Steady and Unsteady Computational Results of Full 2 Dimensional Governing Equations for Annular Internal Condensing Flows

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COMSOL
CONFERENCE
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Boiling/Condensing Flow Applications

Electronics/Data Center Cooling

http://www.pgal.com/portfolio/rice-university-data-center

Space Based Application

Thermal Management Systems and Power Generation Cycles

http://spaceflightsystems.grc.nasa.gov

- Phase change flows with boilers and condensers
- Lesser space/miniaturization – Shear/Pressure driven
- Higher heat loads
- Enables phase-change systems *of high heat removal* and *low weight* requirements

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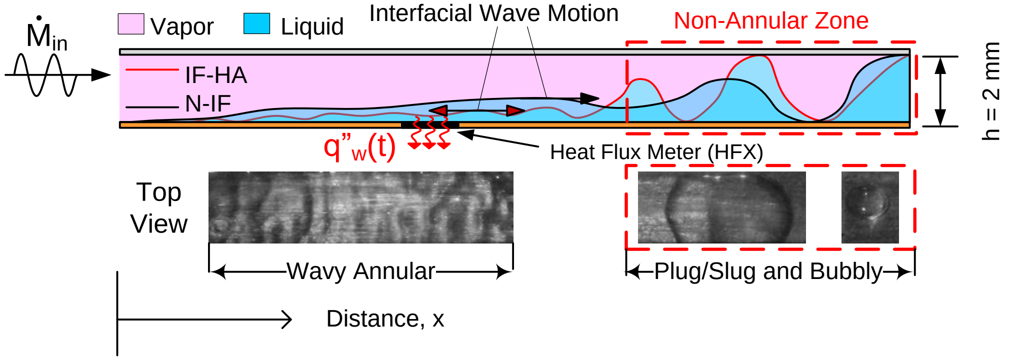
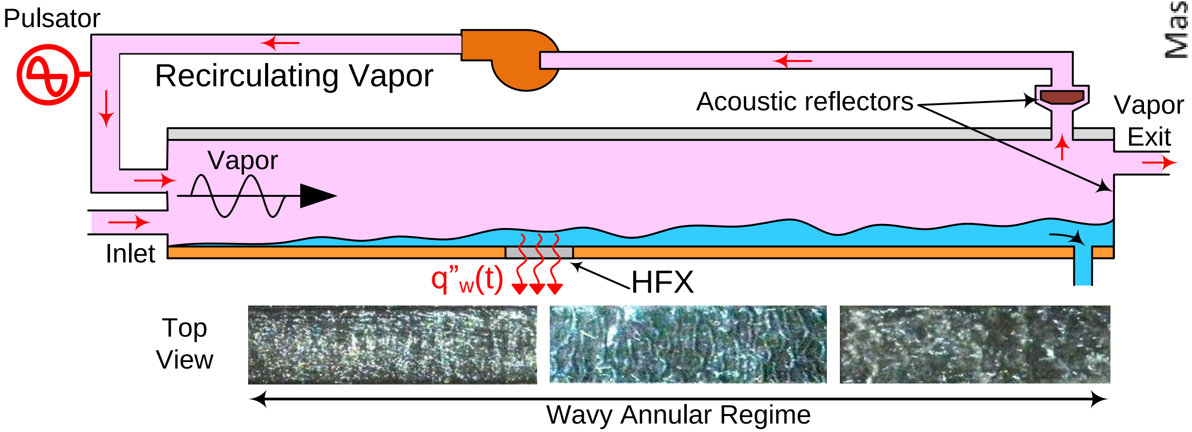
Experimental Observations – Traditional and Innovative

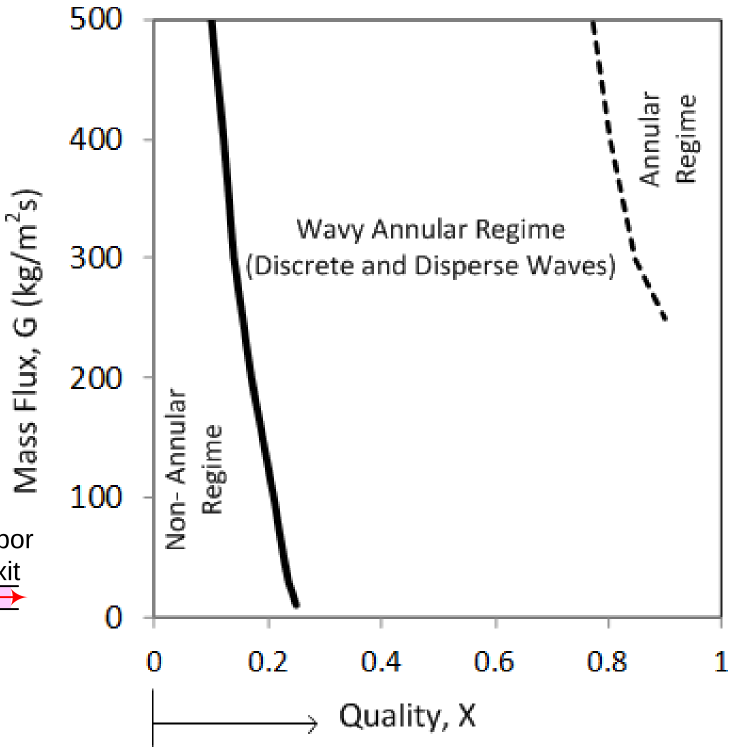
Traditional Condenser



Innovative Condenser



Annular to Non-Annular Transition Maps



Coleman and Garimella (2003)

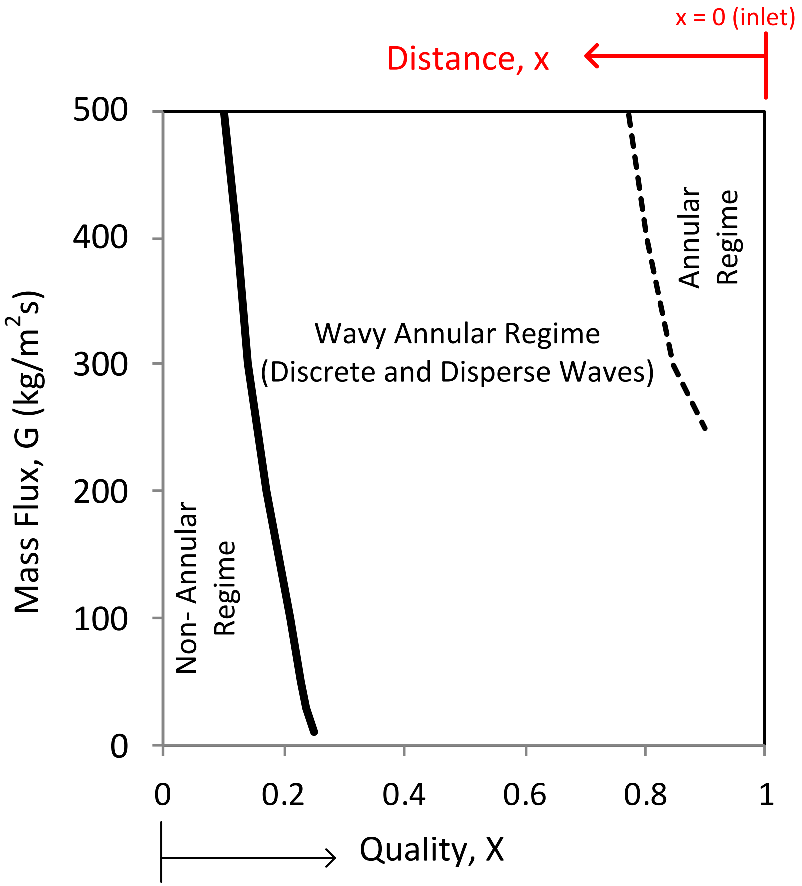
Enhancements

Kivisalu et al., MGST, 2012 and Kivisalu et al., IJHMT, 2013

Need for Predictive/Simulation Capabilities

- **Reliable steady annular flow predictions**
  - design innovative boilers/condensers
  - different fluid and thermal boundary conditions
- **Experiments - theory synthesized map of annular to non-annular transition**
  - Current Transition Maps – insufficient for engineering purpose
  - Enables design/functioning of innovative device operation (G_{in} =?, X_{in} =? X_{out} =?)
- **"Pulsatile" conditions simulation**
  - Better understand the experimental heat-flux enhancements

