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Modeling of Cryogenic Heated-Tube Flow Boiling Experiments of Hydrogen and Helium with GFSSP

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Introduction

- Accurate prediction of two-phase flow boiling is required to design and analyze cryogenic transfer systems.
- Poor models penalize us: increased margins and higher costs.
- Two types of flow boiling in cryogenic transfer
  - Quenching / Chill Down (Unsteady)
  - Heating (Steady)
- Many boiling correlations are based on experimental data with water and refrigerants, rather than cryogenic fluids.
- Purdue University has assembled a cryogenic database of thousands of data points from heated tube experiments since 1959.
  - LHe, LH2, LNe, LN2, LAr, LCH4

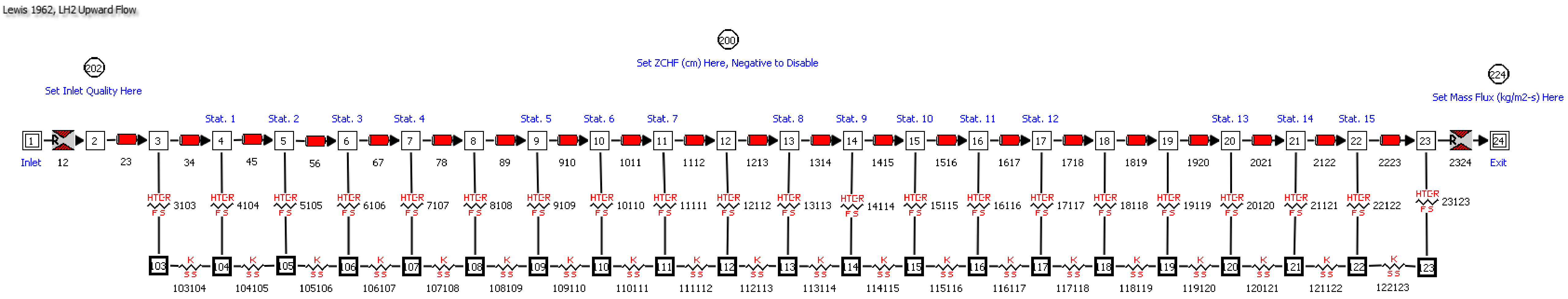
Purdue Universal Cryogenic Flow Boiling Correlation

- Onset of Nucleate Boiling (ONB)
- Nucleate Boiling (NB)
  - Nominal inlet conditions
  - High-quality inlet conditions
- Critical Heat Flux (CHF) as a function of axial distance Z
  - Departure from Nucleate Boiling (DNB)
  - Dryout (DRY)
- Film Boiling (FB)
  - Dispersed Flow Film Boiling (DFFB)
    - Saturated
    - Superheated
  - Inverted Annular Film Boiling (IAFB)

GFSSP Overview

- GFSSP stands for Generalized Fluid System Simulation Program.
- It is a general-purpose computer program to compute pressures, temperatures, and flow rates in a fluid network.
- Fluid networks are discretized into nodes and branches.
    - Mass and energy equations are solved in the fluid nodes to get pressures and enthalpies/temperatures.
    - Momentum equation is solved in the branches to get flow rates.
    - Solid energy equation is solved in the solid nodes to get wall temperatures.
- Convection and pressure drop correlations can be programmed in Fortran user subroutines.

Lewis LH2 (1962)



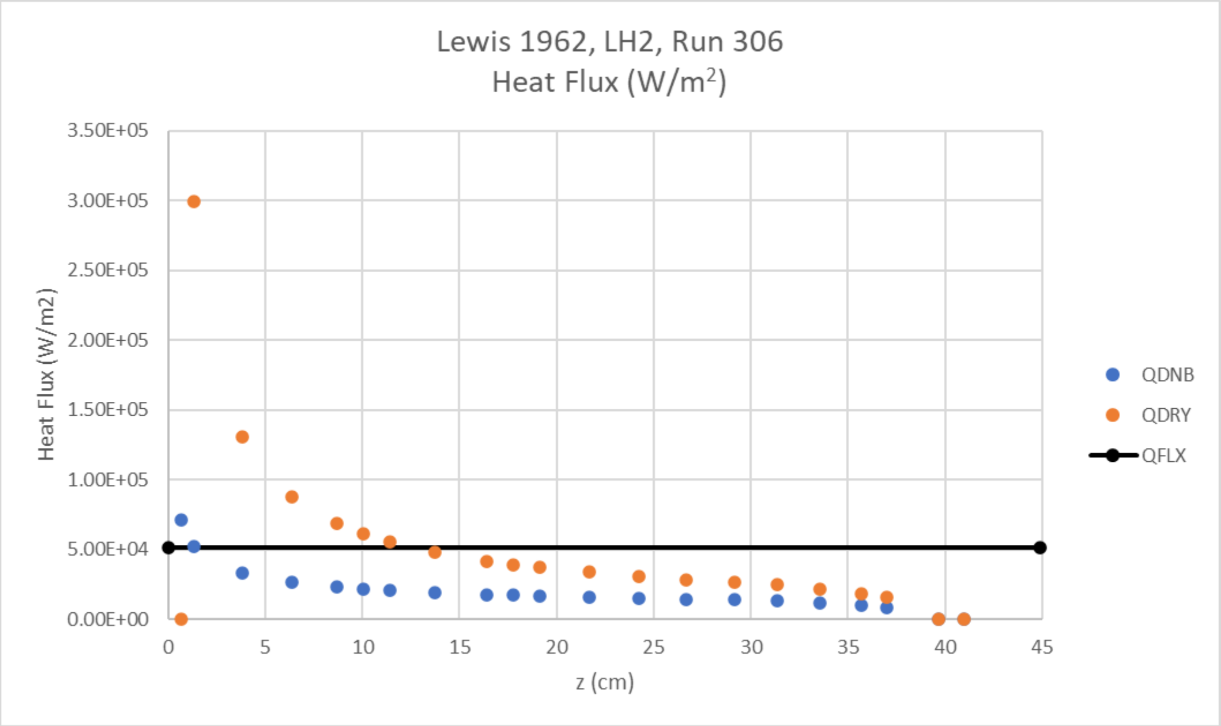
L = 16.125 in = 40.96 cm

Di = 0.555 in = 1.4097 cm

- 28 runs
- L = 41 cm
- ID = 1.41 cm
- t = 0.089 cm
- Stainless Steel

- P: 207-355 kPa
- G: 4-12 kg/m^2-s
- Q: 29-57 kW/m^2
- Pipe lengths are set so that nodes match TC locations.

