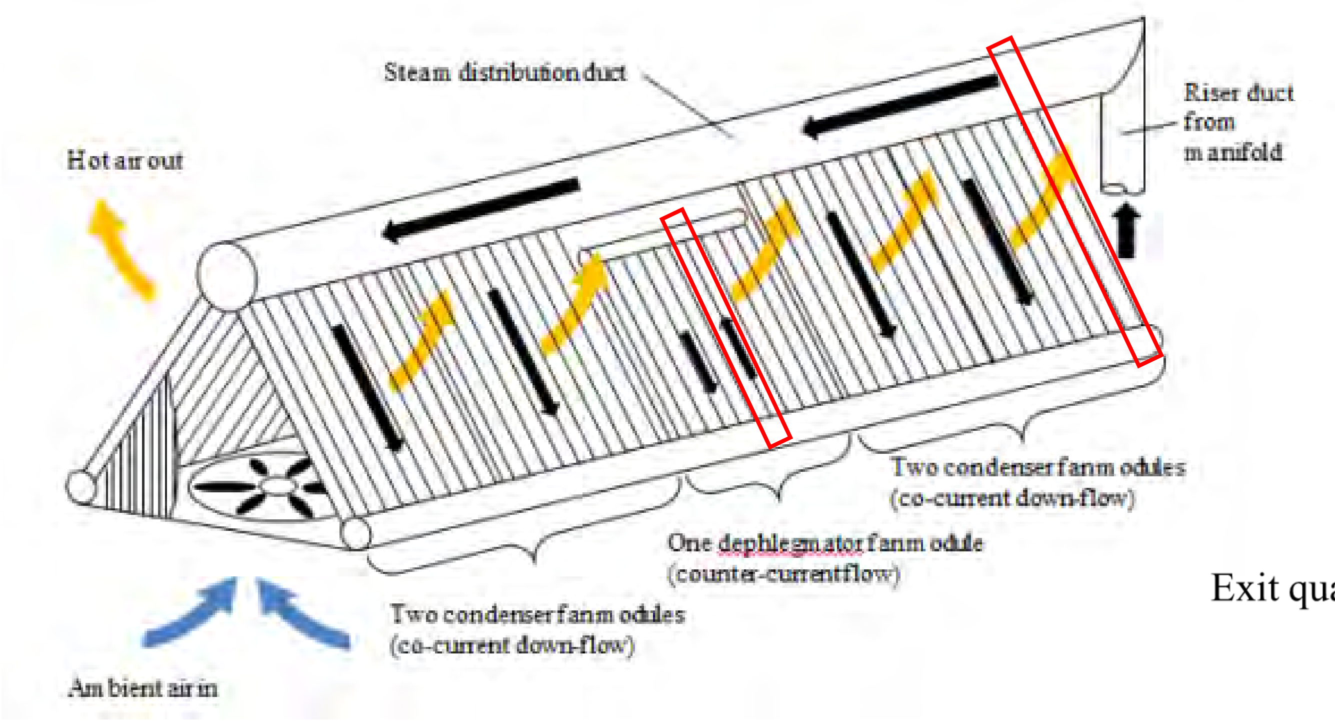
Exponent
Natick, MA

**Senior Engineer**
**Thermal Sciences**

- Failure analysis/root cause investigation
- Design
- Aging infrastructure assessment and risk management
- Regulatory and litigation support
- Laboratory testing

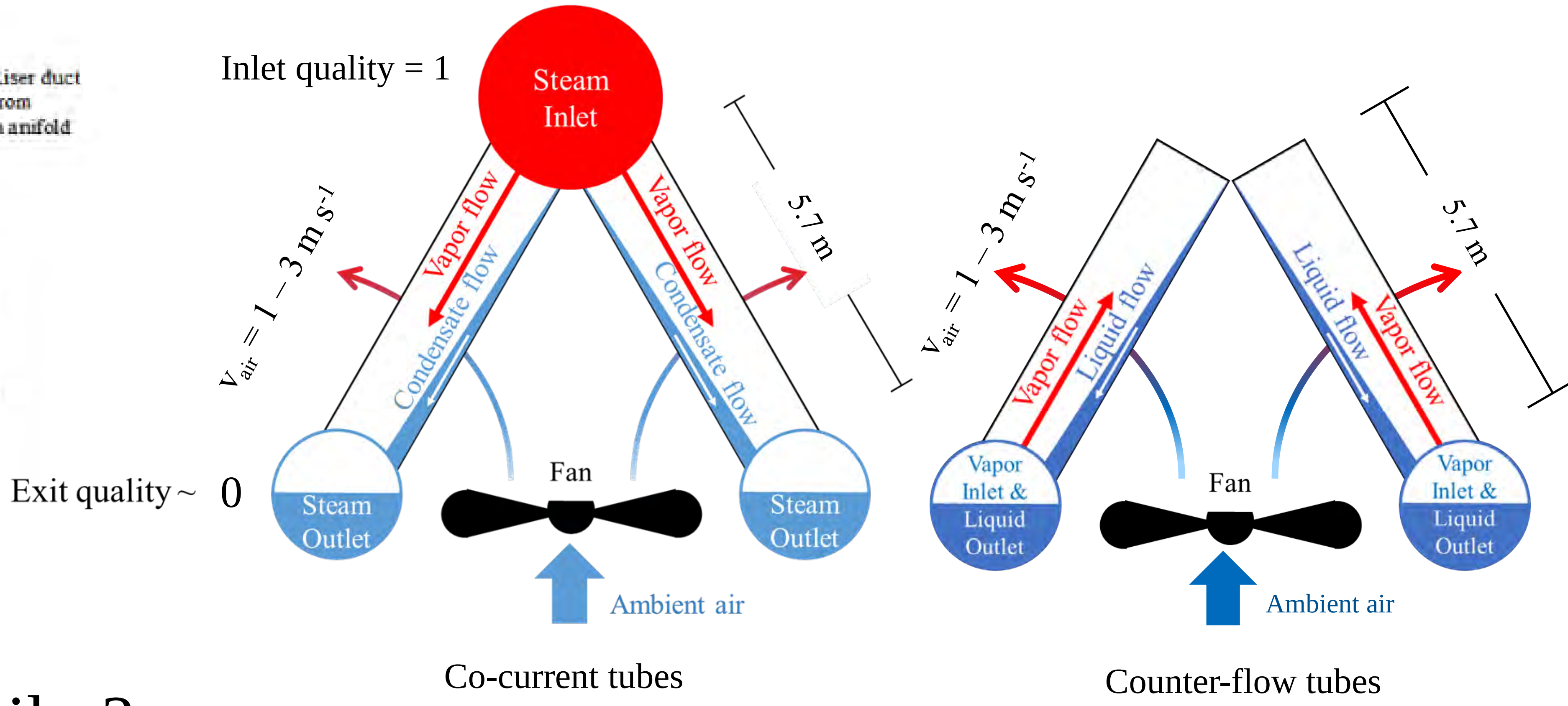
# Background

- A-frame forced-draft condensers with flattened steel tubes




(EPRI 2015)

Experimental pressures: 52-108 kPa [7.5-15.7 psi]




- Are liquid flow patterns similar?
- Are cooling capacities equivalent?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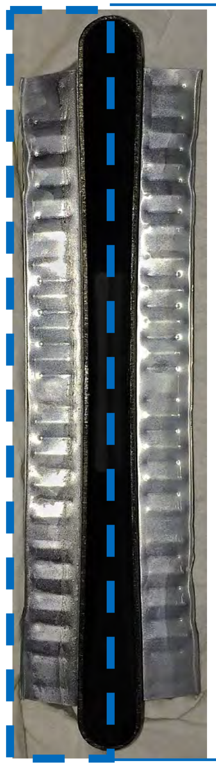
# Visualization

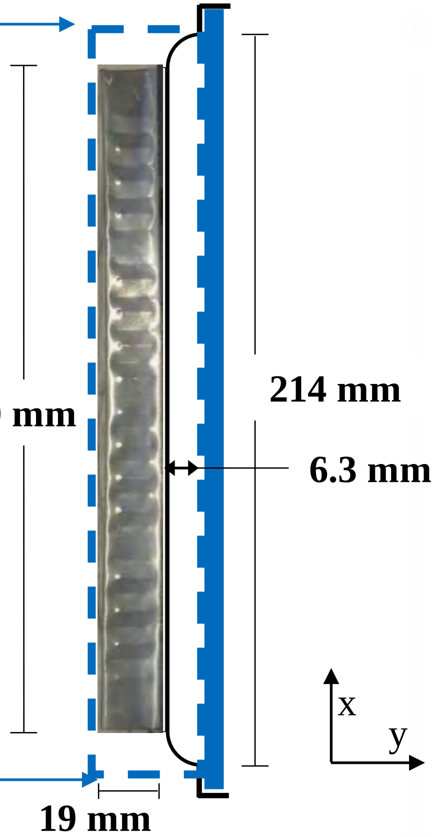
# Co-Current: Visualization along Length of Tube (10.7 m)

