Validation of Universal Cryogenic Flow Boiling Correlations in Thermal Desktop for Liquid Hydrogen

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Outline

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Introduction

- Cryogenic transfer systems are essential for the development of future ground and low-g systems
- Two-phase flow will be present in these systems
- Currently there is a need for more accurate, direct cryogenic data-anchored models for various boiling and two-phase phenomena

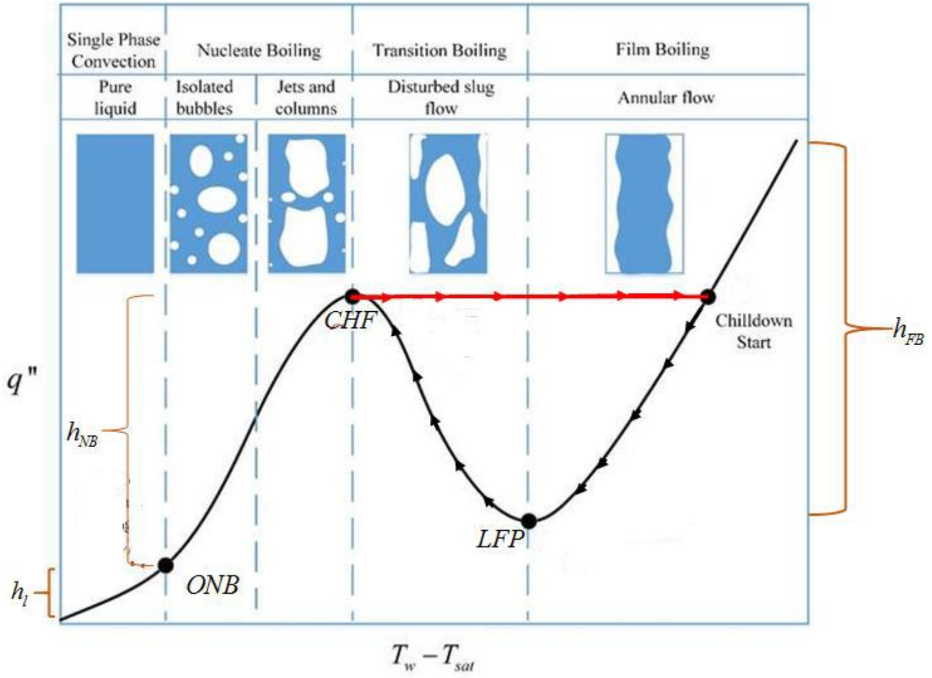
LH2 Storage Tank and transfer line at NASA's KSC

Introduction, Cont'd

- Existing room-temperature based boiling correlations do a poor job at predicting cryogenic flow phenomena
  - For steady state or heated tube, the disparity between these existing correlations and cryogenic data is as high as 400%
- New universal cryogenic flow boiling correlations were recently developed and anchored to the largest cryogenic flow boiling database assembled in the world to-date
- Current work will show implementation of these new correlations into Thermal Desktop (TD) and compare against TD's built-in code for two historical datasets using liquid hydrogen
  - Recent work has been performed to validate the new cryogenic correlations for other cryogens and results show an improvement over TD's built-in correlations

Background

- For flow boiling in the heating (or steady-state) case, single phase liquid flow is already established
- External heat source gradually boils the liquid
  - The heating configuration follows the boiling curve from left to right



A typical boiling curve.
from *Mercado et al., 2019*

Built-in Thermal Desktop Correlations

	Low Flow Quality (x<XNB)	High Flow Quality (XNB<x<1.0)
Low Wall Superheat (below T_{CHF})	Chen (1963)	Linear interpolation between Chen and Dittus-Boelter (Nu=0.023Re0.8Pr0.4)
Transition (between T_{CHF} and the smaller of T_{leid} and T_{dfb})	Non-linear interpolation between nucleate and film boiling using scaling laws by Ramilison and Leinhard	Non-linear interpolation between nucleate and film boiling using scaling laws by Ramilison and Leinhard
High Wall Superheat (above the smaller of T_{leid} and T_{dfb})	Bromley	Groeneveld

XNB: cut-off quality for nucleate boiling, default is 0.7 but can be changed by user
T_{CHF}: critical heat flux temperature
T_{leid}: Ledienfrost temperature
T_{dfb}: departure from film boiling temperature

