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

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Outline

- Introduction
- Background
- Built-In Thermal Desktop Flow Boiling Correlations
- New Universal Correlations
- Model Set-Up
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- Discussion and Future Work

Introduction

- Cryogenic transfer systems are an emerging technology in both ground and low-g systems
- Two-phase pipe flow will be an inevitable part of these systems
- Accurate models are required to develop efficient, cost effective, and safe two-phase flow boiling/heat transfer systems
- Recently, attention has been drawn to the fact that existing room-temperature based models and correlations do a poor job in predicting cryogenic flow phenomena
  - For steady state or heated tube, the disparity between these models and cryogenic HTC data is as high as 400%
- To address this concern, direct cryogenic data anchored correlations and subroutines are systematically being developed and validated across the board for multiple cryogenic propellants and transfer phenomena

SpaceX Starship Cryo Proof Test

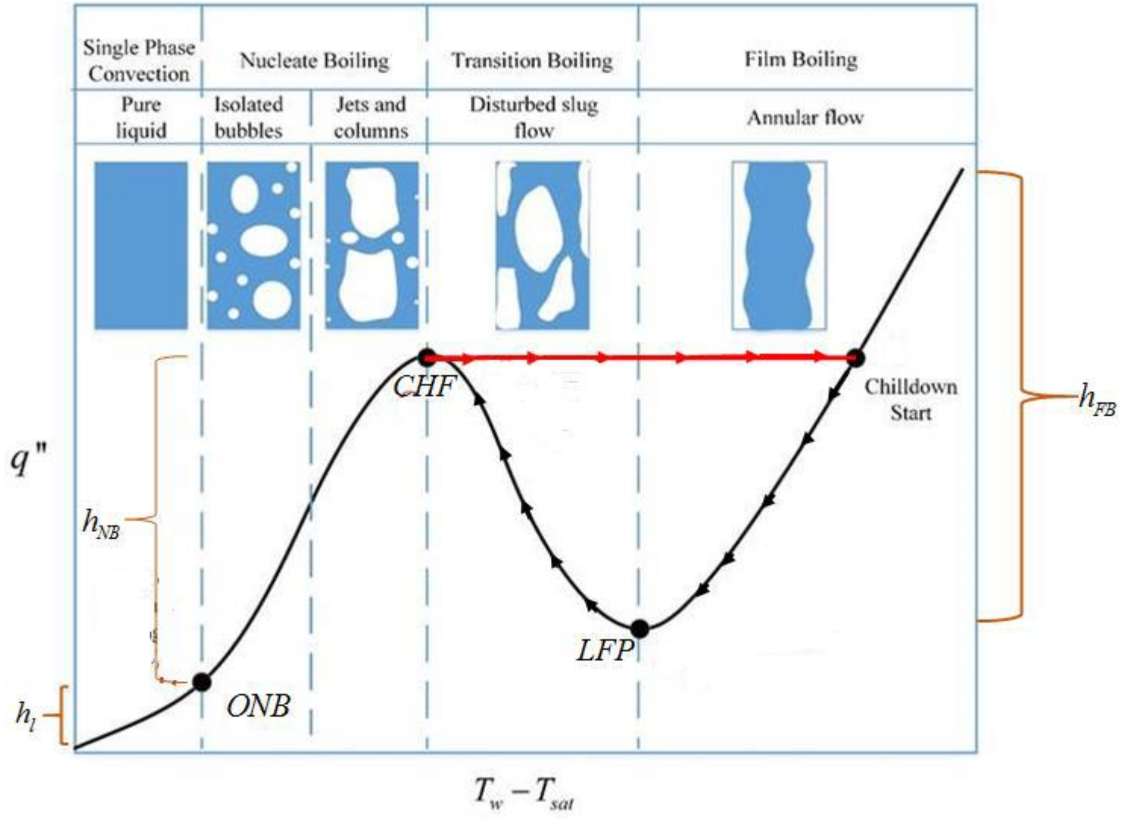
From https://www.nasaspaceflight.com/2020/04/starship-sn4-set-for-test/

LH2 Storage Tank and transfer line at NASA KSC

From https://www.nasa.gov/feature/kennedy-plays-critical-role-in-large-scale-liquid-hydrogen-tank-development

Background

- In heating, or steady state case, single phase liquid flow is already established, and an external heat source gradually boils the liquid
  - The heating configuration follows the boiling curve from left to right
- Existing correlations used for two phase flow are typically based on room temperature fluids and do not do a good job at prediction cryogenic behavior
- Universal correlations have been developed using existing cryogenic experimental data to cover the different boiling phenomena for cryogenic fluids
- Current work will show implementation of universal correlations into Thermal Desktop and compare against the Built-In TD code for a historical dataset using Helium



