Modeling of Cryogenic Heated-Tube Flow Boiling Experiments of Nitrogen and Methane with the Generalized Fluid System Simulation Program

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Agenda

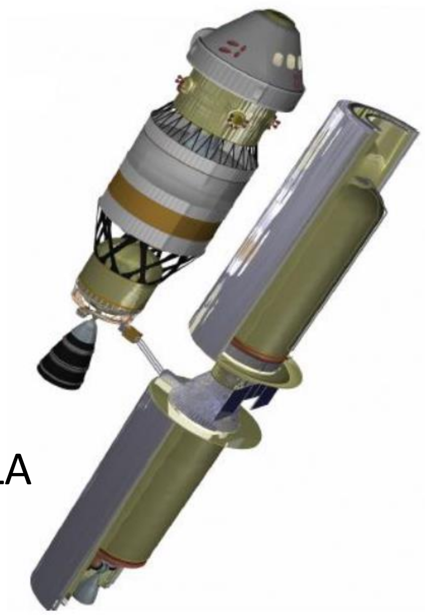
- Motivation for heated-tube boiling modeling
- Background
  - Flow boiling
  - Purdue University universal cryogenic boiling heat transfer correlations
  - Generalized Fluid System Simulation Program (GFSSP)
- Model Inputs
- Results
  - Glickstein and Whitesides [1] CH_4
  - Lewis et al. [2] N_2
  - Qi et al. [3] N_2
- Conclusions

Motivation for Heated-Tube Boiling Modeling

In-space tank-to-tank propellant transfer line

Application:

-Cryogenic fuel depots



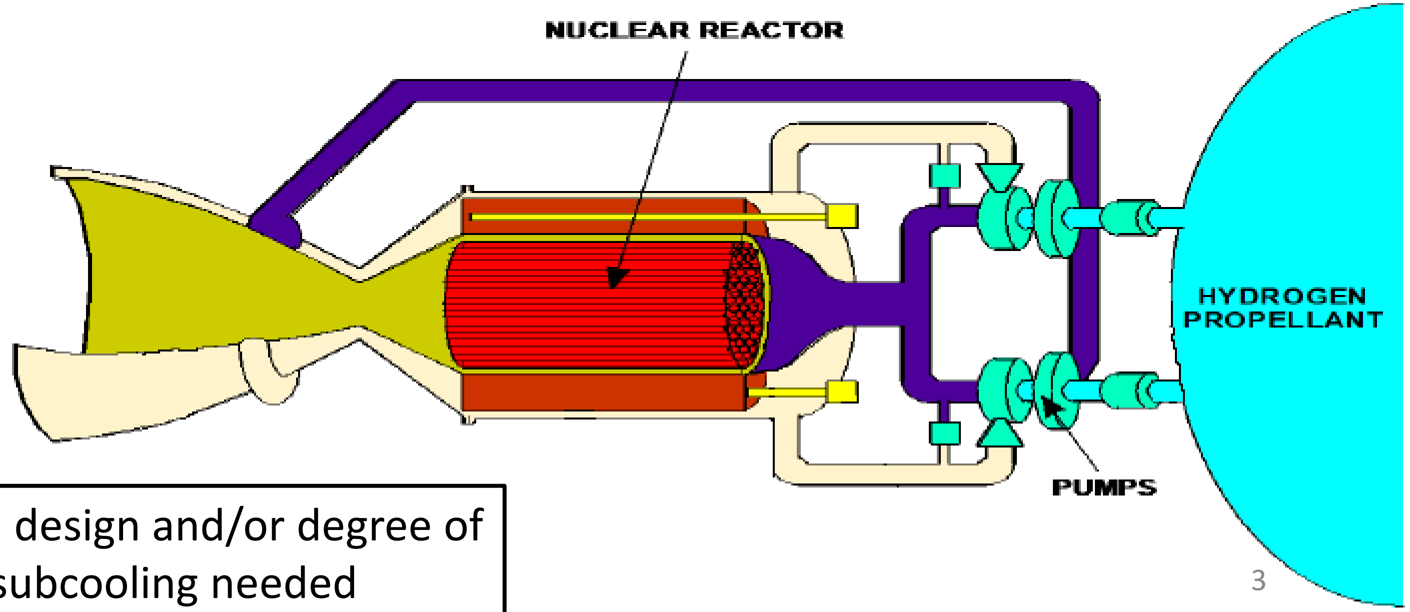
Credit: ULA

Tank-to-pump propellant feedline

Application:

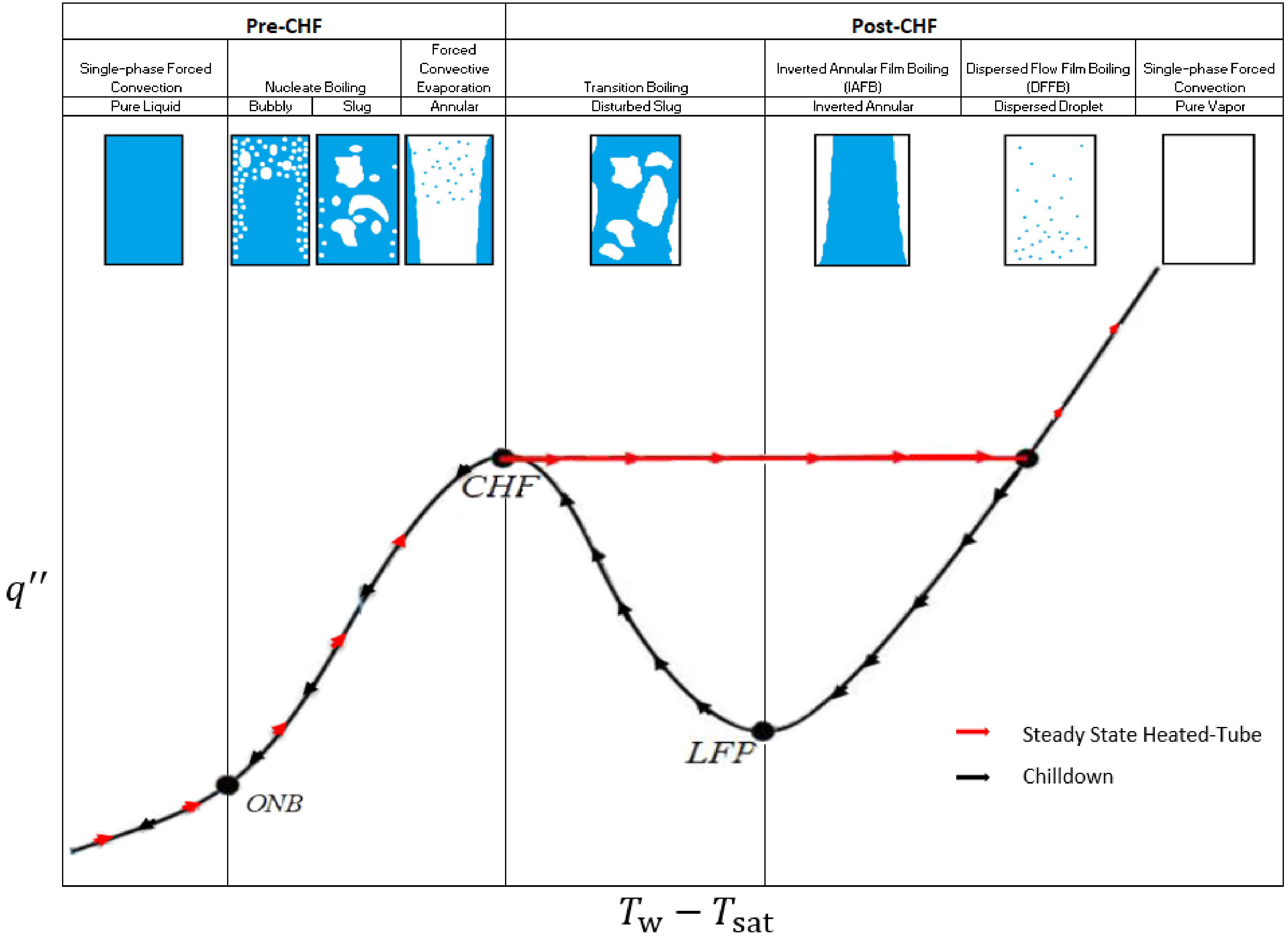
-Ascent and Descent Stages

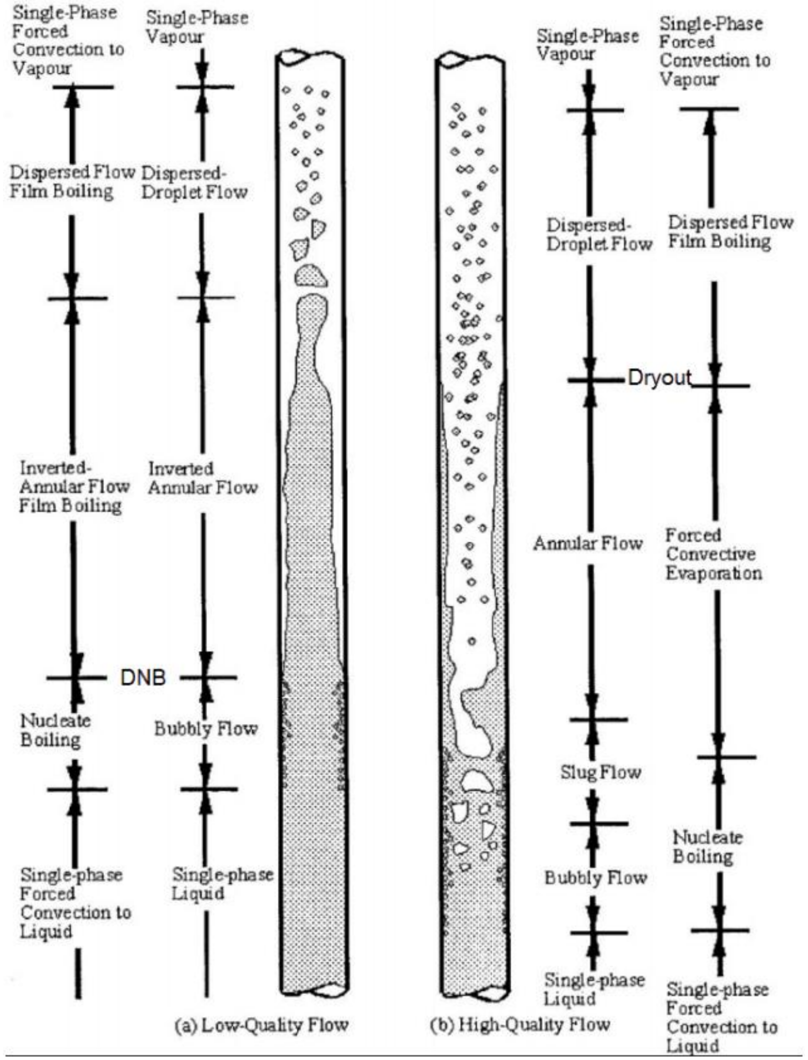
-Nuclear Thermal Propulsion (NTP)



Informs insulation design and/or degree of propellant subcooling needed

Background: Flow Boiling





[4]

Background: Cryogenic Boiling Heat Transfer Correlations

- Most codes use non-cryogenic correlation to model cryogenic boiling
- Starting in 2019, Purdue University in collaboration with NASA Glenn Research Center developed the first-ever set of **universal** cryogenic flow boiling correlations
- After careful filtering of the data, over **9,000 usable cryogenic data points** resulted

Fluids include:

He, H_2, Ne, Ar, N_2, CH_4

Correlations developed:

- Onset of nucleate boiling (ONB)
- Nucleate boiling
- Critical heat flux (CHF)
- Rewet temperature
- Inverted annular film boiling (IAFB)
- Dispersed flow film boiling (DFFB)
- Steady state two-phase pressure drop