**Full condenser tube**

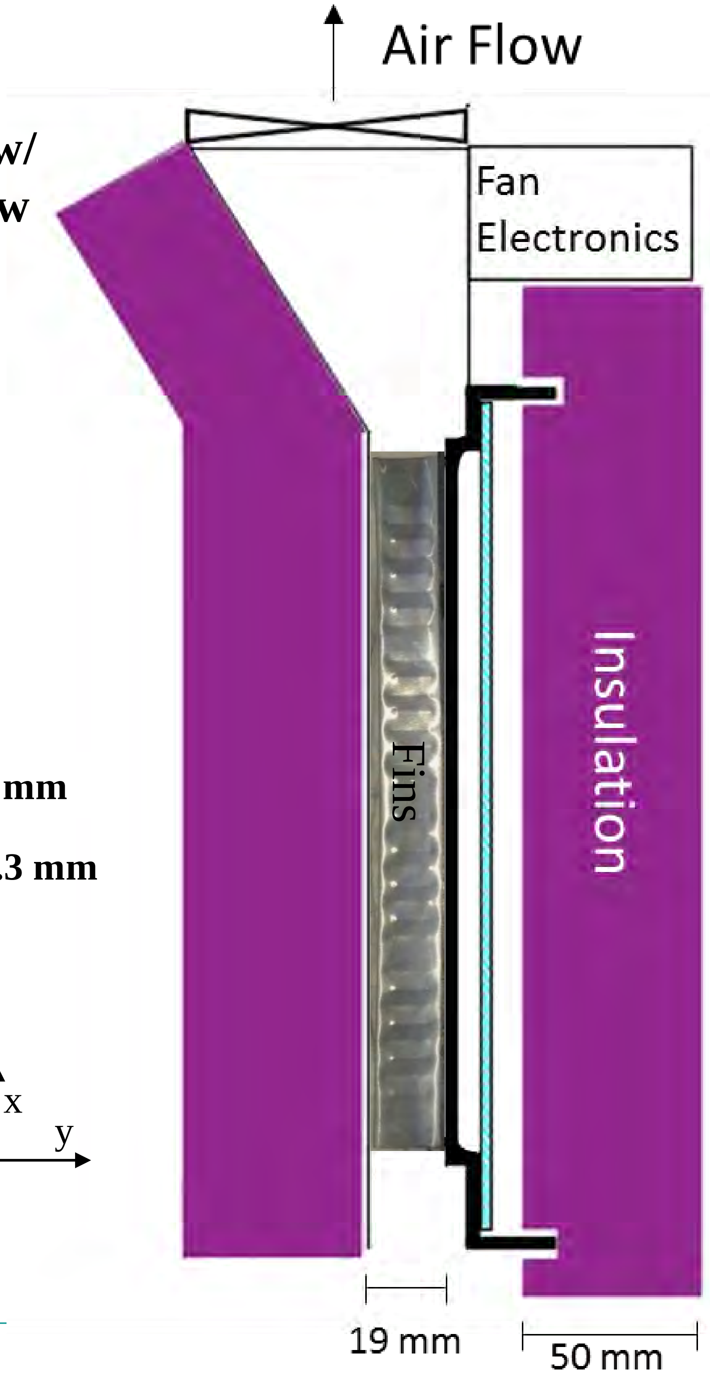


- Cut on centerline
- Polycarbonate window added

**Half condenser tube w/ polycarbonate window**



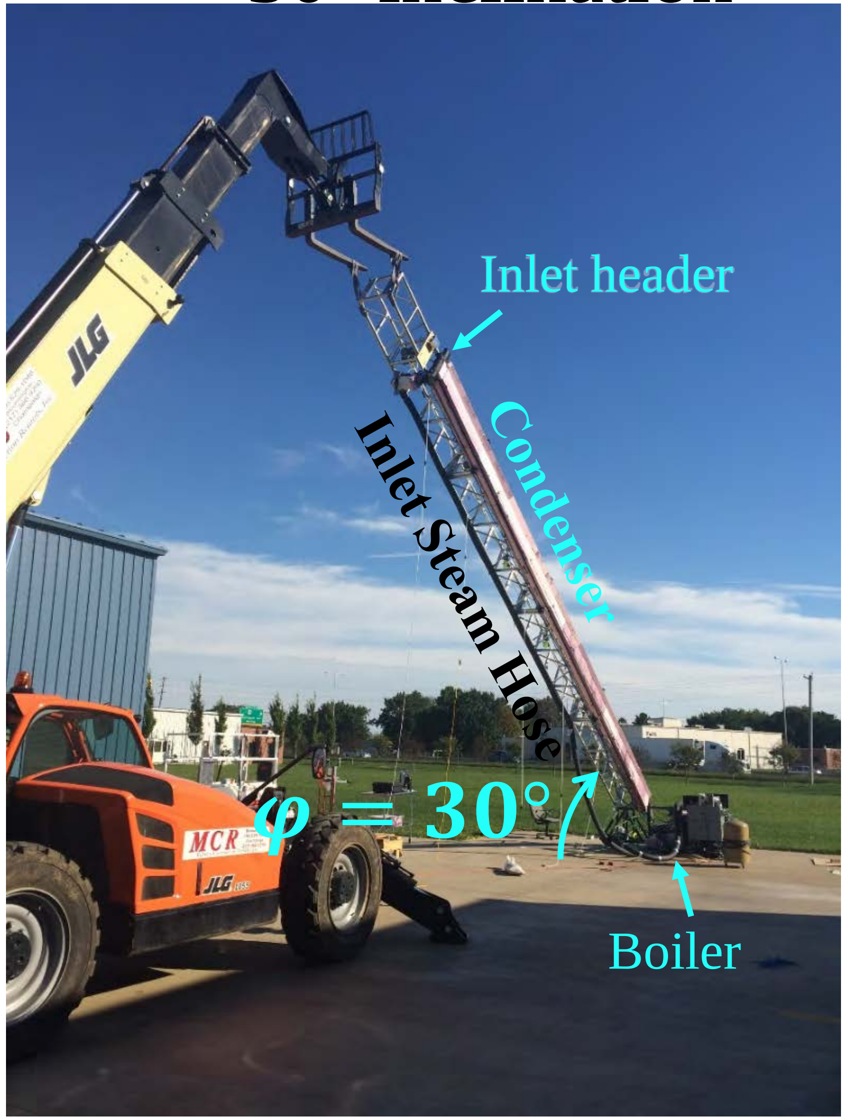

**Half tube installed in facility**




**Half tube inlet w/ flanges (no PC window)**

# Flow Pattern Observed while Varying Tube Inclination

30º inclination




75º inclination

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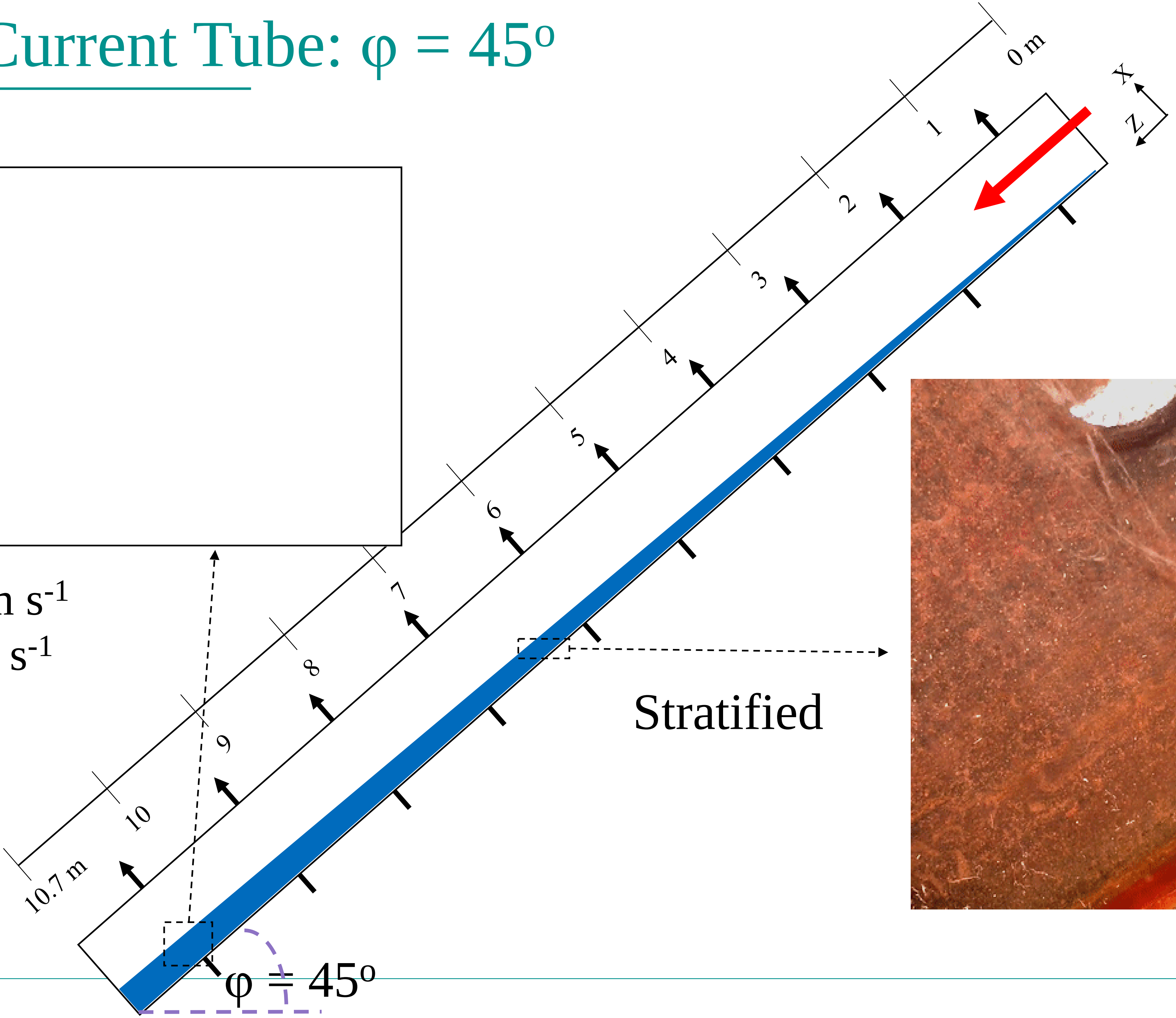
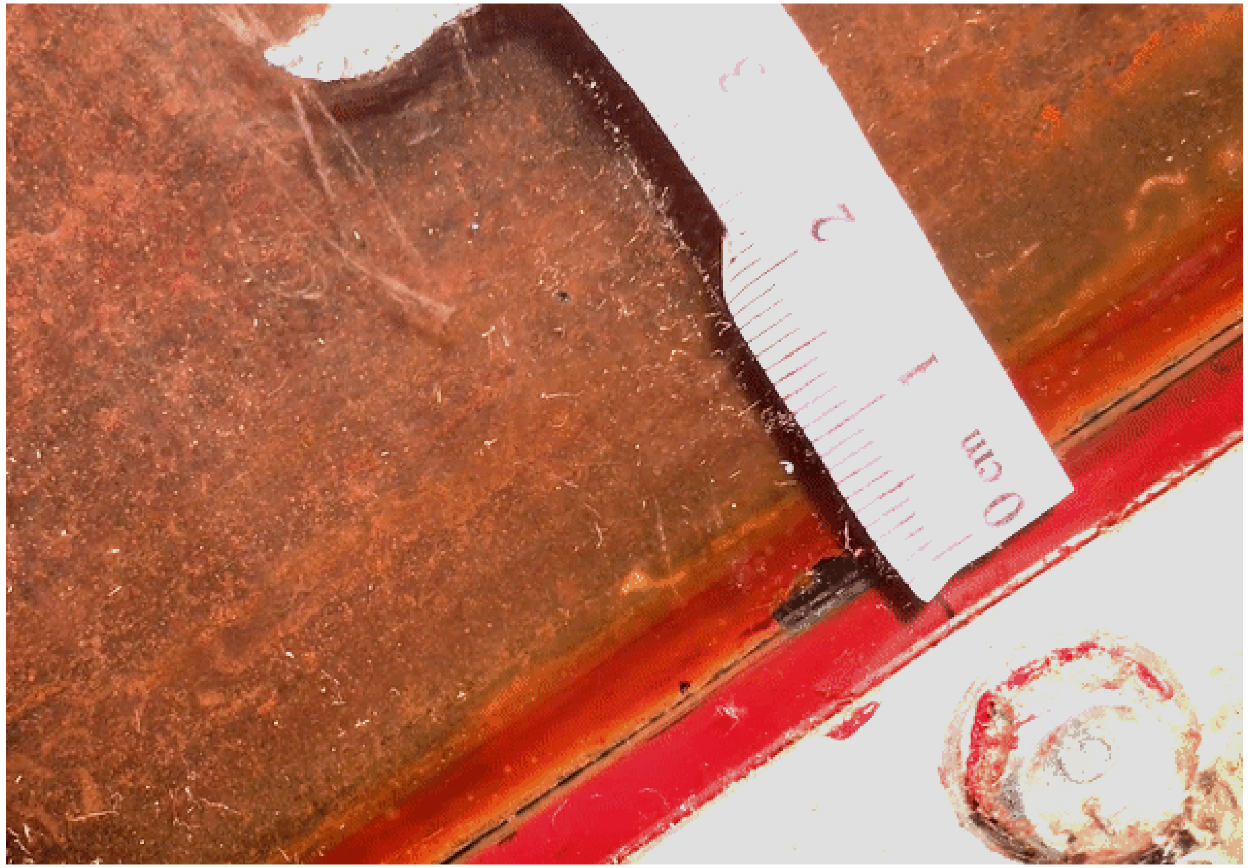
# Co-Current Tube: $\varphi = 45^o$

$q'' = 12\ kW\ m^{-2}$
$G = 9.3\ kg\ m^{-2}\ s^{-1}$

$v_l = 0.88\ m\ s^{-1}$
$v_v = 0.2\ m\ s^{-1}$

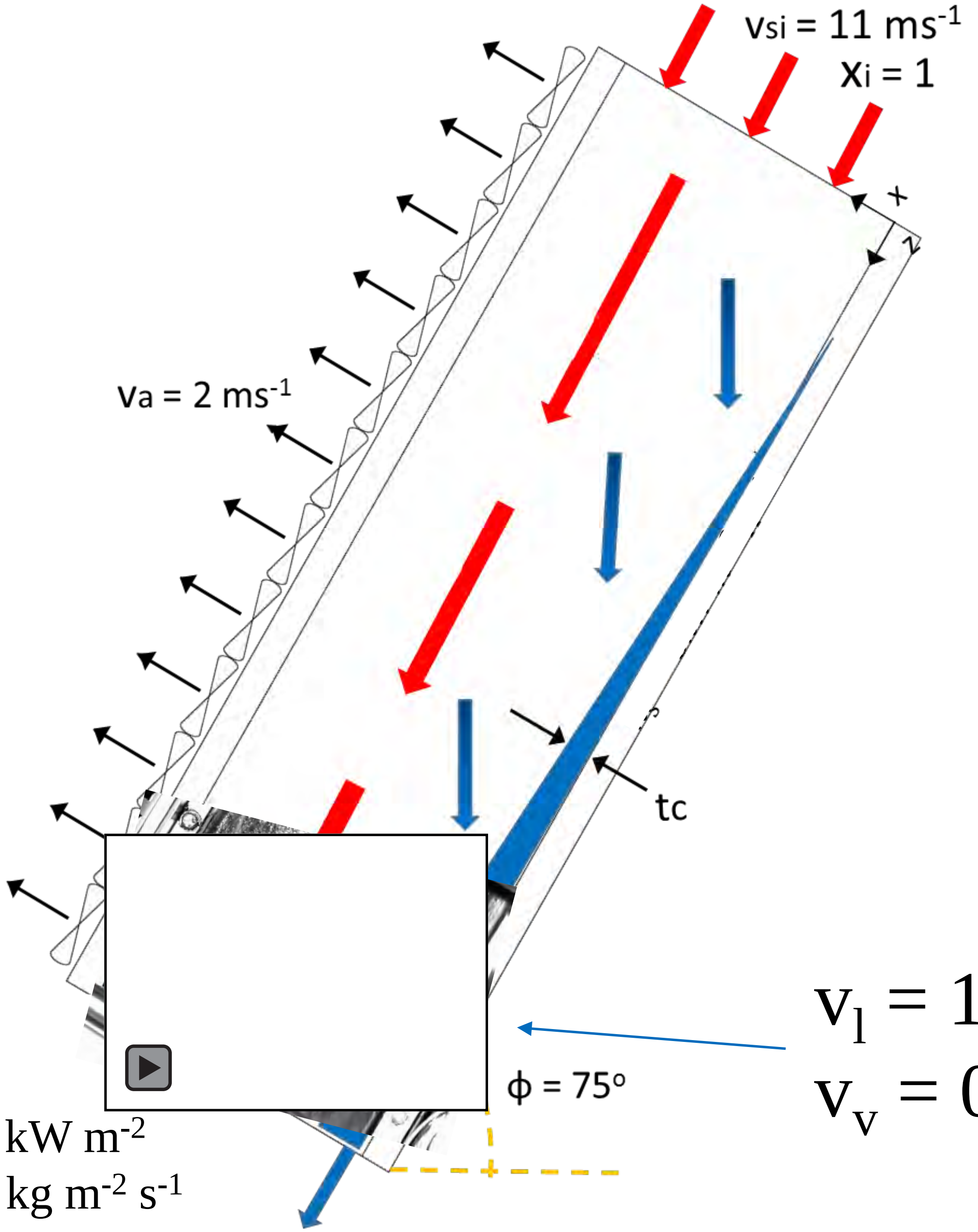




Exponent

# Co-Current Tube: $\varphi = 75^o$

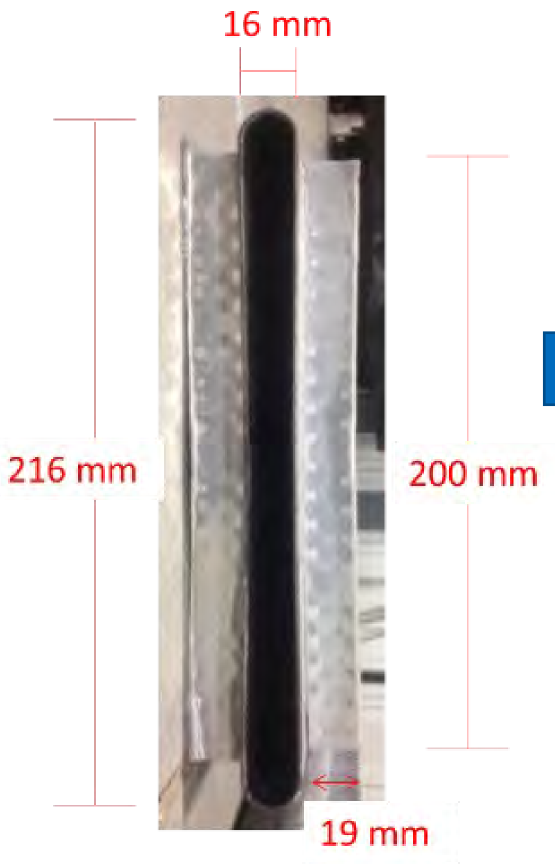


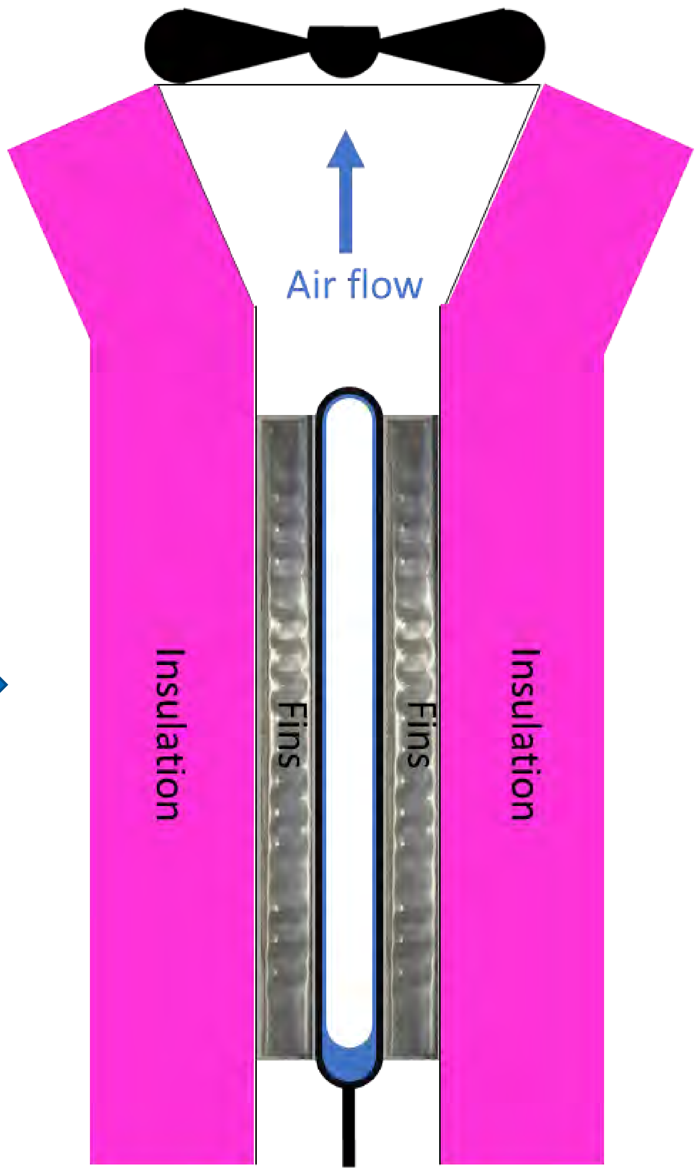

$q'' = 12\ kW\ m^{-2}$
$G = 9.9\ kg\ m^{-2}\ s^{-1}$

$v_l = 1.4\ m\ s^{-1}$
$v_v = 0.2\ m\ s^{-1}$


Exponent

# 5.7 m Tubes: Co-Current and Counterflow



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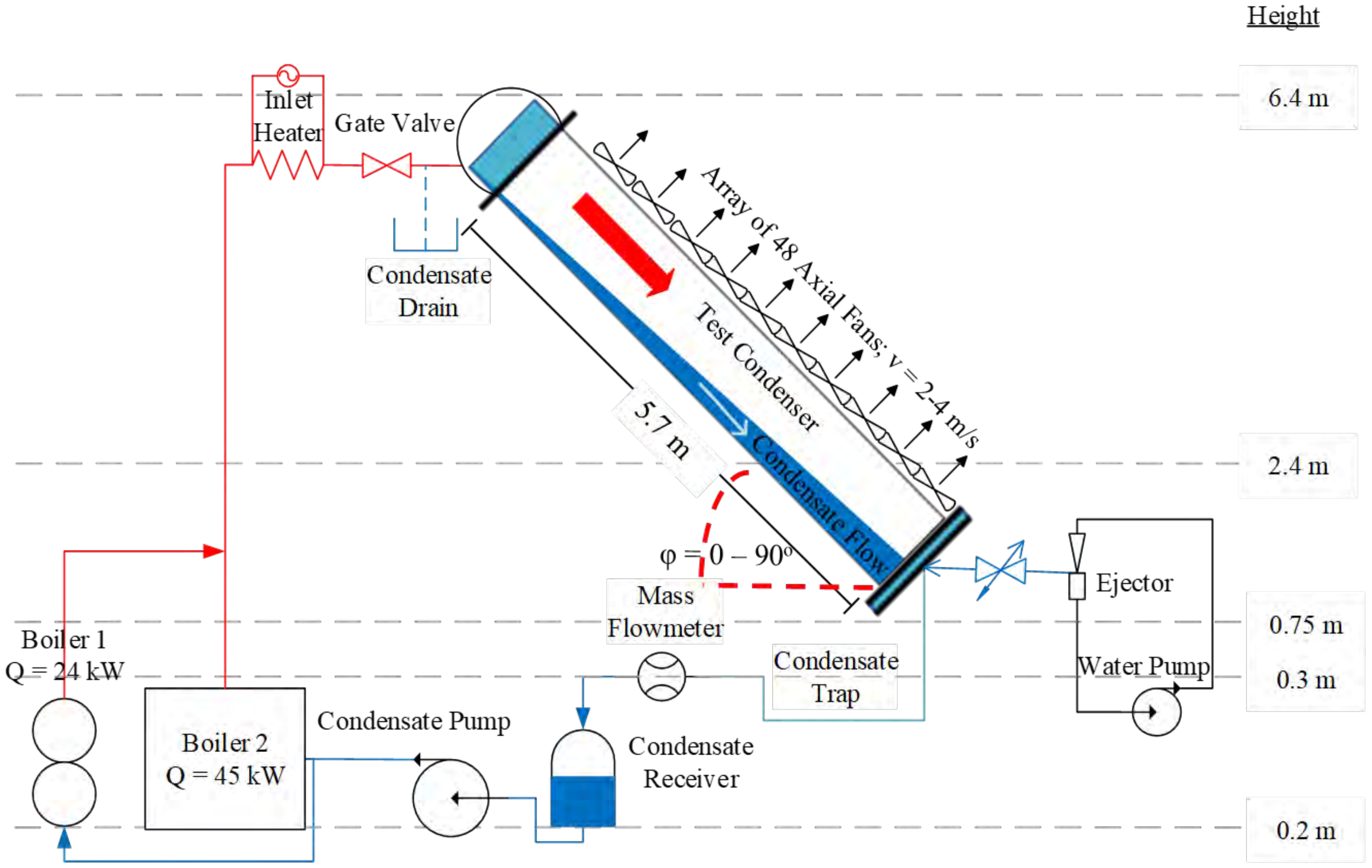
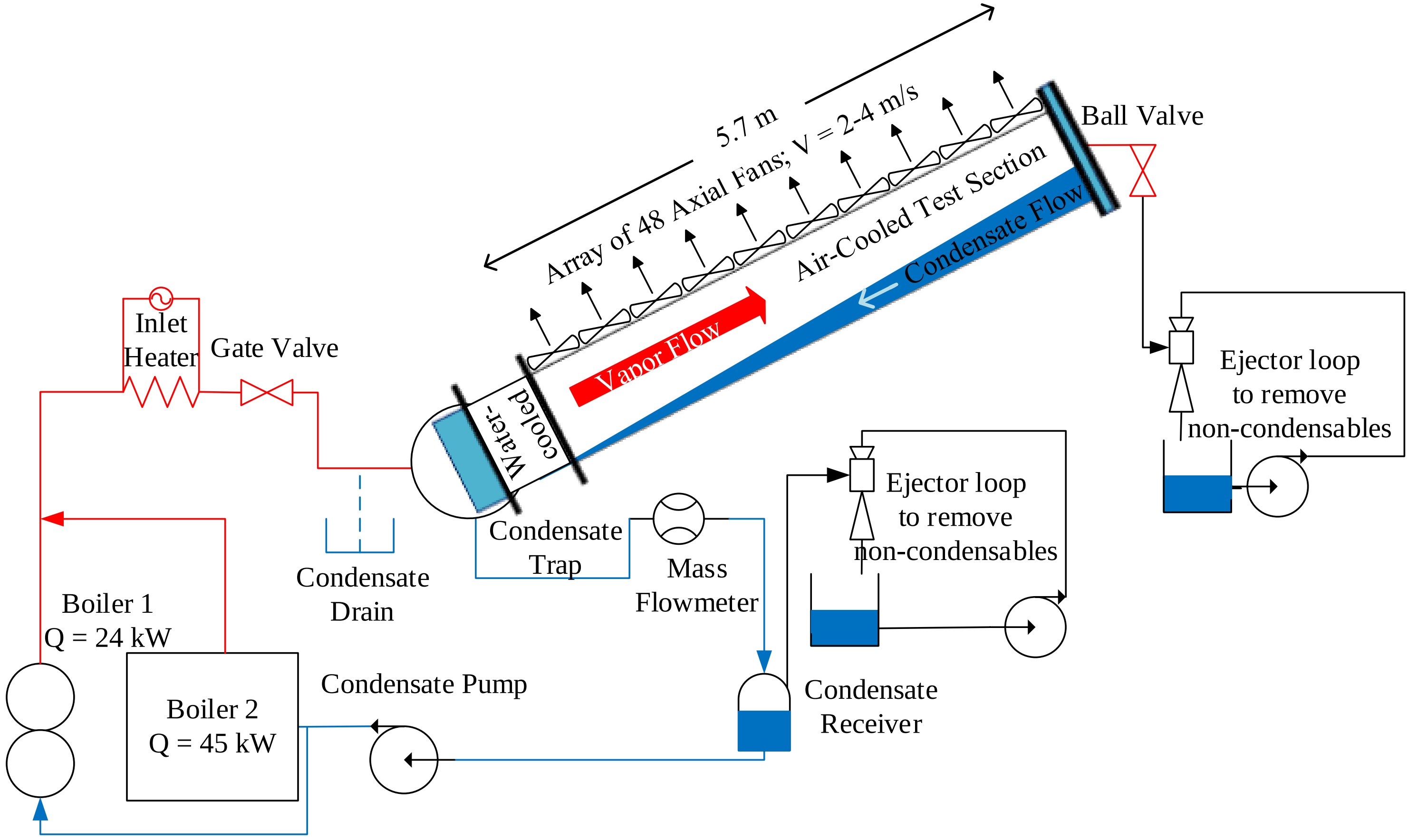
# 5.7 m Tubes: Co-Current and Counter-Flow