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

Built-in Thermal Desktop Correlation

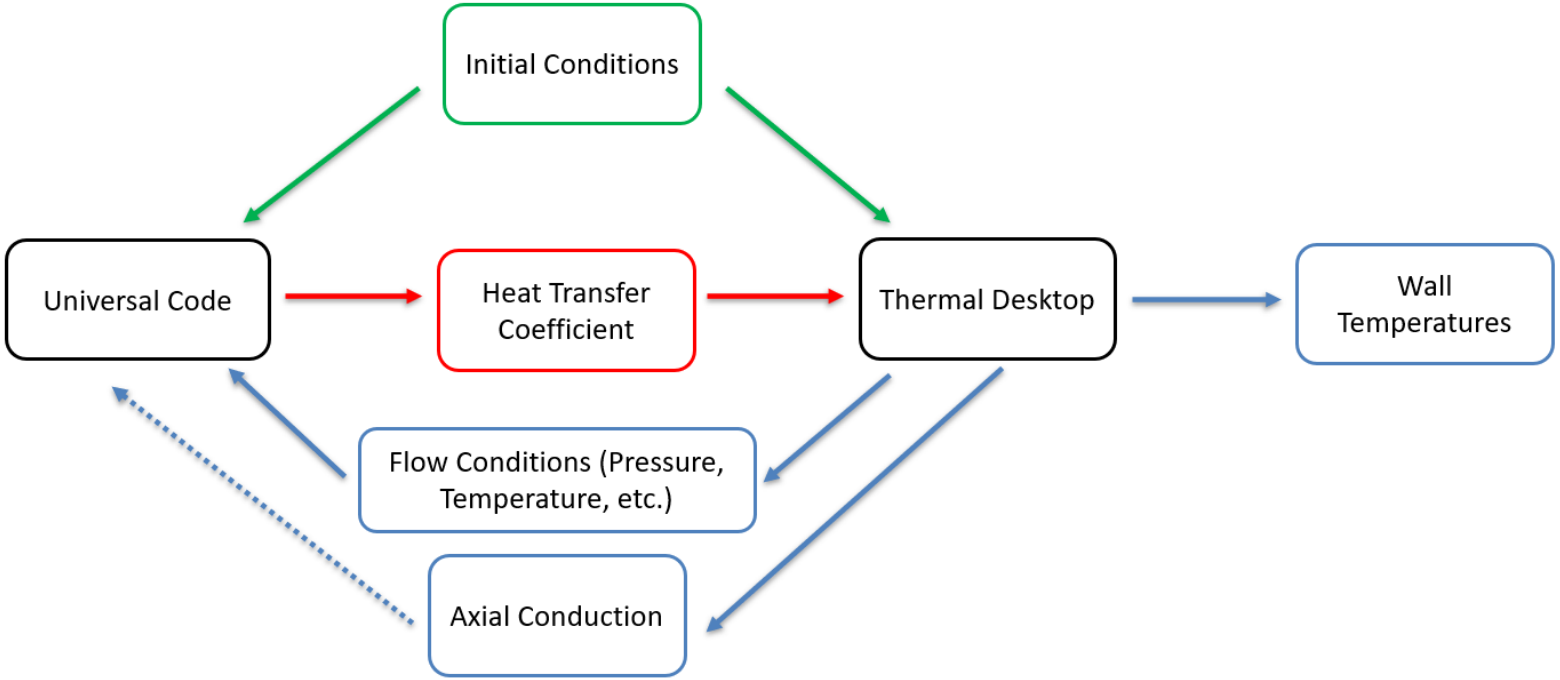
- By default, Thermal Desktop recognizes two fundamental boiling heat transfer regimes: nucleate and film.
- Thermal Desktop decides which boiling correlation to use based on the wall superheat and flow quality in each fluid lump

	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 ($Nu = 0.023 Re^{0.8} Pr^{0.4}$)
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}: Leidenfrost temperature
T_{dfb}: departure from film boiling temperature

New Universal Correlations

- New Universal Cryogenic Correlations were developed at Purdue University
- The aim of these correlations was to create a continuous predictive model along the entire boiling curve
- Correlation was developed for pre-Critical Heat Flux (CHF) heat transfer coefficient, post-CHF heat transfer coefficient, and location of the CHF
- Universal Correlations originally developed in MATLAB
- Ported over into Thermal Desktop using a User Subroutine



Experimental Set-Up

- Heated tube experiments are by definition steady state experiments
  - Typically, fluid and tube wall begin at the same temperature and heat is slowly delivered until the system reaches steady state for a fixed heat flux
- Giarrantano (1973):
  - Liquid Helium
  - Constant Heat Flux
  - Vertical Pipe
  - 10 cm length, 2.1 mm diameter
  - 10 data sets
  - 10 wall thermocouples