New Universal Correlations

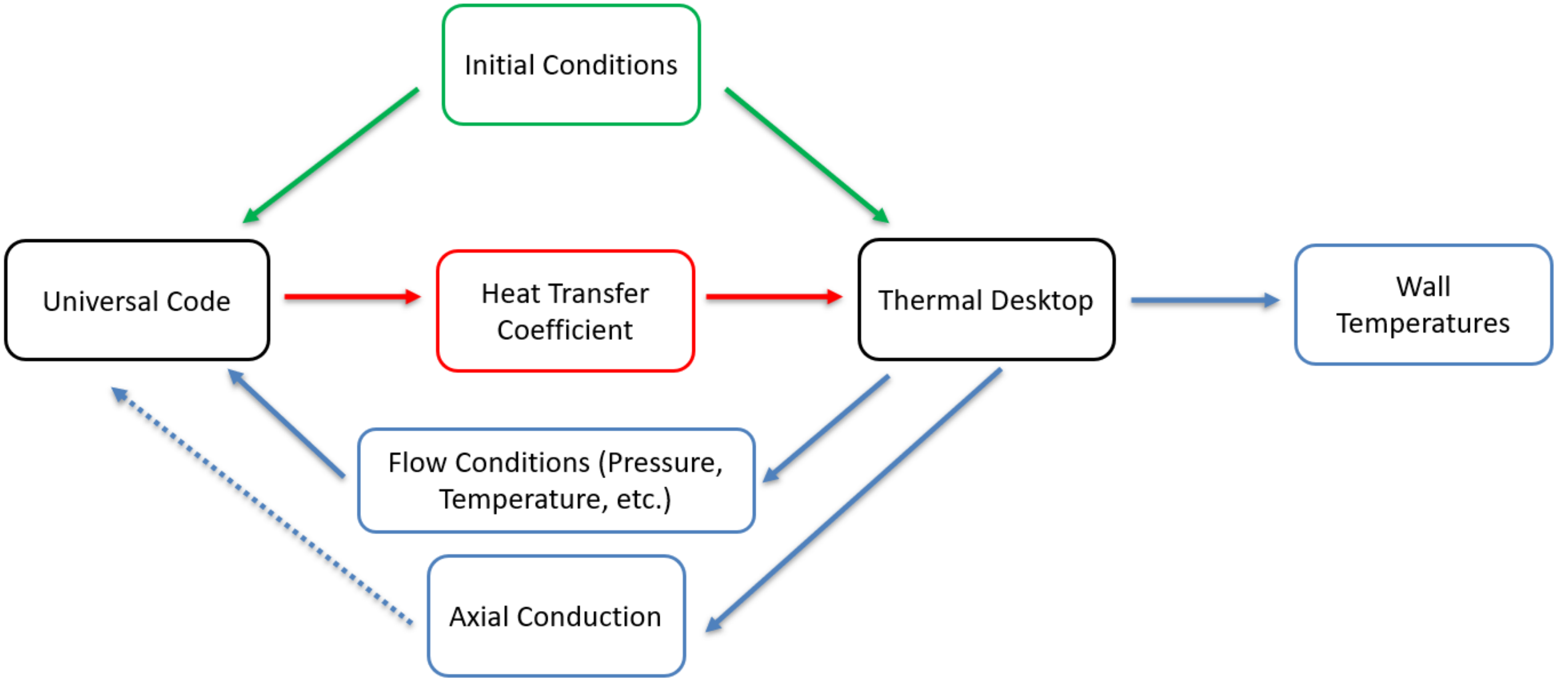
- New Universal Cryogenic Correlations were developed at Purdue University in collaboration with NASA Glenn
- Correlations were developed for the location of onset of nucleate boiling (ONB), pre-Critical Heat Flux (CHF) heat transfer coefficient, post-CHF heat transfer coefficient, and the location of the CHF. Subcooled film boiling was not included
- The aim was then to create a smooth, continuous predictive curve for wall superheat as a function of heat flux by patching the individual correlations together

New Universal Correlations

- Correlations are ported into Thermal Desktop using a User Subroutine
- Work has already been completed showing the improvement of the Universal Correlations over TD's Built-in Correlations for liquid helium, nitrogen, and methane

		Built-in Correlations			**Universal Correlations**						
		Overall			**Calculated Z_{CHF}**			**Fixed Z_{CHF}**			
Case	Fluid	MAPE	SMAPE	Z_{CHF} % Error	MAPE	SMAPE	Z_{CHF} % Error	NB MAPE	NB SMAPE	FB MAPE	FB SMAPE
Lewis	Nitrogen	141.4%	78.3%	67.7%	18.5%	19.5%	11.4%	4.2%	4.6%	23.6%	16.3%
Qi	Nitrogen	33.0%	33.1%	43.6%	47.8%	27.6%	36.7%	2.8%	2.8%	4.8%	5.0%
Glickstein	Methane	43.0%	56.1%	21.7%	15.7%	13.4%	6.5%	9.9%	10.5%	18.2%	12.8%
	Average	**72.5%**	**55.8%**	**44.3%**	**27.3%**	**20.2%**	**18.2%**	**5.6%**	**6.0%**	**15.5%**	**11.4%**

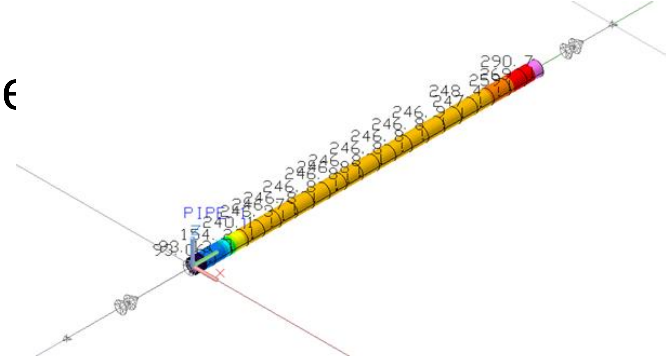
New Universal Correlations TD Implementation