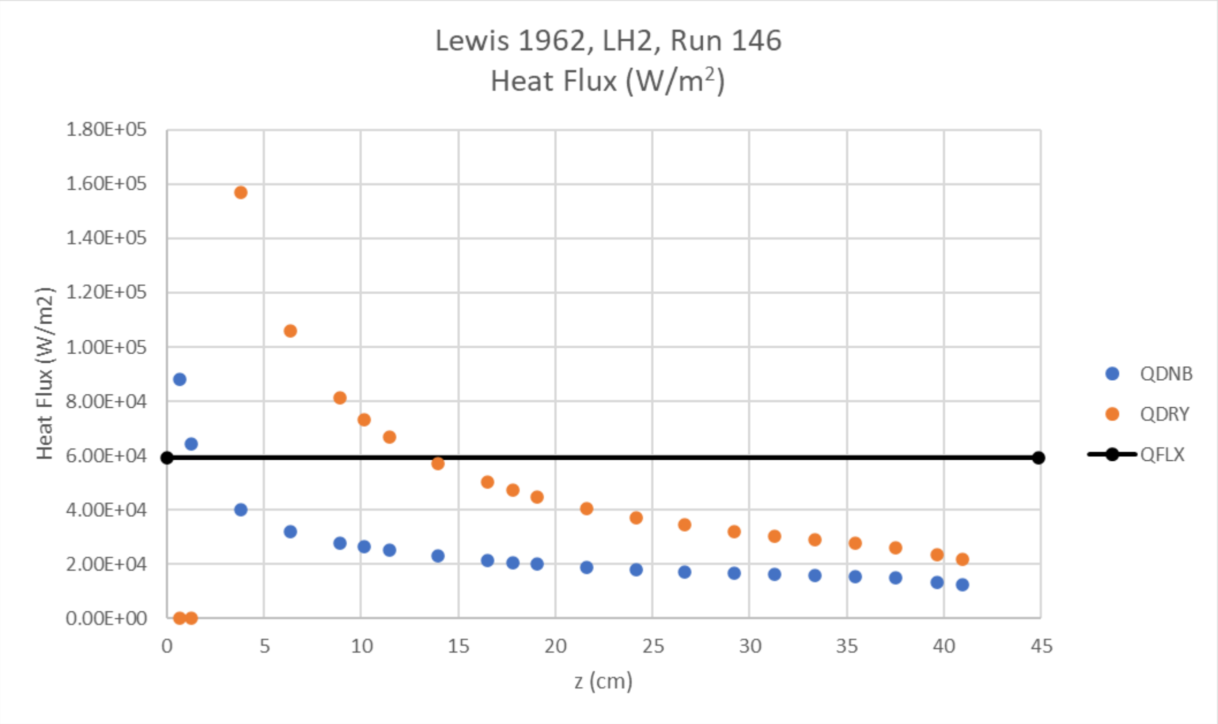
Lewis LH2 (1962), Run 306

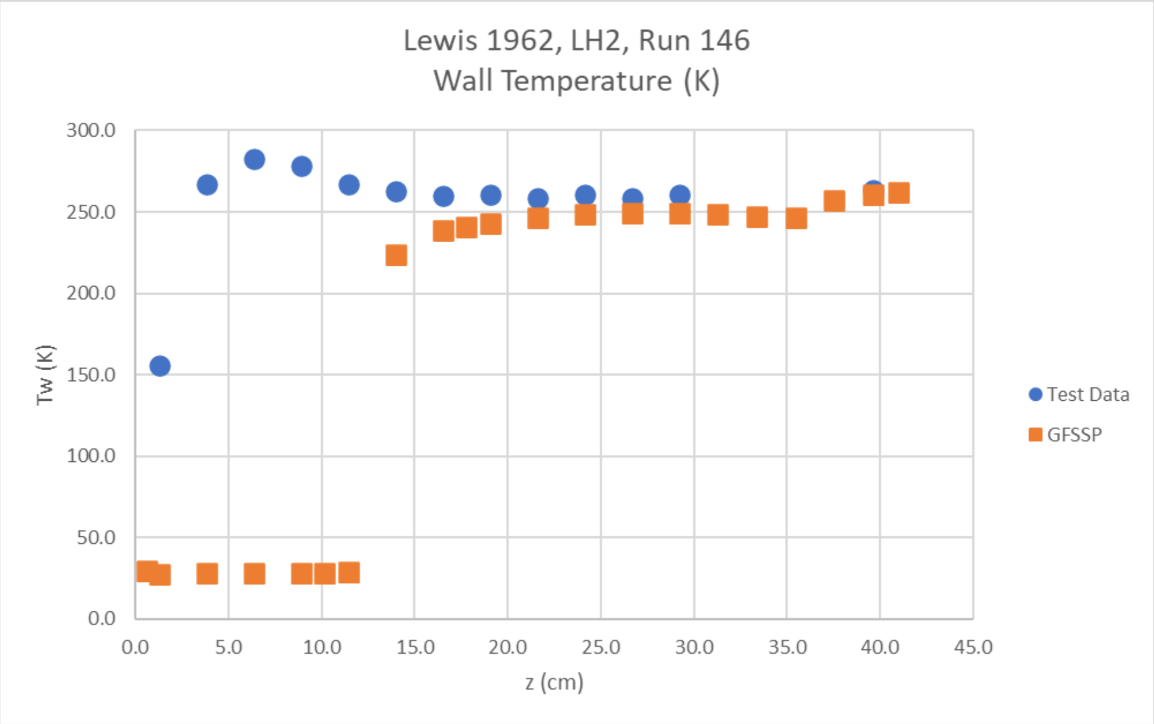


- Critical length (Z_{CHF}) is determined where the CHF curve intersects the test heat flux.
- Reported Z_{CHF} = 10.2 cm
- Predicted Z_{CHF} = 12.3 cm

- Because of error in Z_{CHF}, wall temperature is under-predicted at 11.4 cm.

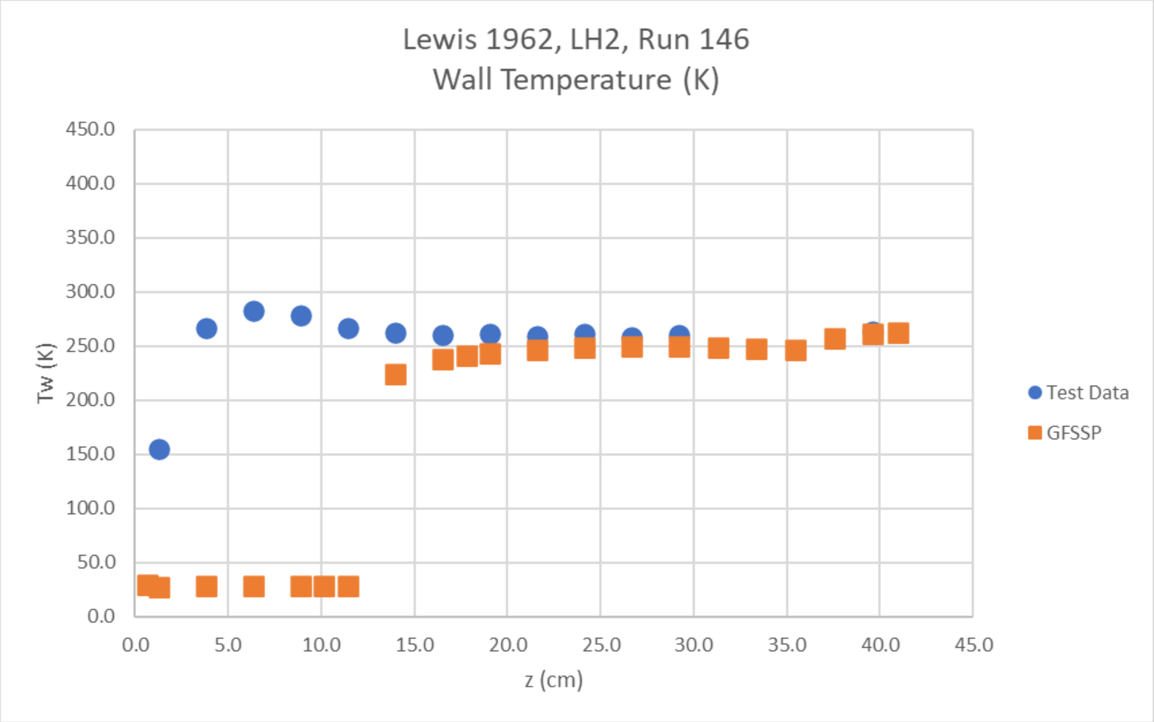
Lewis LH2 (1962), Run 146



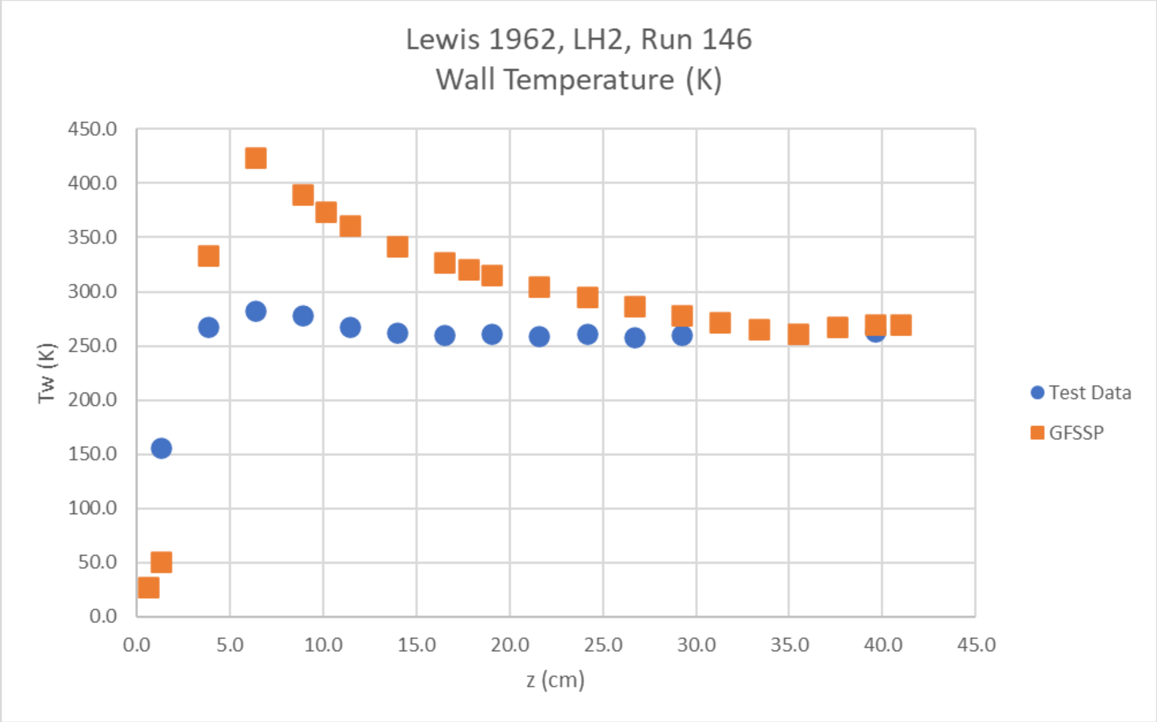


- Code chose DRY instead of DNB.
- Reported $Z_{CHF} \approx 0$ cm
- Predicted $Z_{CHF} = 13.1$ cm