## Co-current



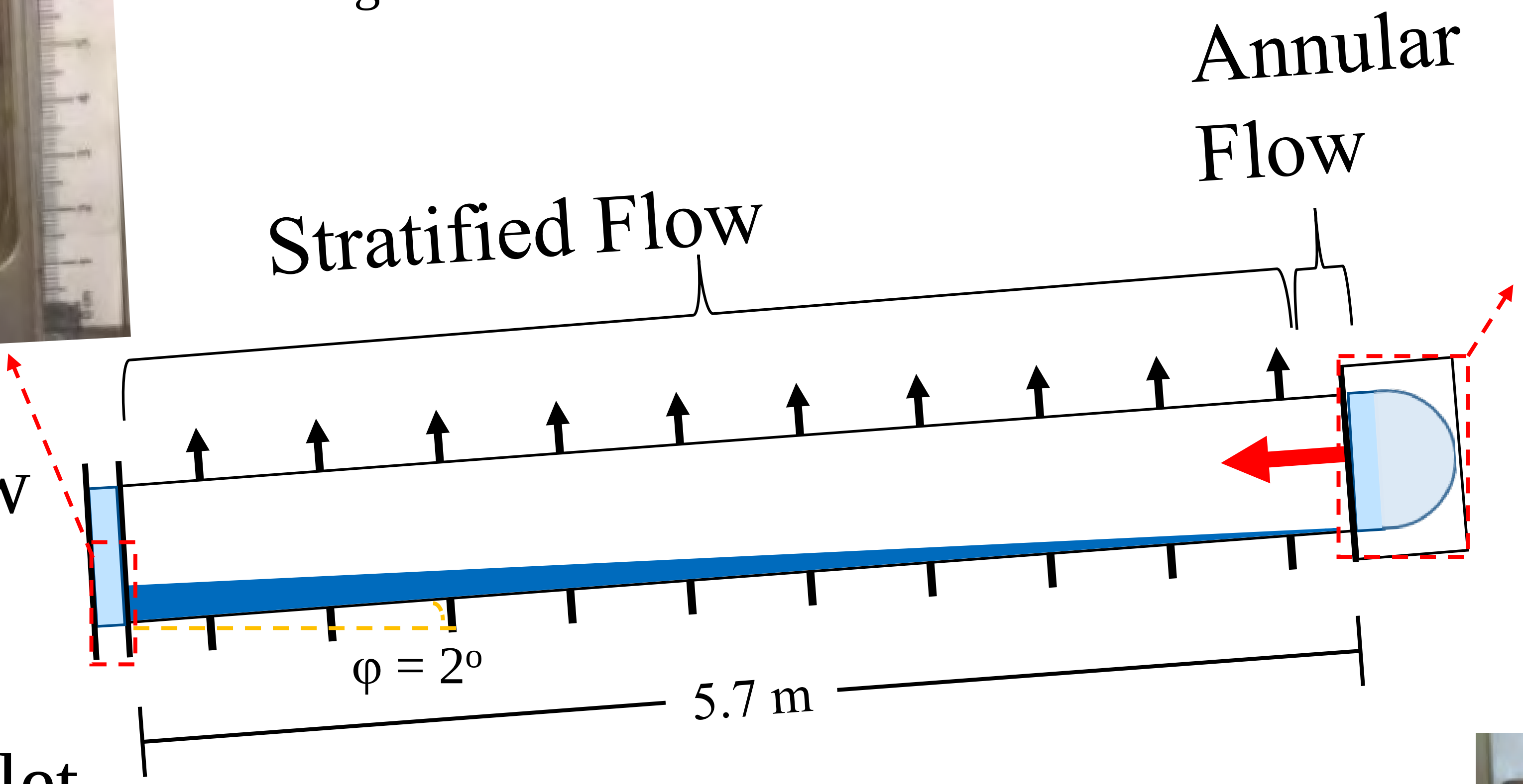

## Counter-flow



# Co-Current Tube: φ = 2º

Ps = 70 kPa
G = 2.7 kg m$^{-2}$ s$^{-1}$

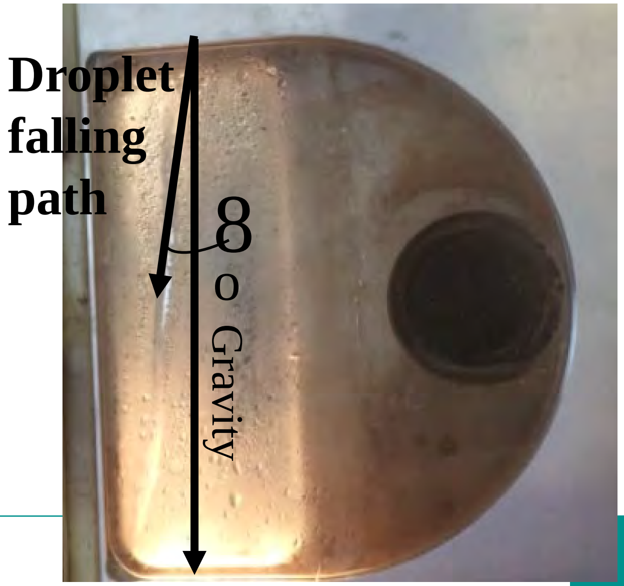
Stratified flow w/ smooth condensate surface at outlet




Ps = 78 kPa
G = 2.8 kg m$^{-2}$ s$^{-1}$

Ps = 78 kPa
G = 2.8 kg m$^{-2}$ s$^{-1}$

Falling angle of droplets indicates annular flow at inlet will quickly become stratified:



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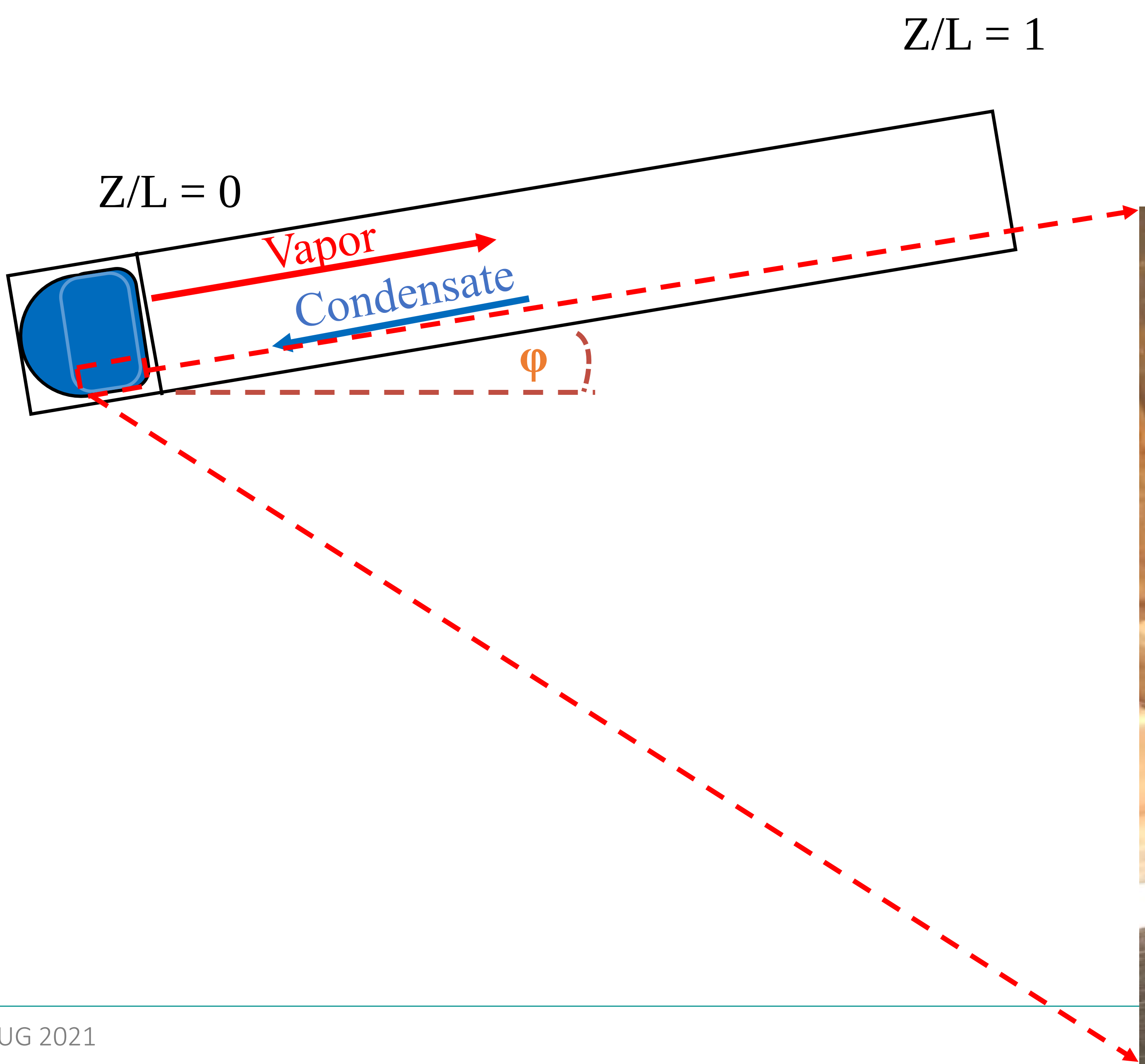
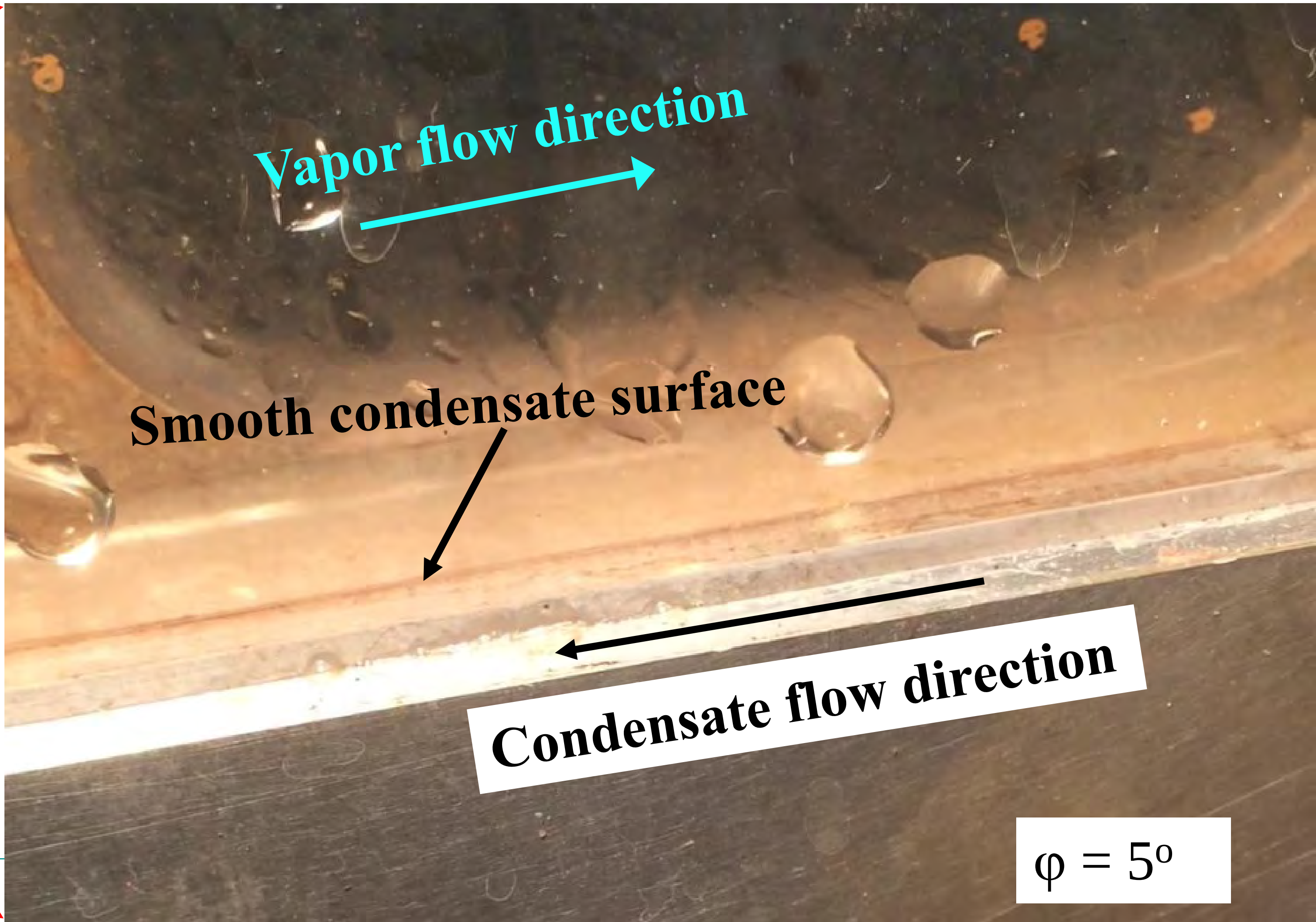
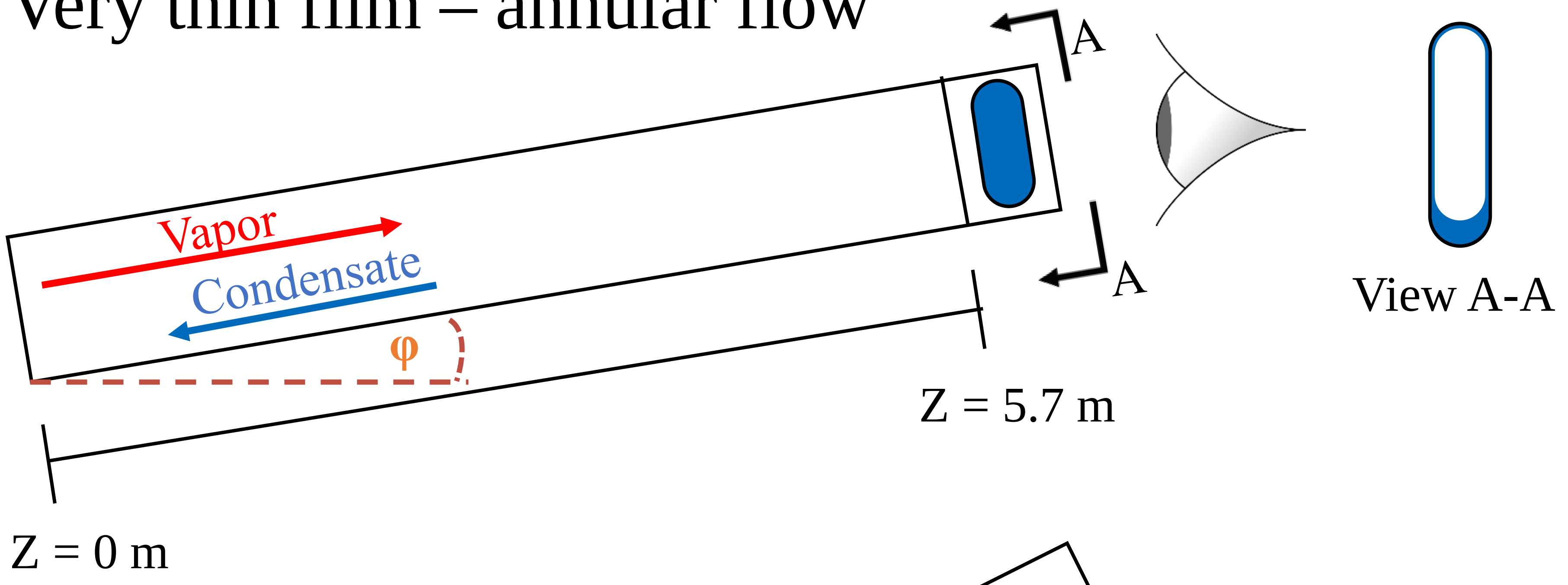
# Counter-Flow Tube: Stratified Flow at Condensate Outlet, φ = 5°

