

A Summary of Recent SBIR and STTR Projects in Support of Cryogenic Fluid Management Modeling



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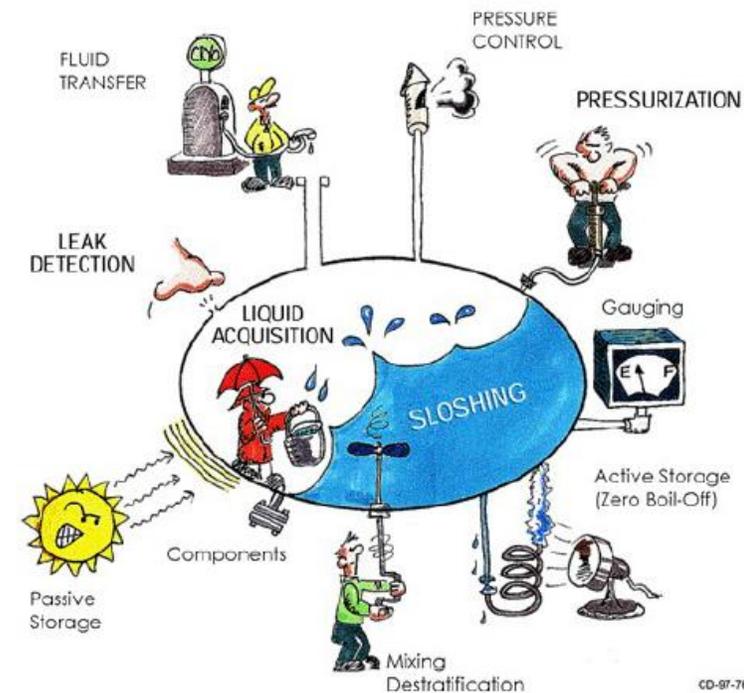


SBIR and STTR



- SBIR = Small Business Innovation Research
 - Small Business
- STTR = Small Business Technology Transfer
 - Small Business + Academic Institution

- NASA's Cryogenic Fluid Management (CFM) Modeling Portfolio, under the CFM Portfolio Project, has been investing in SBIR/STTR contracts within the CFM subtopic
- Investment in sub-model development to improve the current prediction capabilities of CFD codes utilized for CFM applications
- CFD models can be used to reduce risk and increase efficiency in systems requiring CFM
 - On-orbit propellant transfer/refueling
 - Settling & Sloshing
 - Tank Pressurization
 - Line Chillover
 - Tank Chillover
 - Tank Fill
 - Liquefaction
 - Cryocoolers, BAC
 - Film Condensation



Credit:
J. Jurns



NASA's CFD Codes for CFM



- Glenn Research Center
 - ANSYS Fluent
 - Flow Science, Inc. Flow3D
 - Siemens Simcenter STAR-CCM+
- Marshall Space Flight Center
 - Streamline Numerics Loci-Stream



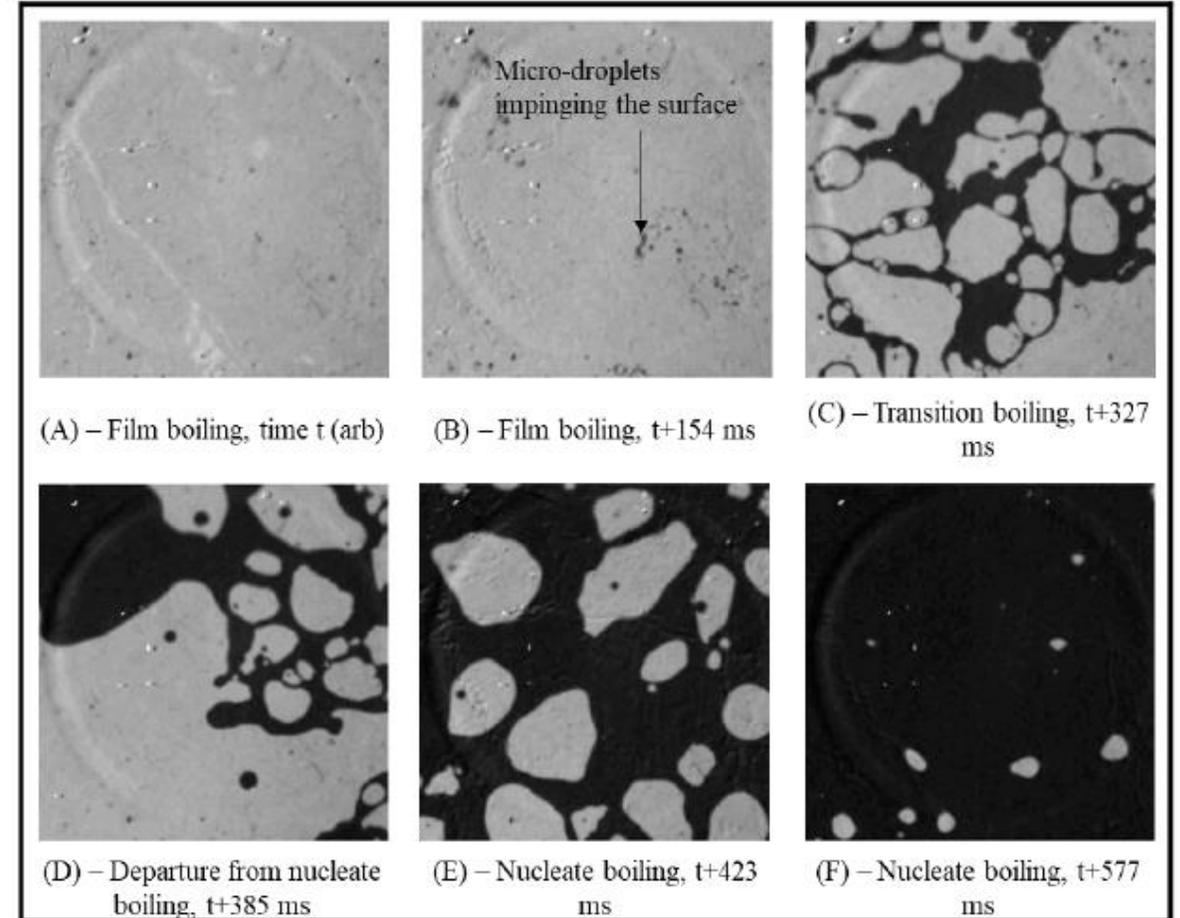
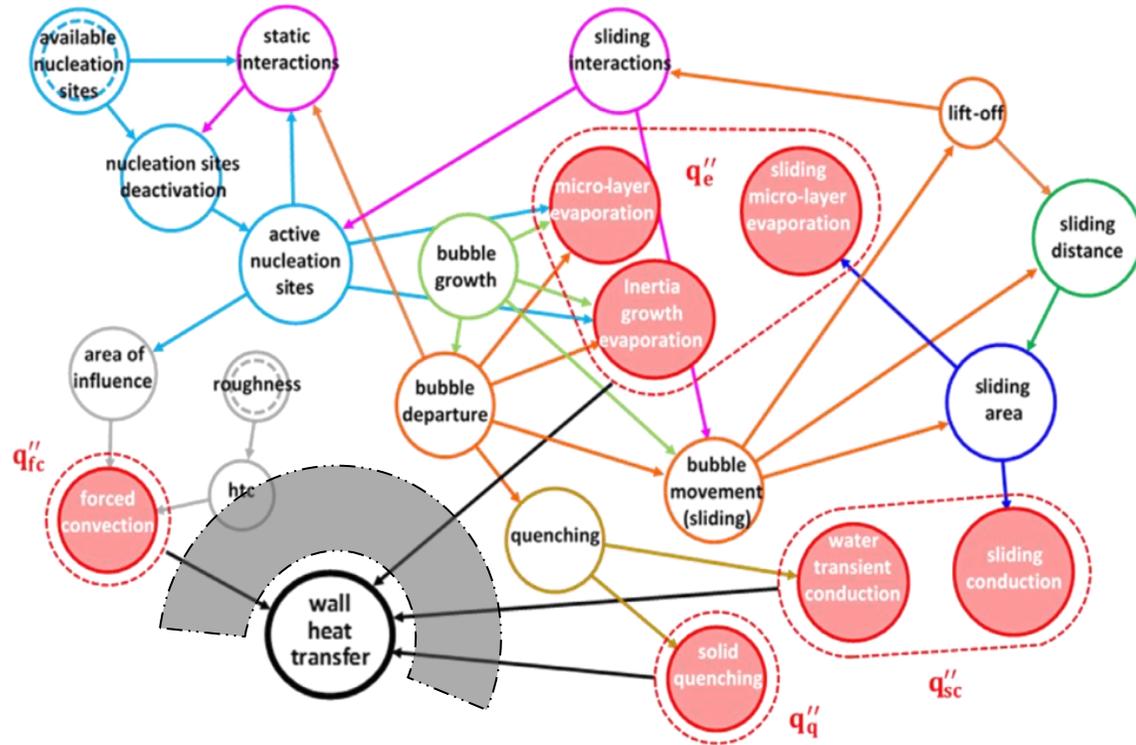
Sub-Grid Boiling Model for Line Chillover (1 of 3)