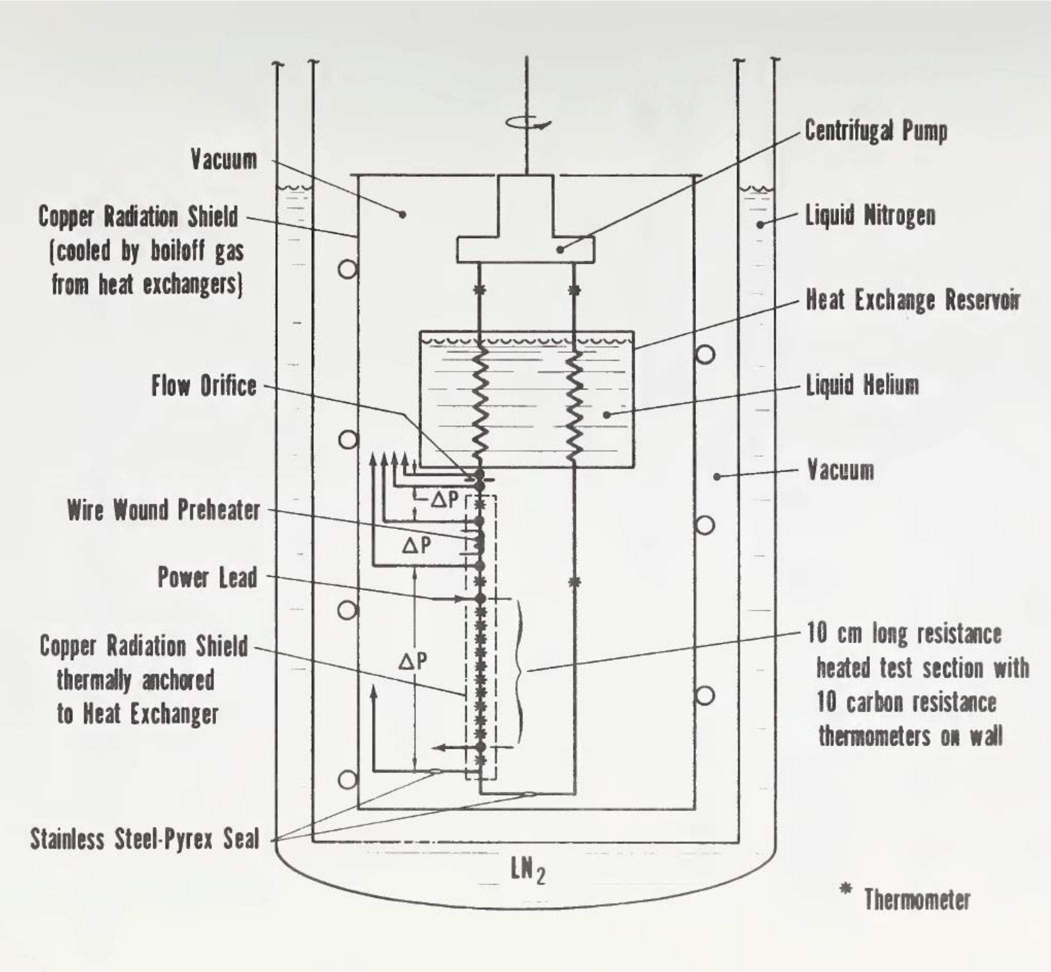
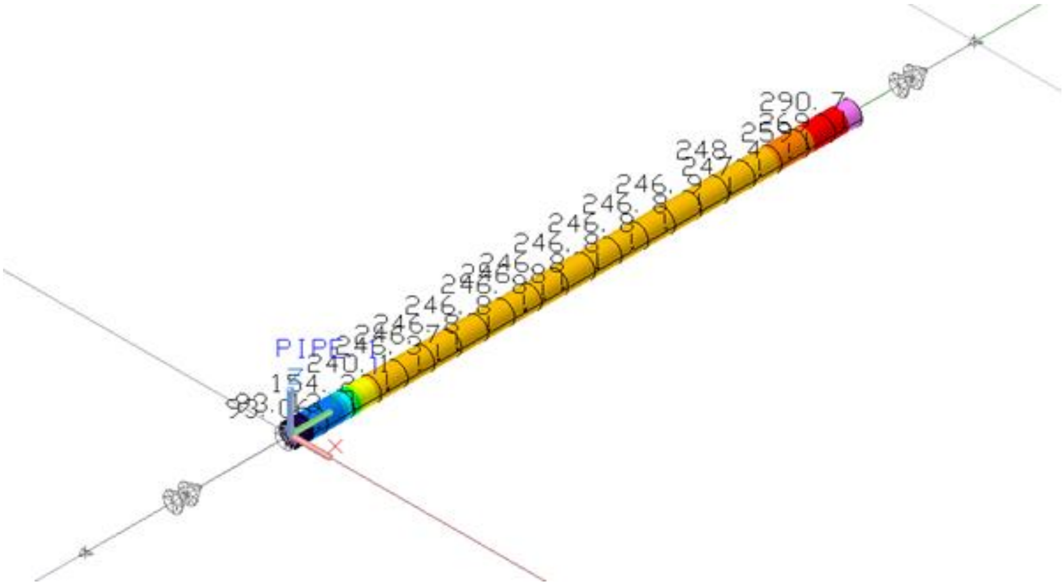


Figure 1. Schematic of the boiling heat transfer flow loop.

Experimental Set Up
from *Giarrantano et al., 1973*

Experimental Set-Up

- Experiment test sections are modeled in Thermal Desktop as a single pipe object
- Inlet plenum fixes the inlet conditions going into the pipe
- Setflow path dictates the flow rate
- Constant heat flux is applied using a heat load on the inner surface of the pipe
- Fluid Lumps and Solid Nodes represent each segment of the pipe
- Lump and Nodes connected by Tie which dictates the heat transfer coefficient between the fluid and wall
  - Built-In Code: TD calculates HTC
  - Universal Code: User Subroutine calculates HTC
- 10 Lump/Nodes to match Girrantano test data