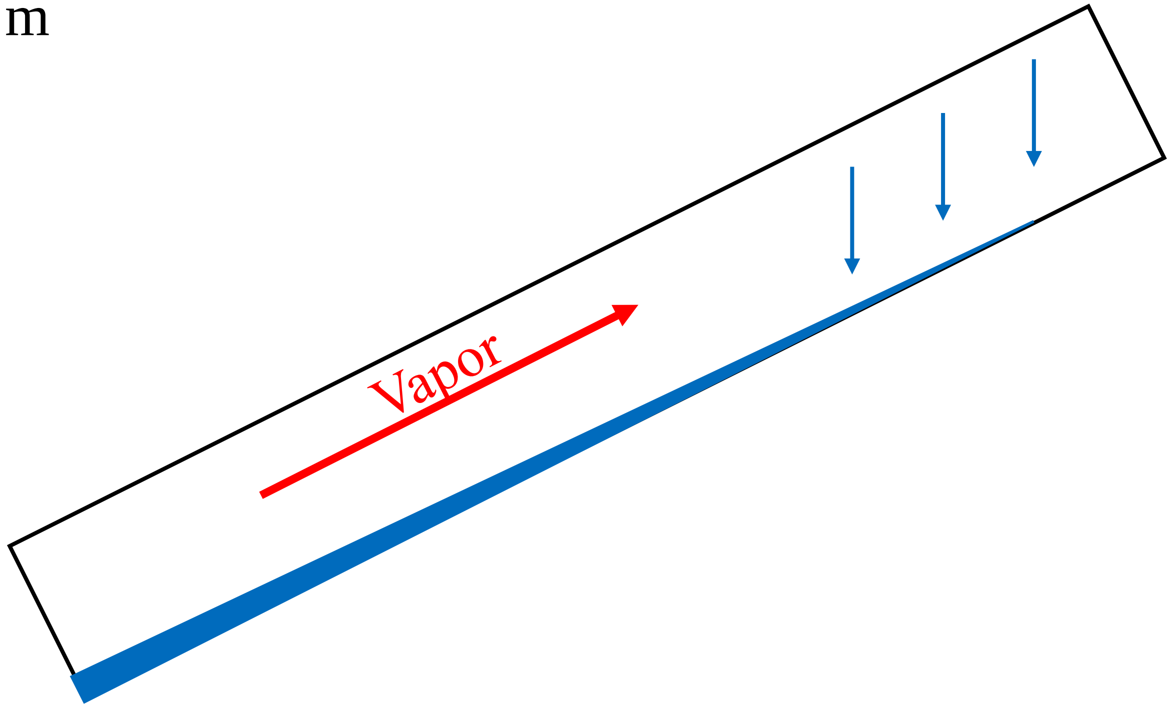


# Counter-Flow Tube, φ = 20°

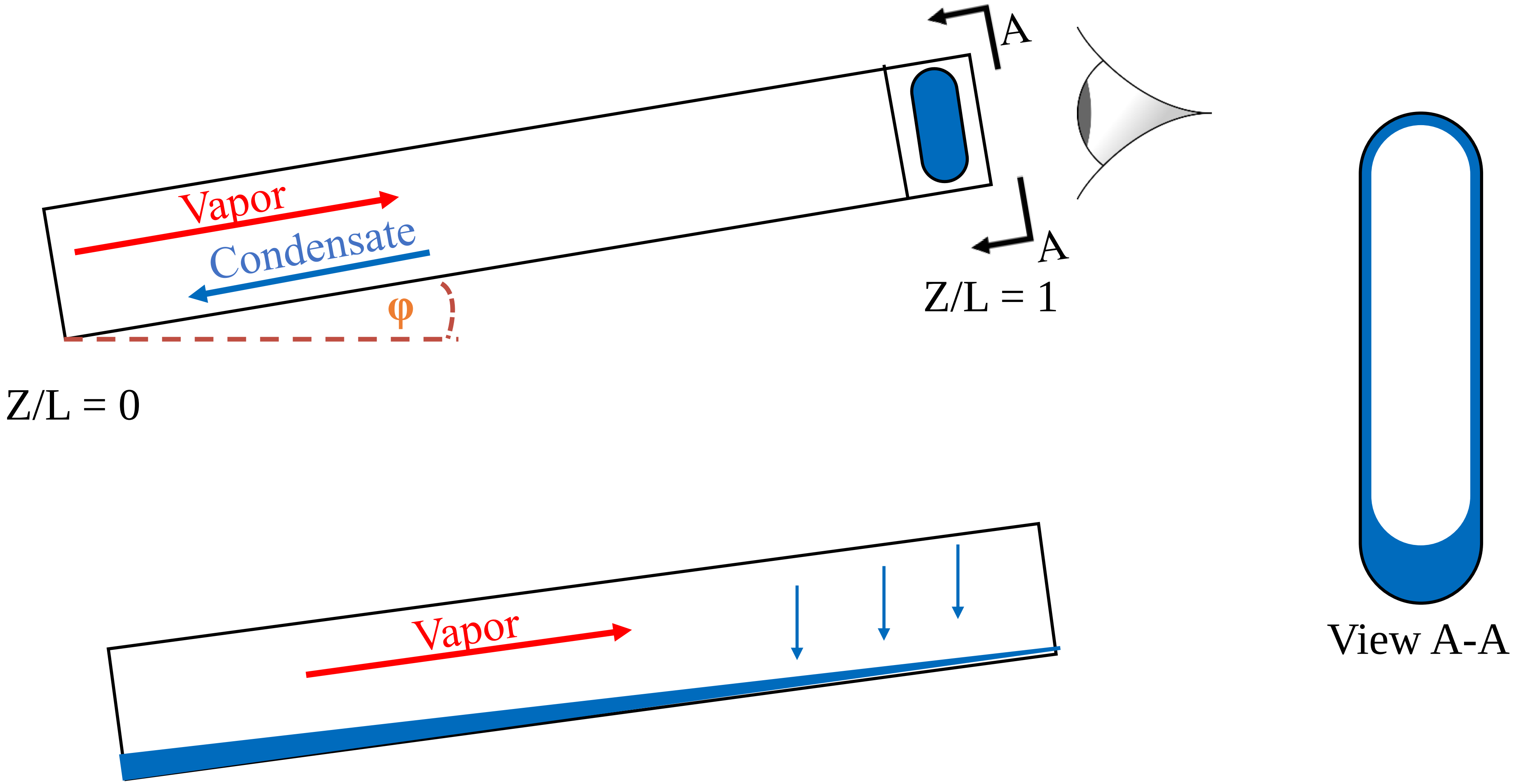
- Very thin film – annular flow

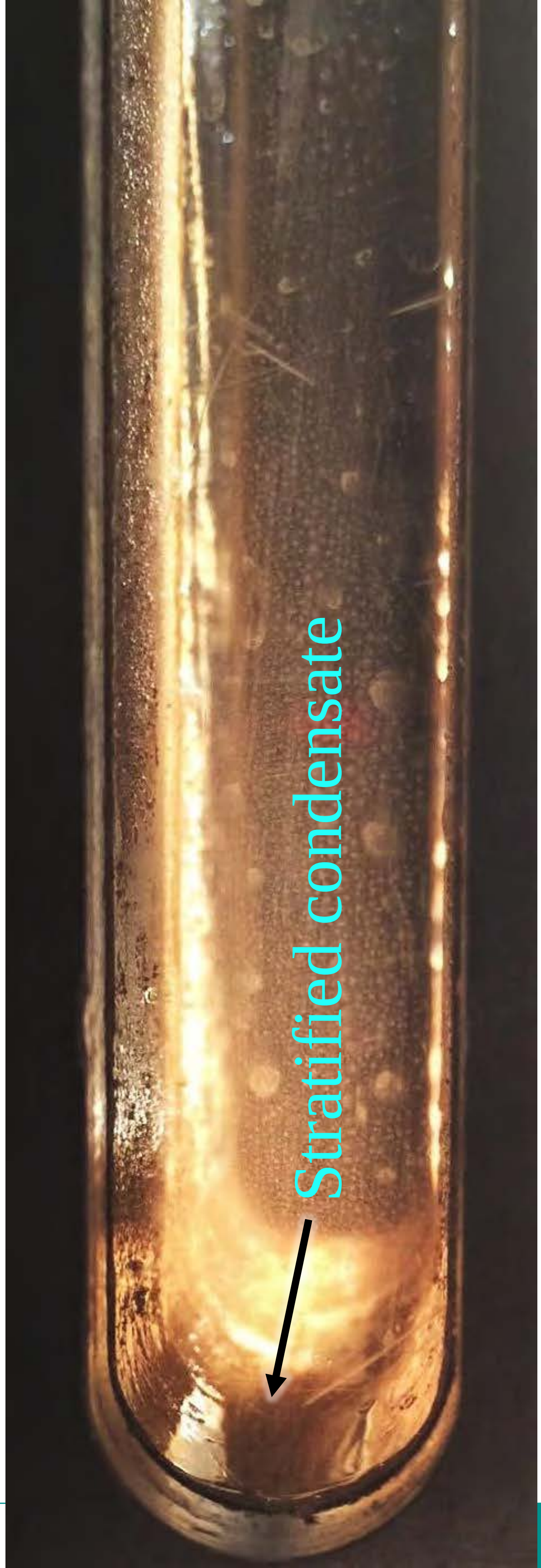



# Counter-Flow Tube, $\varphi = 5^o$

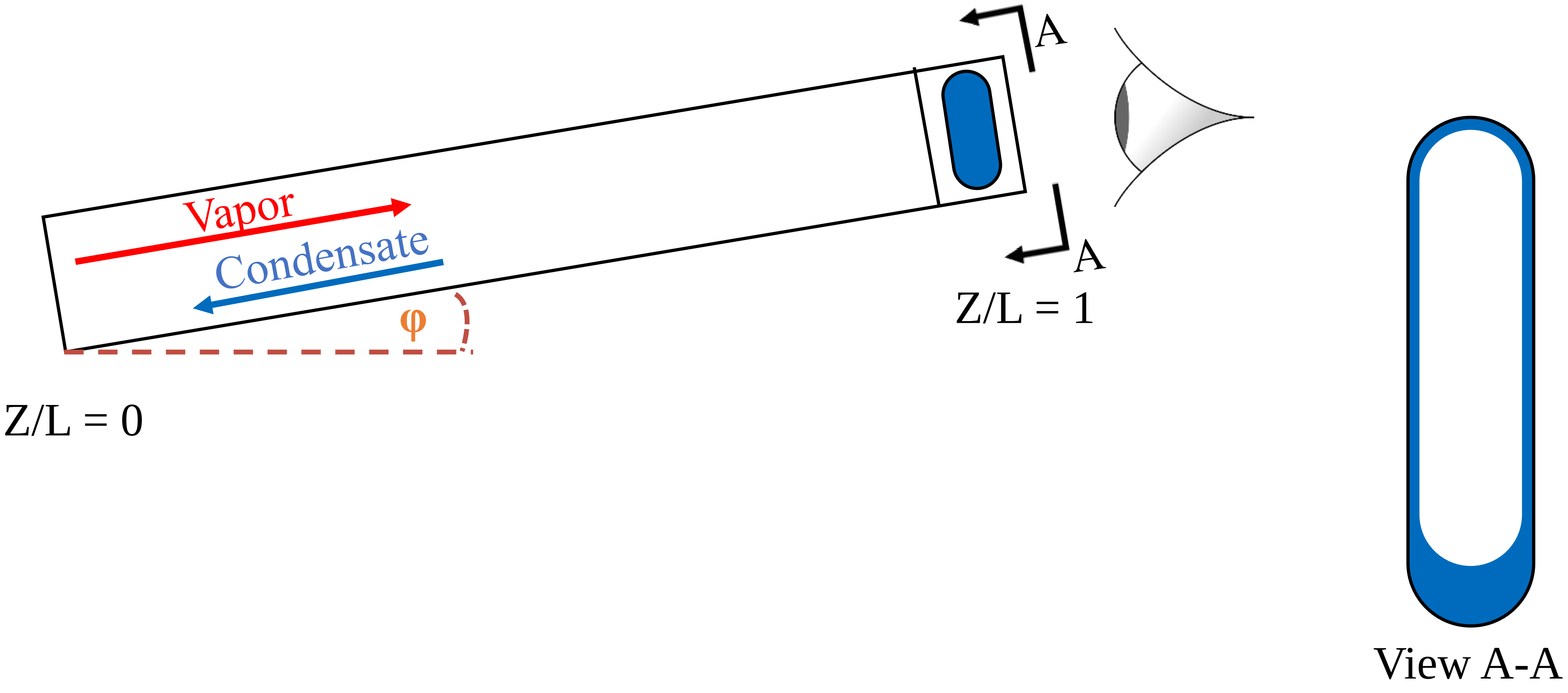
- Film depth increases slightly – onset of ‘flooding’

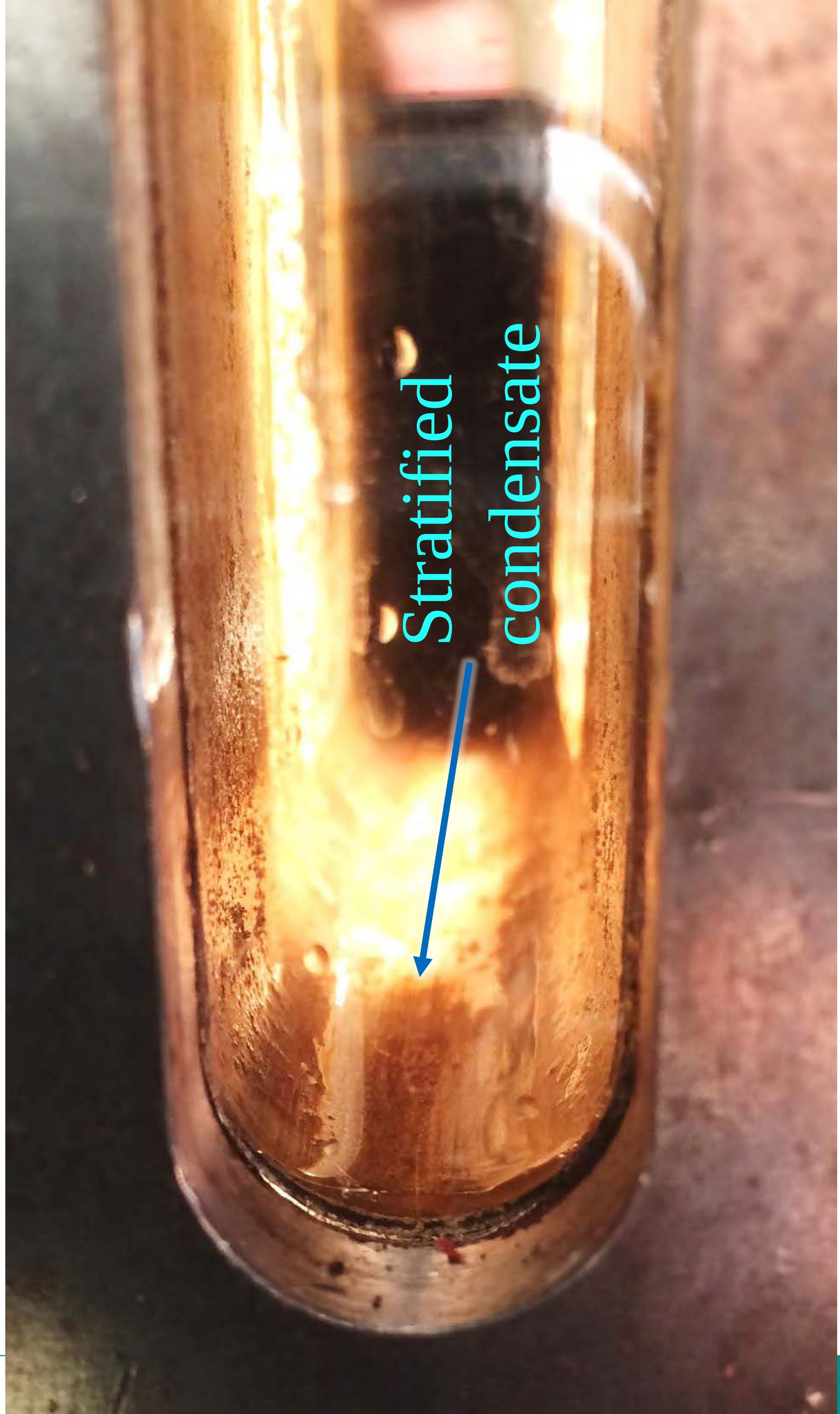


# Counter-Flow Tube, $\varphi = 1.5^o$

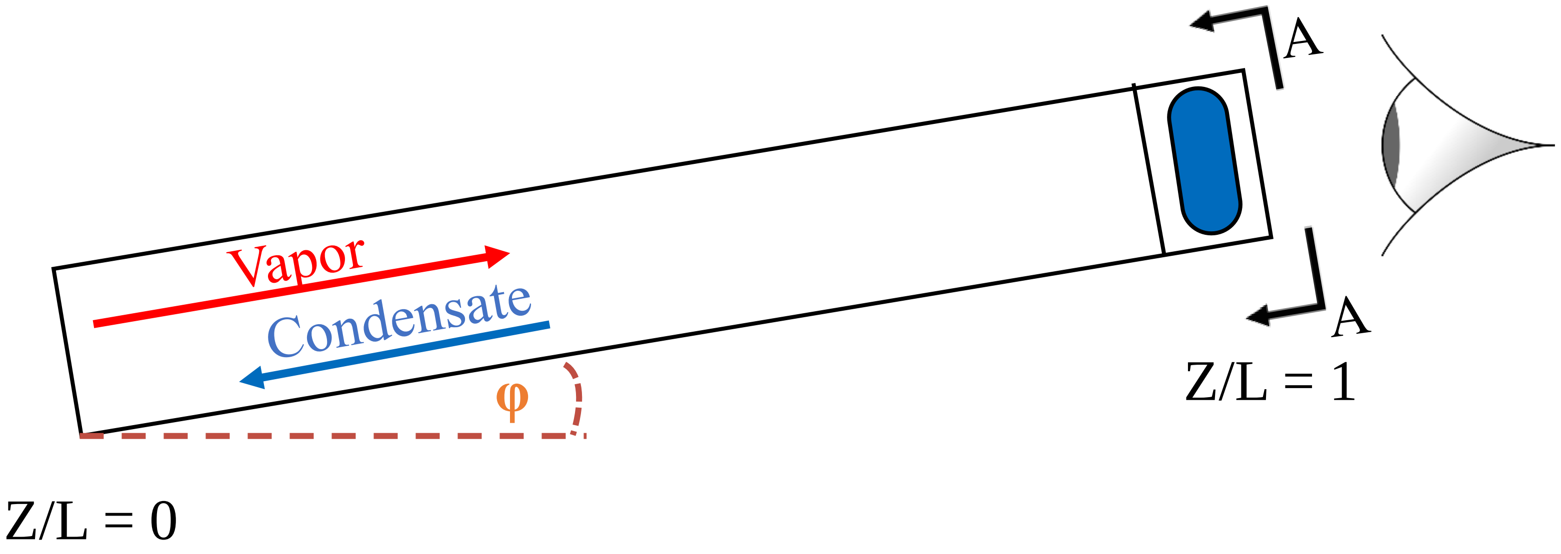
- Film depth increases due to ‘flooding’