- CRAFT Tech and MIT, Contract # 80NSSC21C0619
- Phase I – Phase III (Aug 2019 – June 2024)
- Development/Enhancement of RPI boiling model closures to predict film boiling, transition boiling, and nucleate boiling for line chillover
- Used LN2 pool boiling experimental data to adjust coefficients in bubble departure diameter, bubble departure frequency, and nucleation site density closures
- In Phase I, CRAFT Tech implemented MIT's new boiling model into CRUNCH CFD using mixture model
- In Phase II Dr. Mo Kassemi's team implemented model into Fluent using mixture model
- In Phase III, MIT implemented model into STAR-CCM+
 - VOF
 - Eulerian Multiphase
 - Mixture Model

Pool Boiling LN2 Experiment

Generalized Map of Boiling Heat Transfer Mechanisms

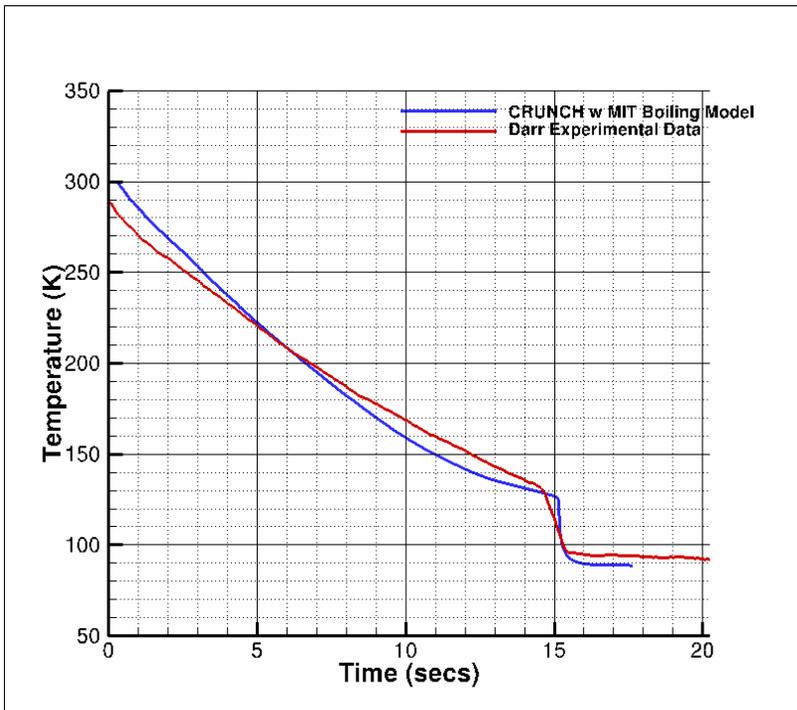


Credit: L. Gilman and E. Baglietto, MIT 2017

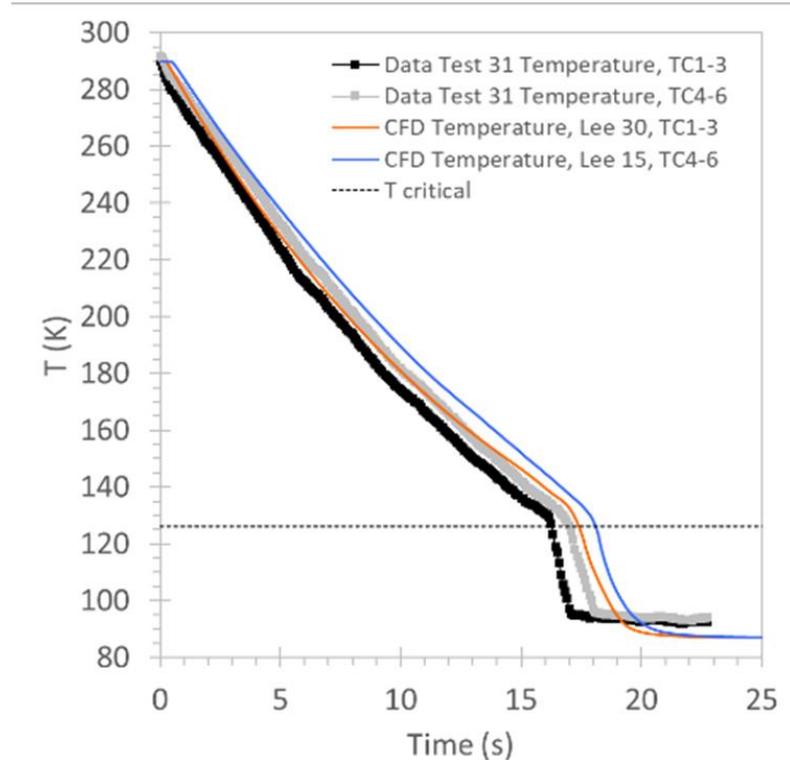
Credit: Dr. Florian Chavagnat, MIT

- Line chillover model validation was performed using data from Darr et al.
 - Darr, S. R., et al., "An experimental study on terrestrial cryogenic transfer line chillover I. Effect of mass flux, equilibrium quality, and inlet subcooling," *Intl J. of Heat and Mass Transfer*, Vol. 103, 2016.