Lewis LH2 (1962), Run 146



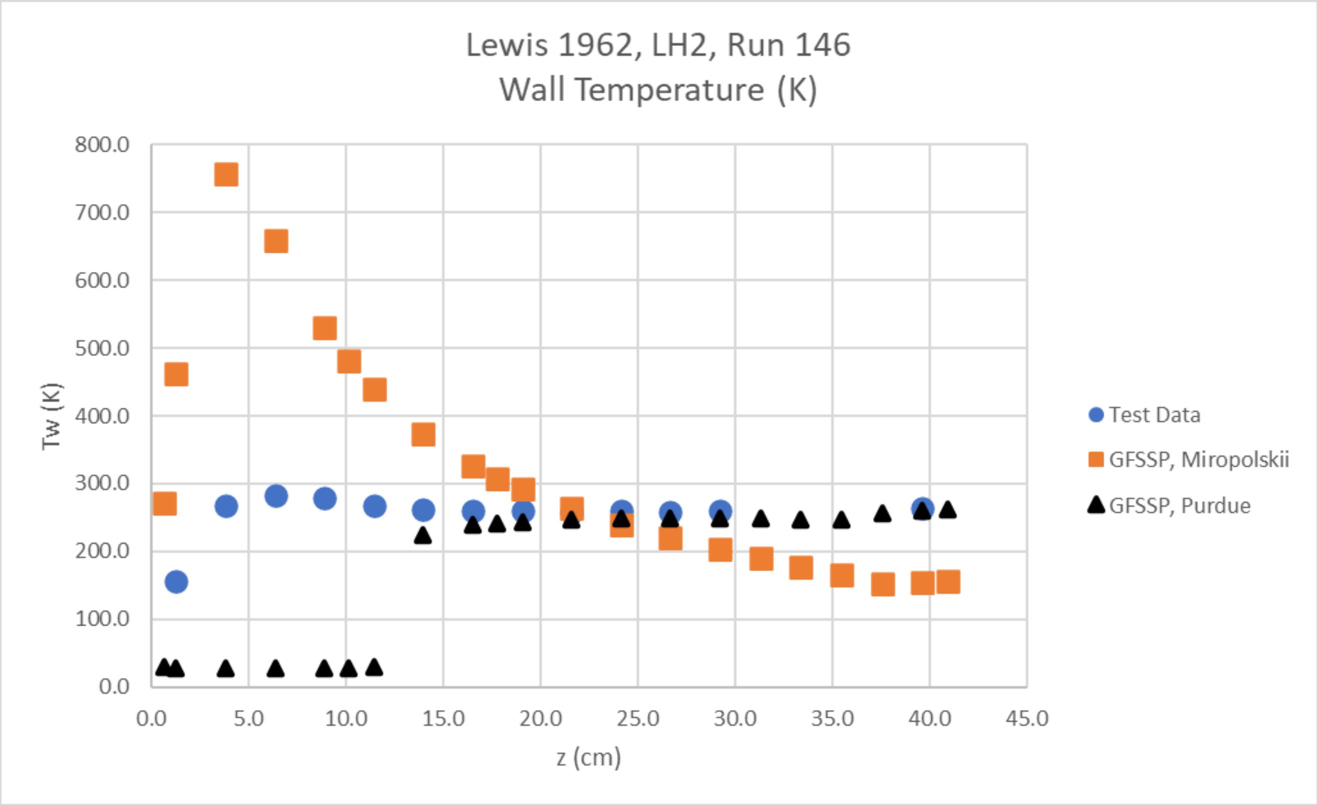
Finding ZCHF, MAPE = 38%



Fixing ZCHF, MAPE = 27%

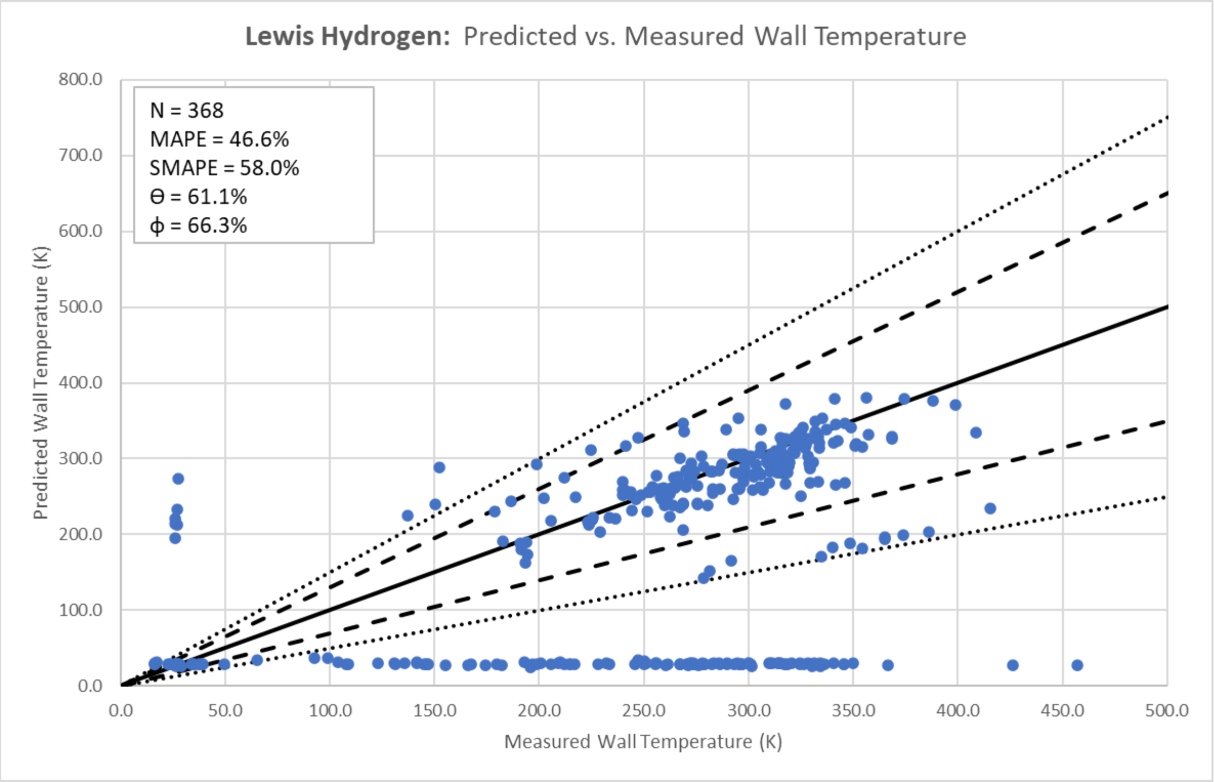
- To better evaluate performance of NB and FB correlations, all runs were performed twice: Finding Z_{CHF} and Fixing Z_{CHF}.