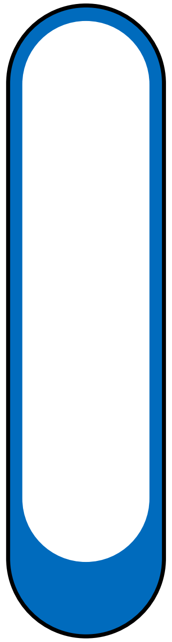


# Counter-Flow Tube, φ = 0.5°

- Thicker layer of condensate due to ‘flooding’



View A-A

# Counter-Flow: Onset of Flooding

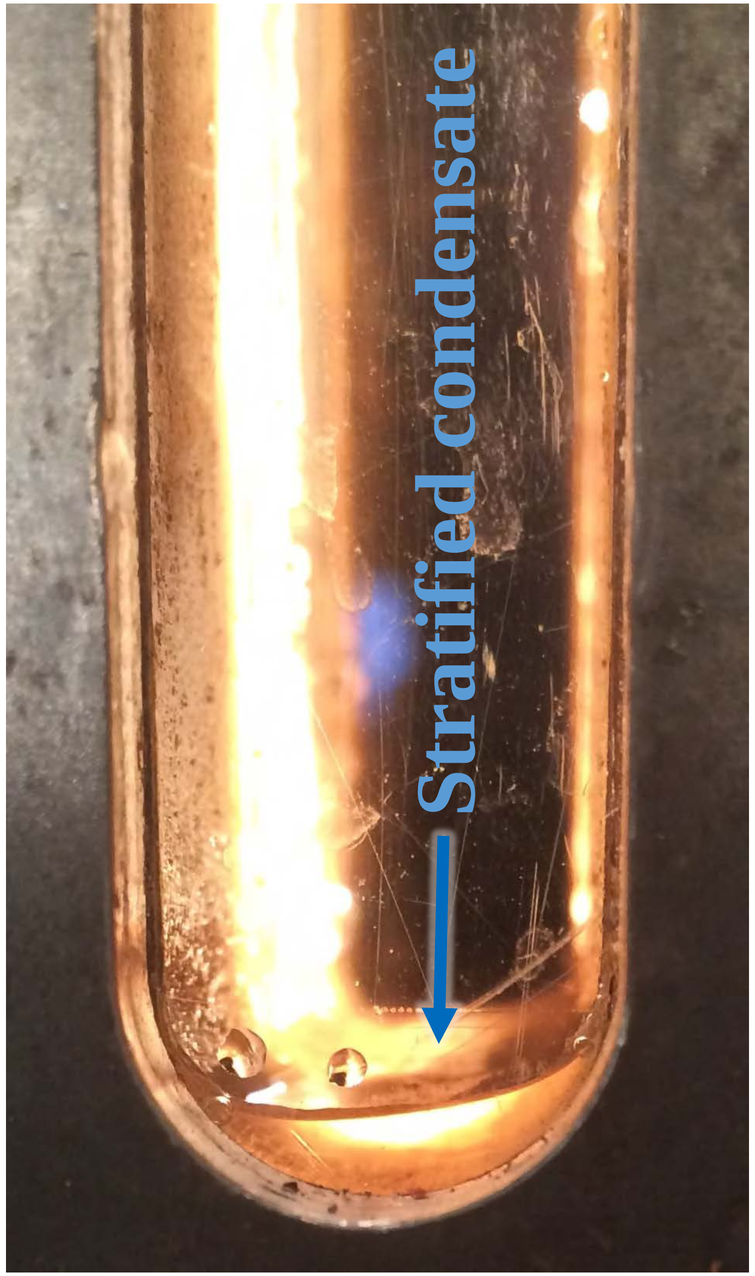
$P$ = 90 kPa (13 psi)
$v_{si}$ = 8 ms$^{-1}$ (26 fps)
$v_a$ = 2.5 ms$^{-1}$

$\varphi = 20^o$


$\varphi = 5^o$

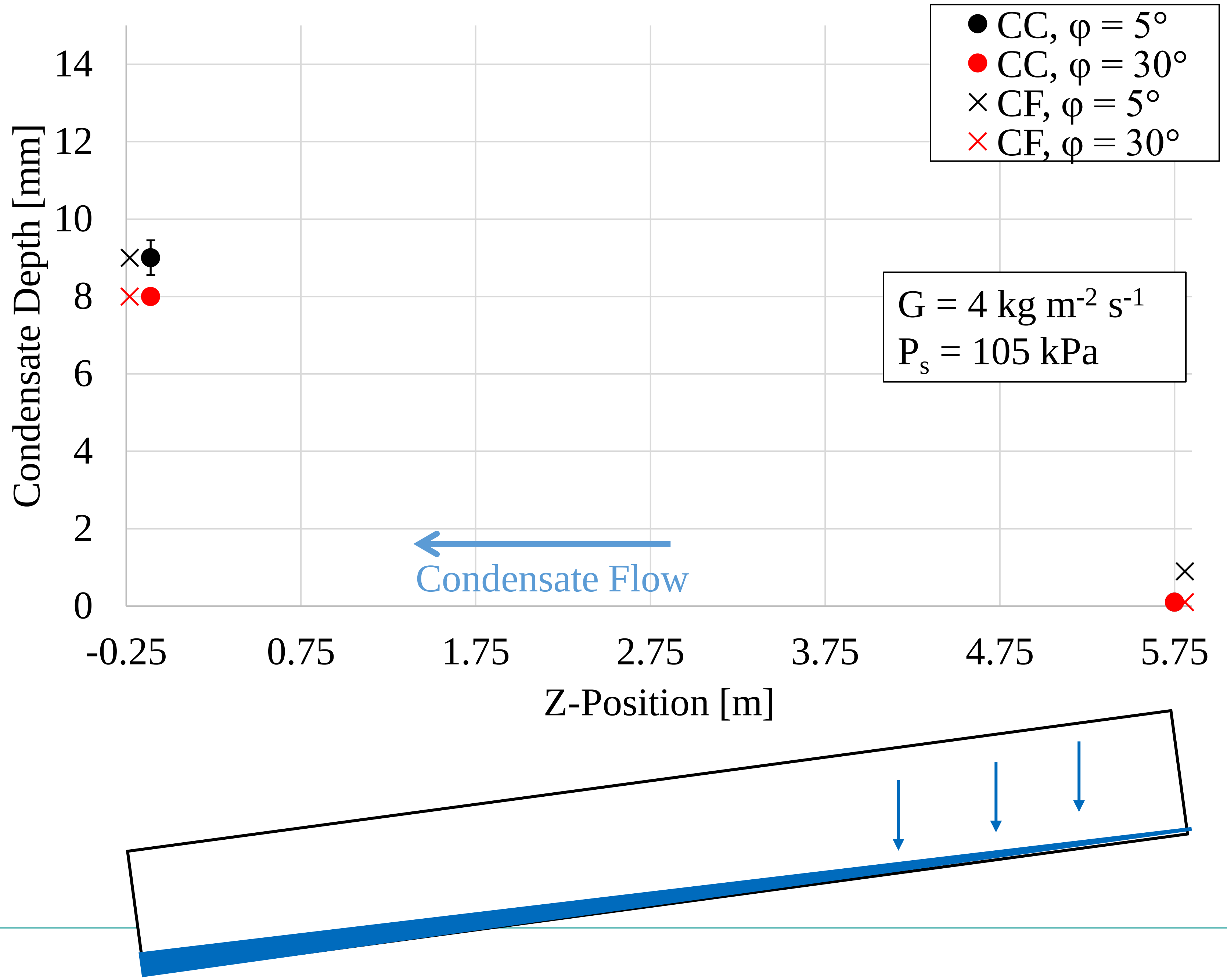

$\varphi = 1.5^o$


$\varphi = 0.5^o$



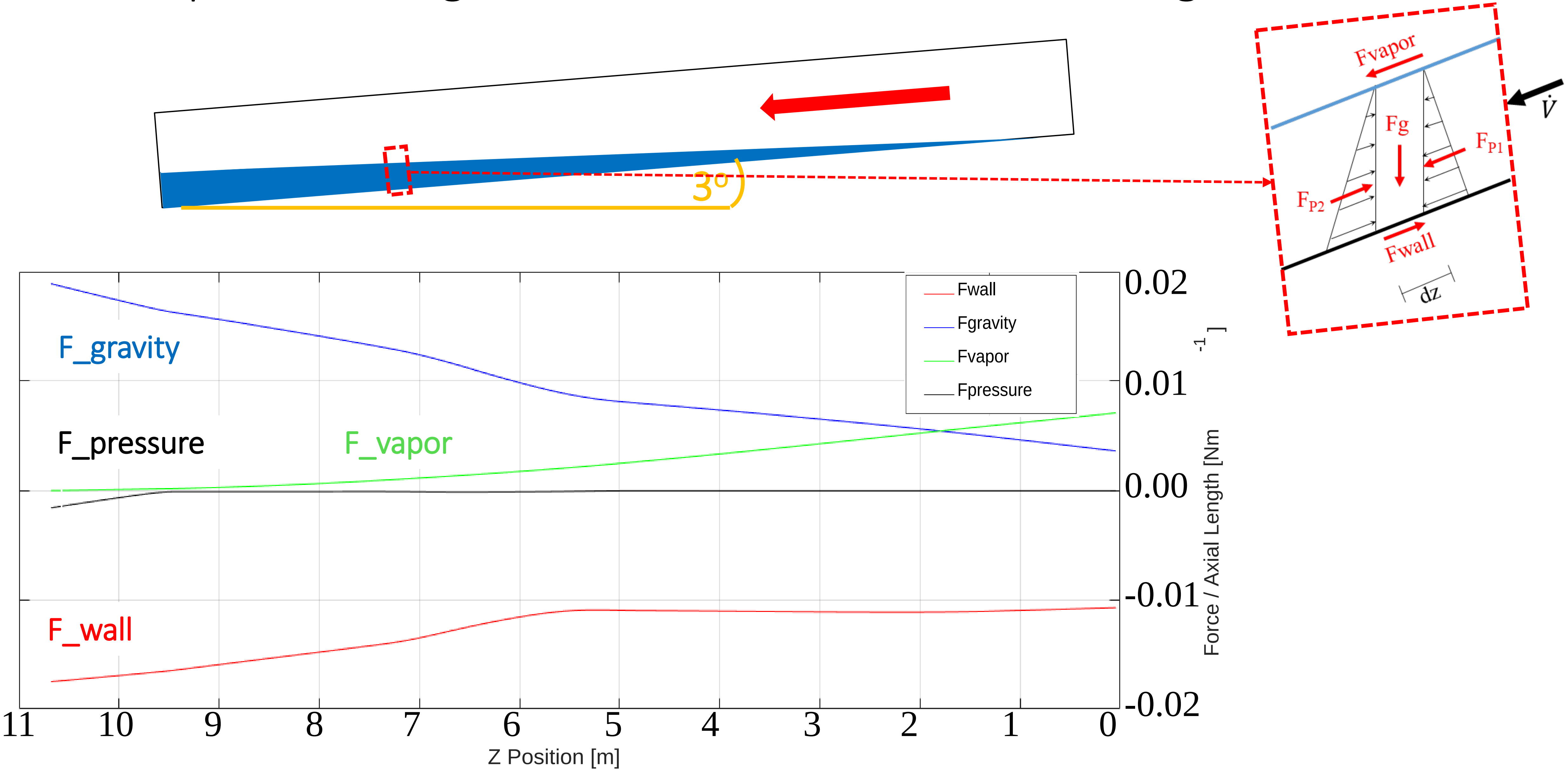
# Condensate Depth

- Condensate depth is equivalent for co-current and counter-flow condensation



# Comparison of Forces on Condensate: φ = 3°

At low inclination, vapor shear significant for half of condenser length




φ = 3°

G = 8 kg m$^{-2}$ s$^{-1}$
Ps = 10 kPa
ΔTai = 73 °C
L = 10.7 m



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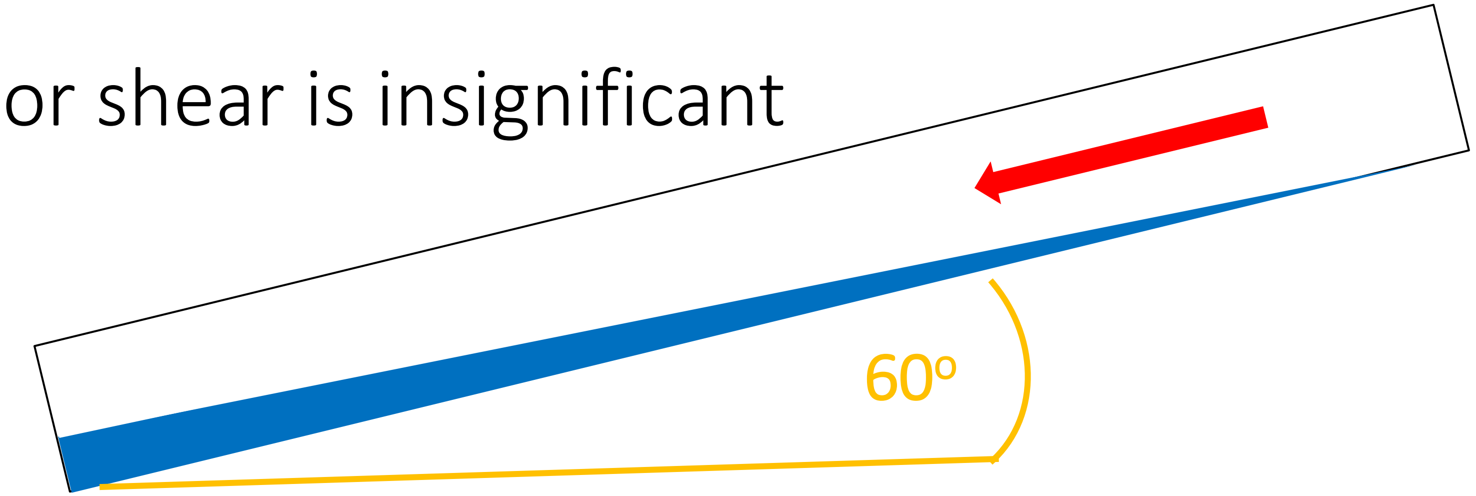
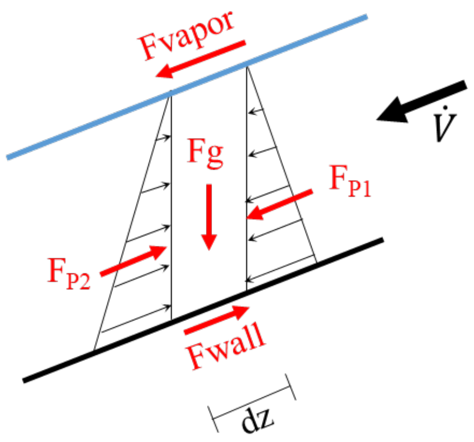
# Comparison of Forces on Condensate: $\varphi = 60^o$