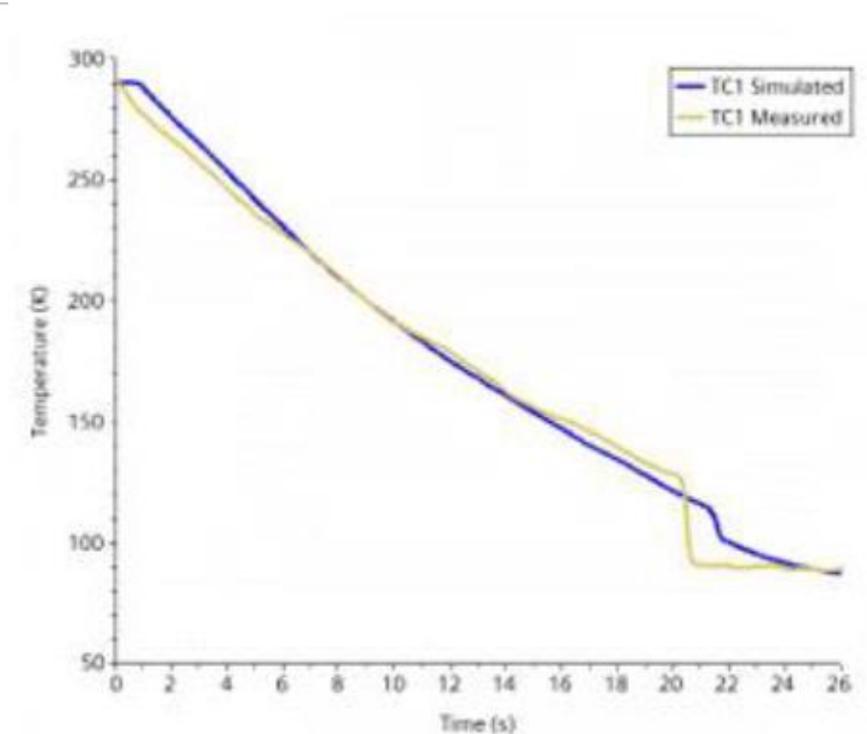
CRUNCH CFD / CRAFT Tech



Fluent / Dr. Mo Kassemi



STAR-CCM+ / MIT





Spray Chillardown Modeling for Tank Chill-n-Fill (1 of 5)



- CRAFT Tech and UCONN, Contract # 80NSSC22CA018
- Phase I – Phase II (Aug 2020 – on-going)
- Development/Enhancement of Reitz-Diwakar spray break-up model closures to predict cone angle, droplet size distribution, and droplet velocity, in addition to implementing wall impingement modes and heat transfer correlations
- Phase I:
 - Performed LN2 spray testing with novel visualization techniques to measure spray characteristics and heated plate chilldown for model validation
 - Adjusted Reitz-Diwakar model coefficients to validate CFD spray model
- Phase II:
 - Developed criteria and implemented models for droplet wall impingement modes and wall heat transfer correlations
 - Validated CFD wall impingement and heat transfer models for plate chilldown
 - Preparing for vented-fill and no-vent fill spray test and simulation for a scaled tank

Reitz-Diwakar WAVE model constants adjusted for LN2 (original constants used for diesel spray)

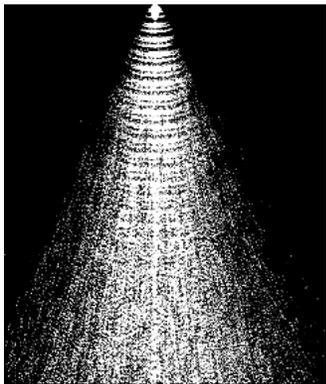
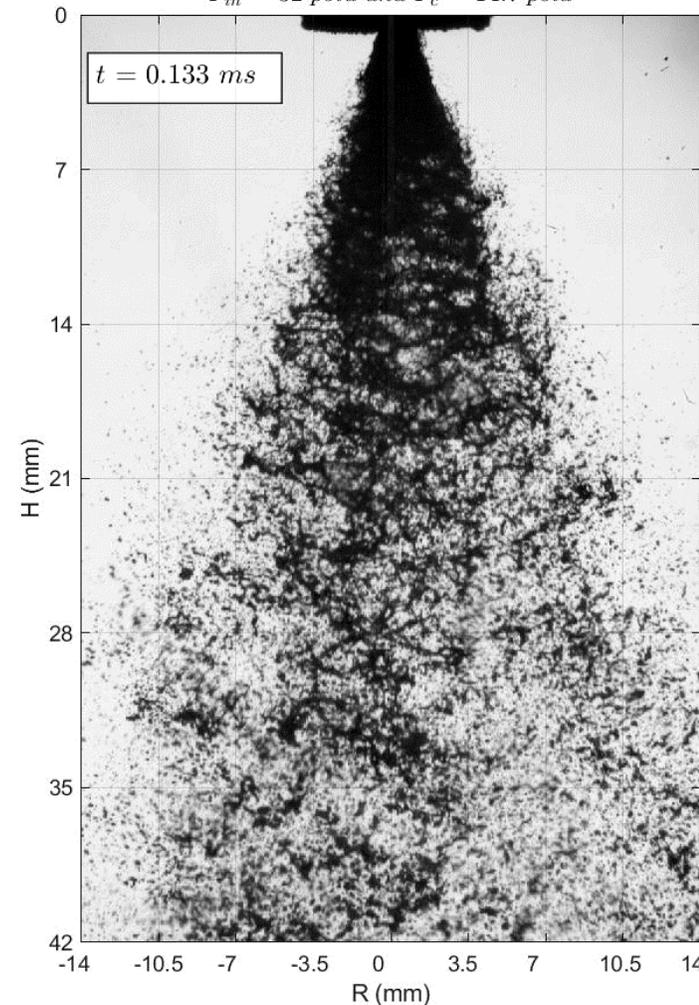
Model Constant	Original Value ¹	Modified Value for N2 Injector
A_1	0.188	0.6
B_0	0.61	2.0
B_1	1.73	0.1