Schematic of Universal Correlation implementation into Thermal Desktop model

Model Overview

- Test section represented as pipe (Fluid Lumps and Wall Nodes)
- Inlet conditions fixed
- Constant heat flux applied to inner surface pipe
- Lump and Nodes connected by Tie
  - Built-In Code: TD calculates HTC
  - Universal Code: User Subroutine calculates HTC
- Number of Lumps/Nodes matches locations of test data temperature locations



Model Set-Up

- Calculated zCHF vs. Fixed zCHF
  - First Set-Up, Calculated zCHF:
    - Pre-CHF heat transfer coefficients
    - Post-CHF heat transfer coefficients
    - CHF location
  - Second Set-Up, Fixed zCHF:
    - Pre-CHF heat transfer coefficients
    - Post-CHF heat transfer coefficients
    - CHF calculation is FIXED, given as input

Experimental Test Setup

Lewis (1962)

- Vertical Pipe, Upward Flow
- 0.41m pipe length
- 1.4cm diameter
- SS304 outer wall
- 28 datasets
- 14 data points each

Hendricks (1966)

- Vertical Pipe, Upward Flow
- 0.61m pipe length
- 9.5mm diameter
- SS304 or Inconel outer wall
- 11 datasets
- 13 data points each

Error Metrics

- Mean Average Percentage Error

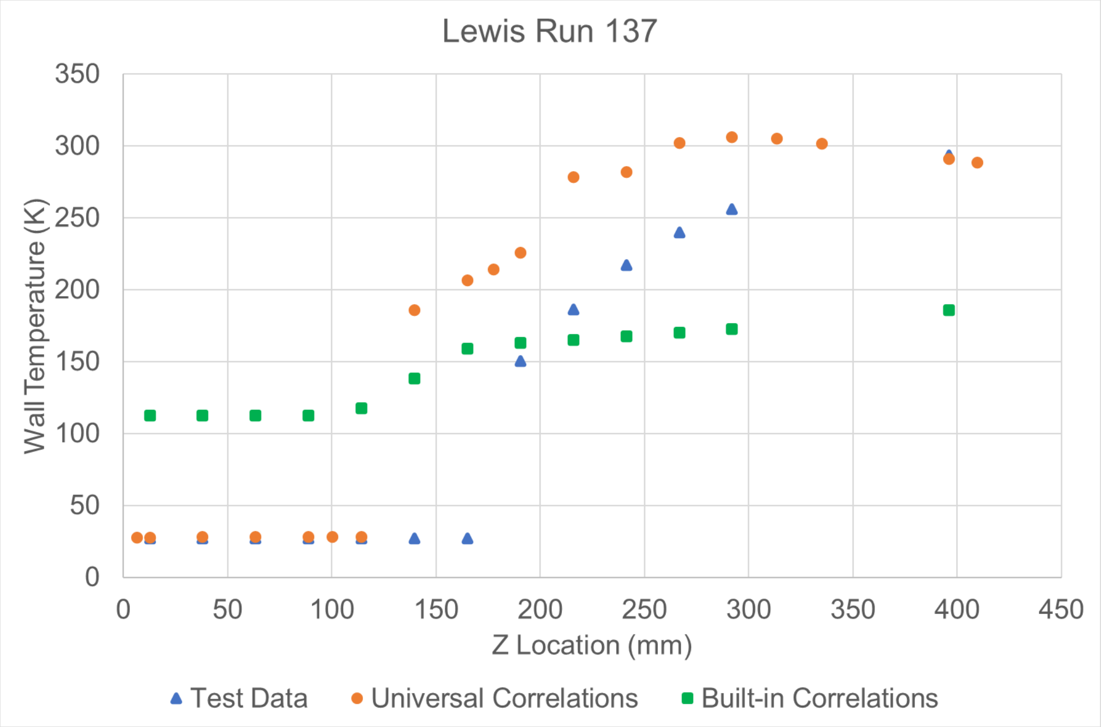
$$\textbf{MAPE} = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right|$$

- Symmetrical Mean Average Percentage Error

$$\textbf{SMAPE} = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{(A_t + F_t)/2}\right|$$

- **θ** : percentage of data points within +/- 30% of the test data points
- **Φ**: percentage of data points within +/- 50% of the test data points