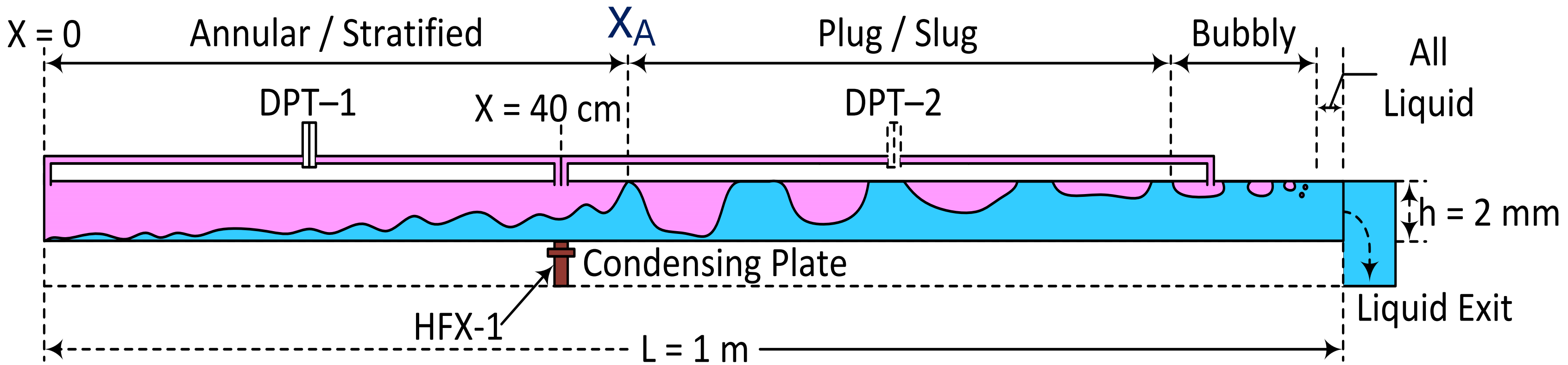
Annular to Non-Annular Transition Map



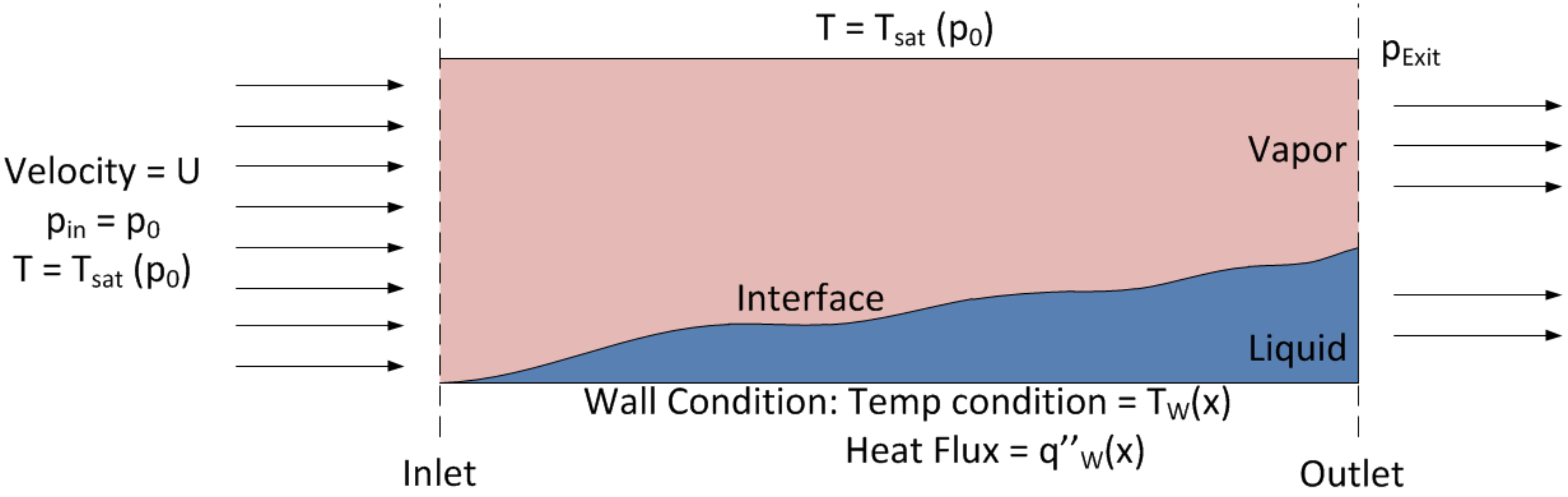
Coleman and Garimella (2003)