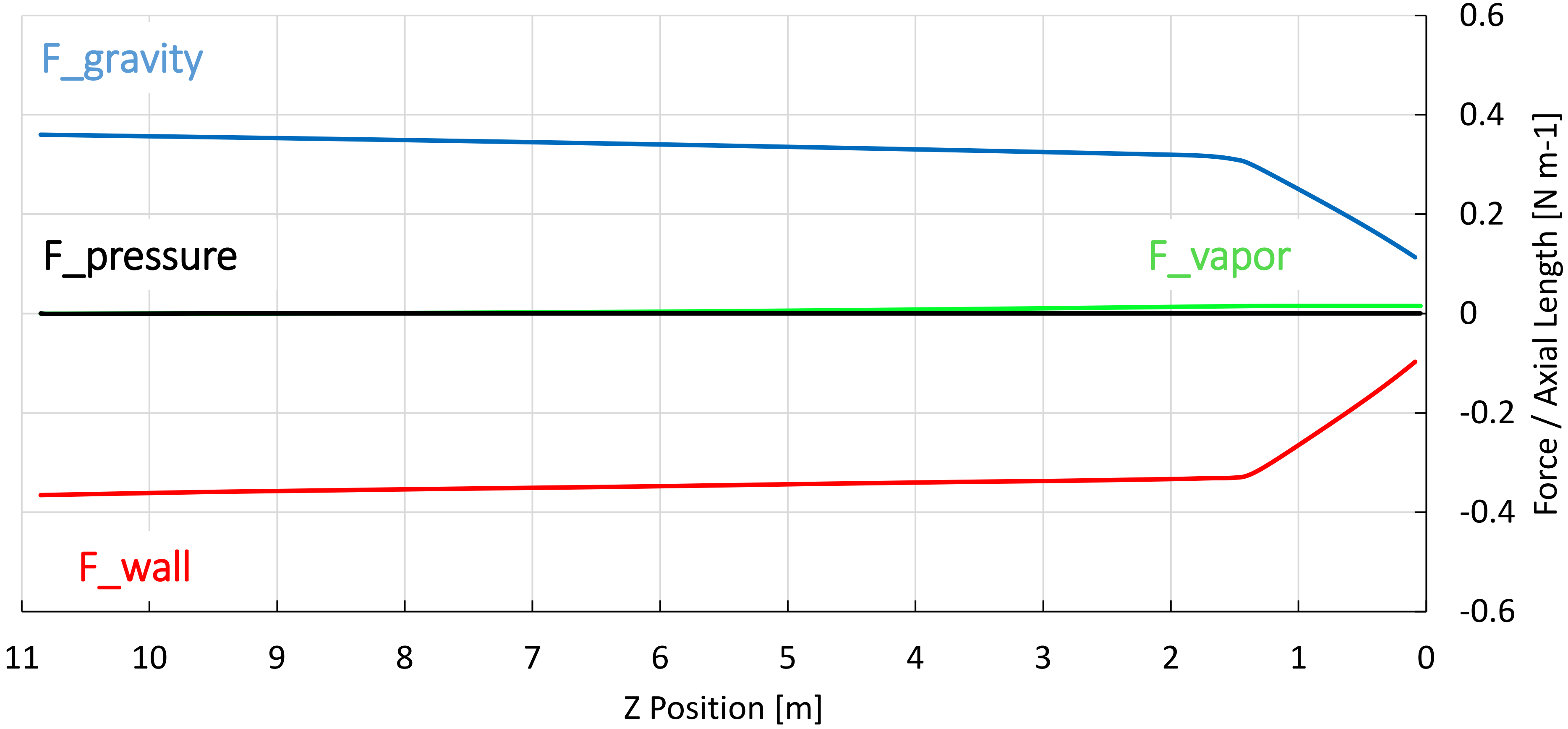
At high inclination, vapor shear is insignificant




$\varphi = 60^o$

$G = 8\ kg\ m^{-2}\ s^{-1}$
Ps = 10 kPa
$\Delta Tai = 73\ ^oC$
L = 10.7 m



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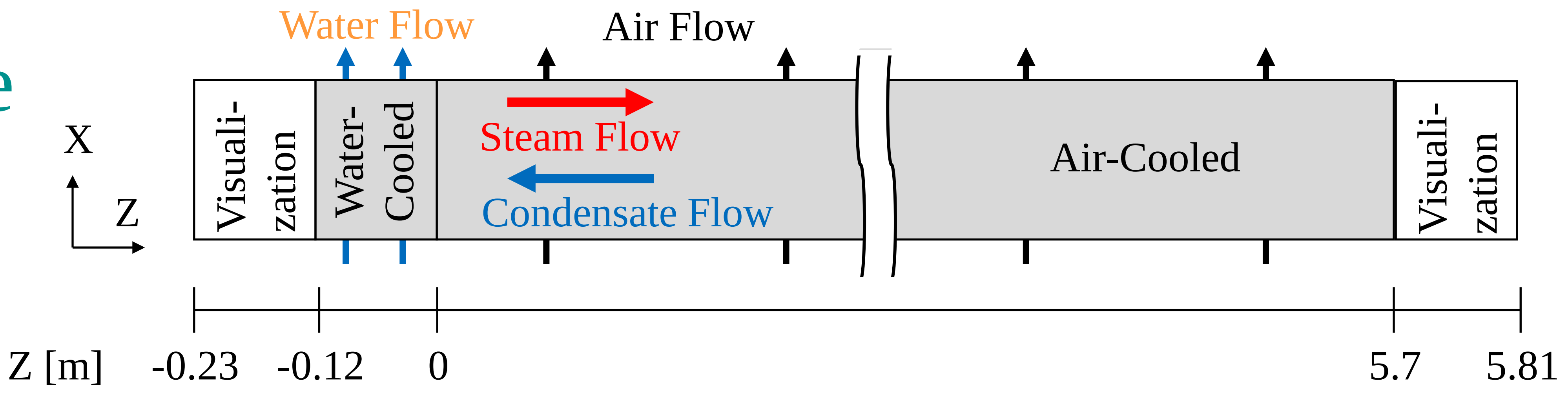
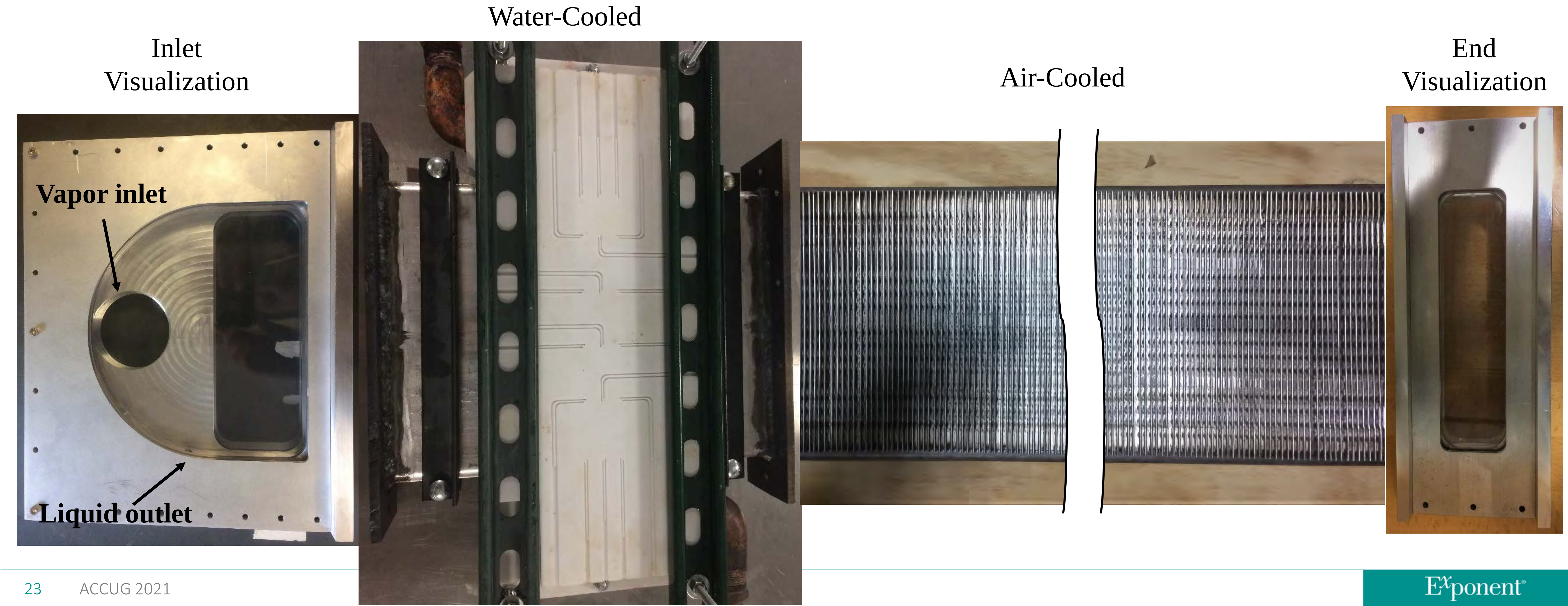
# Cooling Performance Comparison

# Counter-Flow Tube

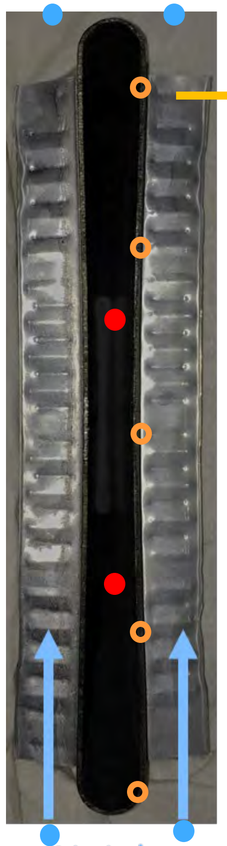


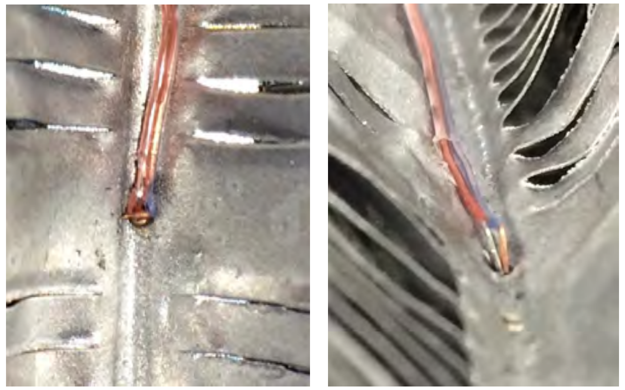
# Temperature Profile Measured in Air- and Water-Cooled Sections

- Water-cooled section to measure local cooling performance
- Equal heat flux in air- and water-cooled sections

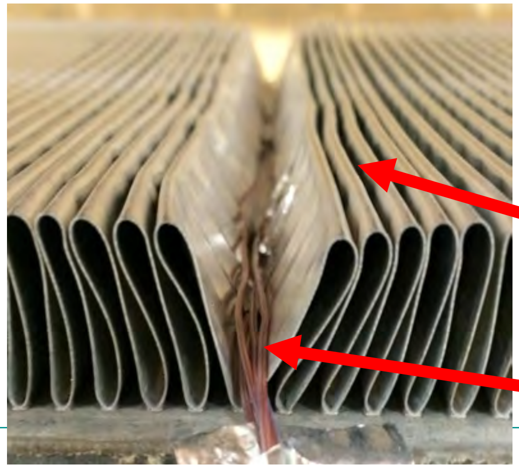
Air-Cooled Section




Demonstration of thermocouple insertion



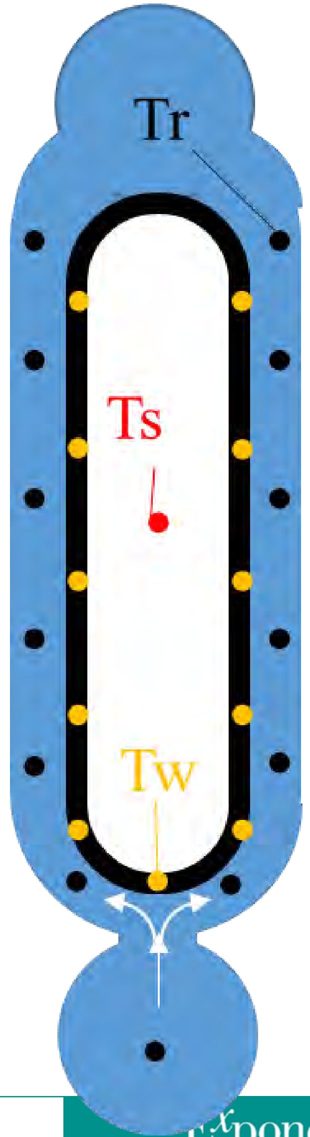
Thermocouple bead covered by epoxy and aluminum tape



Fins returned to original shape after assembly

Thermocouple wires

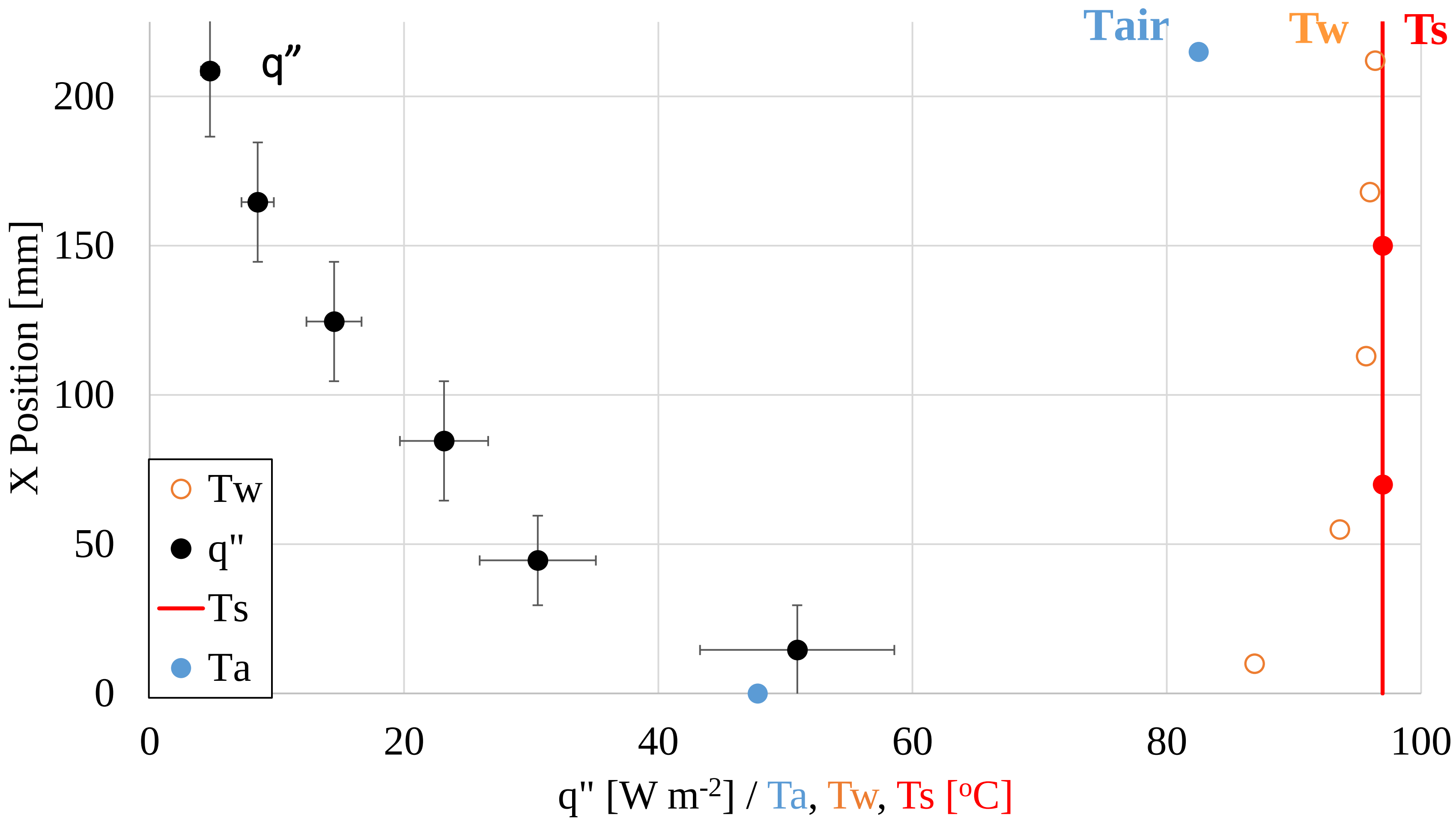
Water-Cooled Section

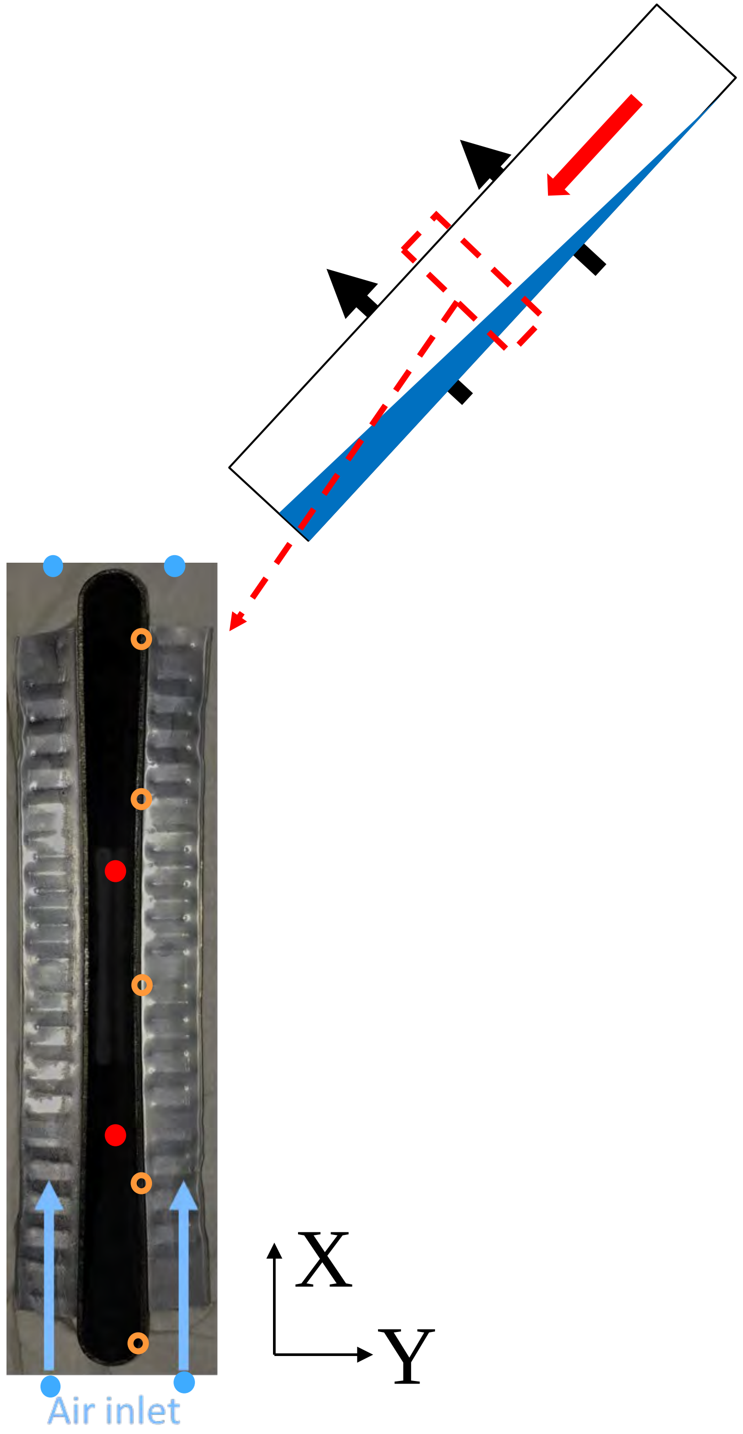


# Co-Current: Heat Flux Greatest at Tube Bottom

- ΔT, q” greatest at bottom of tube
- $q''_{bottom} = 11 \times q''_{top}$

G = 3.7 kg m$^{-2}$ s$^{-1}$
ΔTai = 49.2 $^{o}$C
Ps = 90.2 kPa
quality = 0.4
φ = 0.5$^{o}$