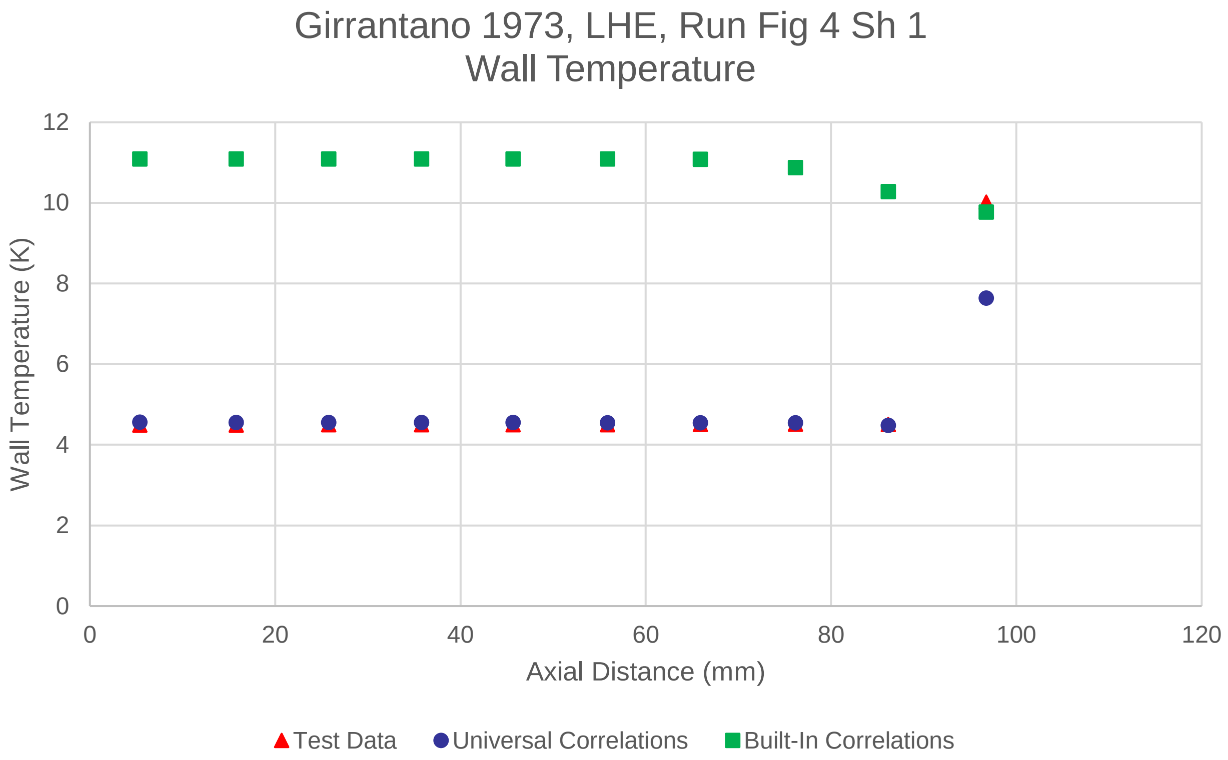


Model Set-Up

- 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
    - Not possible to run the Built-In Correlation with a fixed zCHF
- Mean Average Percentage Error (MAPE) = $\frac{1}{n}\sum_{t=1}^{n}\left|\frac{F_t - A_t}{A_t}\right|$
- Symmetrical Mean Average Percentage Error (SMAPE) = $\frac{1}{n}\sum_{t=1}^{n}\left|\frac{F_t - A_t}{(A_t + F_t)/2}\right|$
- θ : percentage of data points within +/- 30% of the test data points
- Φ: percentage of data points within +/- 50% of the test data points