Problem Description

Problem Description for Internal Condensing Flows

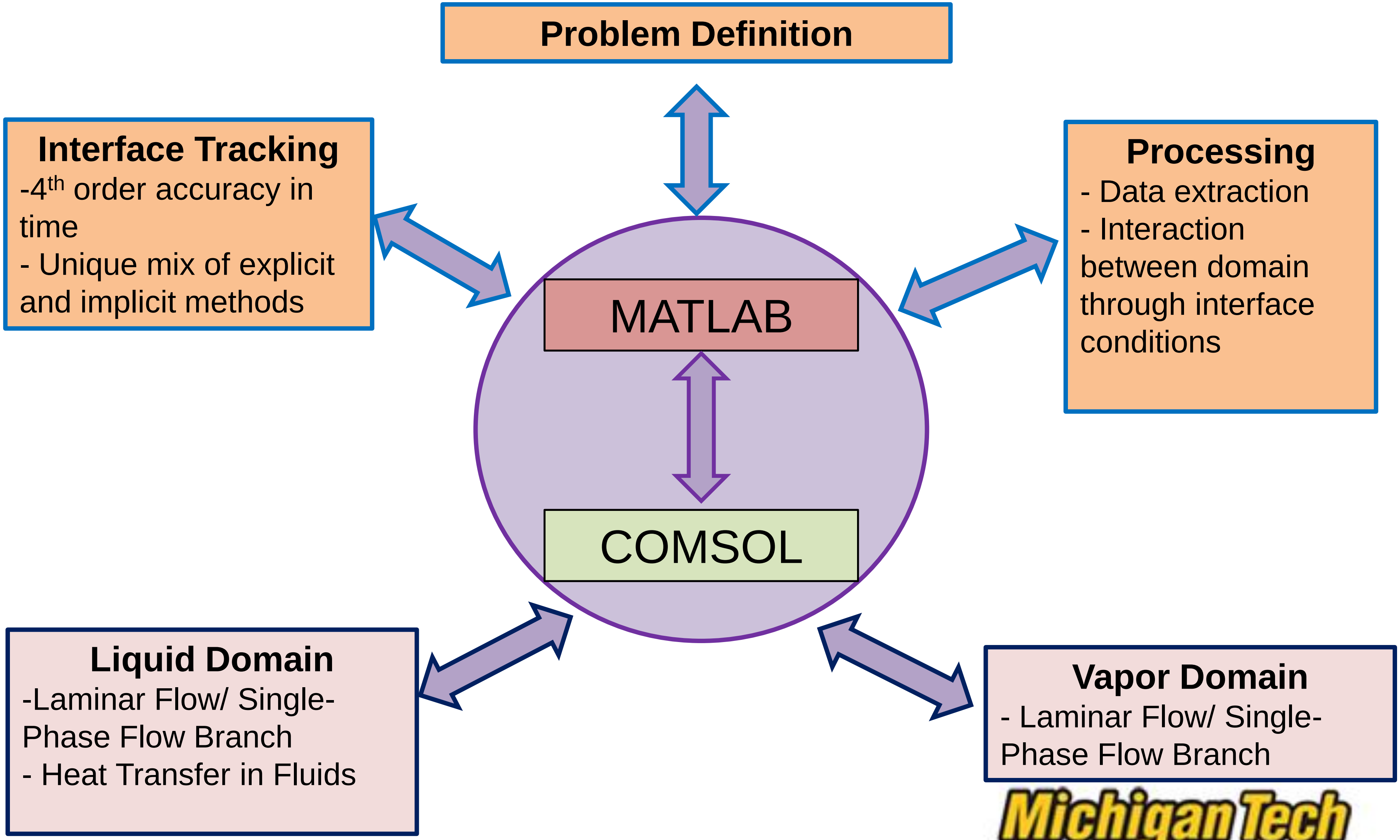


Side view schematic of a shear-driven condensing flow



- Governing Equations
- Interface Conditions

2- D Simulation Strategy



Problem Definition

Interface Tracking

-4th order accuracy in time

- Unique mix of explicit and implicit methods

Processing

- Data extraction
- Interaction between domain through interface conditions

MATLAB

COMSOL

Liquid Domain

-Laminar Flow/ Single-Phase Flow Branch

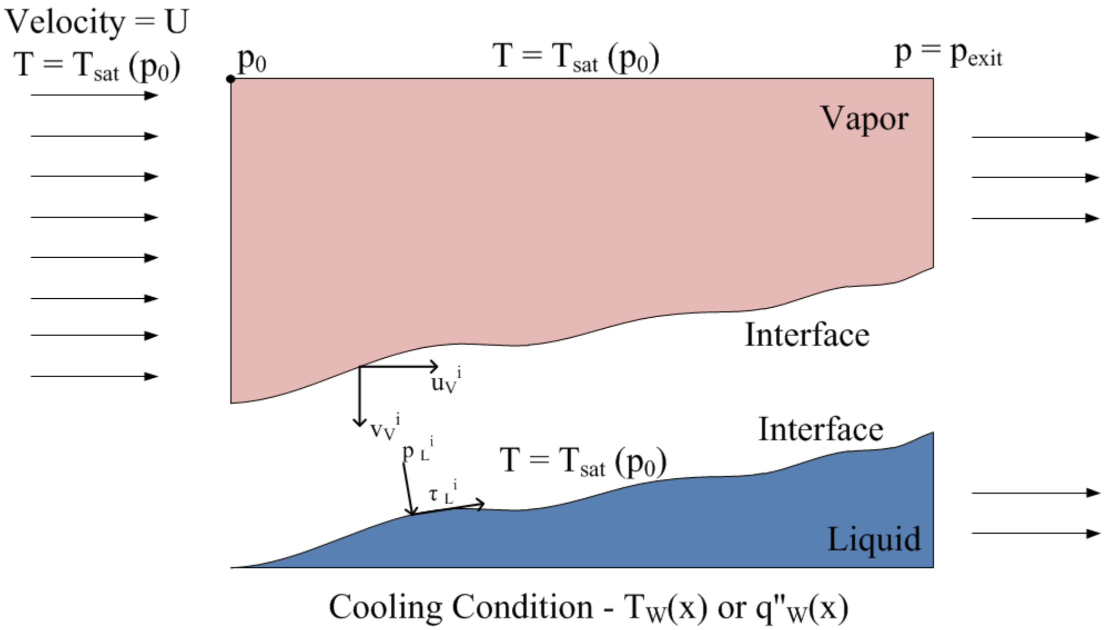
- Heat Transfer in Fluids

Vapor Domain

- Laminar Flow/ Single-Phase Flow Branch

2- D Simulation Strategy

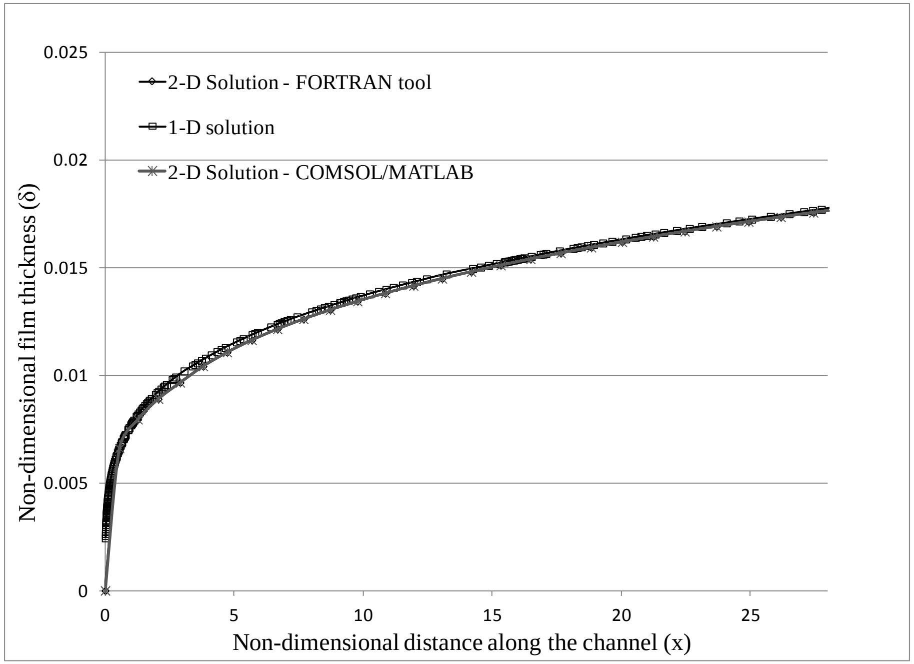
- Single Phase Domain Approach
- COMSOL/MATLAB Platform
- COMSOL – Solve the Individual Domain
- MATLAB subroutines
  - Data Extraction
  - Interface Tracking

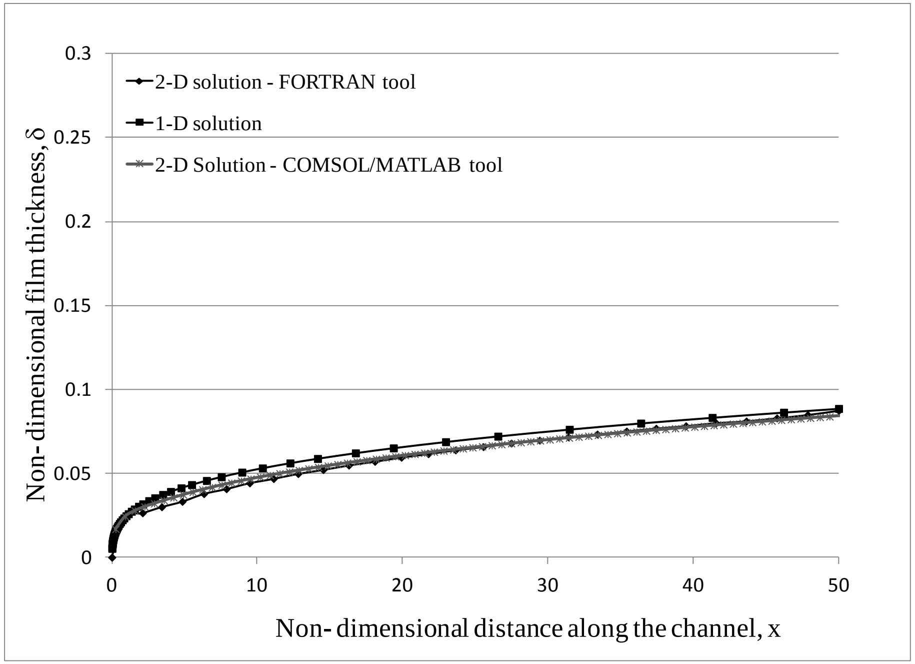


Governing Equations Interface Conditions Algorithm

Results
(Completed and In-progress)

Consistency Between Completely Different Steady Simulation Tools





Gravity Driven – R113

U = 0.41 m/s , ΔT = 5 °C, h = 0.004 m

Shear Driven – R113

U = 0.6 m/s , ΔT = 5 °C, h = 0.004 m

Plot of non-dimensional film thickness along the non-dimensional distance of the channel – showing consistency of different codes.

Mitra et.al., 2012

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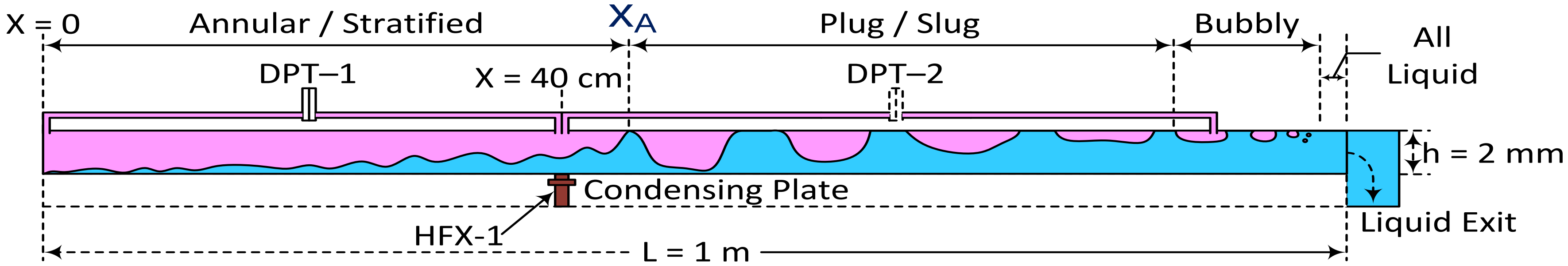
Steady Code Validation with Experiments (annular regime)



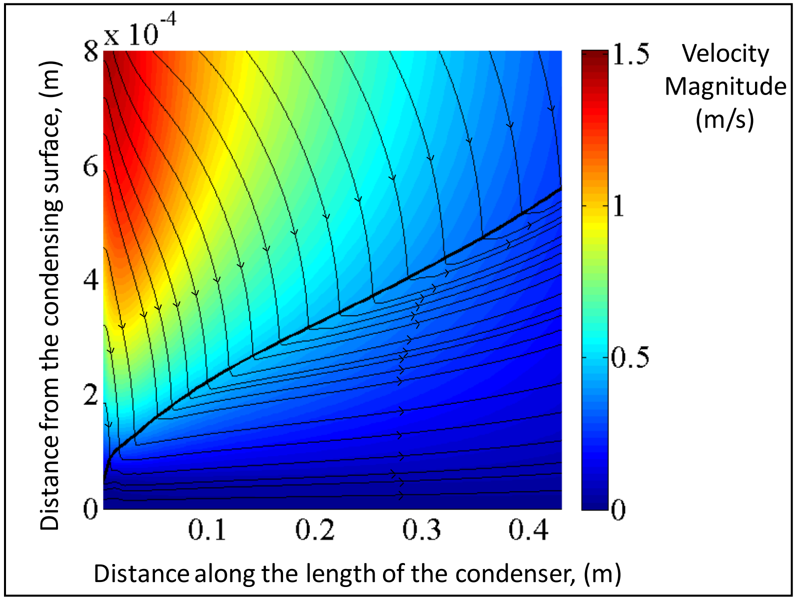
Side view schematic of a shear-driven condensing flow

Case	$\overline{\dot{M}}_{in}$	$\overline{p}_{in}$	$\overline{T}_W$	$\overline{q''}_{W\|Expt}$ @ x = 40	$\overline{q''}_{W\|2\text{-}D}$ @ x = 40 cm	% Error for 2-D	x_A (Expt)	x_A (Theory)
	g/s	kPa	° C	W/cm^2	W/cm^2		cm	cm
Error	± 0.05	± 0.15	± 1	± 25%			± 12 %	
1	0.702	99.98	48.6	0.18	0.19	4.1	71	Ongoing
2	0.700	99.99	49.8	0.16	0.14	13.4	90	
3	0.700	99.99	50.0	0.15	0.13	11.5	93	
4	0.698	99.99	50.7	0.12	0.11	4.2	95	
5	1.000	101.07	44.0	0.40	0.40	0.6	57	