→ Cone angle
 → Droplet radius
 → Droplet breakup time

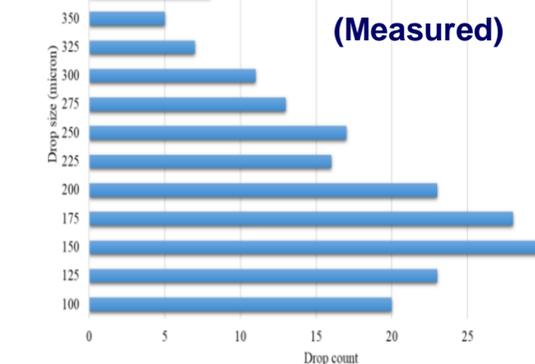
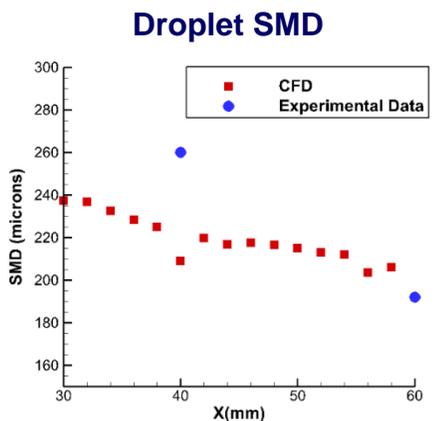
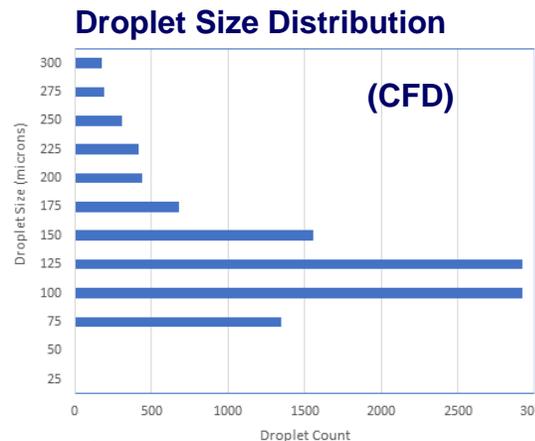
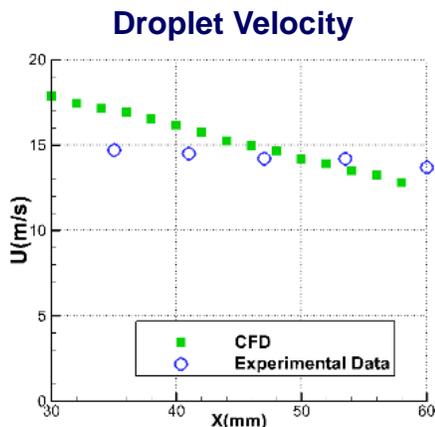
Spray Cone Angle
 31deg – 40psia
 35deg – 50psia

Spray Characteristics Test

$P_m = 32 \text{ psia}$ and $P_c = 14.7 \text{ psia}$



CFD



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Measured

Credit: UCONN and CRAFT Tech

Wall impingement modes and heat transfer correlations were implemented based on experimental observations of droplets at various Weber numbers and plate temperatures

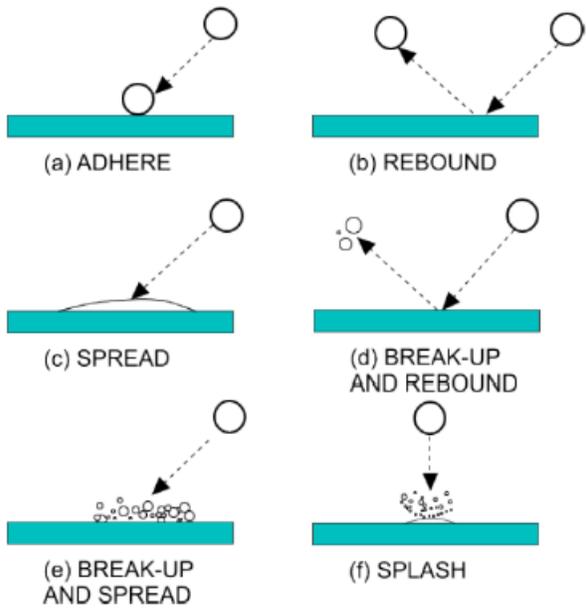
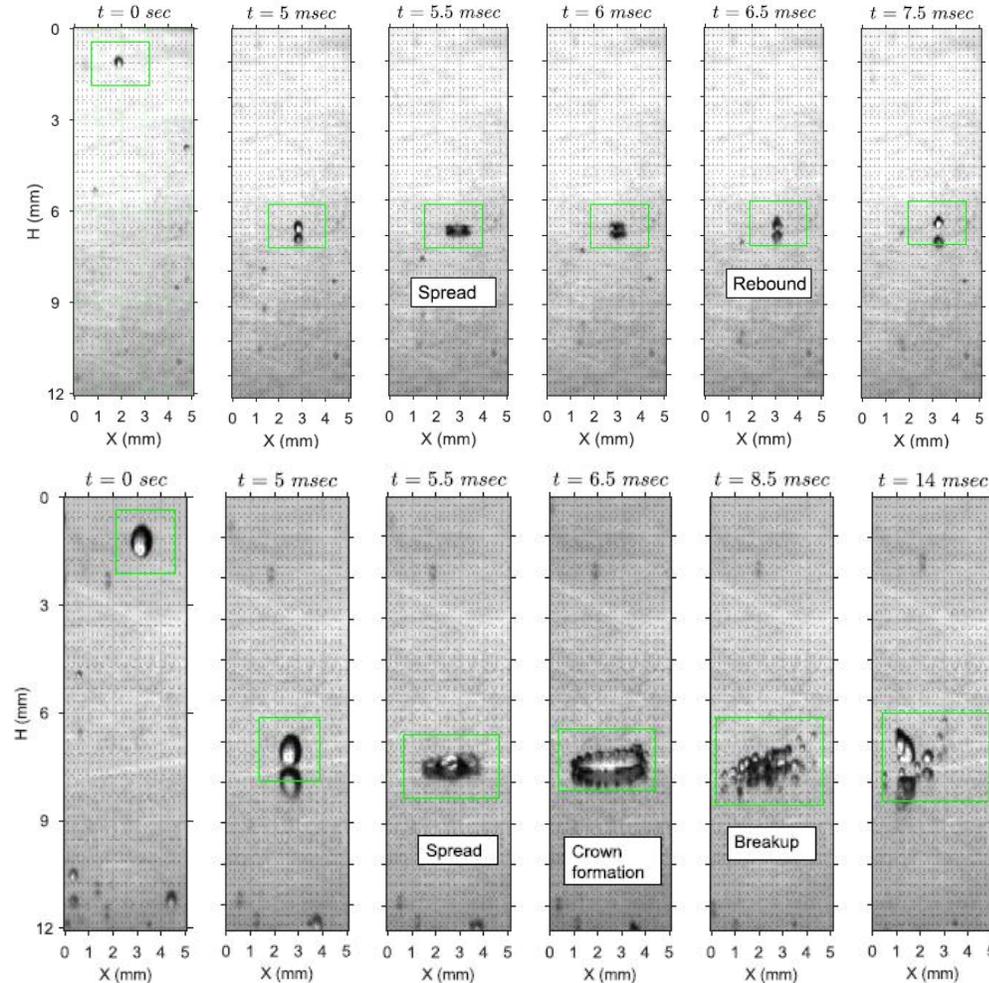
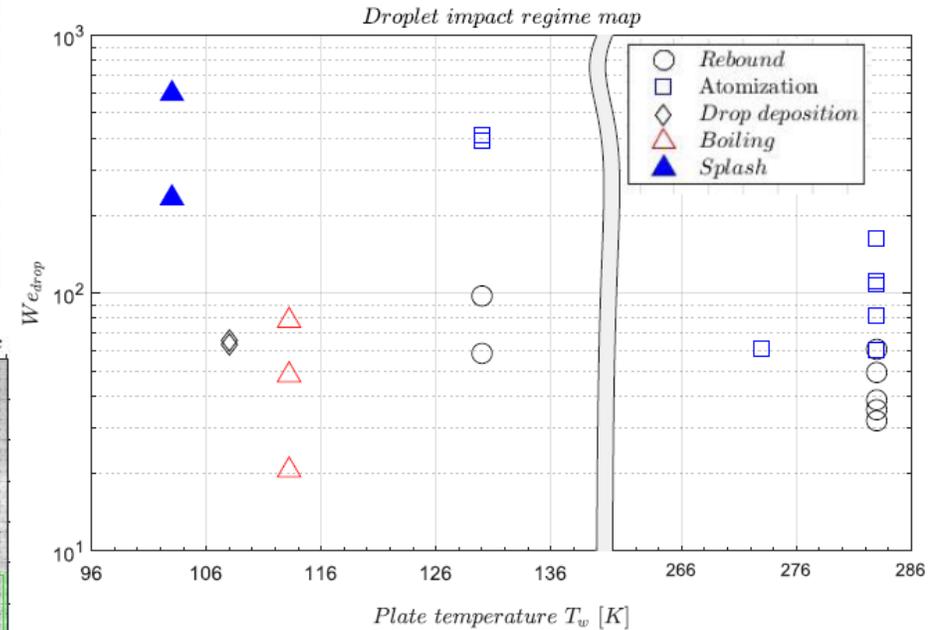