CALCULATED ZCHF MODEL RESULTS

Calculating zCHF Results



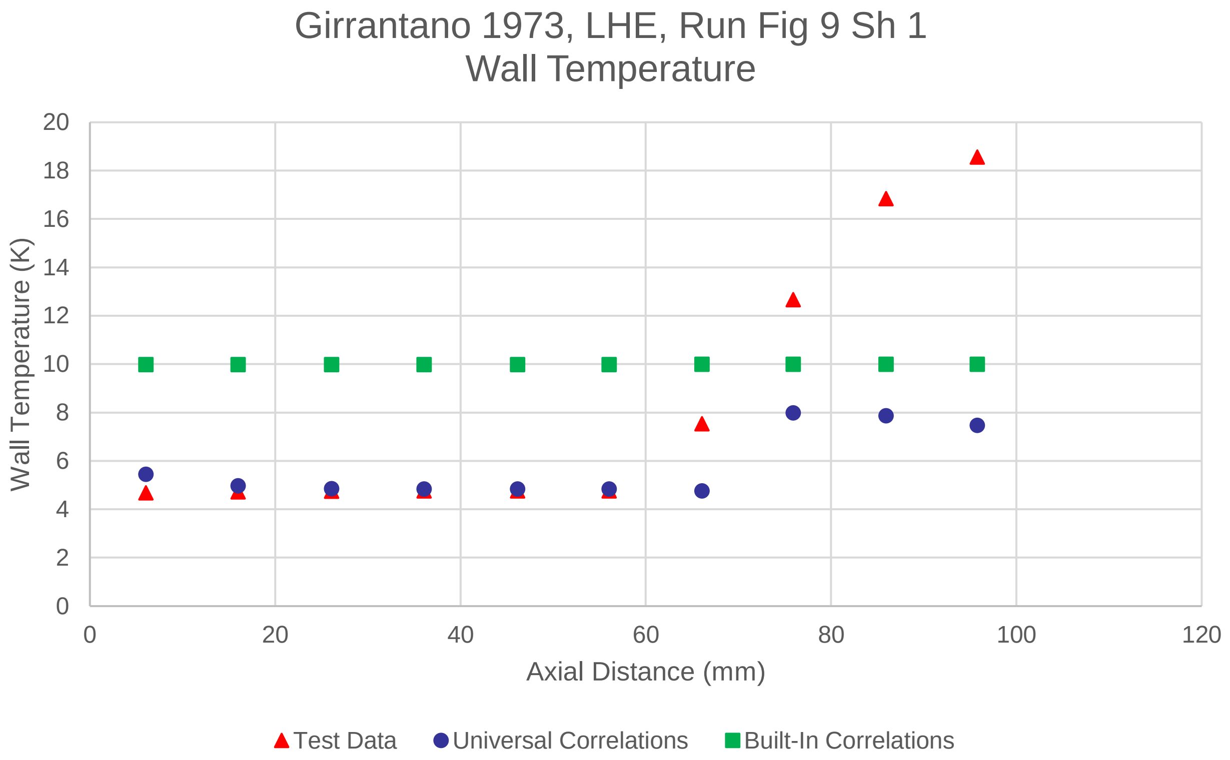
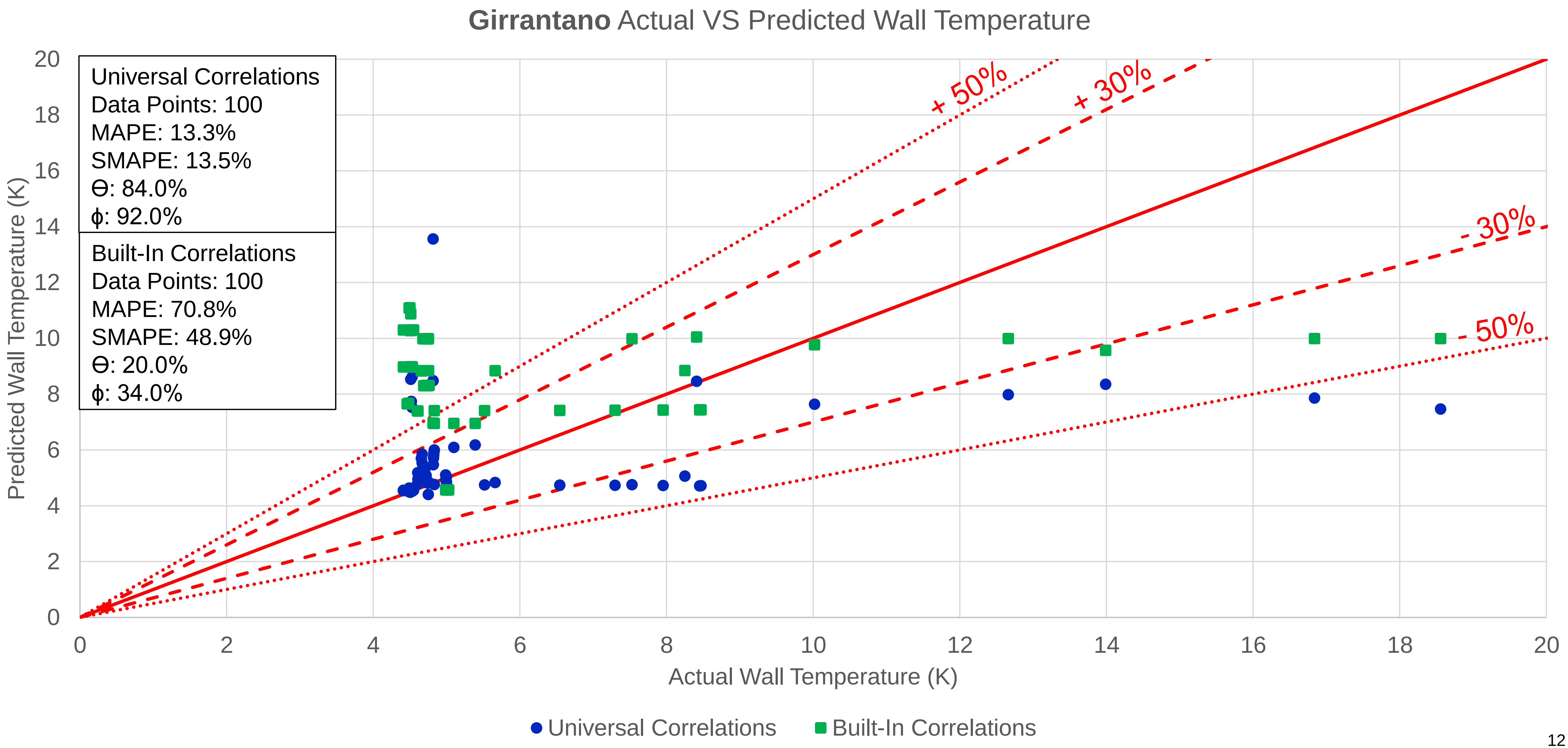


Fig 4 Sh 1	Universal Correlation	Built in Correlation
MAPE	3.4%	129.8%
SMAPE	3.7%	75.5%
zCHF Error %	8.3%	96.4%