Lewis LH2 (1962), Run 146

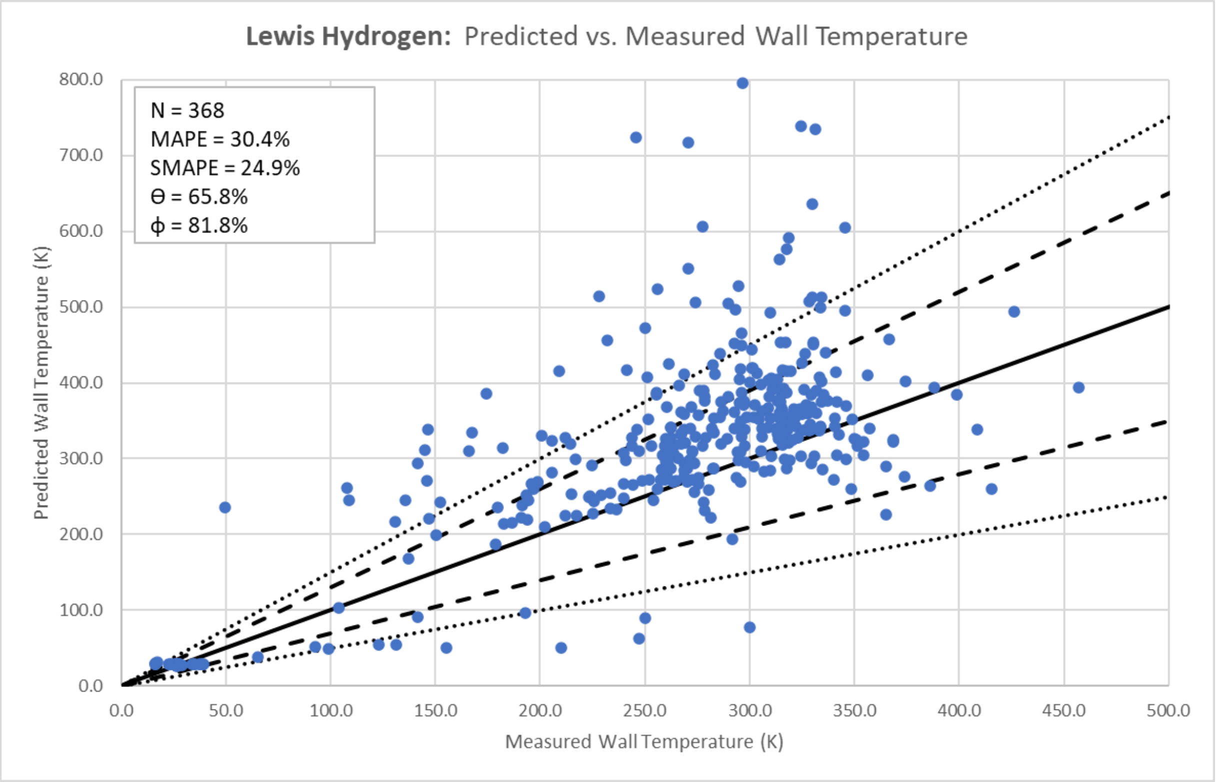


- The Purdue correlations show an improvement over the Miropolskii film boiling correlation built into GFSSP (MAPE: 38% vs. 64%).