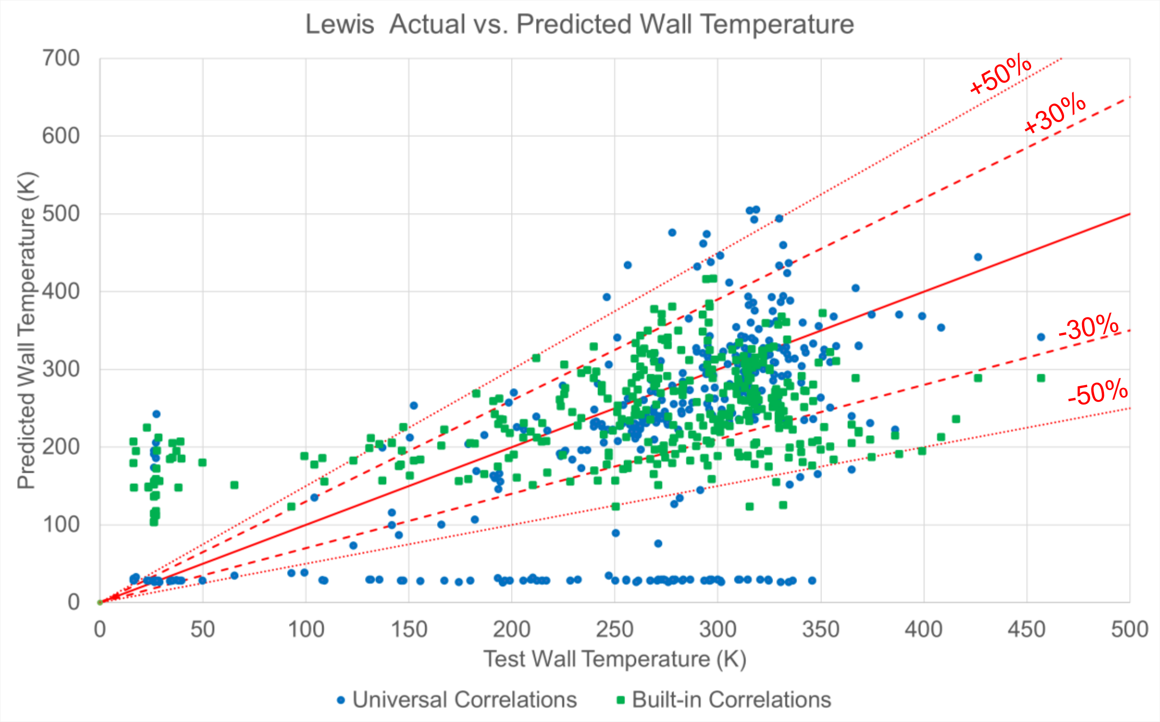
Lewis Calculated zCHF Results



	Built-in Correlations
MAPE	201.8%
SMAPE	81.0%
zCHF Error	44.9%

	Universal Correlations
MAPE	102.0%
SMAPE	29.2%
zCHF Error	10.4%

Lewis Calculated zCHF Results

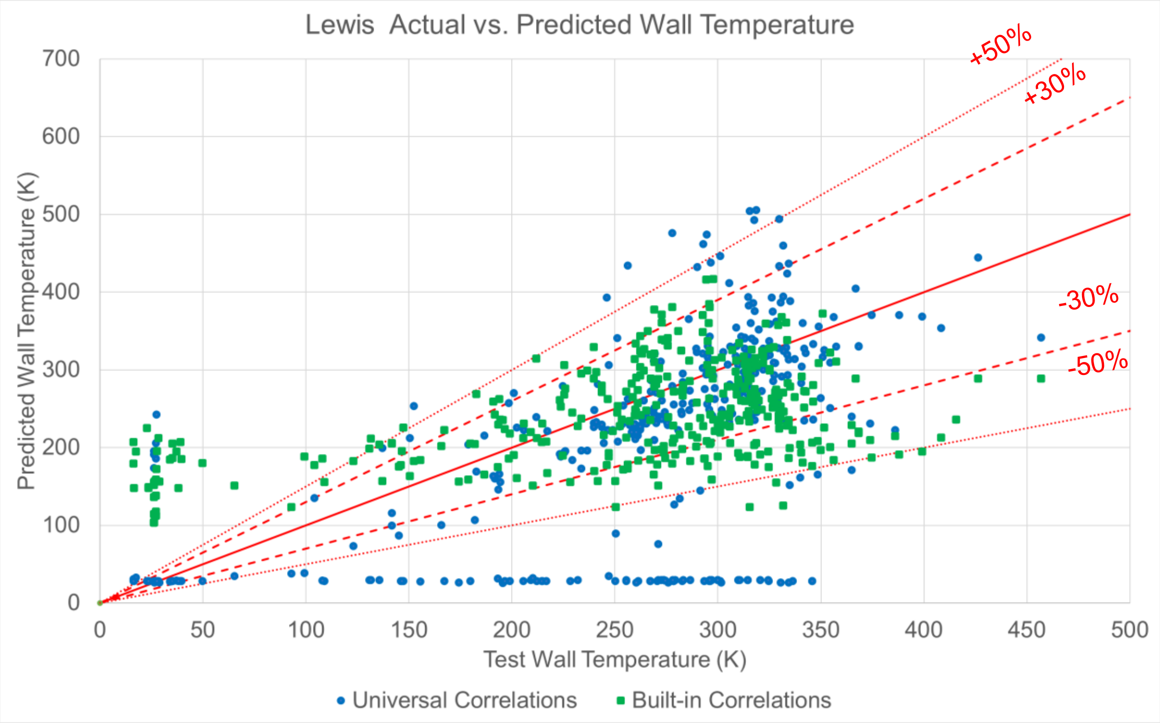