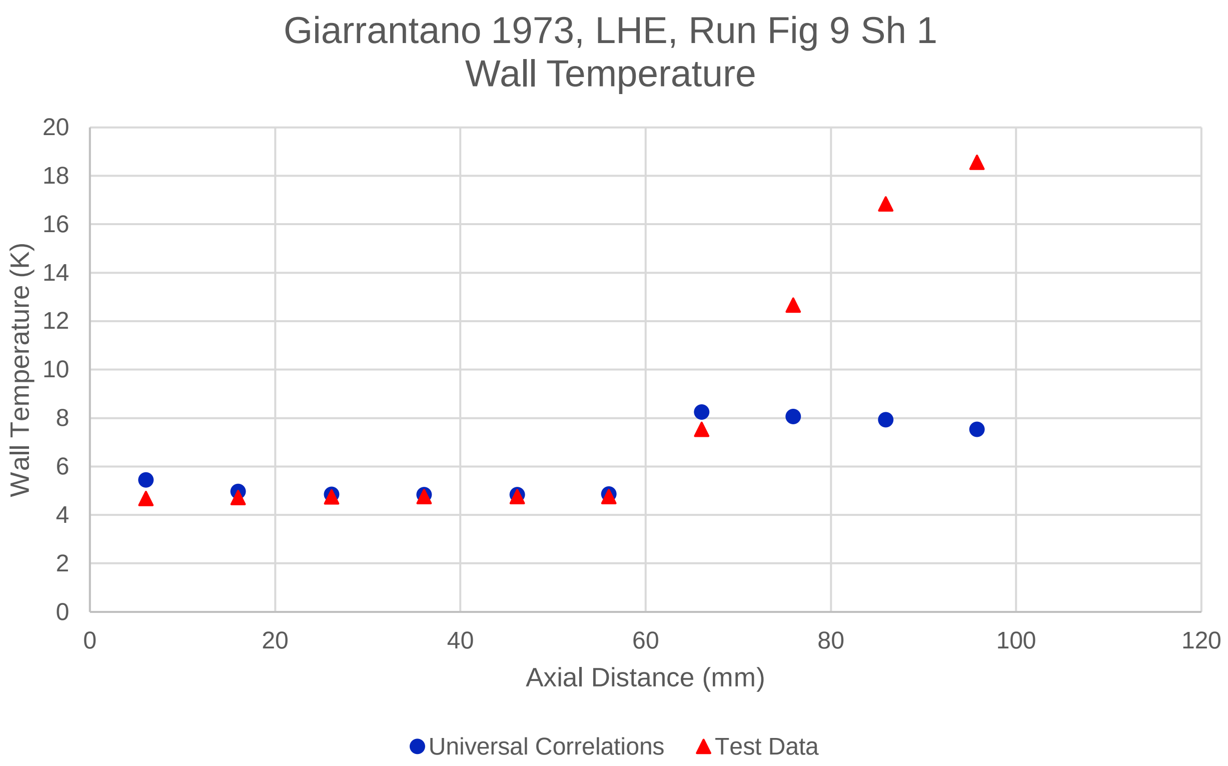
Fig 9 Sh 1	Universal Correlation	Built in Correlation
MAPE	21.7%	80.7%
SMAPE	27.7%	59.1%
zCHF Error %	4.8%	96.4%

Calculating zCHF Results



FIXED ZCHF MODEL RESULTS

Fixed zCHF Results



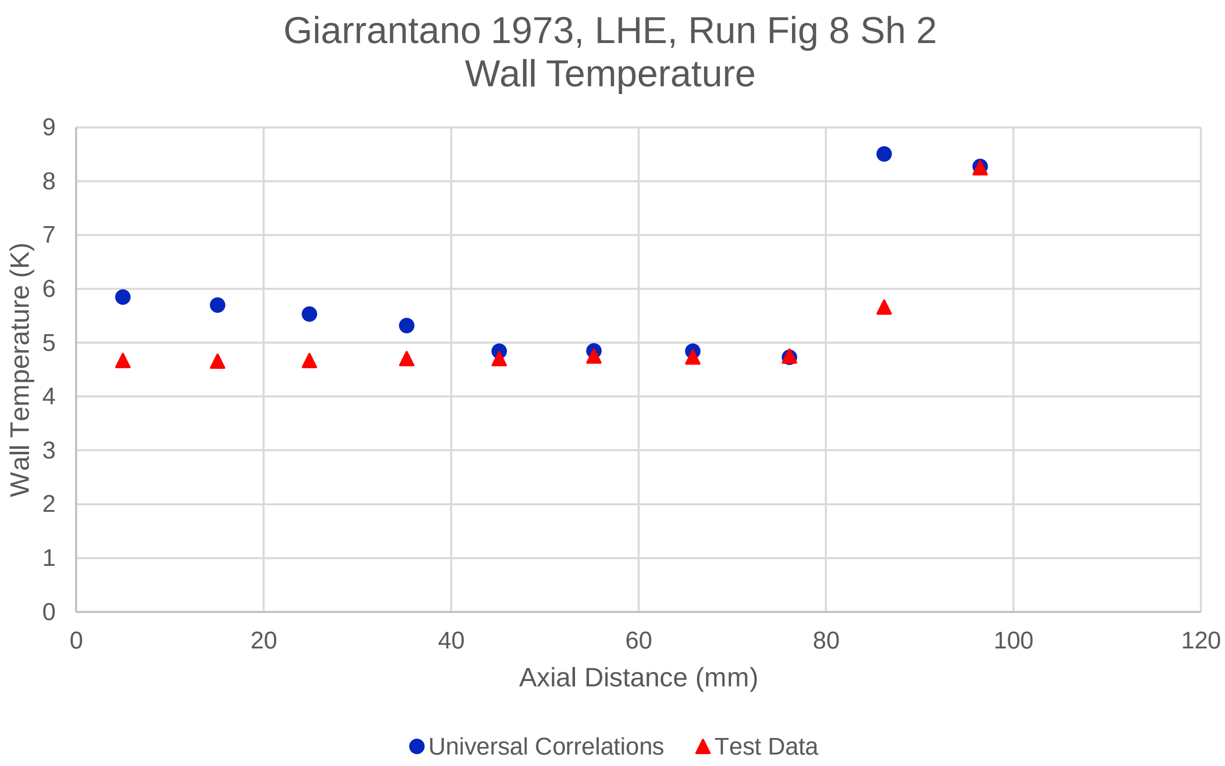
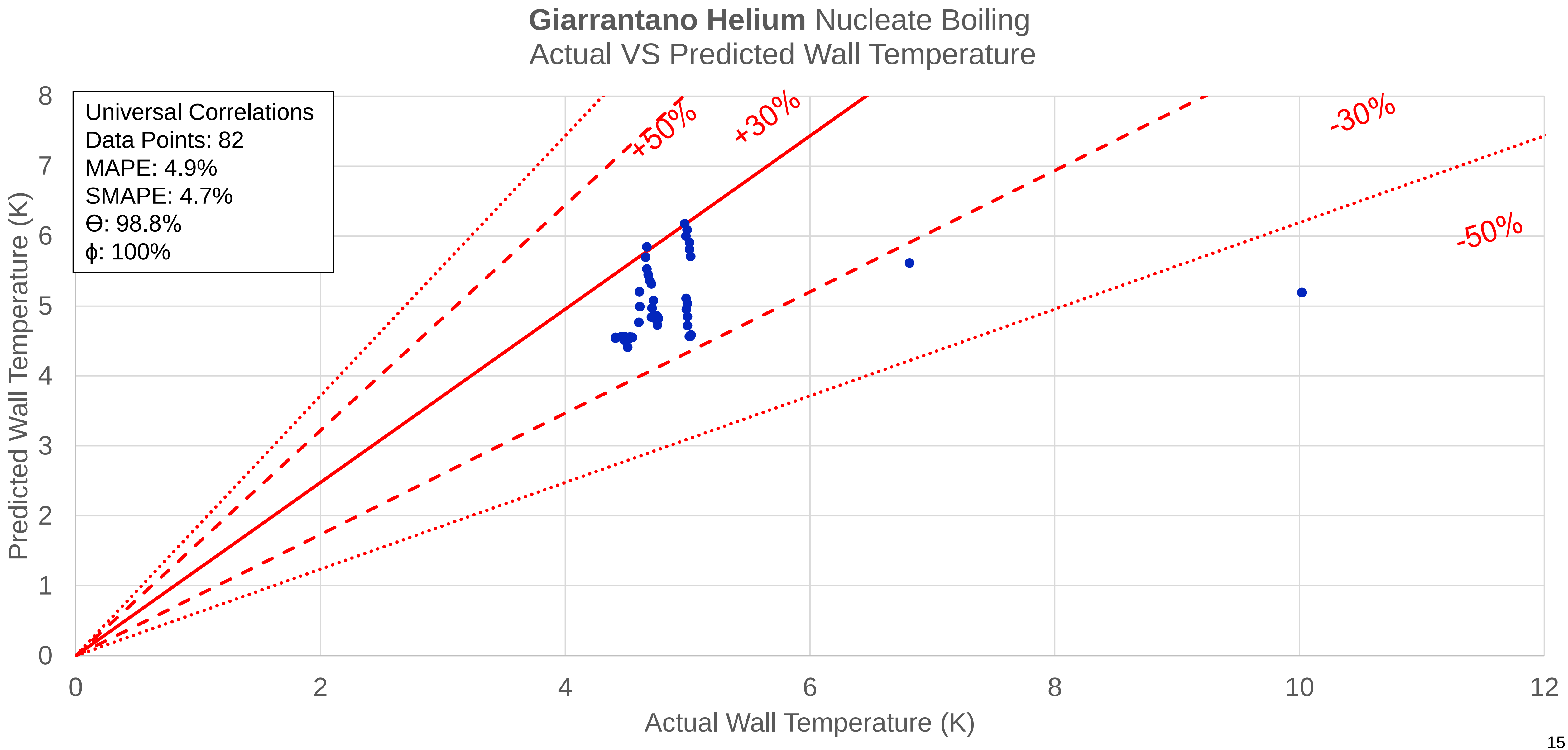