Figure 12: Droplet Impact Regimes.

Credit: Siemens STAR-CCM+



$$We\# = \frac{\rho u^2 l}{\sigma}$$



Credit: UCONN

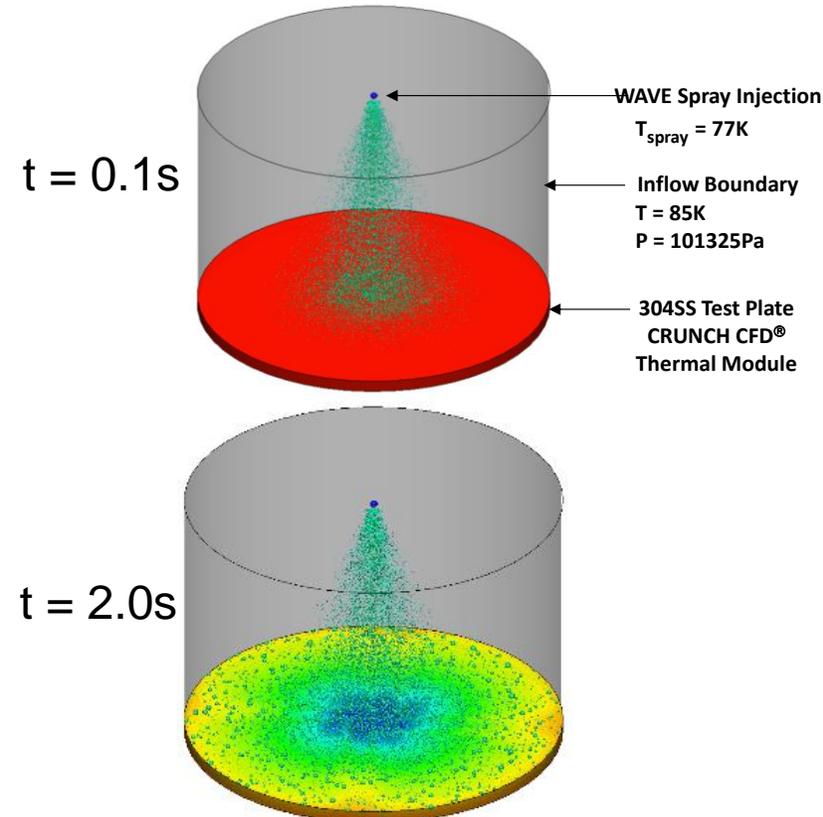
Rohsenow pool boiling correlation and Zuber critical heat flux used for plate chilldown heat transfer calculations: C_{CHF} and C_{min} must be calibrated

Rohsenow $Q_B = A_s \frac{h_{fg} \mu_l}{Pr_l^n} \left(\frac{g(\rho_l - \rho_v)}{\sigma} \right)^{1/2} \left(\frac{c_{p,l} \Delta T_w}{h_{fg} C_{sf}} \right)^{3.03}$ **Zuber**

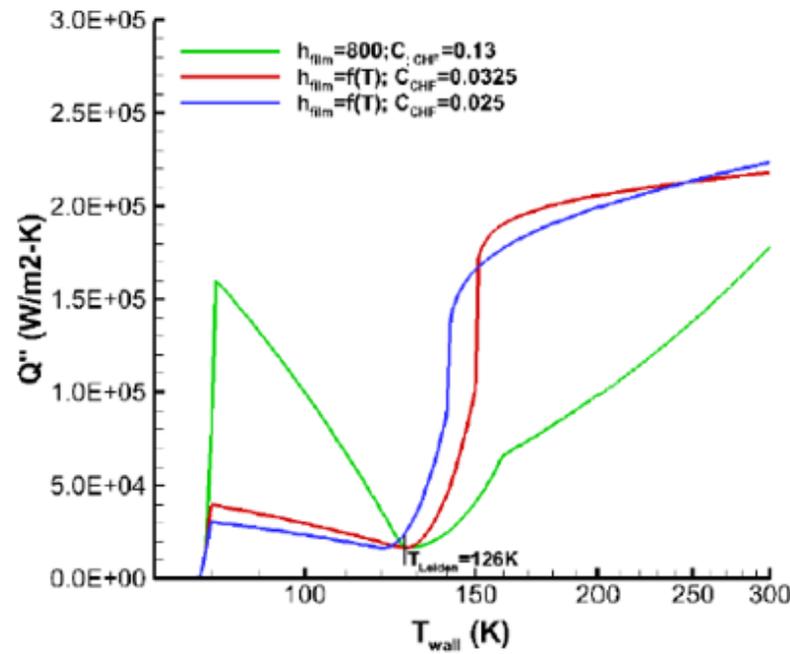
$$q_{CHF} = Q_{CHF} / A_s = C_{CHF} h_{fg} \rho_v \left(\frac{\sigma g (\rho_l - \rho_v)}{\rho_v^2} \right)^{1/4}$$

$$q_{min} = Q_{min} / A_s = C_{min} h_{fg} \rho_v \left(\frac{\sigma g (\rho_l - \rho_v)}{(\rho_l + \rho_v)^2} \right)^{1/4}$$