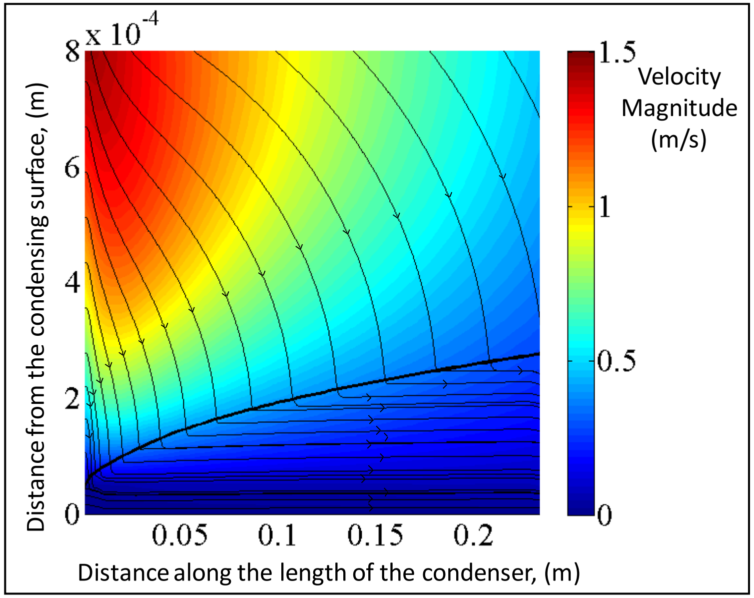
Base Flow Predictions for g_y = -g are in Agreement with Experimental Runs

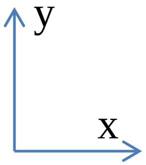
Physics Differences Between Shear and Gravity Driven Steady Condensing Flows

Shear Driven



Gravity Driven





Horizontal channel

$g_y = - g$ and $g_x = 0$

Tilted channel, 2 deg

$g_y = - g \cos(2°)$ and $g_x = g \sin(2°)$

Flow Situation

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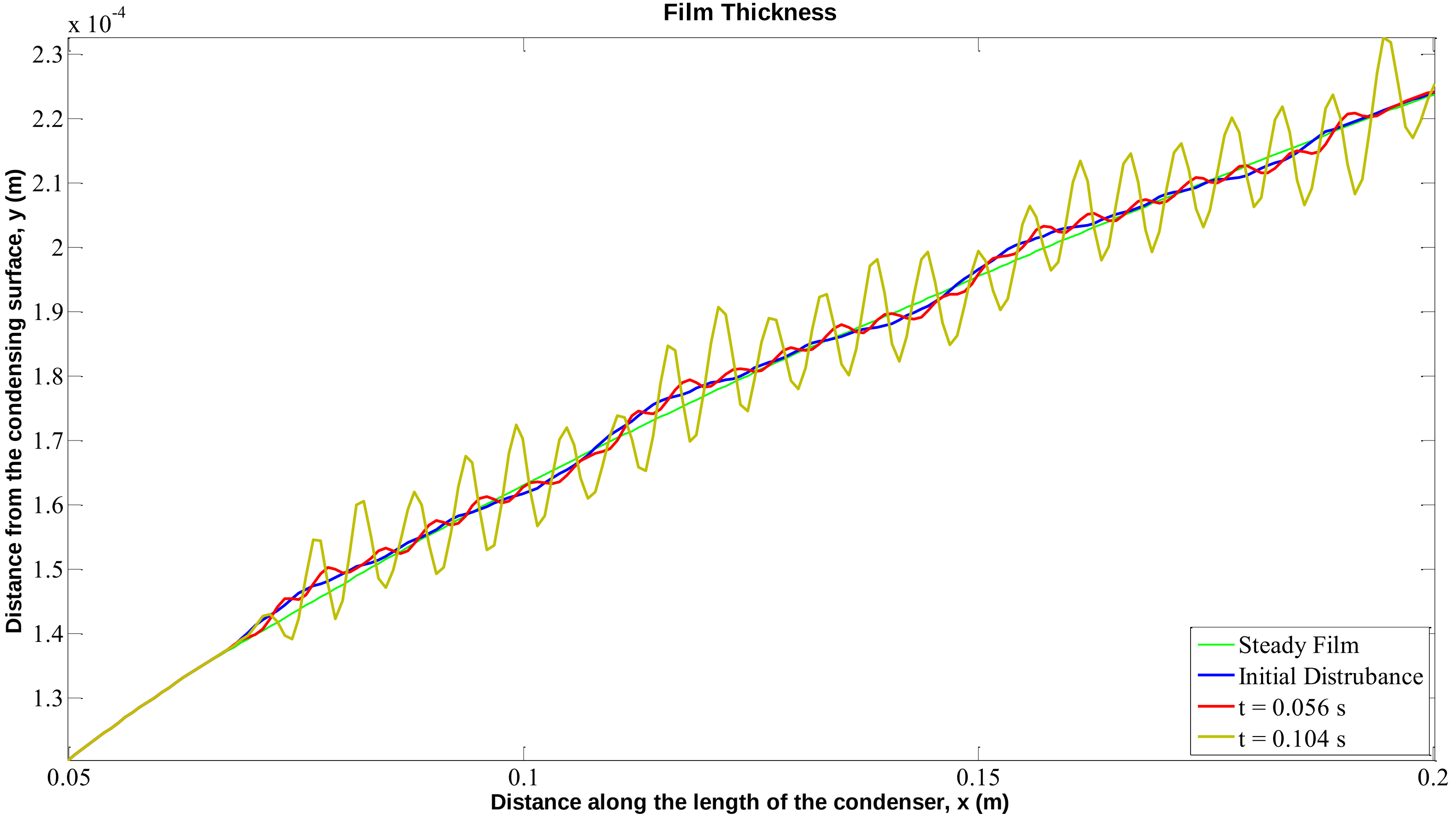
Unsteady Simulation Capability - Wave Resolution

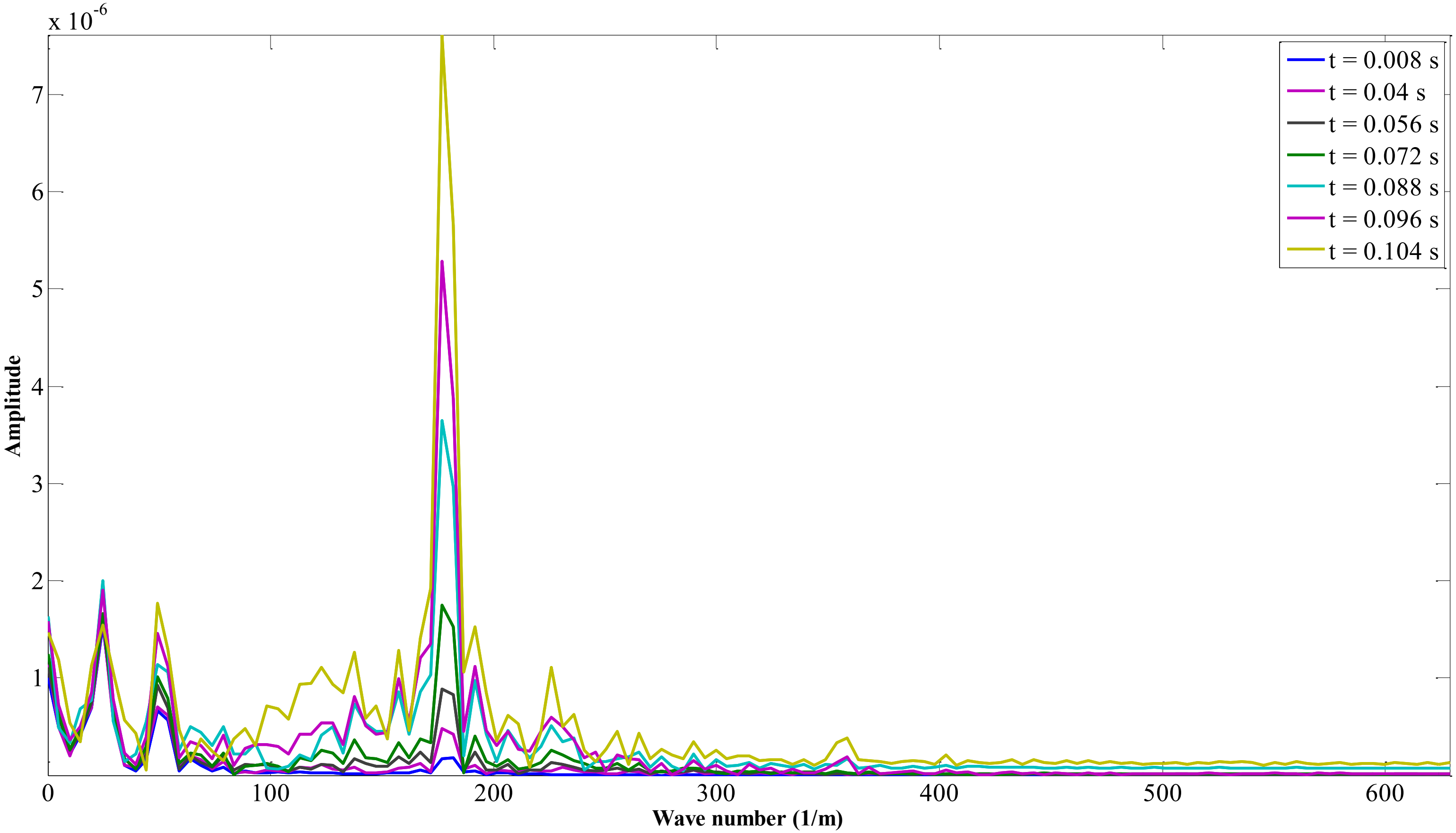
Inlet Vapor Speed = 2.53 m/s, ΔT = 13.1°C