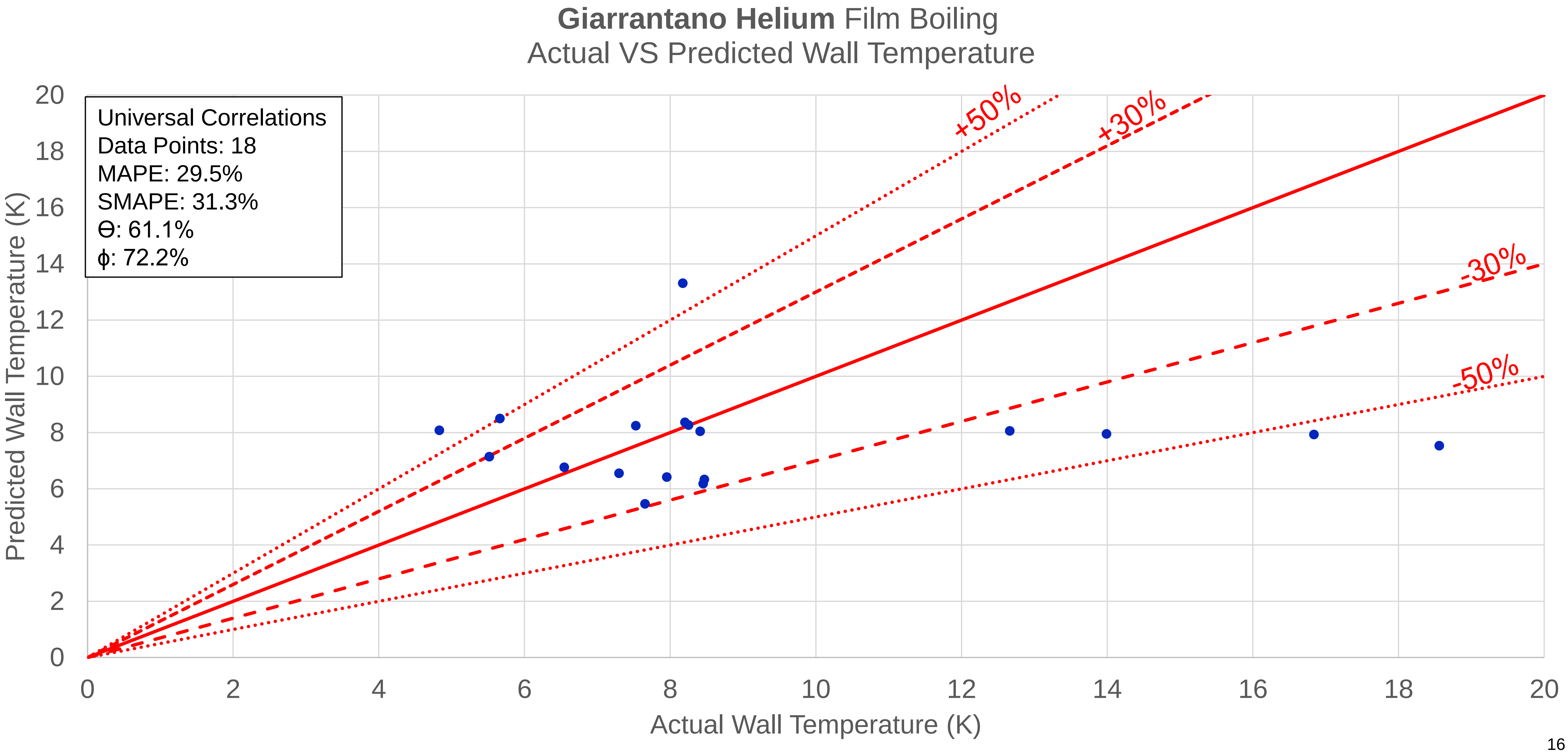
Fig 9 Sh 1	Overall	Nucleate Boiling	Film Boiling
MAPE	18.8%	5.0%	39.5%
SMAPE	23.8%	4.8%	52.5%