	Built-in Correlations
# Data Points	368
MAPE	64.4%
SMAPE	34.6%
ɵ	63.9%
ɸ	86.4%

	Universal Correlations
# Data Points	368
MAPE	41.5%
SMAPE	46.9%
ɵ	66.8%
ɸ	73.4%

Lewis Calculated zCHF Results

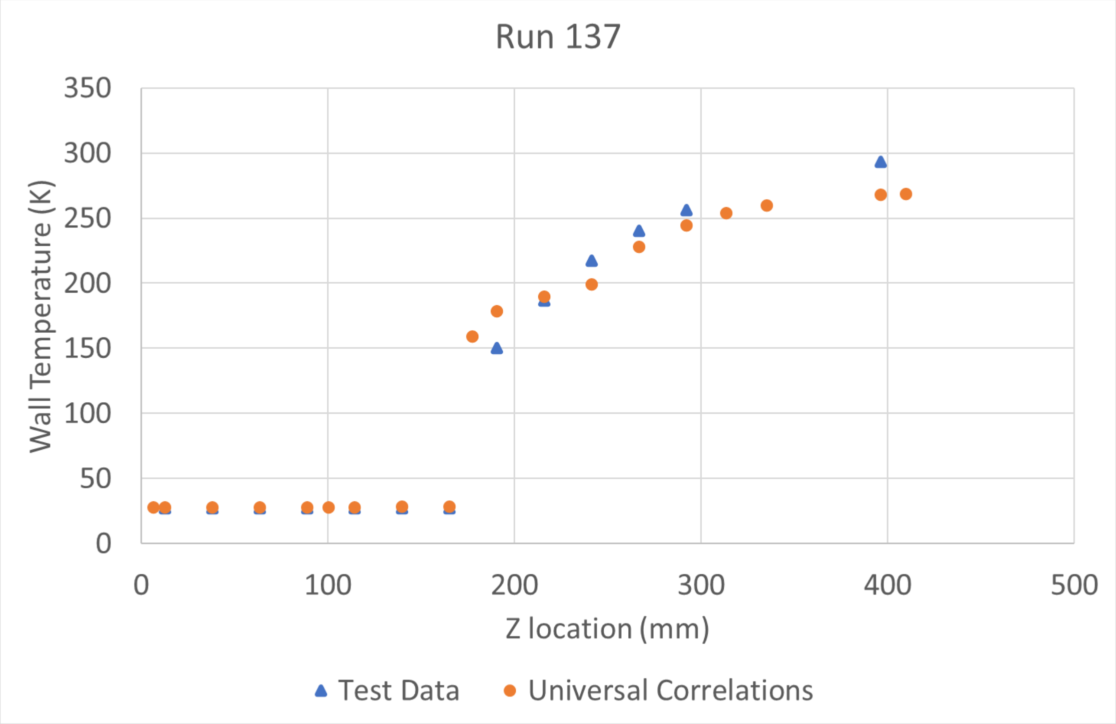
Results Excluding Subcooled Film Boiling Data Points