Plot of film thickness along the length of channel for condensing flow

Unsteady Simulation Capability - Wave Resolution

Inlet Vapor Speed = 2.53 m/s, ΔT = 13.1°C



Plot of Fast Fourier Transform as a function of wave number identifies critical wave-number

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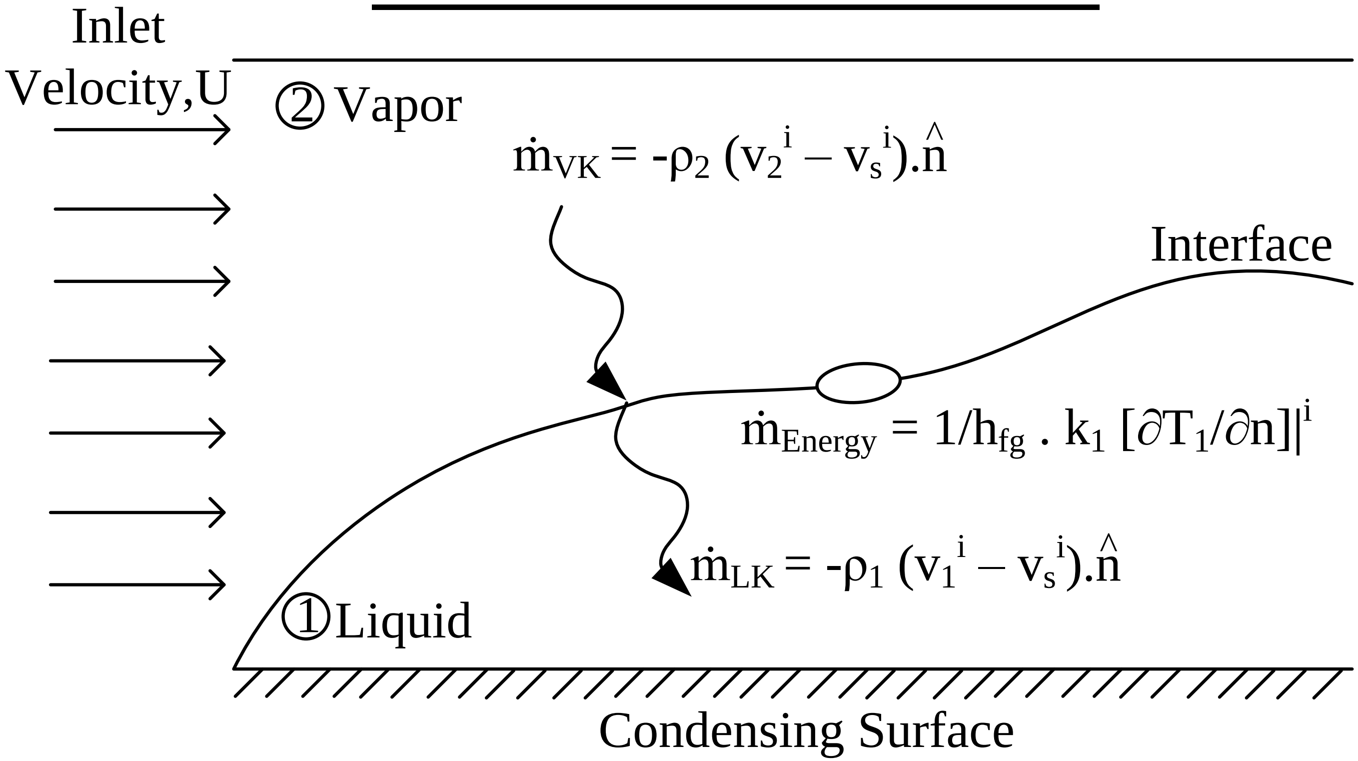
Unsteady Simulation Capability – Interfacial Mass Flux Resolution



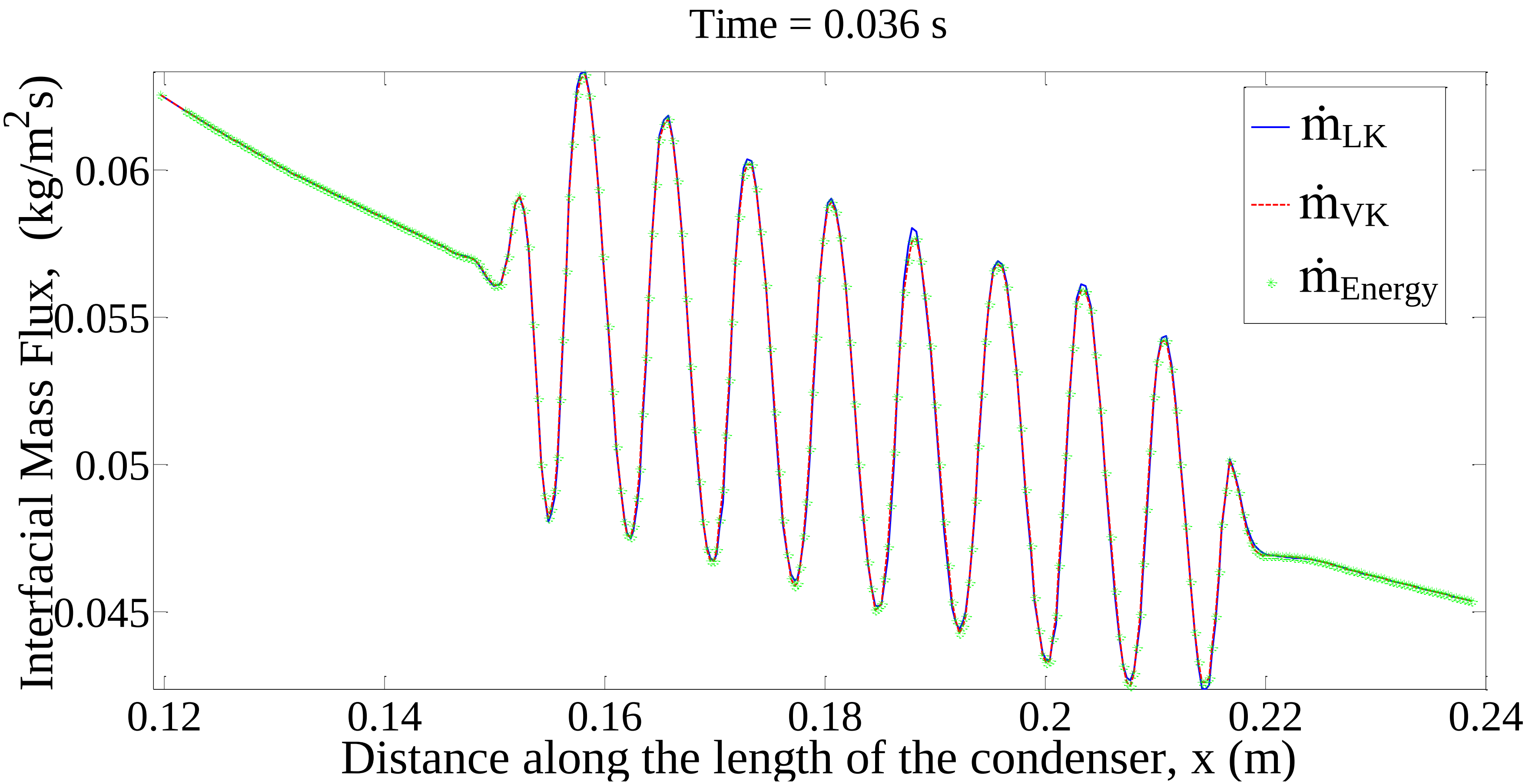
Interfacial mass flux (kg/m²s)

$\dot{m}_{VK}$ - Based on kinematic constraints on the interfacial values of vapor velocity fields

$\dot{m}_{LK}$ - Based on kinematic constraints on the interfacial values of liquid velocity fields

$\dot{m}_{Energy}$ - Based on based on net energy transfer constraint

Unsteady Simulation Capability – Interfacial Mass Flux Resolution



Plot of unsteady interfacial mass flux along the length of the condenser showing convergence of the interfacial variables.

Conclusions

- Developed *Fundamental 2-D steady/unsteady predictive tools* for annular flow condensation (and flow boiling – not discussed).
  - With regard to convergence and satisfaction of the interfacial conditions in the presence of waves, it shows **unsurpassed accuracy (relative to other methods).**
- Developed *Engineering 1-D approx. tools* for annular condensing and boiling flows.
- *Validated the scientific tool* by comparison with the experimental data (MTU).
- Suitable integration of simulations and experiments will aid in building of *next generation thermal management systems involving phase change.*

Thank You.

Questions?