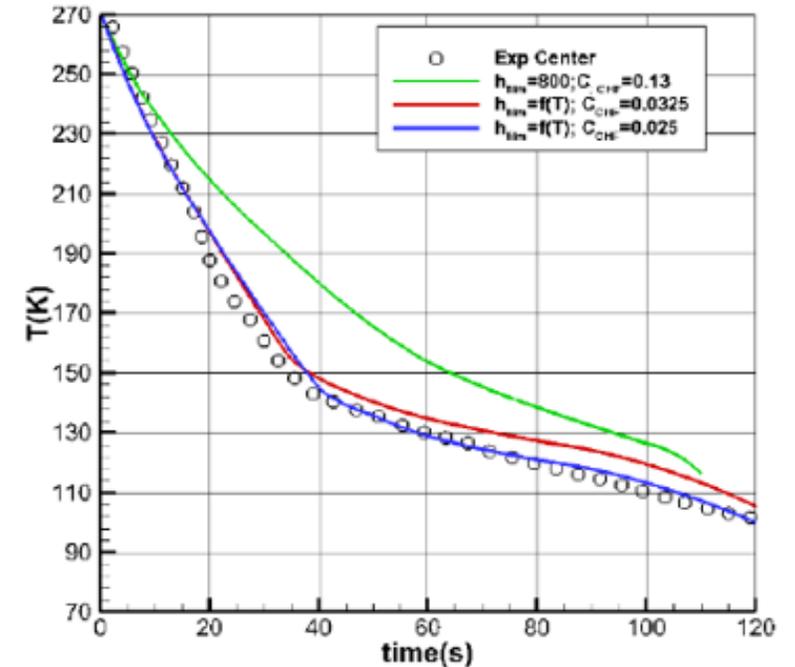
CRUNCH CFD Simulation



Wall Heat Transfer/Boiling Curve



Chillardown Curves

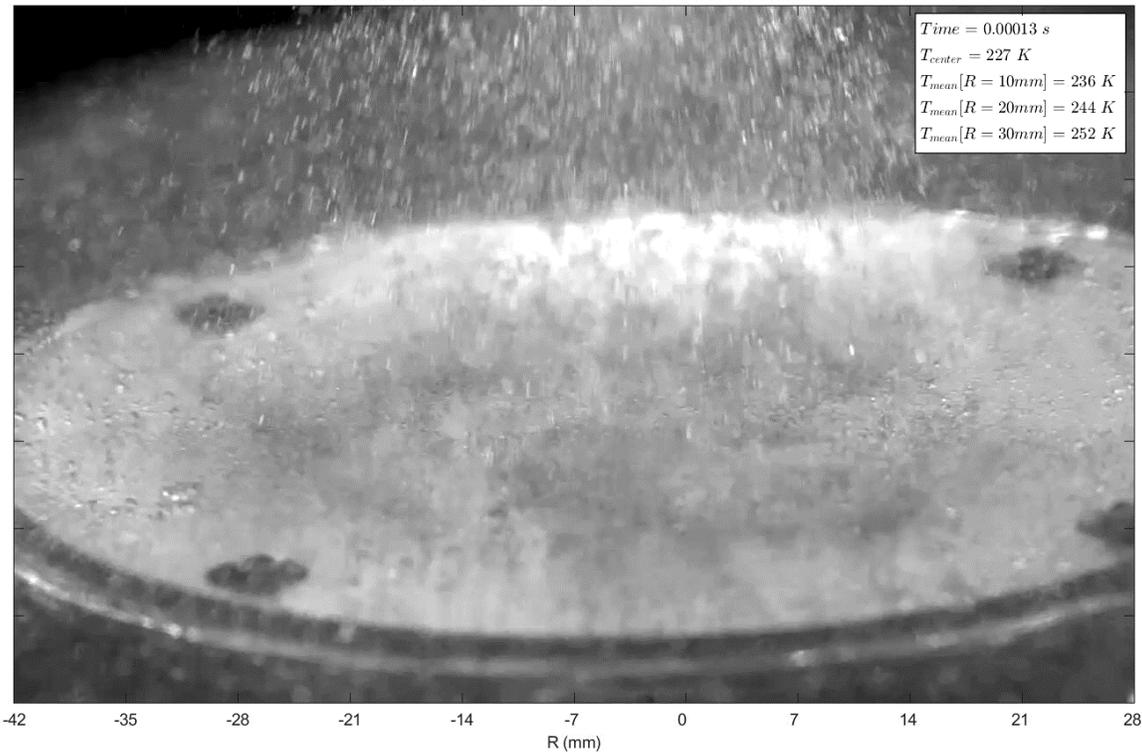


UCONN's expertise in experimental visualization techniques tremendously helps CFD validation