	Built-in Correlations
# Data Points	353
MAPE	68.8%
SMAPE	35.2%
ɵ	64.9%
ϕ	87.3%

	Universal Correlations
# Data Points	353
MAPE	40.5%
SMAPE	44.5%
ɵ	69.1%
ϕ	74.8%

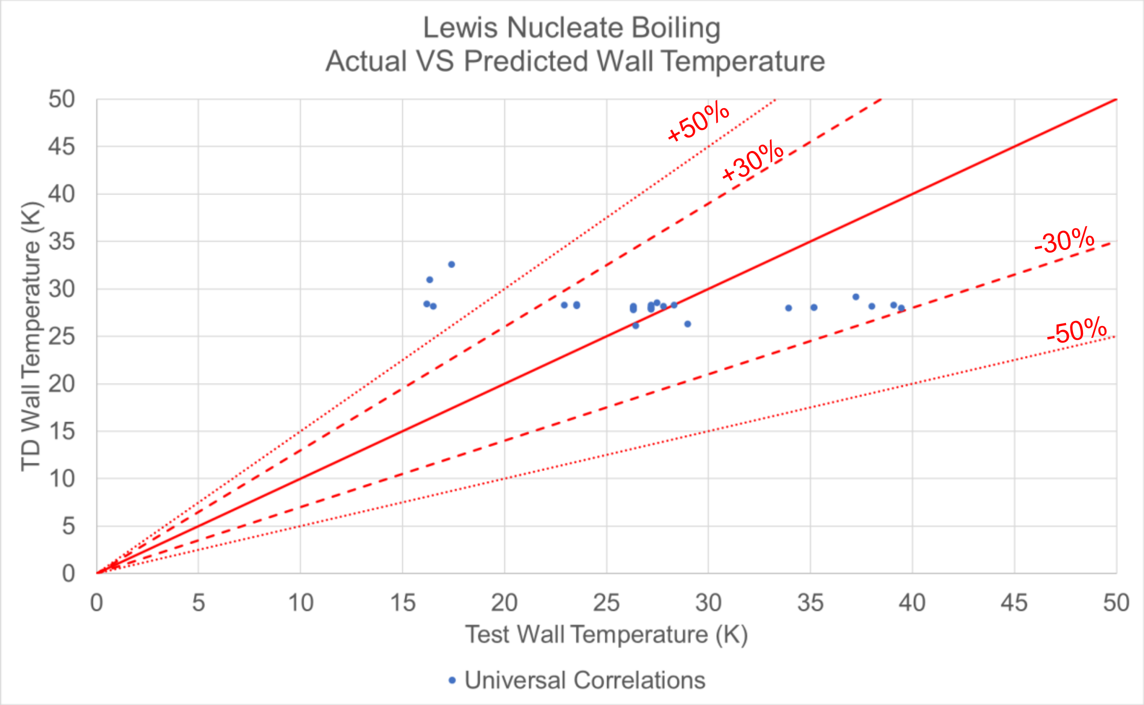
Lewis Fixed zCHF Results



	Universal Correlations
MAPE	5.3%
SMAPE	5.2%
Pre-CHF MAPE	3.1%
Pre-CHF SMAPE	3.1%
Post-CHF MAPE	7.9%
Post-CHF SMAPE	7.8%

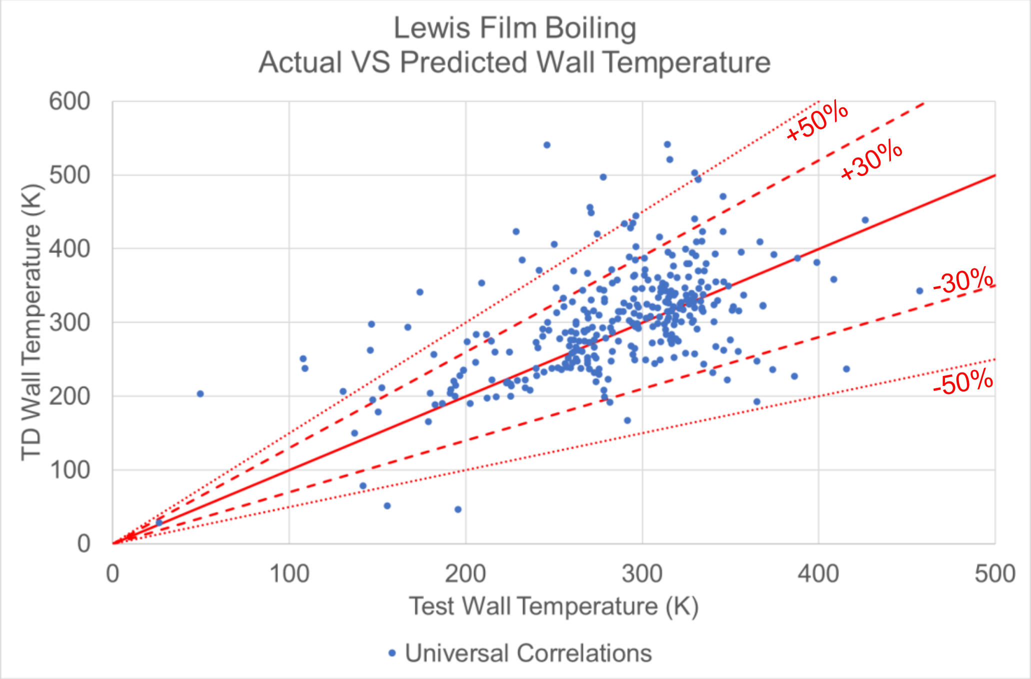
Note: No results shown for Built-in Correlations as zCHF cannot be fixed using this method