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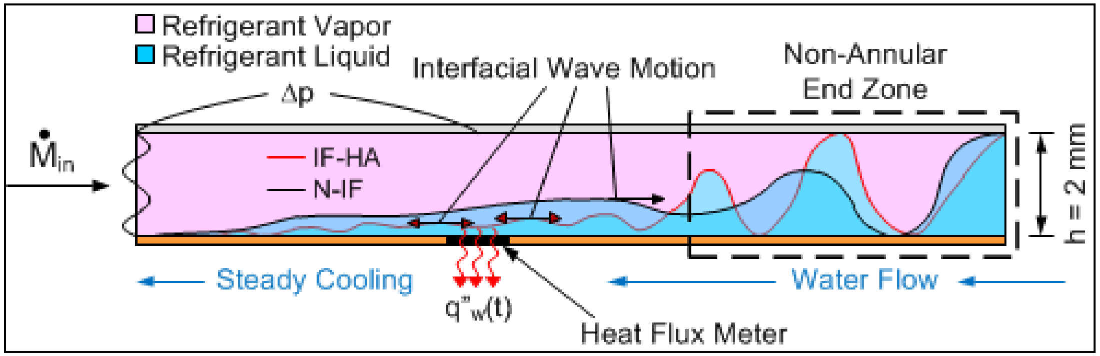
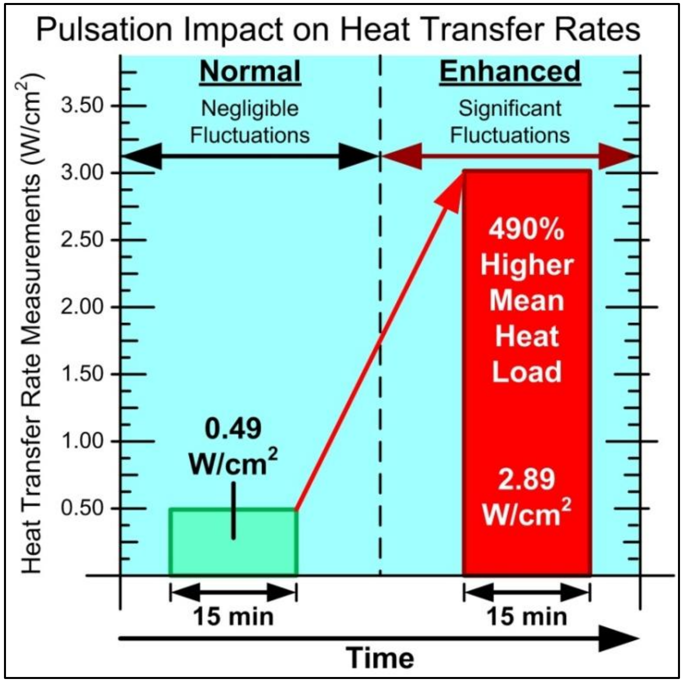
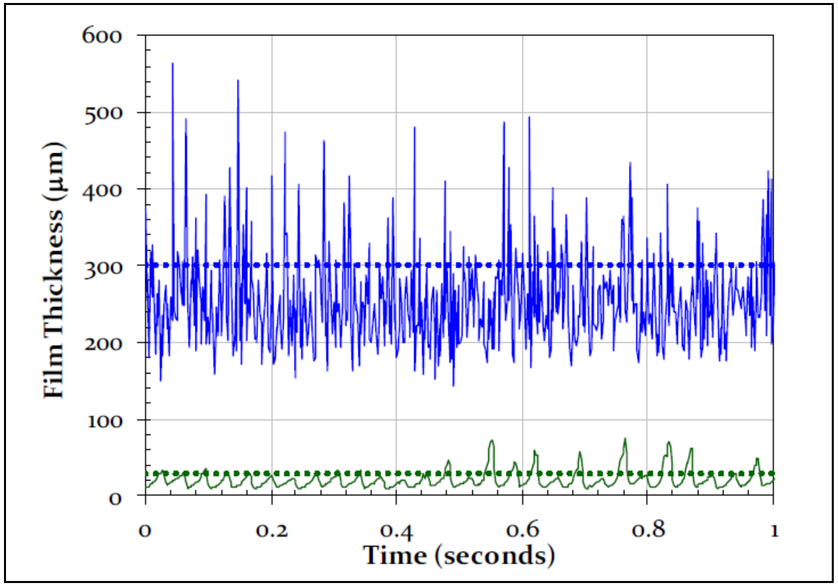
Heat Transfer Enhancements for Annular Flows

Effects of externally imposed pressure-difference or inlet mass flow rate pulsations







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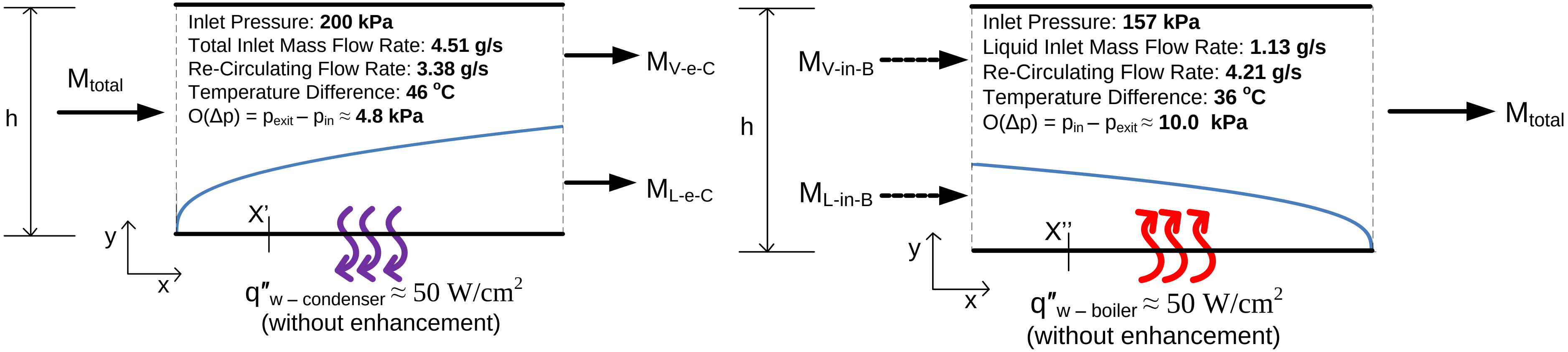
Kivisalu et al., MGST, 2012 and Kivisalu et al., IJHMT, 2013

Simulation Tools

Engineering 1-Dimensional tool (IJHMT, 2012)

- Annular flow condensation (Assisted Dr. Soumya Mitra)
- Annular flow boiling (Current Ph. D. Work)


Inlet Pressure: **200 kPa**
Total Inlet Mass Flow Rate: **4.51 g/s**
Re-Circulating Flow Rate: **3.38 g/s**
Temperature Difference: **46 °C**
O(Δp) = $p_{exit} - p_{in} \approx$ **4.8 kPa**

$q''_{w-condenser} \approx 50\ \mathrm{W/cm^2}$
(without enhancement)

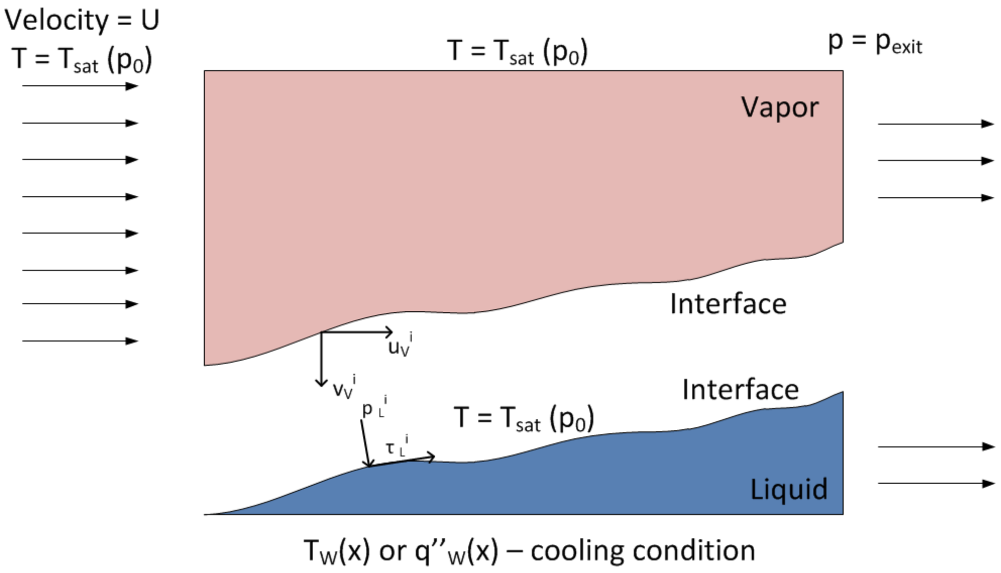
Inlet Pressure: **157 kPa**
Liquid Inlet Mass Flow Rate: **1.13 g/s**
Re-Circulating Flow Rate: **4.21 g/s**
Temperature Difference: **36 °C**
O(Δp) = $p_{in} - p_{exit} \approx$ **10.0 kPa**

$q''_{w-boiler} \approx 50\ \mathrm{W/cm^2}$
(without enhancement)

Plot of film thickness along the length of channel for condensing and boiling flow

Computational Approach

Iterative solution strategy



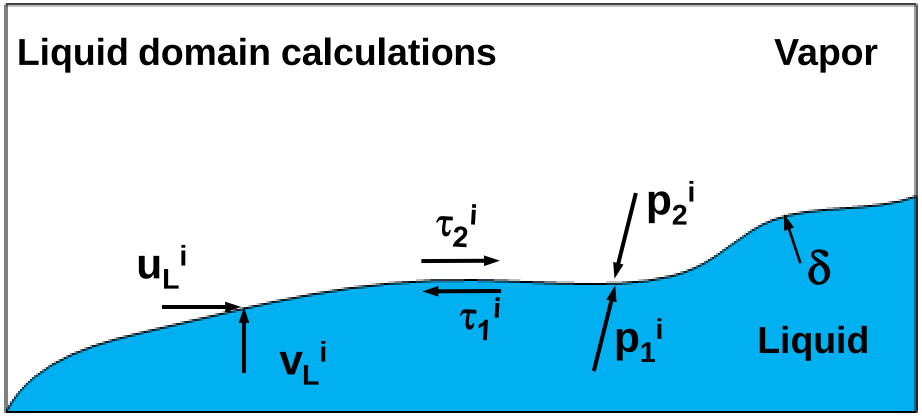
- At discrete number of spatial locations, make an **initial guess** of interface variables - $\{\delta, \tau^i, p^i, T_L^i, u_V^i, v_V^i, T_V^i\}$ for the steady problem.
- For the unsteady problem, start with known or specified values of these variables at t = 0.