Lewis LH2 (1962), Parity Plots

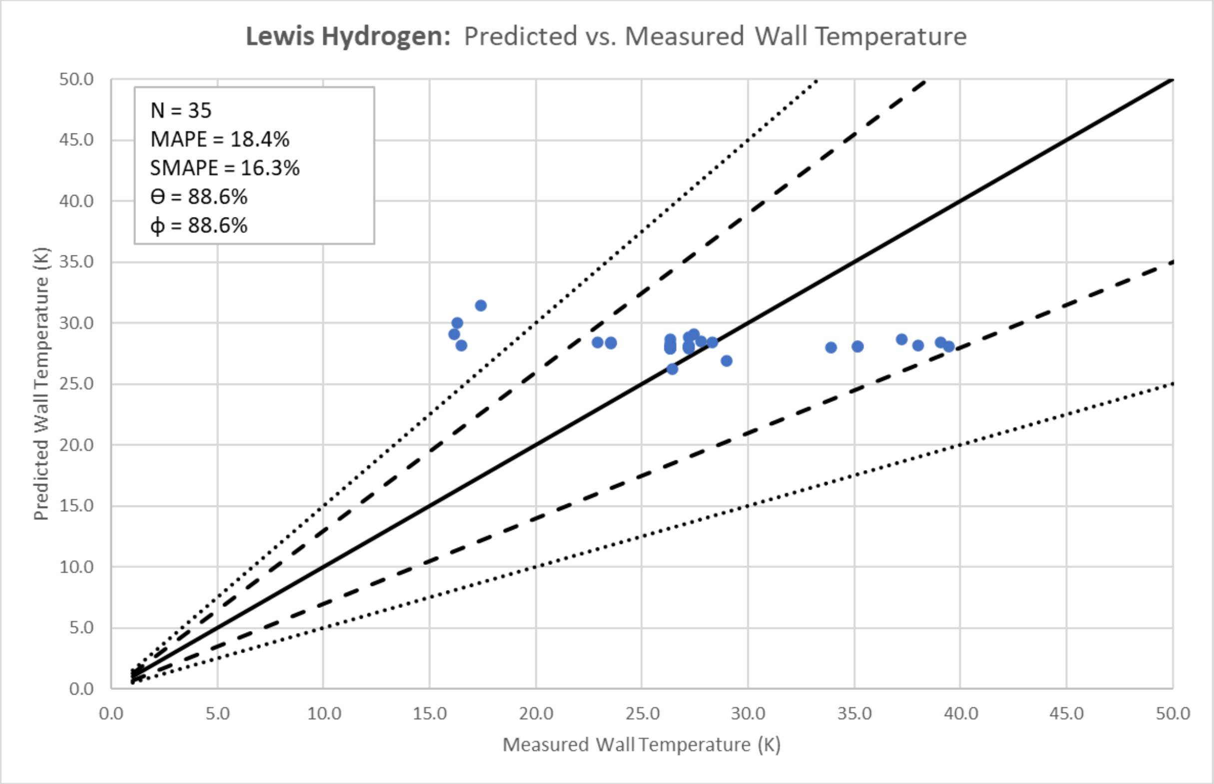


Finding ZCHF, MAPE = 47%

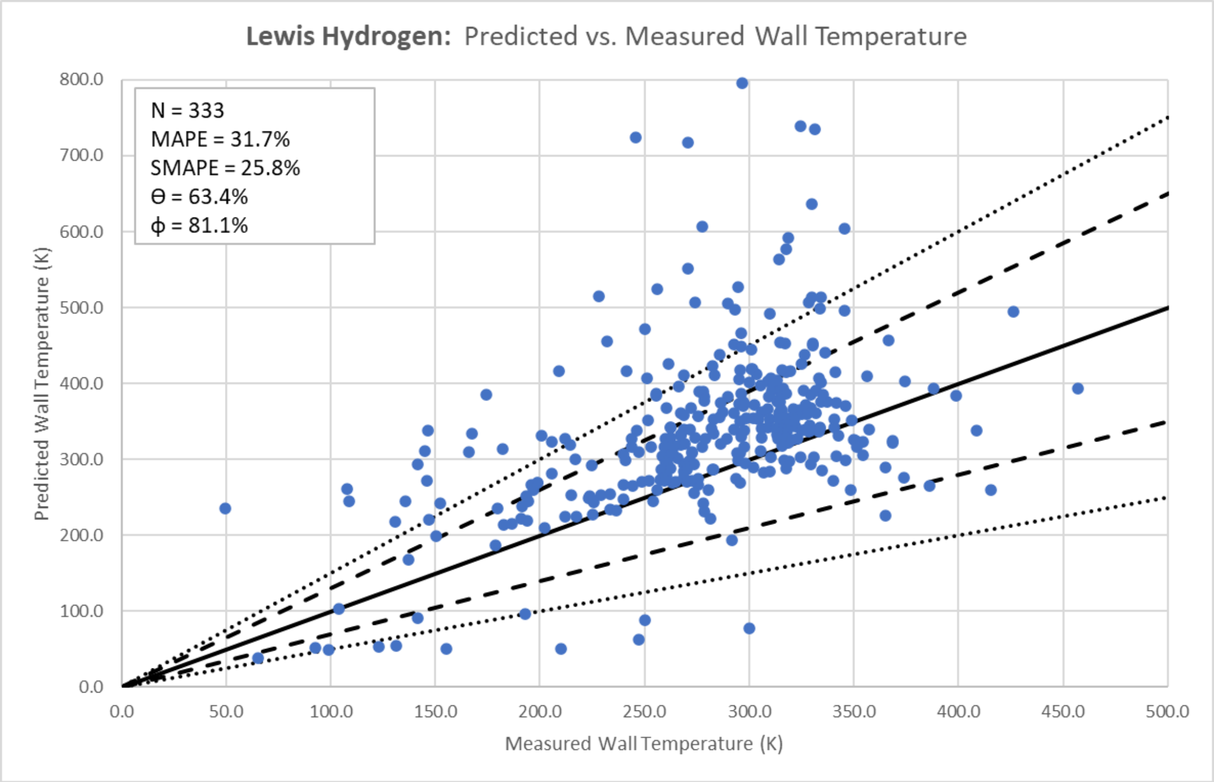


Fixing ZCHF, MAPE = 30%

Lewis LH2 (1962), Parity Plots



Fixing ZCHF, NB Only, MAPE = 18%



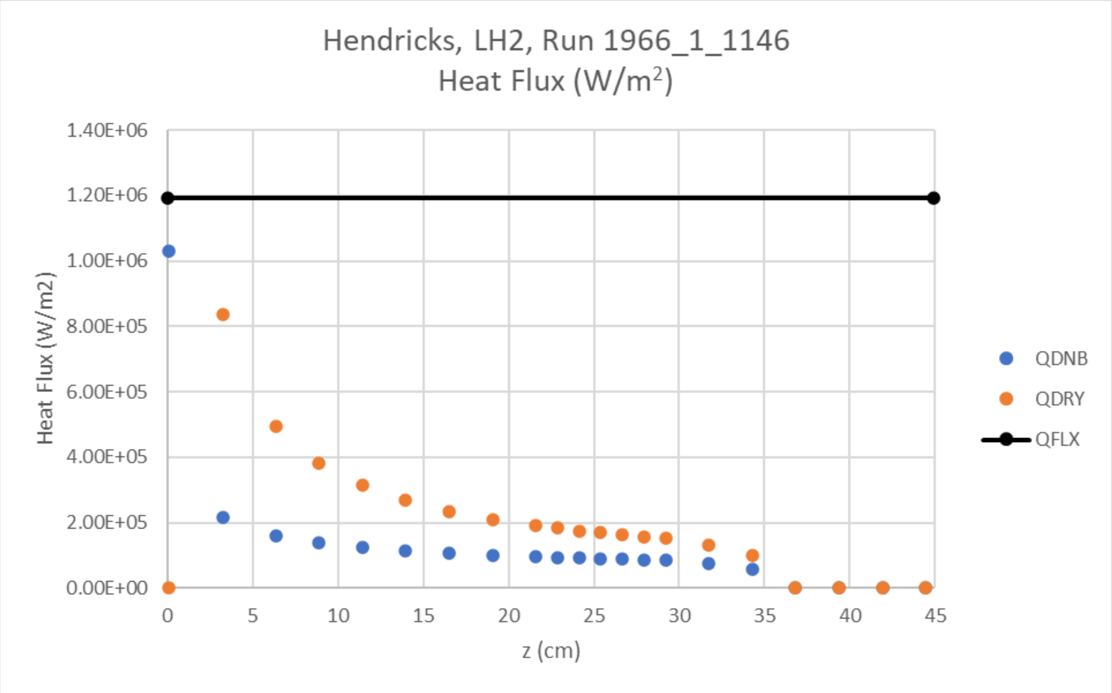
Fixing ZCHF, FB Only, MAPE = 32%

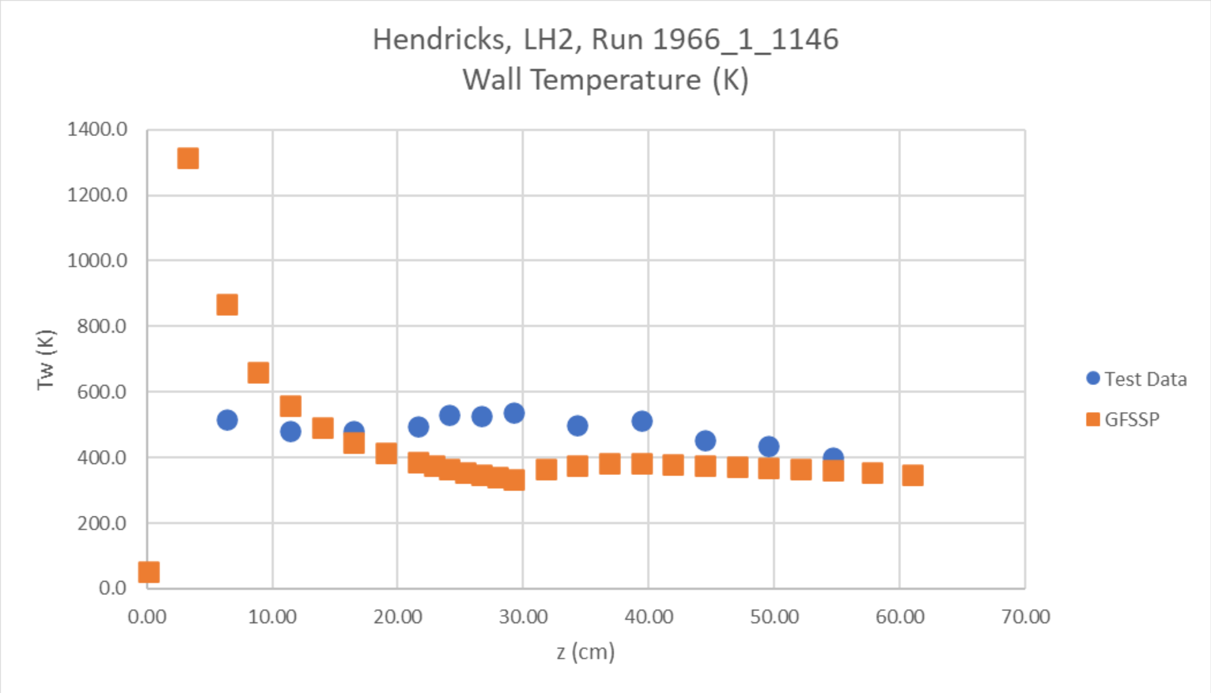
- When Z_{CHF} is fixed to the observed value, we can separate the NB and FB points.

Hendricks LH2 (1966)

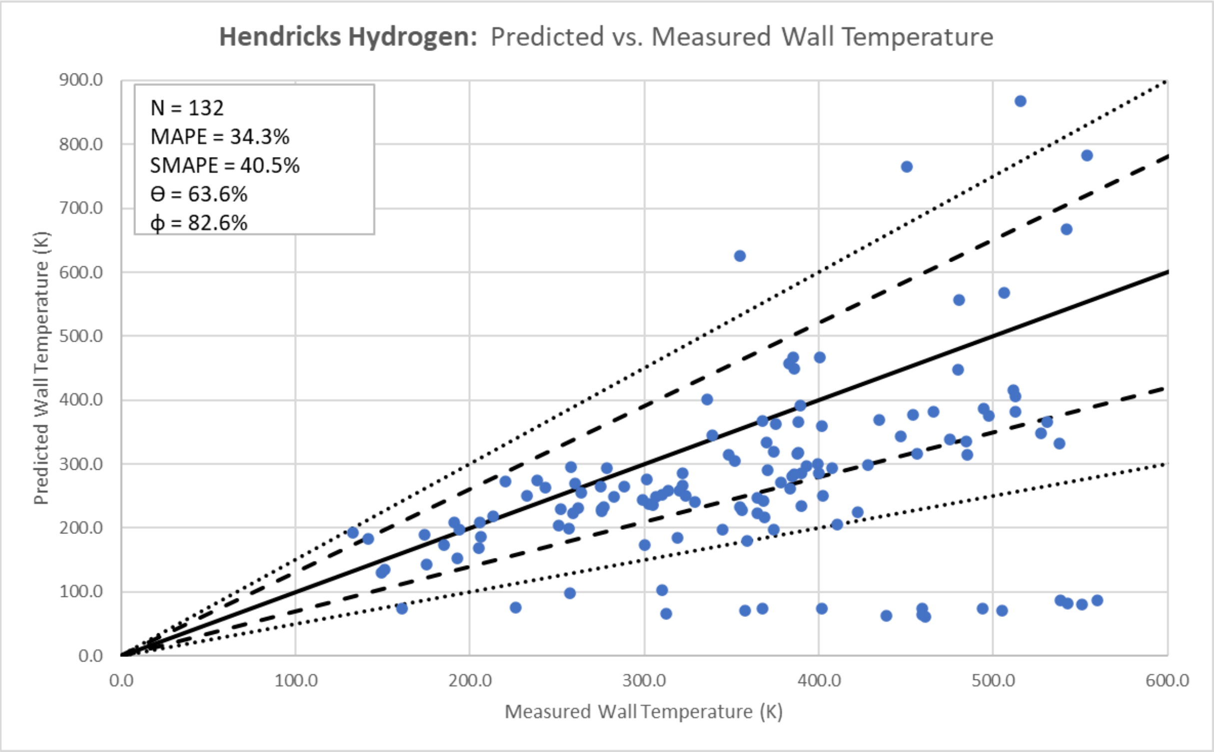
- 11 runs
- L = 61 cm
- ID = 0.85-1.29 cm
- t = 0.025-0.081 cm

- Inconel or Stainless Steel
- P: 616-1113 kPa
- G: 327-1438 kg/m^2-s
- Q: 735-2092 kW/m^2