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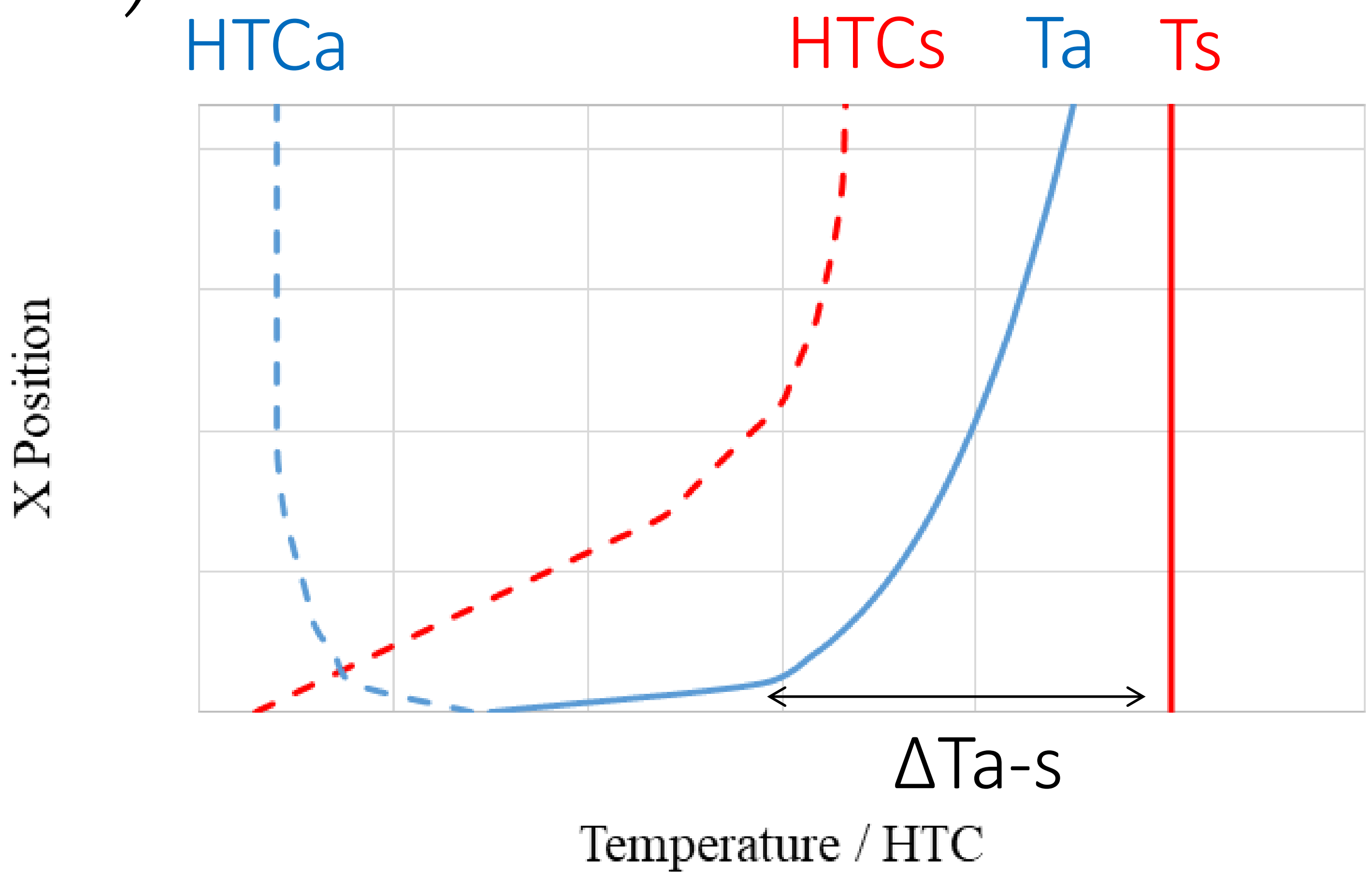
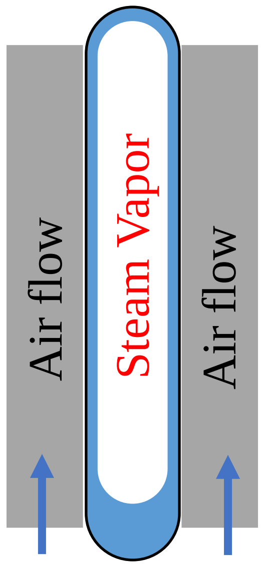
# Capacity Depends on HTCs, HTCa, ΔTa-s

- $Q = UA \times LMTD$
- $U = \left(\frac{A_s}{HTC_a \eta_f A_a} + \frac{t_w}{k_w} + \frac{1}{HTC_s}\right)^{-1}$
- $LMTD = \left(\frac{(T_s - T_{ai}) - (T_s - T_{ao})}{\ln \frac{T_s - T_{ai}}{T_s - T_{ao}}}\right)$





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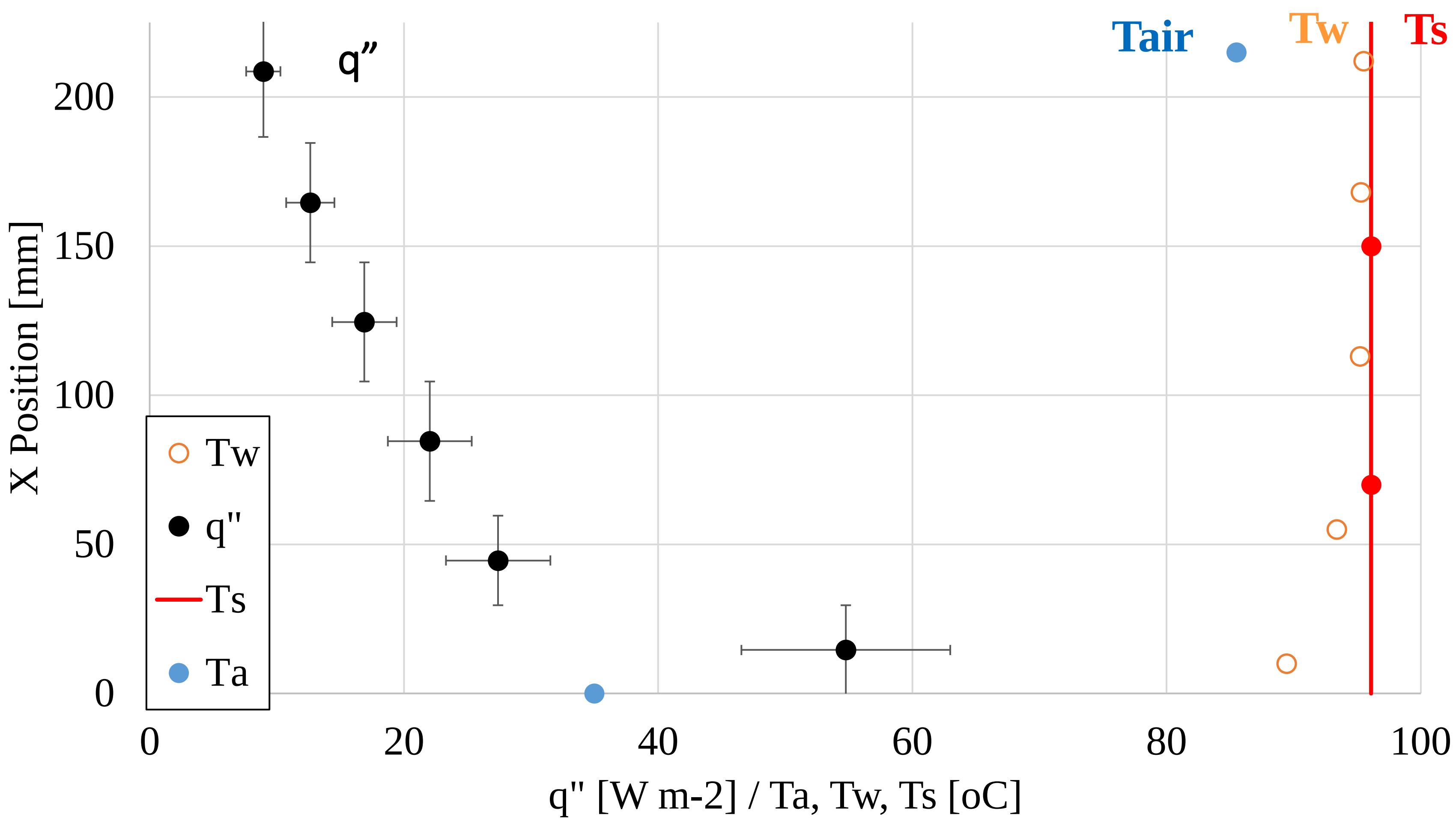
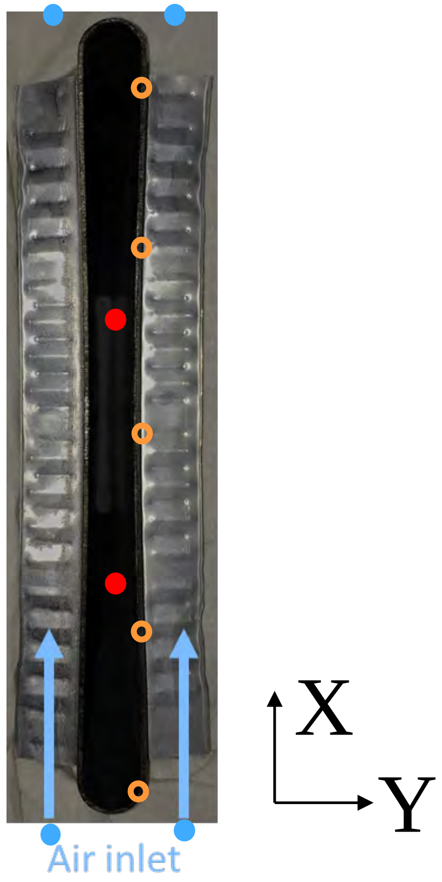
# Counter-Flow: Heat Flux Greatest at Tube Bottom

- ΔT, q" similar to co-current

$G = 4.2$ kg m$^{-2}$ s$^{-1}$
ΔTai = 61.1 $^{o}$C
Ps = 87.6 kPa
quality = 0.4
φ = 0.5$^{o}$



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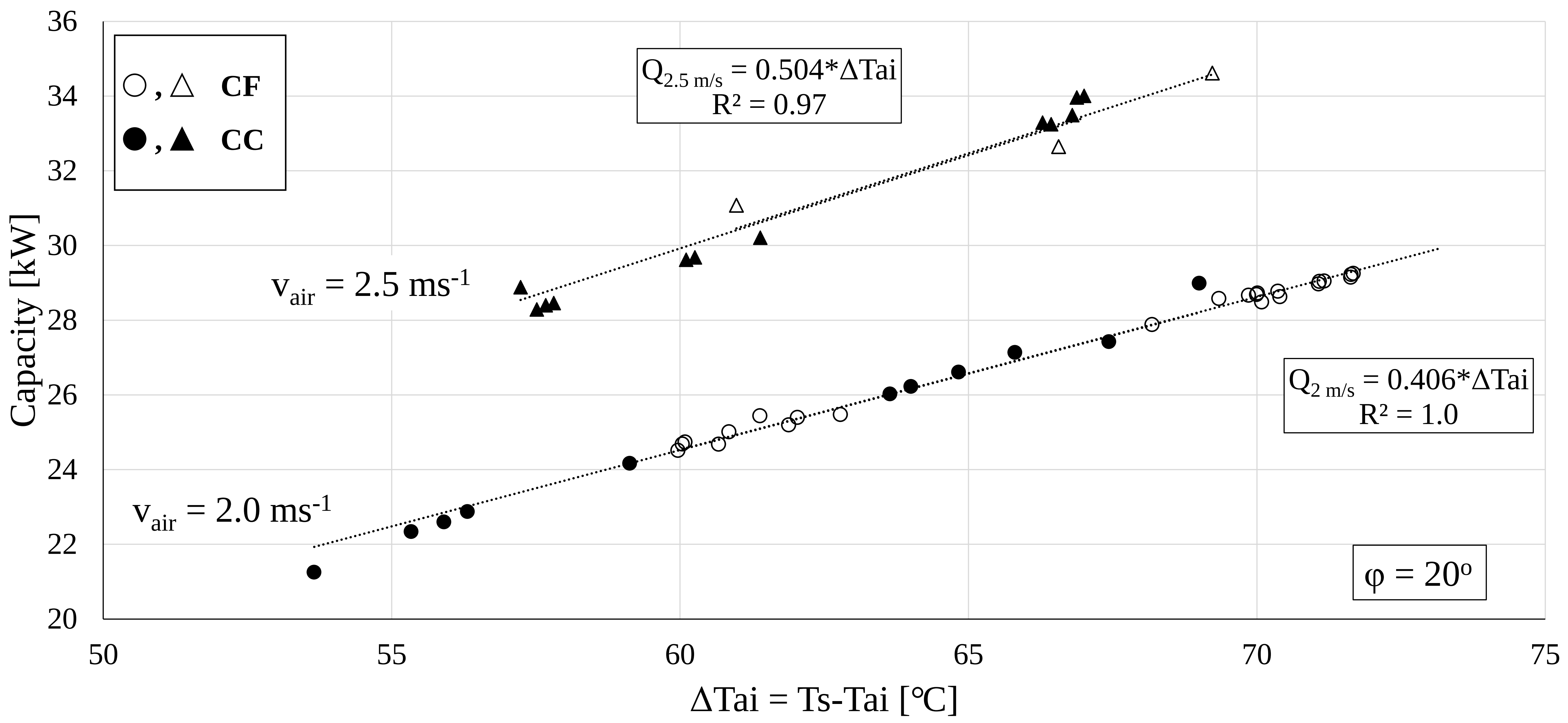
# Equal Capacity in Co-Current and Counter-Flow Tubes