Governing Equations

Interface Conditions

Computational Approach

Iterative solution strategy



- Solve liquid domain by a *finite-element* method on COMSOL, using stress boundary conditions {i.e. tangential stress (shear) and normal stress (pressure) specified}, and saturation temperature conditions at the interface.
- Post-process the solution to obtain {u_L^i, v_L^i, T_L^i}.

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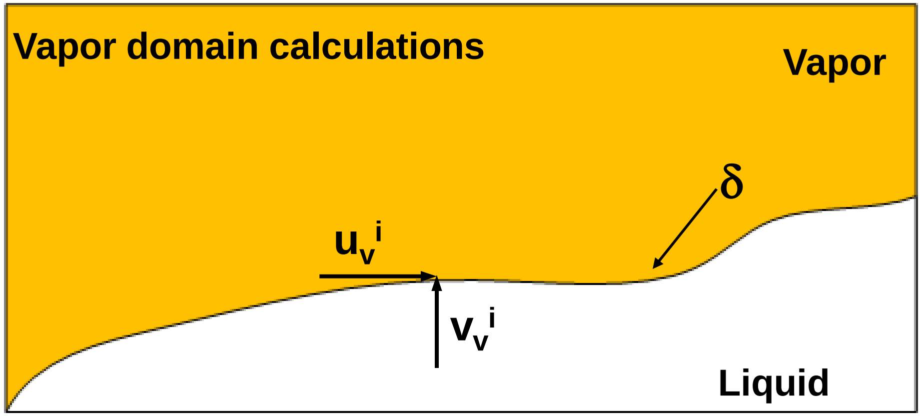
Computational Approach

Iterative solution strategy



- Using the liquid domain solution, compute u_V^i from continuity of tangential velocity, v_V^i from interfacial mass flux equality $\dot{m}_{VK} = \dot{m}_{Energy}$ and T_V^i using saturation temperature conditions at the interface.
- Using the computed $\{u_V^i, v_V^i, T_V^i\}$ on the current location of interface δ, solve the vapor domain by the finite element method on COMSOL.
- Post-process the solution to obtain new values of tangential and normal stresses. For this, use momentum-balance condition at the interface and the computed values of vapor domain interfacial stresses.

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Computational Approach

Interface Tracking

Update δ on moving grid which remains fixed over a time interval [t, t+Δt] of interest.

- The interface is tracked through the reduced form of $\dot{m}_{LK} = \dot{m}_{Energy}$ given as:

$$\frac{\partial\delta}{\partial t} + \bar{u}(x,t)\frac{\partial\delta}{\partial x} = \bar{v}(x,t)$$

$$\delta(0,t) = 0$$

$$\delta(x,0) = \delta_{steady}(x) \quad \text{or} \quad \text{other prescriptions}$$

Computational Approach

Interface Tracking

- **EXPLICIT MARCHING:** The evolution equation – wave equation (1st order hyperbolic PDE)
- We predict a location of interface at $t = t^* + \Delta t$
- Map the existing/current solution to the new domain.
- Obtain a new predicted solution.

- **IMPLICIT MARCHING** – Predict new interface with 4th order accuracy in time with the help of its well defined characteristics equation.
- Map the current/existing solution on to the new domain implied by the new interface location (corrected location or the value for the time t*+Dt).
- Repeat above steps for convergence and march in time.

Back

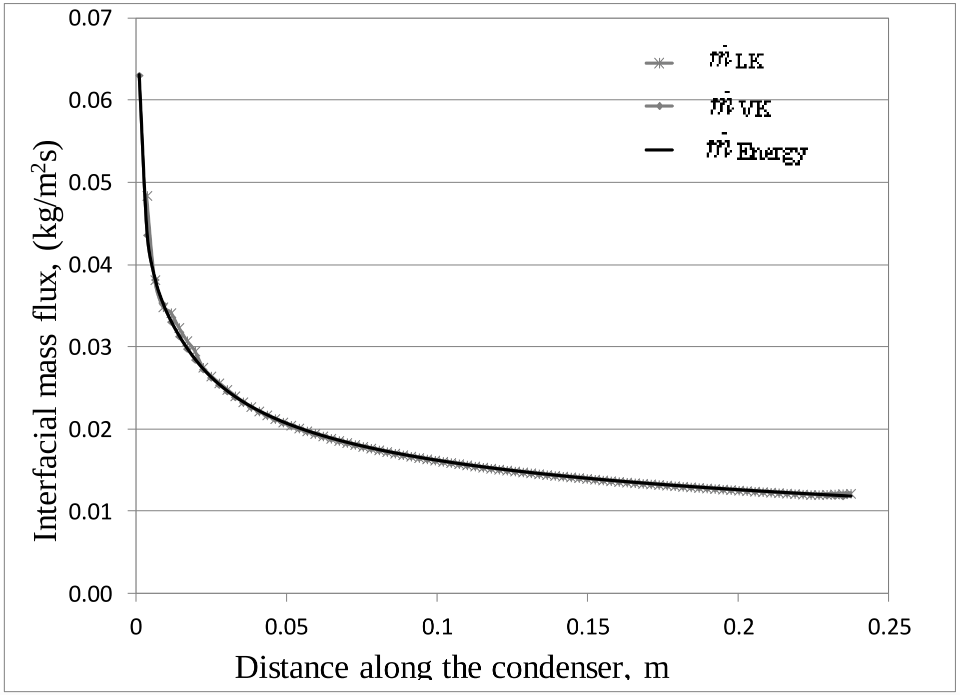
Accuracy of 2-D Computational Tool

The accuracy of the 2-D solution is ensured through satisfaction of the following:

✓ the convergence of the flow variables in the interior of each fluid domain

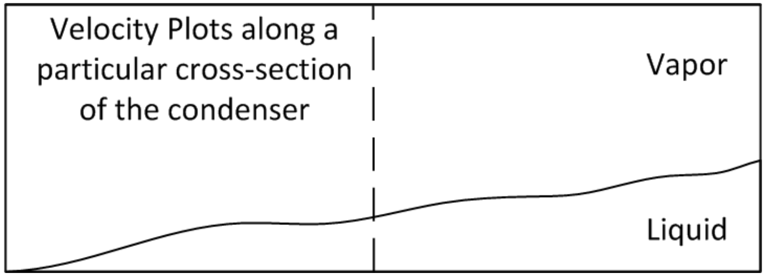
✓ satisfaction of all the interface conditions,

✓ grid independence of each domain and the flow problem

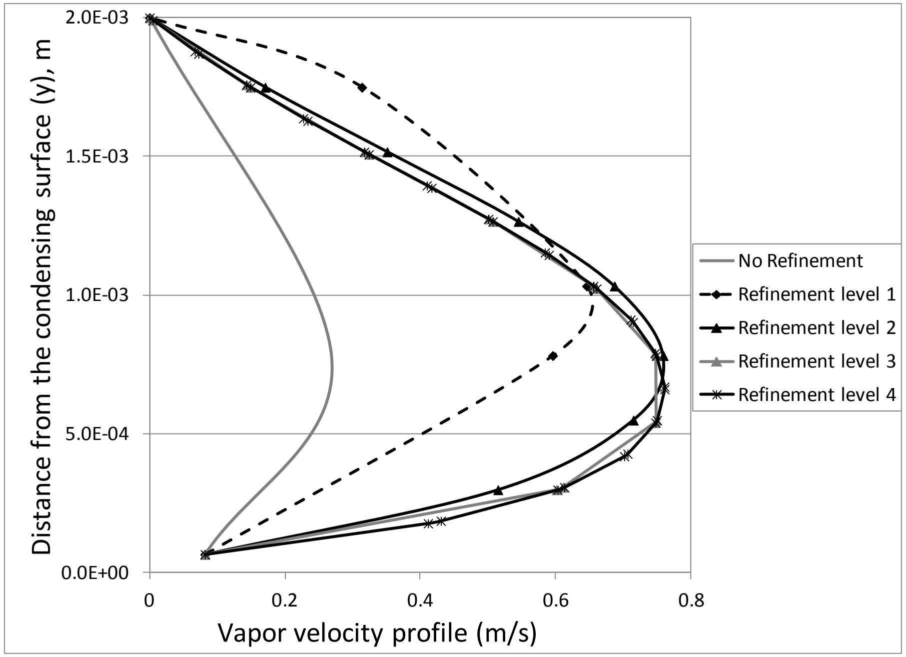


Plot of interfacial mass flux along the length of the condenser showing convergence of the interfacial variables (Mitra (2012)).