Plate Chillover Test

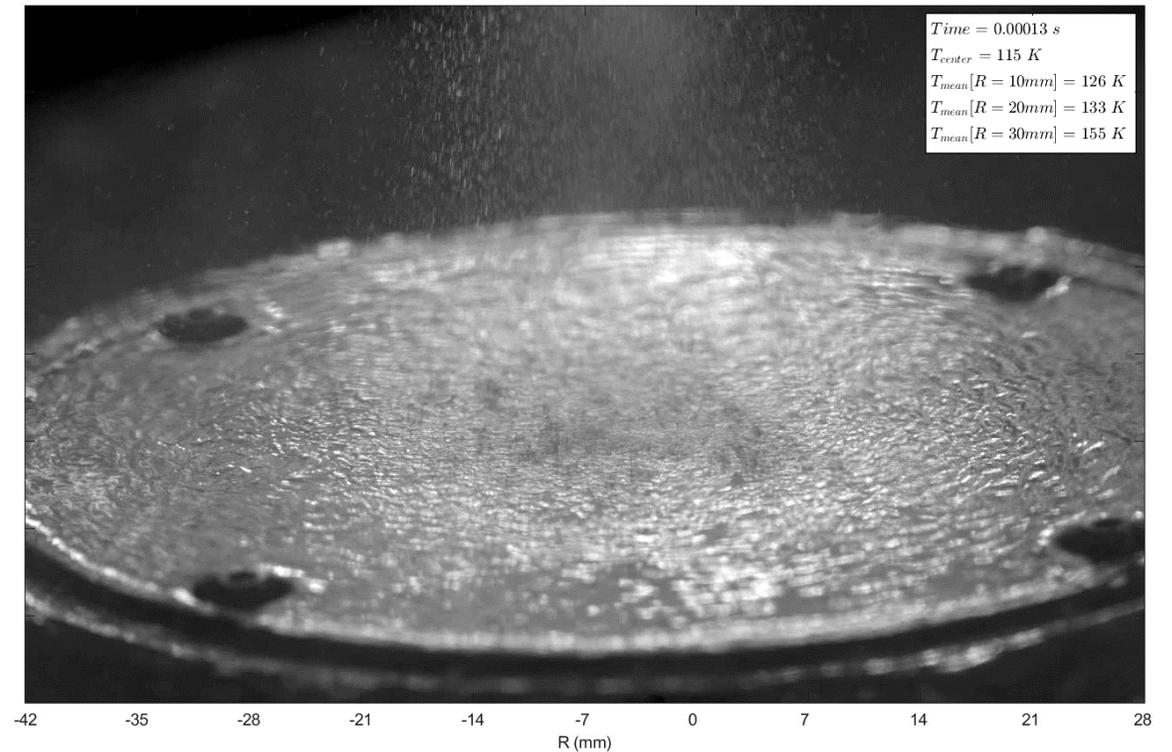
Film Boiling Regime

Cryogenic spray impingement in film boiling regime : Full flow



Post-Quench Flowing Film

Cryogenic liquid film after the completion chillover





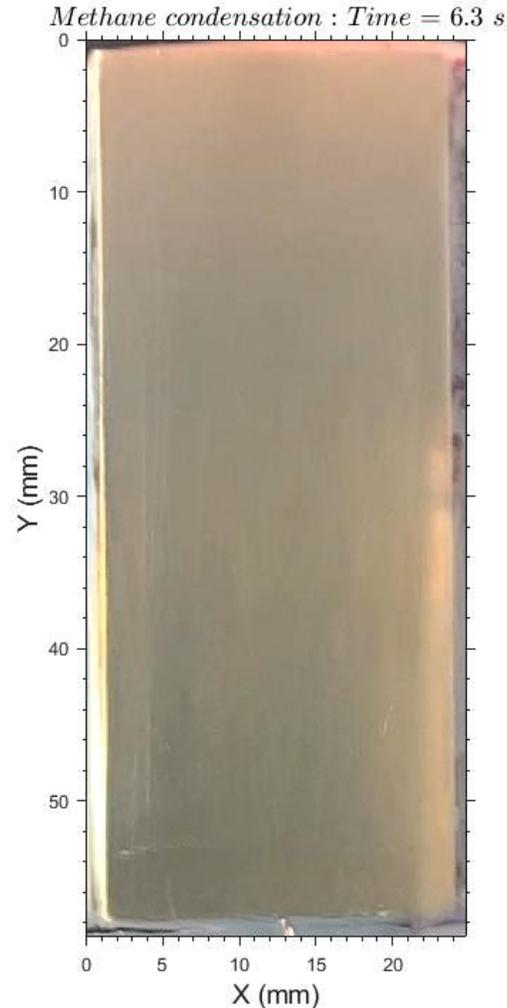
Film Condensation Modeling for Liquefaction (1 of 3)



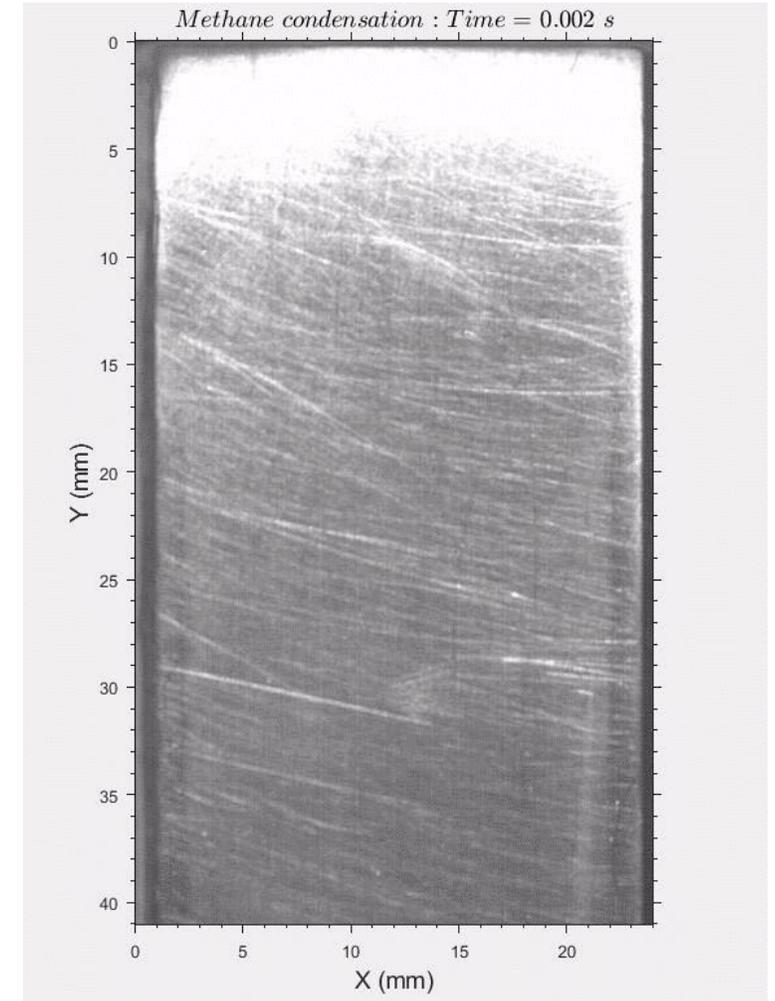
- CRAFT Tech and UCONN, Contract # 80NSSC22PA988
- Phase I (July 2022 – Jan 2023)
- Development of sub-grid film condensation model for liquefaction modeling (CryoFILL, etc.)
- UCONN performed film condensation experiments (LN2, LCH4) on a vertical flat plate to obtain key measurements (wall temperature, film temperature, **film thickness**) for CFD model validation
- CRAFT Tech used two-phase mixture model with a finite rate phase change model to validate CFD model