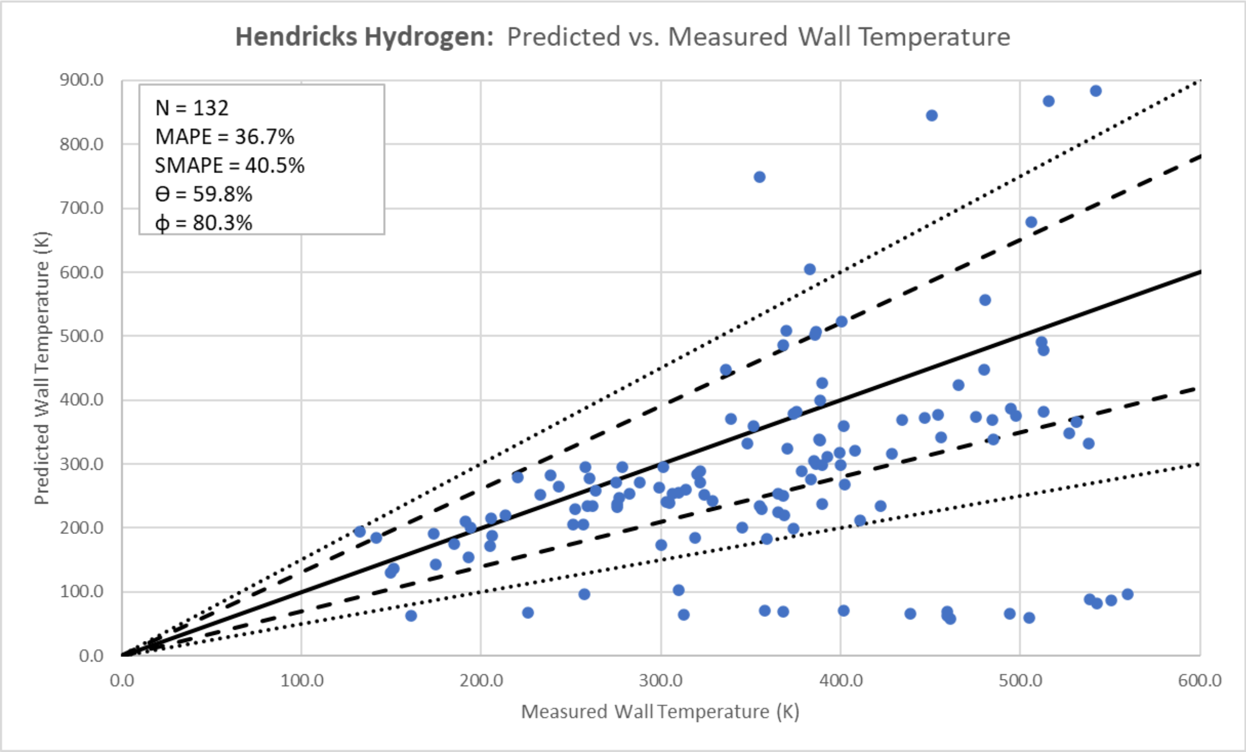




Hendricks LH2 (1966), Parity Plots



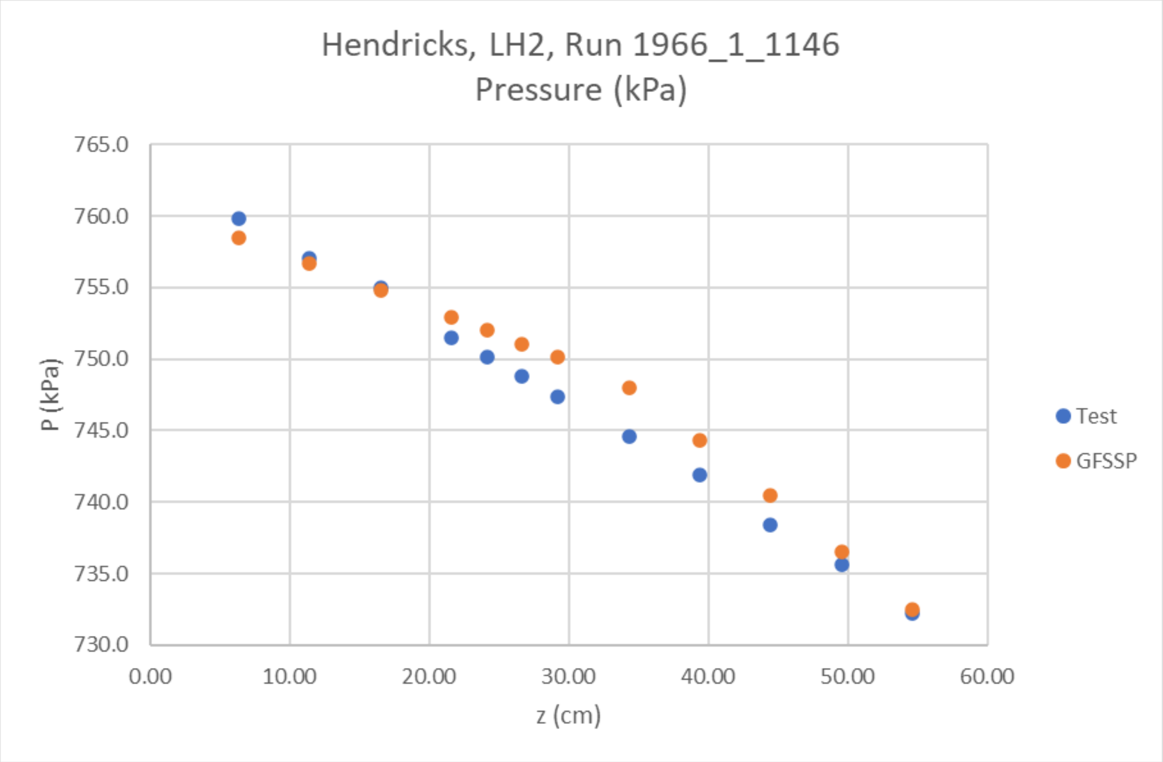
Finding ZCHF, MAPE = 34%

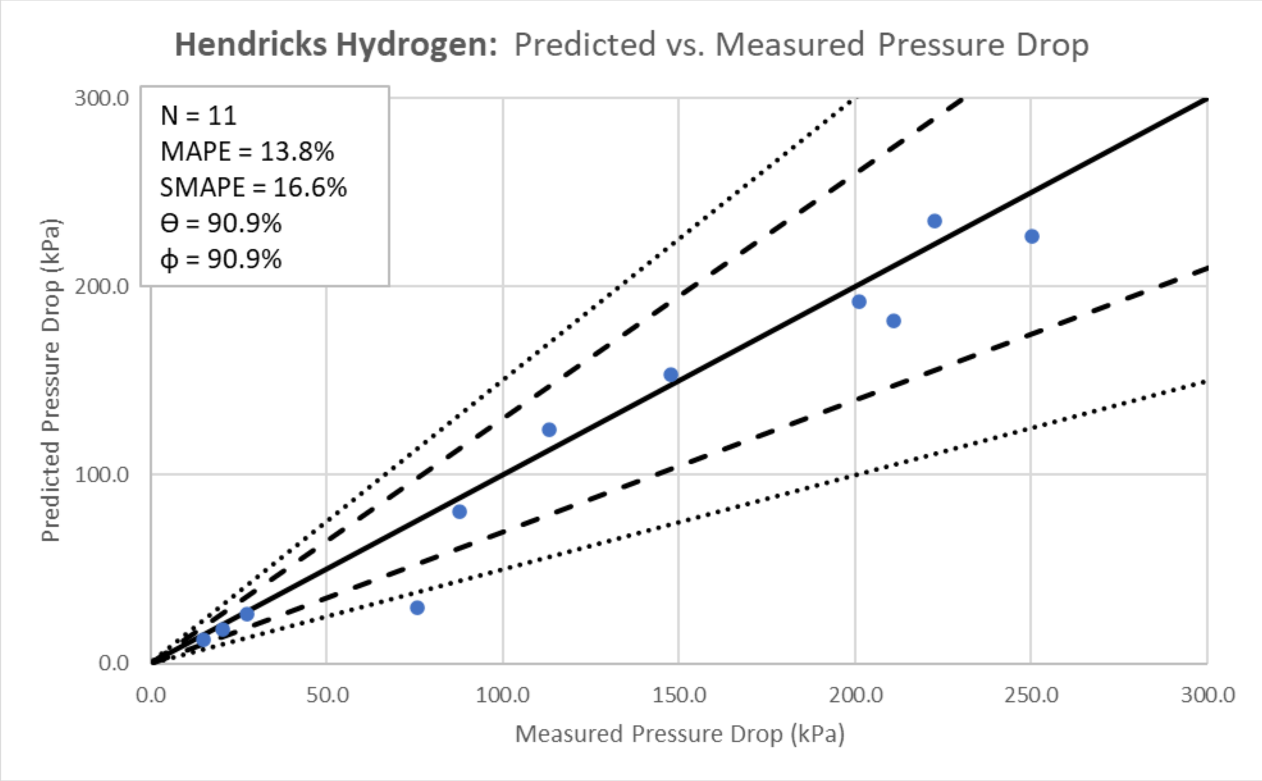


Fixing ZCHF, MAPE = 37%

- All test points are in the FB region.
- Most outliers are in the subcooled FB region.