Lewis Fixed zCHF Nucleate Boiling Results



	Universal Correlations
# Data Points	34
MAPE	16.5%
SMAPE	14.8%
ϴ	88.2%
ϕ	88.2%

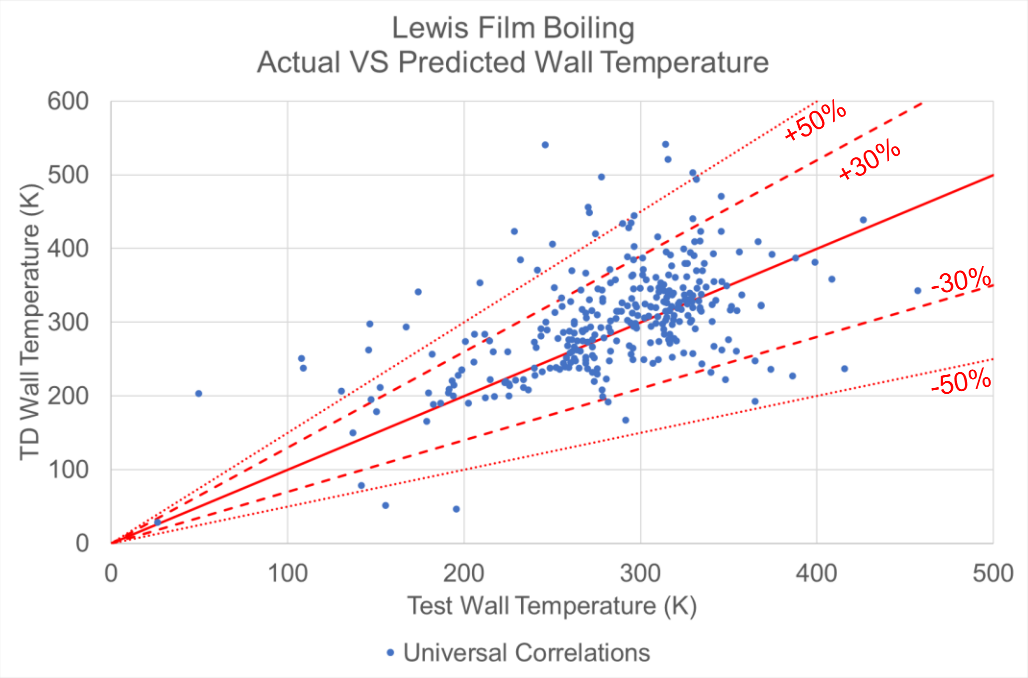
Lewis Fixed zCHF Film Boiling Results



	Universal Correlations
# Data Points	334
MAPE	18.9%
SMAPE	18.4%
ϴ	79.4%
ϕ	90.7%

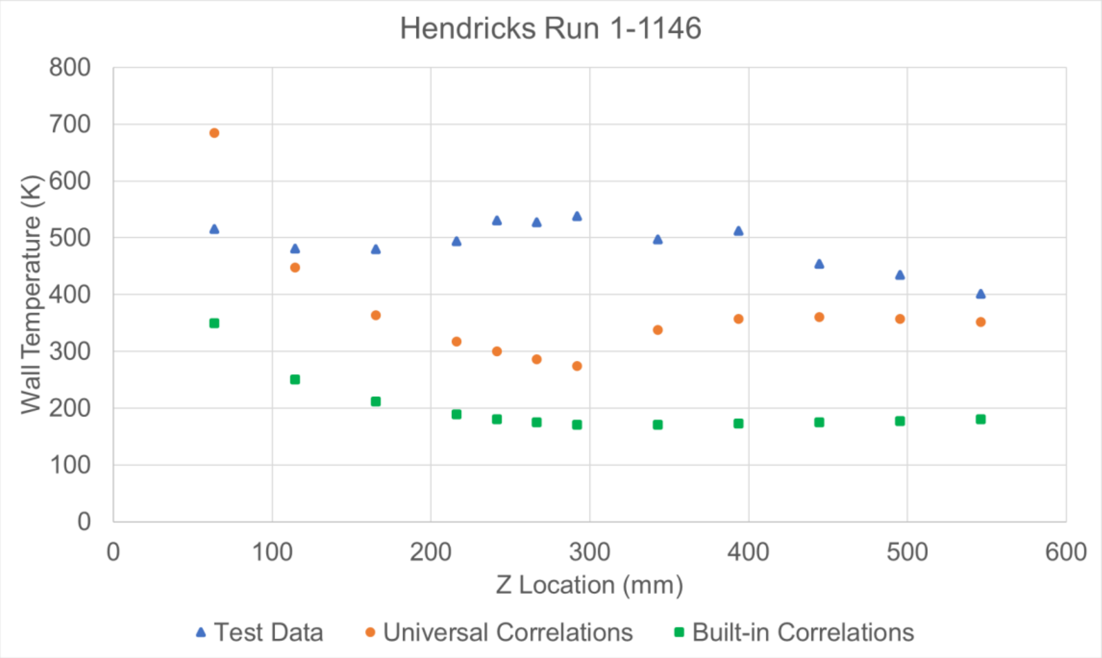
Lewis Fixed zCHF Film Boiling Results

Results Excluding Subcooled Film Boiling Data Points



	Universal Correlations
# Data Points	319
MAPE	18.8%
SMAPE	16.7%
ϴ	64.9%
ϕ	87.3%

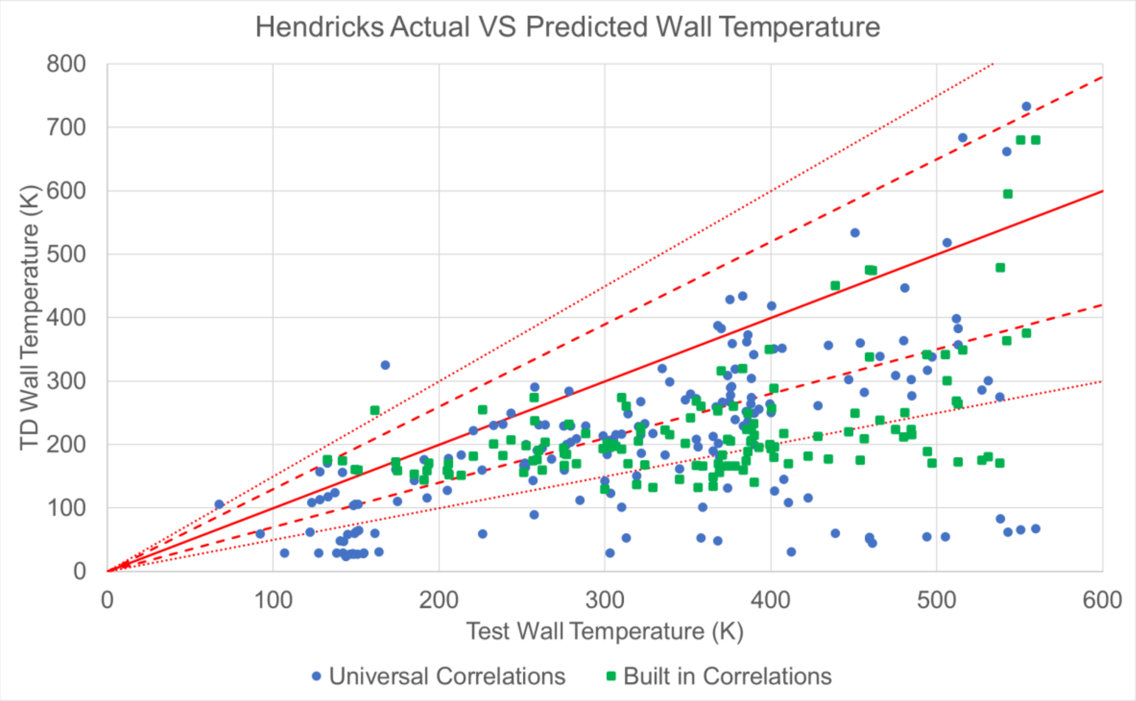
Hendricks Calculating zCHF Results



	Built-in Correlations
MAPE	58.9%
SMAPE	84.7%
zCHF Error	-

	Universal Correlations
MAPE	29.3%
SMAPE	34.7%
zCHF Error	-

Hendricks Calculating zCHF Results

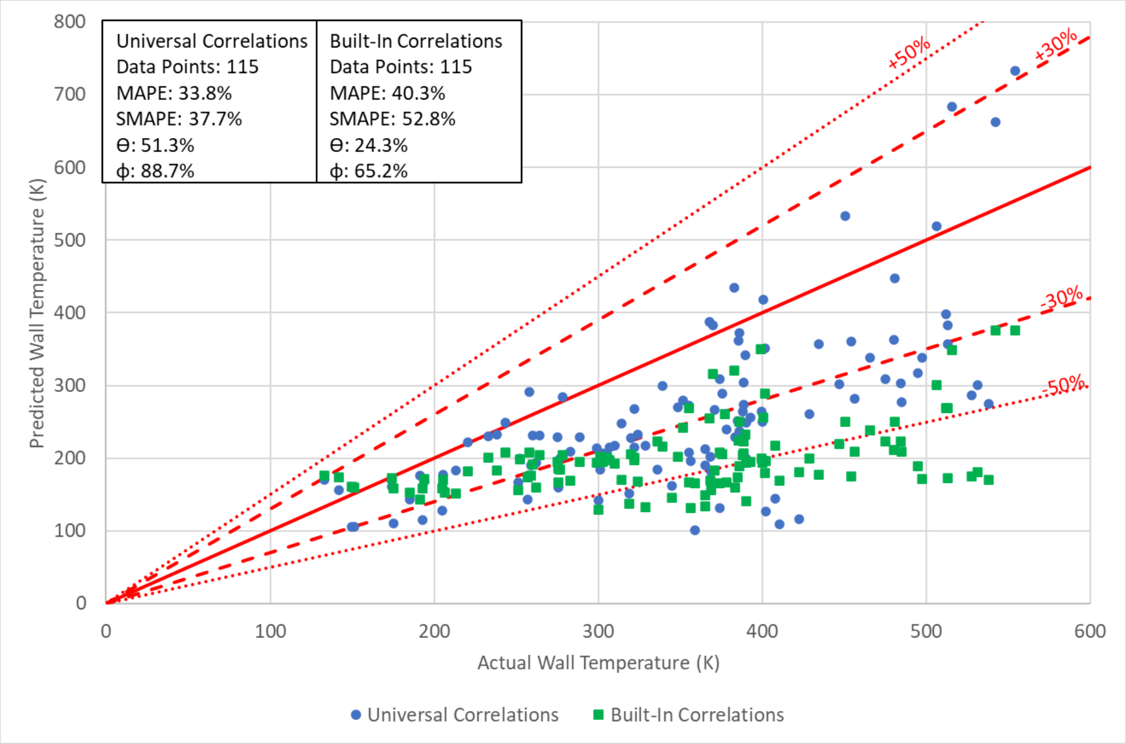


	Built-in Correlations
# Data Points	132
MAPE	37.2%
SMAPE	48.0%
ɵ	32.6%
ɸ	69.7%

	Universal Correlations
# Data Points	132
MAPE	40.1%
SMAPE	51.3%
ɵ	44.7%
ɸ	77.3%

Hendricks Calculating zCHF Results

Results Excluding Subcooled Film Boiling Data Points



	Built-in Correlations
# Data Points	115
MAPE	40.3%
SMAPE	52.8%
ϴ	24.3%
ϕ	65.2%

	Universal Correlations
# Data Points	115
MAPE	33.8%
SMAPE	37.7%
ϴ	51.3%
ϕ	88.7%

Conclusion

- Universal Correlations show modest improvement over Thermal Desktop's Built-in Correlations for liquid hydrogen

  When subcooled film boiling points are excluded Universal Correlations predict Lewis wall temperatures within 20% vs. 69% for Built-in

  - Universal Correlations predict Hendricks wall temperatures within 38% vs. 54% for Built-in

- Future work includes using Universal Correlations for predicting transfer line performance in future systems

  - Correlations have now been validated for 4 different cryogens across a range of flow conditions

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