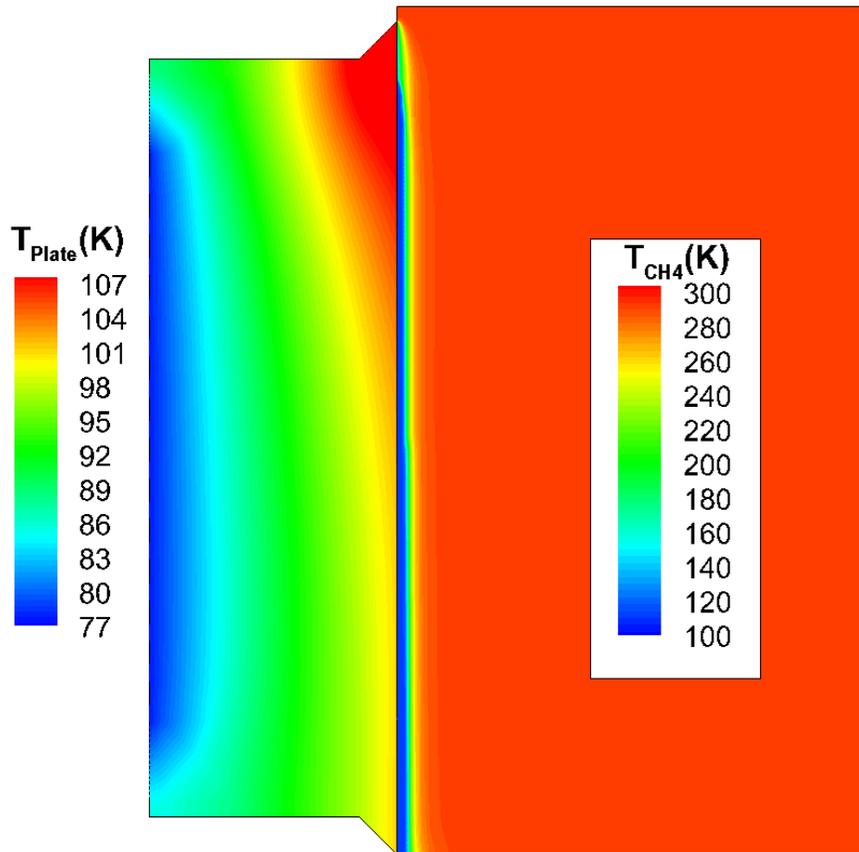
- Truly novel data – no optical film thickness measurements of cryogenic film ever measured
- It was found that small plate subcooling results in film condensation, while large plate subcooling results in dropwise condensation
 - This has implications on how sub-grid model would predict nucleation

Film Condensation Small Subcooling



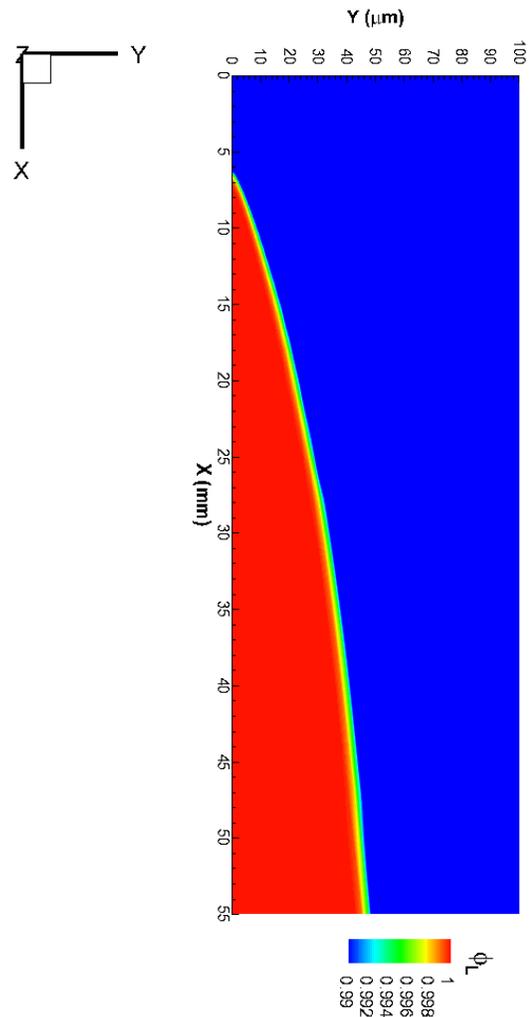
Dropwise Condensation Large Subcooling





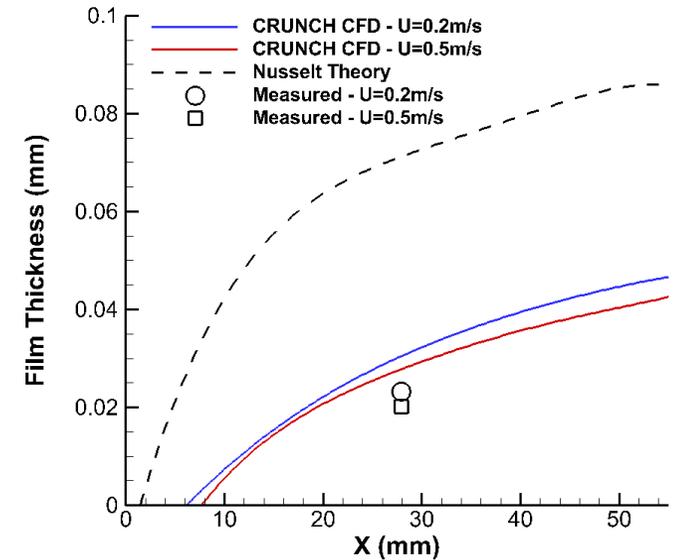
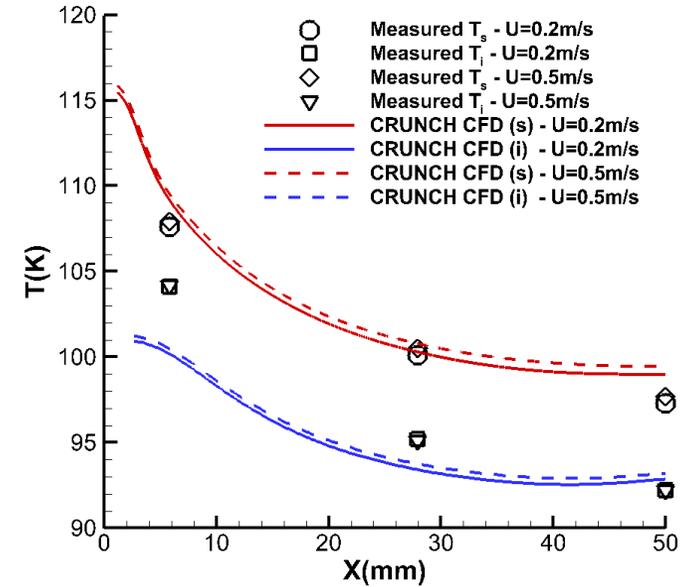
Note the difference in scales

Credit: CRAFT Tech



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$T_{\text{vapor}} = 290\text{K}, T_{\text{bath}} = 77.4\text{K}$





Conclusion



- Over the last 5 years, NASA has invested in development of sub-models and fundamental experiments to improve the current capabilities of CFD codes used for CFM applications through SBIR and STTR contracts
- Sub-model development for line chilldown, spray chilldown/tank chill-n-fill, and film condensation have been very successful
- Fundamental experiments are an attractive feature of SBIR-funded research (much lower cost than NASA-funded experiments)
- Other SBIR/STTR contracts under the CFM sub-topic that are currently ongoing include Liquid-Vapor Interface Gradient Modeling (Phase I) and Film Condensation (Phase I)



Acknowledgments



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