Hendricks LH2 (1966), Pressure Drop



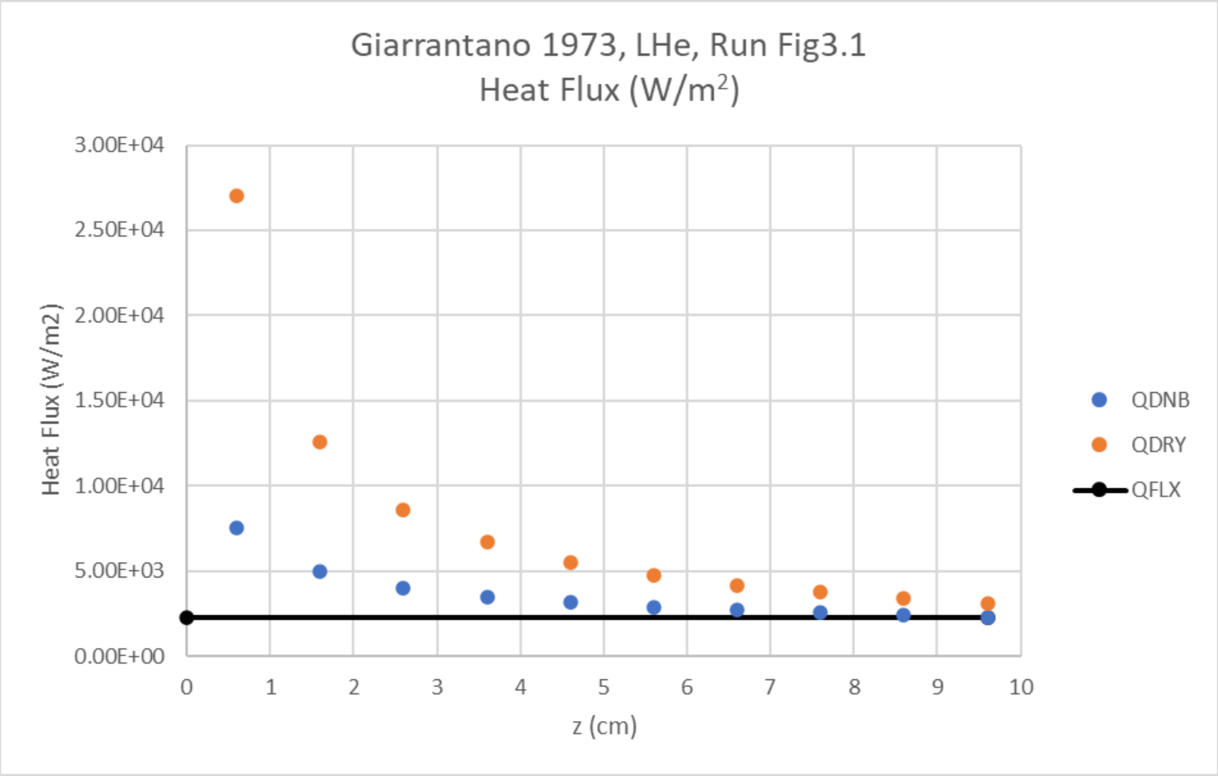


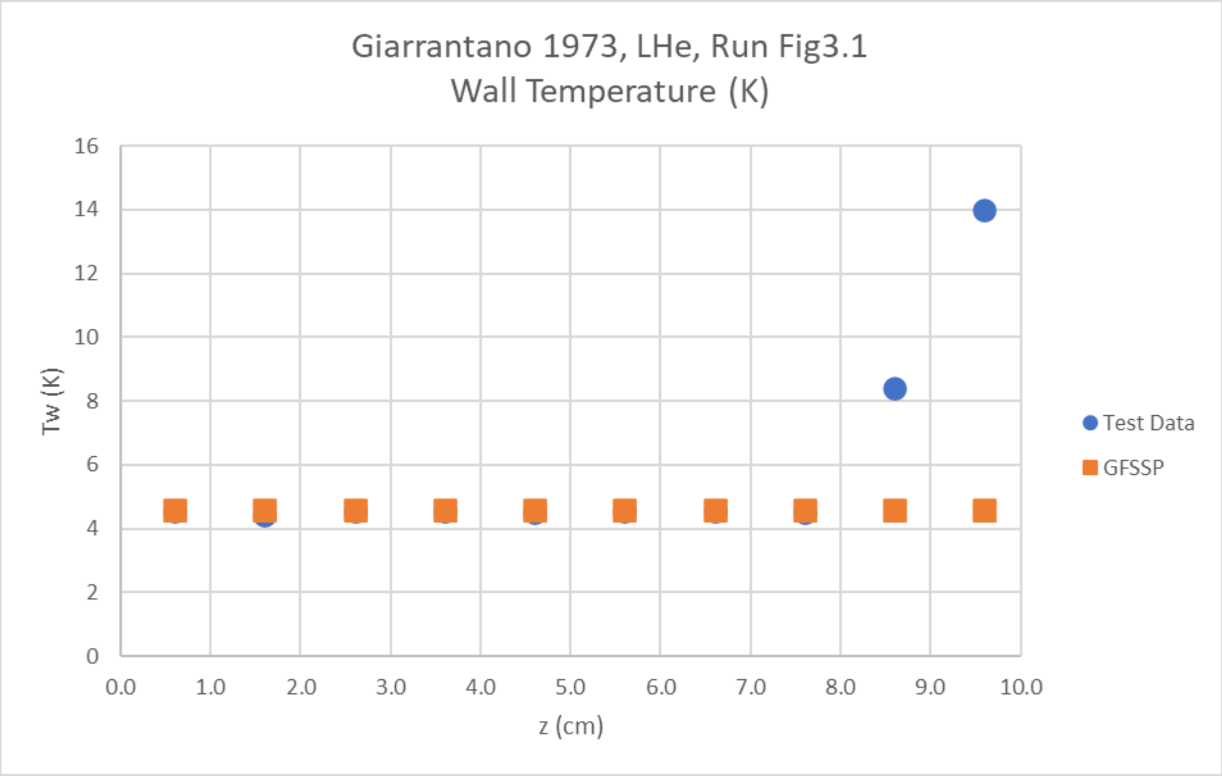
- Pressure drop correlation includes
  - Friction (McAdams or Modified Lockhart-Martinelli)
  - Gravity
  - Acceleration

Giarrantano LHe (1973)

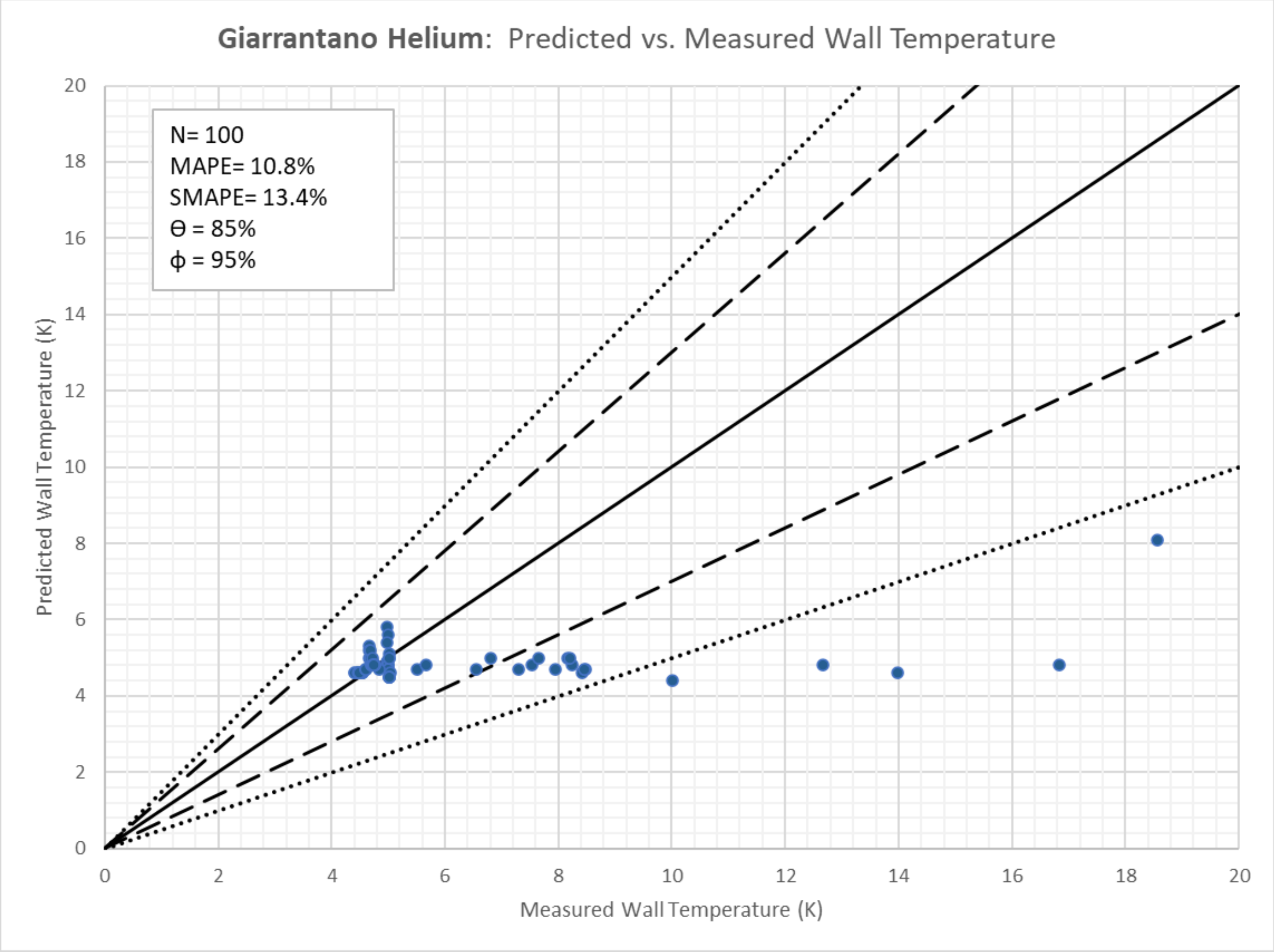
- 10 runs
- L = 10 cm
- ID = 0.213 cm
- t = 0.016 cm