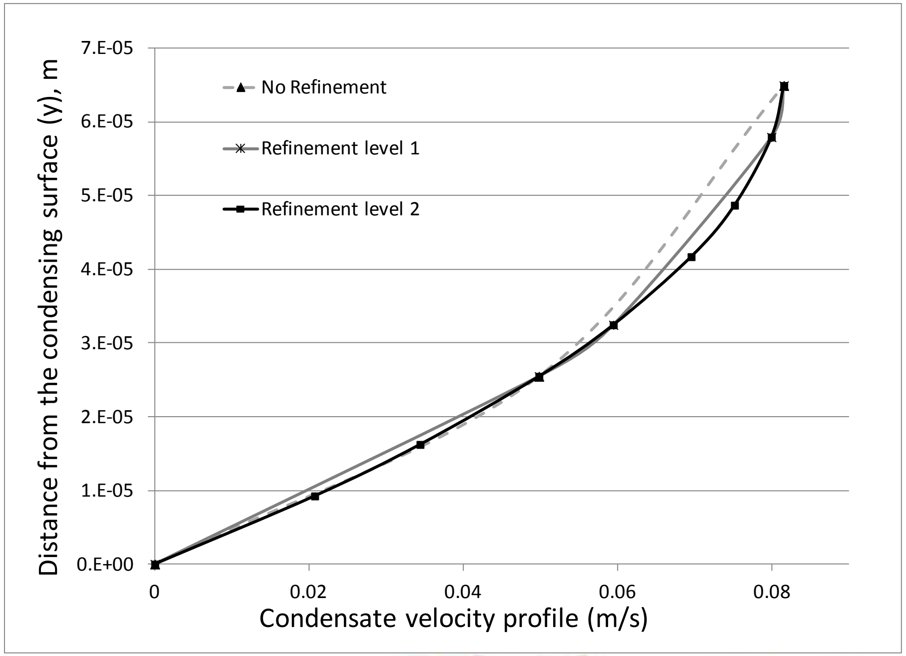
Grid Independence


Velocity Plots along a particular cross-section of the condenser

Grid independence of Vapor domain



Grid independence of Liquid domain



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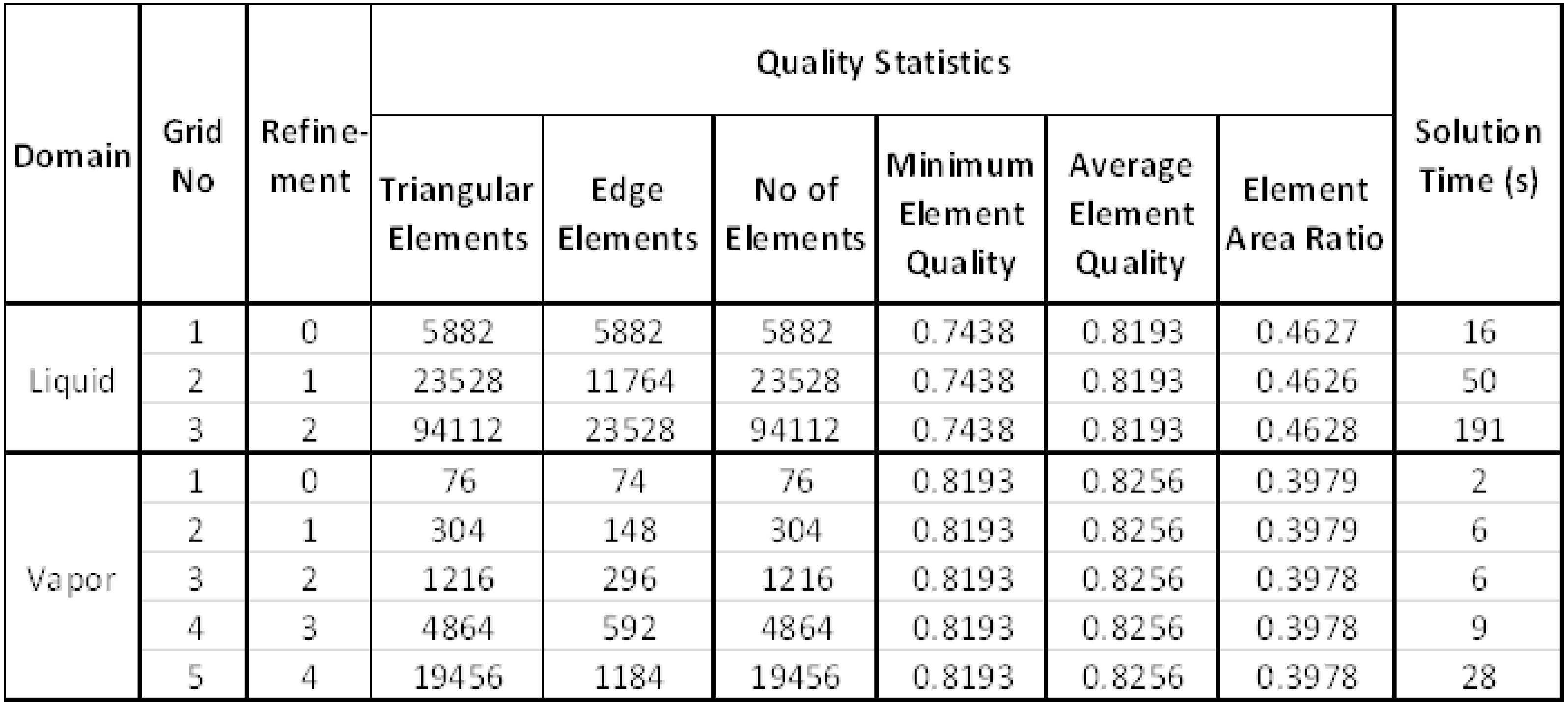
Grid Independence



Domain	Grid No	Refine-ment	Quality Statistics						Solution Time (s)
			Triangular Elements	Edge Elements	No of Elements	Minimum Element Quality	Average Element Quality	Element Area Ratio	
Liquid	1	0	5882	5882	5882	0.7438	0.8193	0.4627	16
	2	1	23528	11764	23528	0.7438	0.8193	0.4626	50
	3	2	94112	23528	94112	0.7438	0.8193	0.4628	191
Vapor	1	0	76	74	76	0.8193	0.8256	0.3979	2
	2	1	304	148	304	0.8193	0.8256	0.3979	6
	3	2	1216	296	1216	0.8193	0.8256	0.3978	6
	4	3	4864	592	4864	0.8193	0.8256	0.3978	9
	5	4	19456	1184	19456	0.8193	0.8256	0.3978	28

Vapor domain is typically solved with refinement level of 3 or 4

Liquid domain is typically solved with refinement level of 2 or 3

Back

Existing Simulation Methodologies

- Single domain solution approach
- Coarse and band approach to track interface – extremely dense grid needed
- Unable to satisfy the mass flux transfer criteria as a result
- Level Set Methods
  - Implicit Method Tracking
- VOF methods
  - Marker Cell Approach

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Flow Specifications

Refrigerant : FC - 72
Channel height = 2 mm
Inlet mass flow rate = 0.4 g/s
Temperature difference =17.45 °C

Back

Assumptions

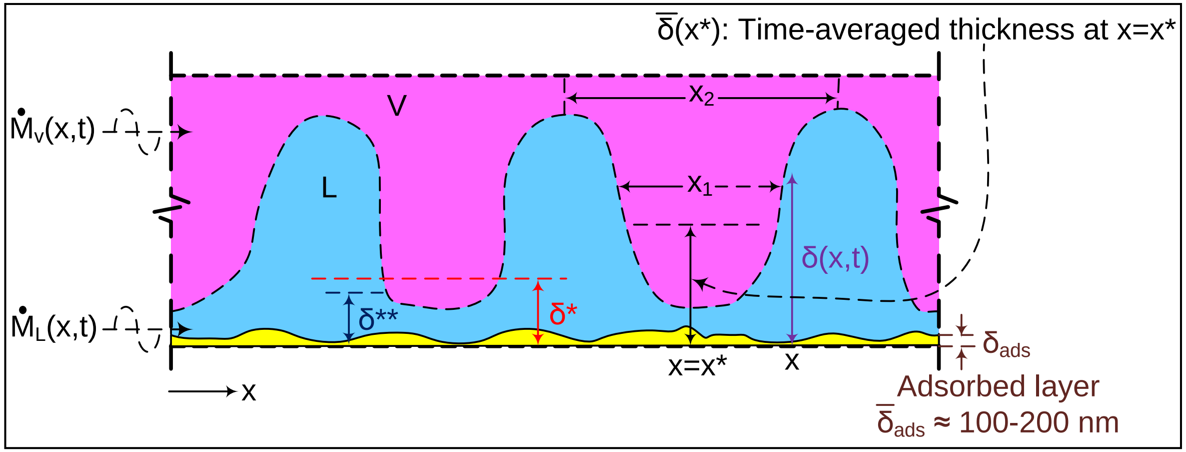
- Negligible interfacial thermal resistance
- Equilibrium thermodynamics on either side of the interface are assumed to hold.
- No non-equilibrium thermodynamic model for the interfacial mass-flux is used to obtain a solution.

Limitations of FORTRAN Code and Benefits of New Code

- Limitations
  - Smaller domain problems
  - Issues with meshing algorithm and noise resolution
  - Slower convergence
  - Inability to simulate non-annular regimes
- Benefits of COMSOL/MATLAB Code
  - Simulate non-annular regimes with some modification
  - Well developed single phase solvers
  - Vapor compressibility effects

Physics of Dramatic Enhancements

Our Hypothesis:



- Adsorbed layer interacts and destabilizes the micro layer – causing wave troughs to stick
- Time of dwell/sticking is significant compared to externally imposed pulsation's time-scale
- Time averages of film thickness is significantly smaller for the pulsatile cases