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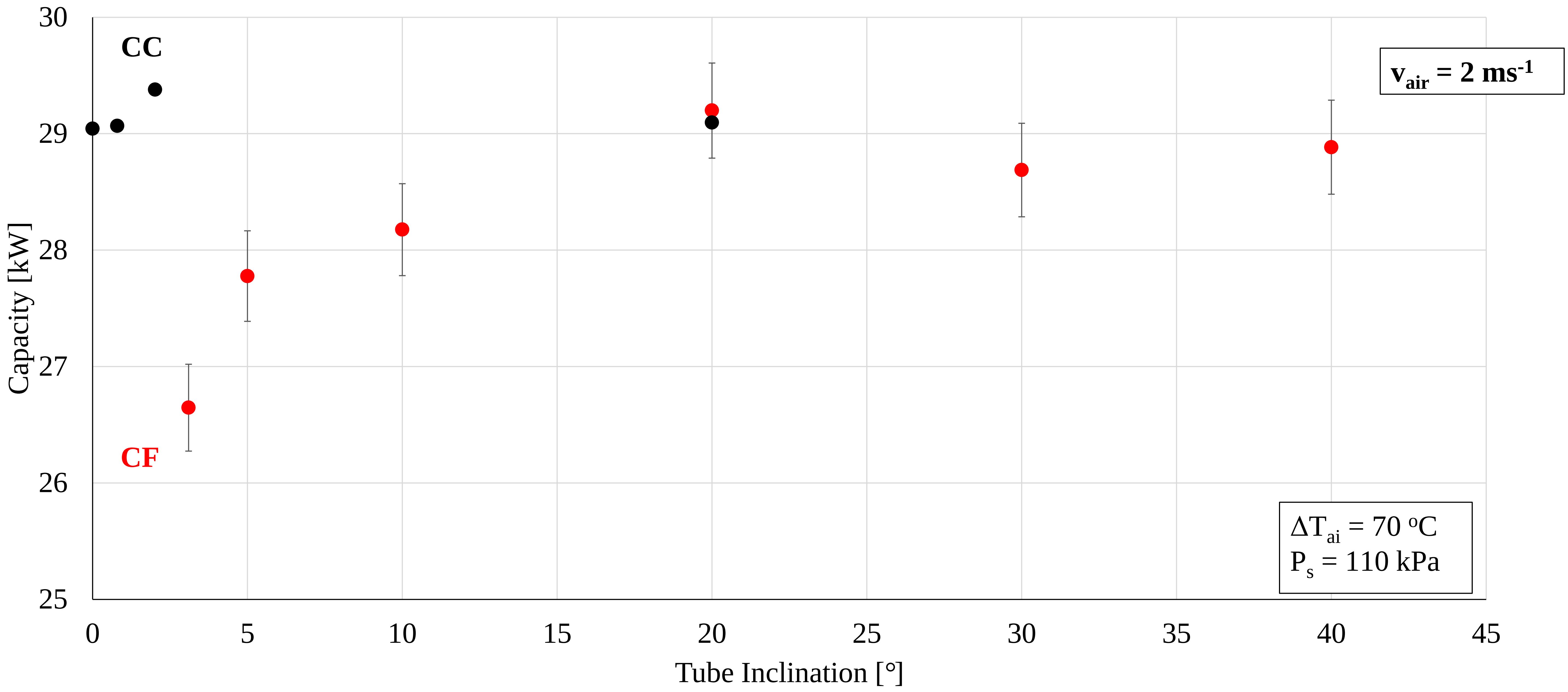
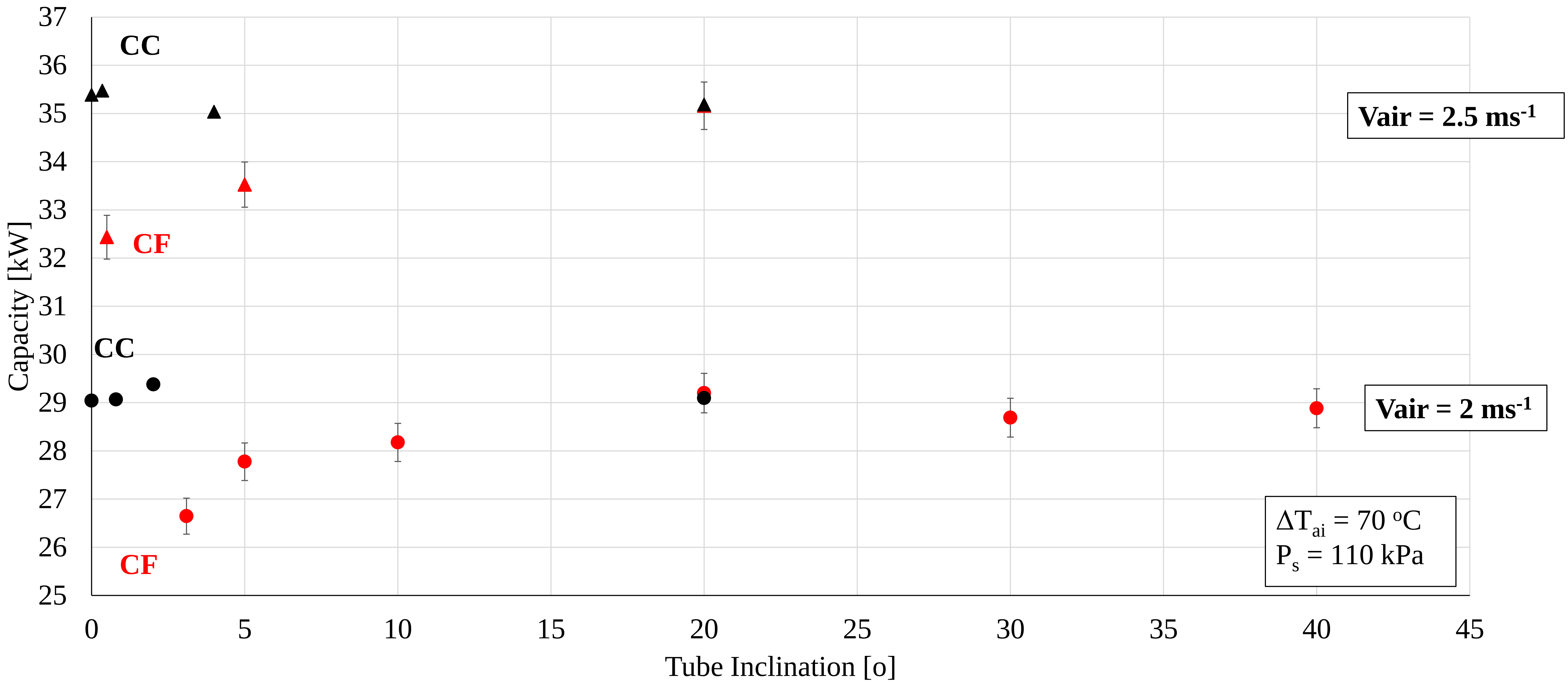
# Flooding of Counterflow Tubes Reduces Capacity



# Flooding of Counterflow Tubes Reduces Capacity



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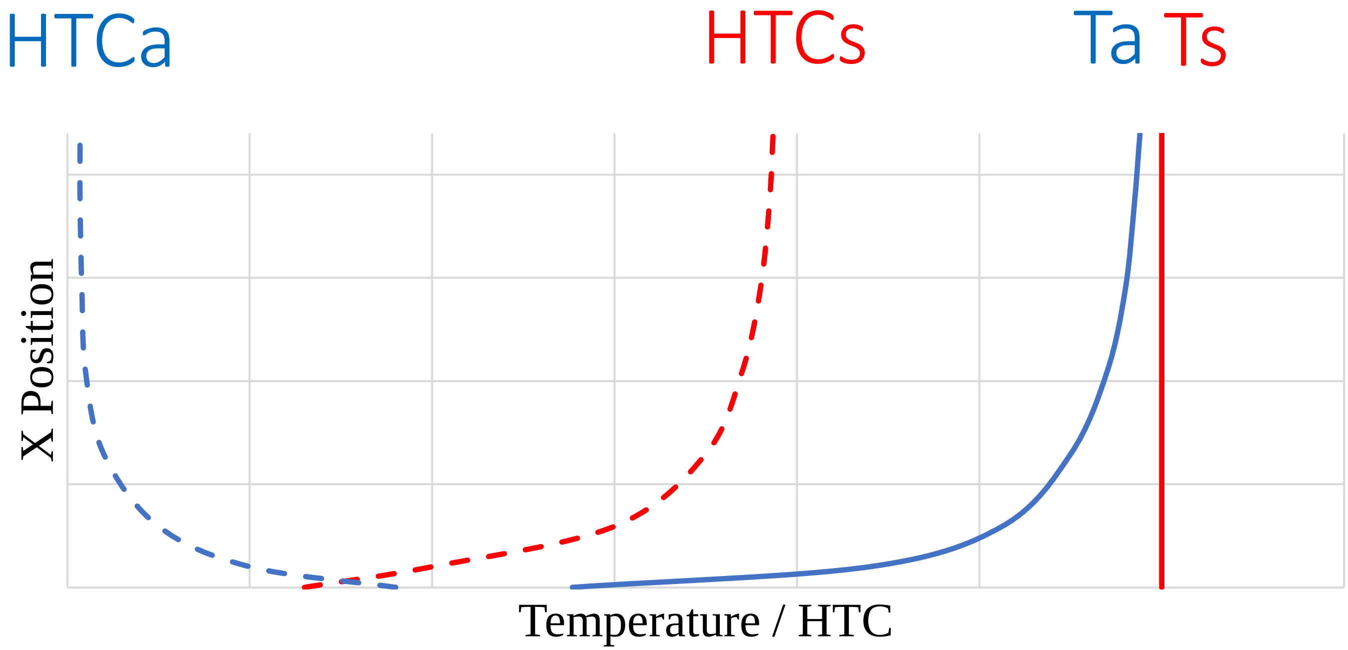
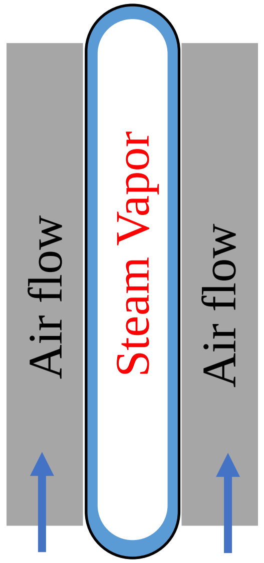
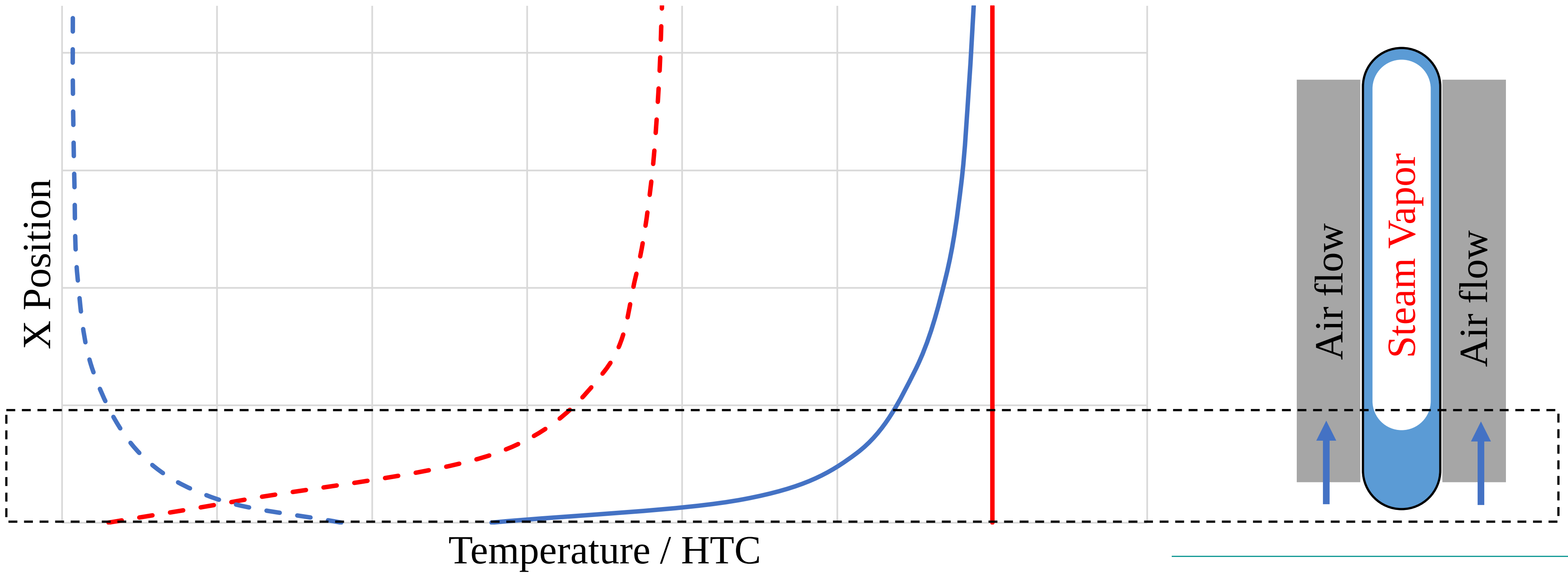
# Flooding Reduces Capacity due to Condensate Accumulation

Not Flooded




Flooded




Increased liquid at bottom of tube decreases heat transfer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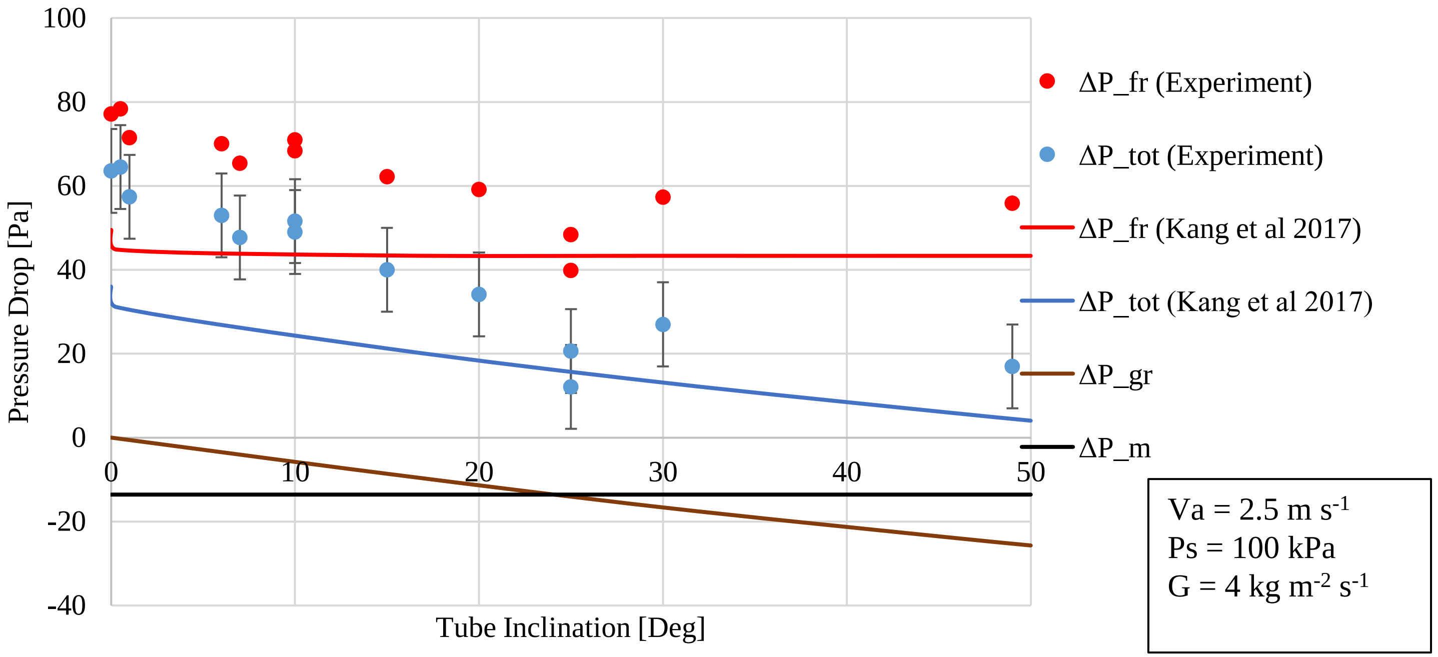
# Pressure Drop

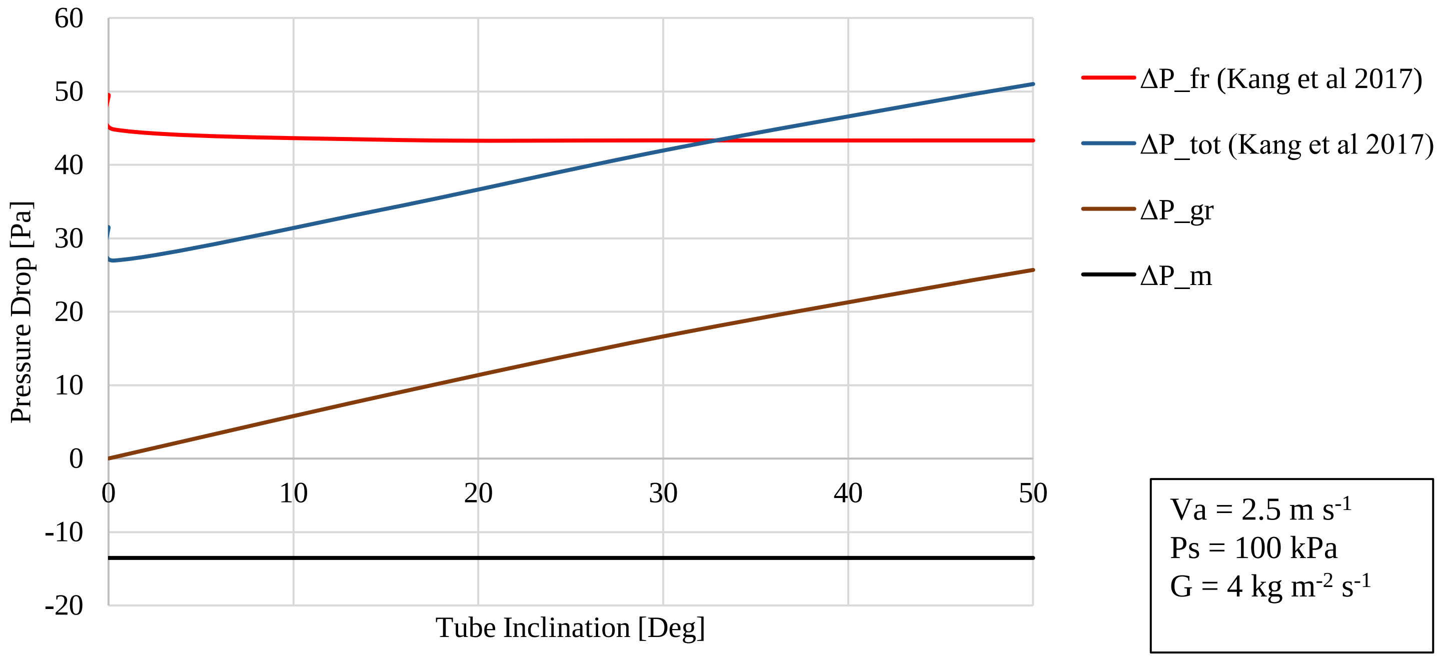
# Pressure Drop Comparison

- Co-current
  - Total pressure drop decreases as inclination increases due to:
    - Increase in gravitational pressure (ΔPg) recovery
    - Decrease in frictional pressure drop ($\Delta P_f$)
- Counter-flow
  - Total pressure drop constant as inclination increases due to
    - Increase in gravitational pressure drop (ΔPg)

Co-Current




Counter-Flow



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# Summary

- Co-current and counter-flow tubes have similar flow patterns and condensate accumulation
- Co-current and counter-flow tubes have equivalent capacities at typical inclination angles
  - Flooding reduces capacity in counter-flow tubes at low inclinations
- Co-current and counter-flow tubes have highest heat transfer at the air inlet (bottom of tube cross-section)
- Pressure Drop
  - Co-Current pressure drop decreases as tube inclination increases
  - Counter-Flow pressure drop increases as tube inclination increases

# Thank you!

Questions?

wdavies@exponent.com



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