Fig 8 Sh 2	Overall	Nucleate Boiling	Film Boiling
MAPE	13.7%	10.8%	25.2%
SMAPE	11.9%	9.9%	20.2%

Fixed zCHF Results



Fixed zCHF Results



Discussion

- Universal Code outperforms Built-In Code in Calculating zCHF model for Helium
  - Universal Code MAPE/SMAPE < 14%
  - Built-In Code MAPE/SMAPE < 71%
  - Both Built-In TD Code and Universal code underpredict film boiling
- Fixed zCHF model using Universal Code gives MAPE/SMAPE <5% in pre-CHF region
- Fixed zCHF model using Universal Code gives MAPE/SMAPE <32% in post-CHF region
- Future Work:
  - Concurrently evaluating performance of Universal Correlations for other cryogens
  - Universal Correlations implementation into Thermal Desktop can be used for future experiments to predict transfer line performance

Questions?

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BACKUP SLIDES

Calculated zCHF model results

Case	**Universal Correlations MAPE (%)**	**Universal Correlations SMAPE (%)**	**Universal Correlations zCHF Error (%)**	**Built-In Correlations MAPE (%)**	**Built-In Correlations SMAPE (%)**	**Built-In Correlations zCHF Error (%)**
Figure 3 Sheet 1	22.5%	18.0%	18.8%	107.4%	67.9%	89.4%
Figure 3 Sheet 3	14.6%	11.1%	21.1%	99.2%	66.3%	100.0%
Figure 4 Sheet 1	3.4%	3.7%	8.3%	129.8%	75.5%	96.8%
Figure 5 Sheet 2	1.1%	1.1%	0.0%	71.0%	52.4%	100.0%
Figure 6 Sheet 2	5.7%	6.0%	0.0%	8.8%	9.2%	100.0%
Figure 7 Sheet 1	23.1%	27.9%	64.3%	31.5%	25.8%	37.1%
Figure 8 Sheet 2	14.1%	14.4%	13.2%	76.6%	53.9%	89.6%
Figure 9 Sheet 1	21.7%	27.7%	5.1%	80.7%	59.1%	68.7%
Figure 9 Sheet 2	4.1%	4.0%	2.7%	75.3%	54.7%	100.0%
Figure 10 Sheet 1	23.1%	21.1%	6.3%	27.5%	24.0%	68.9%
Average	**13.3%**	**13.5%**	14.0%	**70.8%**	**48.9%**	**85.0%**

Fixed zCHF Model Results

Case	Universal Correlations pre-CHF MAPE (%)	Universal Correlations pre-CHF SMAPE (%)	Number of pre-CHF data points	Universal Correlations post-CHF MAPE (%)	Universal Correlations post-CHF SMAPE (%)	Number of post-CHF data points
Figure 3 Sheet 1	1.0%	1.0%	8	23.7%	29.7%	2
Figure 3 Sheet 3	0.8%	0.8%	10	-	-	-
Figure 4 Sheet 1	5.9%	7.4%	10	-	-	-
Figure 5 Sheet 2	1.1%	1.1%	10	-	-	-
Figure 6 Sheet 2	5.7%	6.0%	10	-	-	-
Figure 7 Sheet 1	8.3%	7.9%	3	26.0%	24.5%	7
Figure 8 Sheet 2	10.8%	9.9%	8	25.2%	20.2%	2
Figure 9 Sheet 1	5.0%	4.8%	6	39.5%	52.5%	4
Figure 9 Sheet 2	3.5%	3.3%	10	-	-	-
Figure 10 Sheet 1	18.7%	17.5%	7	31.2%	27.7%	3
Average	**5.5%**	**5.5%**	-	**29.5%**	**31.3%**	-