- Stainless Steel
- P: 109-176 kPa
- G: 48-636 kg/m^2-s
- Q: 0.6-5 kW/m^2





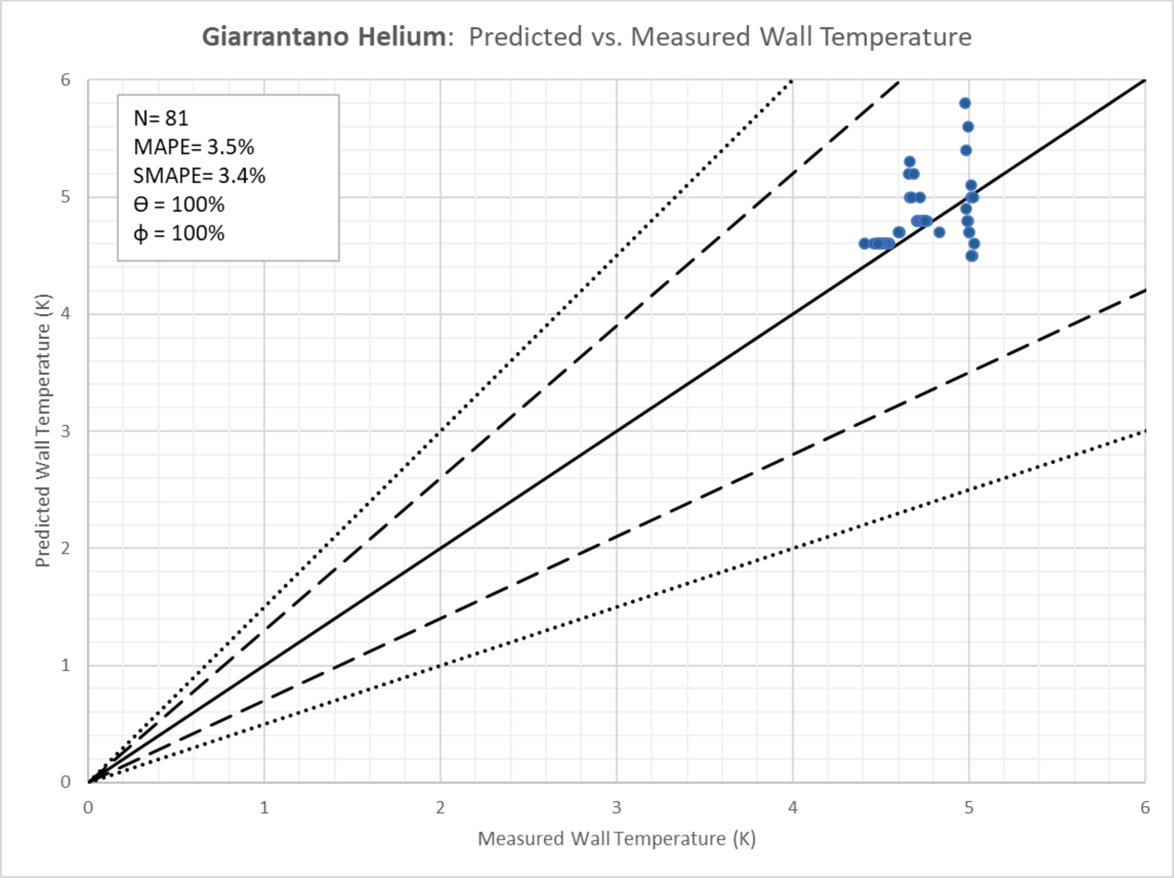
Giarrantano LHe (1973), Parity Plot



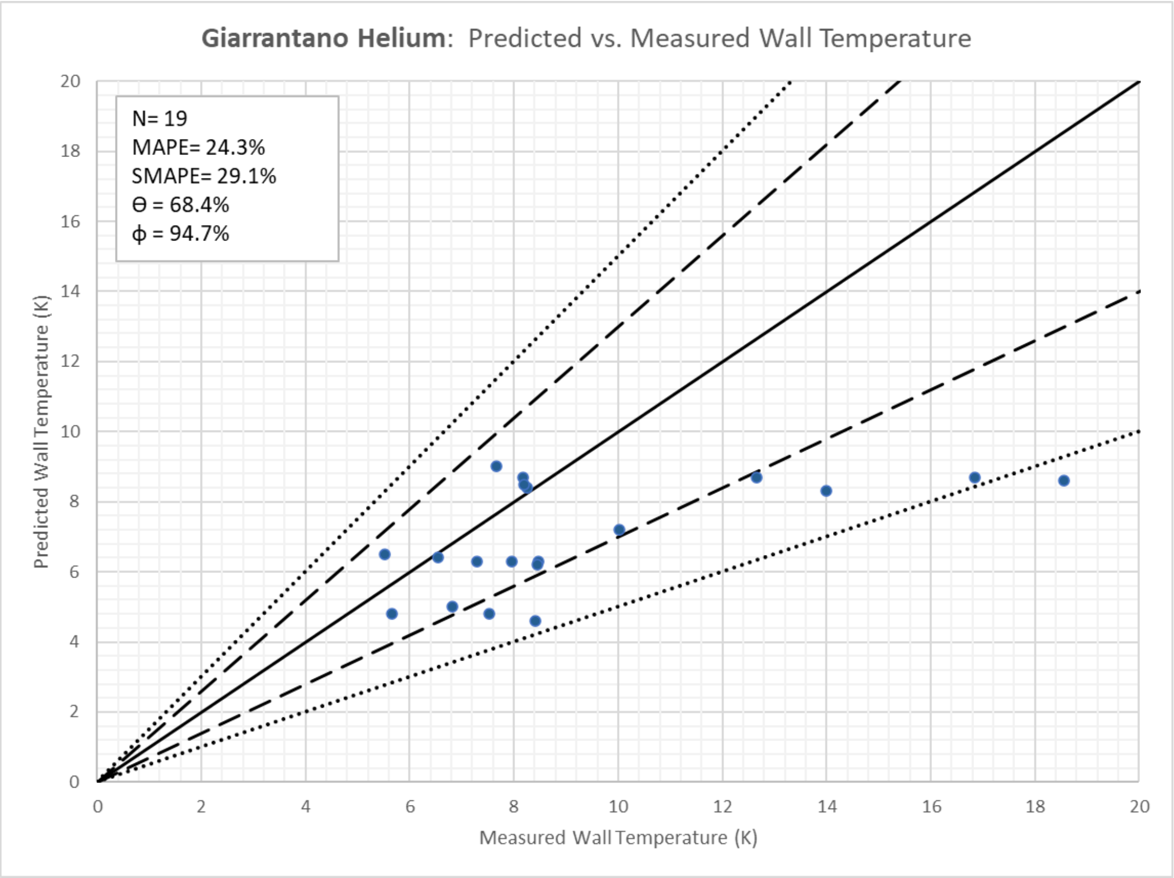
Finding ZCHF, MAPE = 11%

- Outliers occur where code predicted NB instead of FB.

Giarrantano LHe (1973), Parity Plots



Fixing ZCHF, NB, MAPE = 4%



Fixing ZCHF, FB, MAPE = 24%

Conclusions

- The Purdue Universal Cryogenic Correlations are found to model LH2 and LHe boiling flows with reasonable accuracy in most phases.
- A method to determine the critical length Z_{CHF} when both DNB and DRY meet the criteria is needed.
- The development of a subcooled FB correlation is desirable.
- The Purdue correlations predict the FB region more accurately than the Miropolskii correlation.
- The Purdue two-phase pressure drop correlation appears to be accurate, but more testing is needed. Unfortunately, many experiments lack pressure drop data.