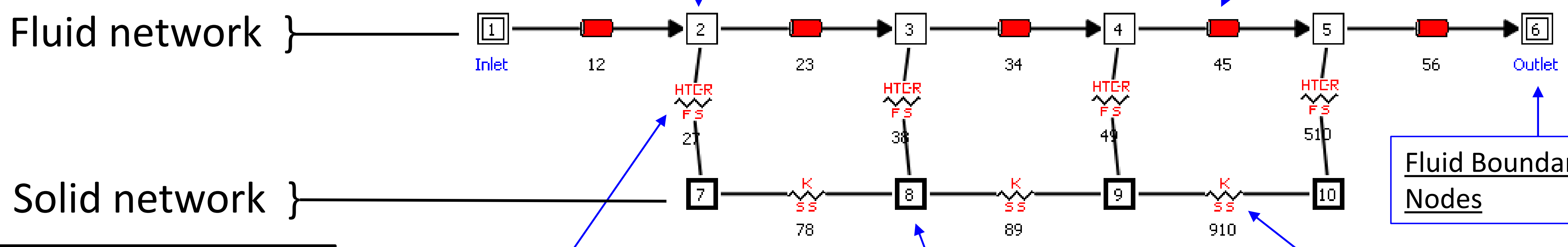
Most of the data are predicted within 25%

Background: Generalized Fluid System Simulation Program (GFSSP)

System level CFD code developed at NASA in the early 90s

Fluid Nodes: mass and energy equations are solved for pressures and enthalpies

Fluid Branches: momentum equation is solved for flowrates



Fluid Boundary Nodes

User subroutines are added for advanced physics

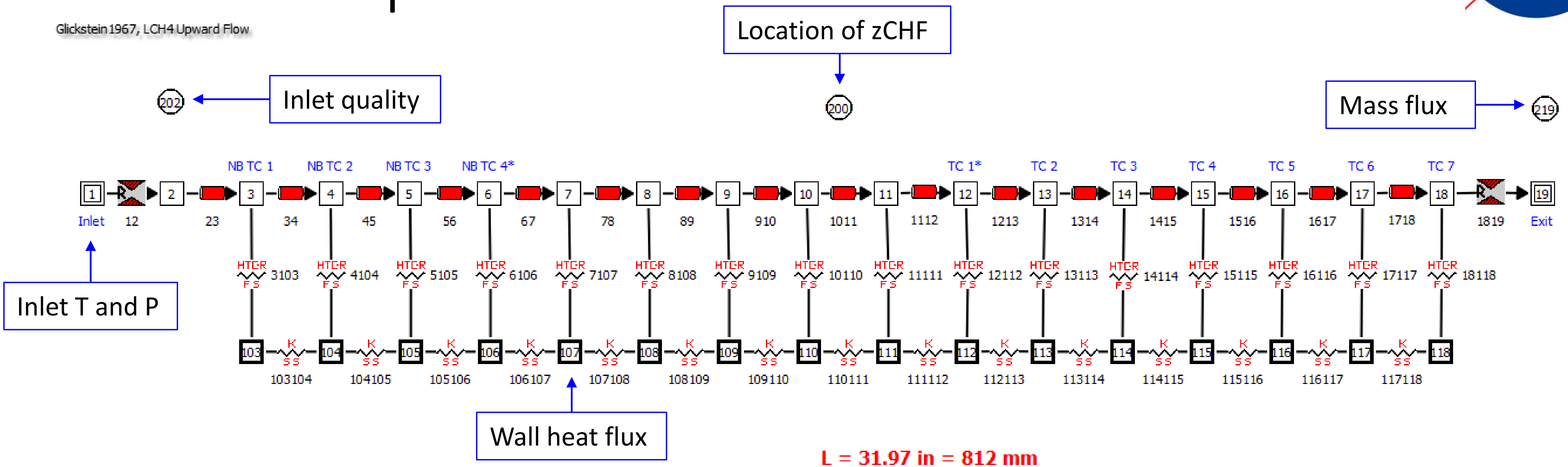
Fluid-to-Solid Conductors: conjugate heat transfer

Solid Nodes: solid energy equation is solved for wall temperature

Solid-to-Solid Conductors

Model Inputs

Glickstein 1967, LCH4 Upward Flow



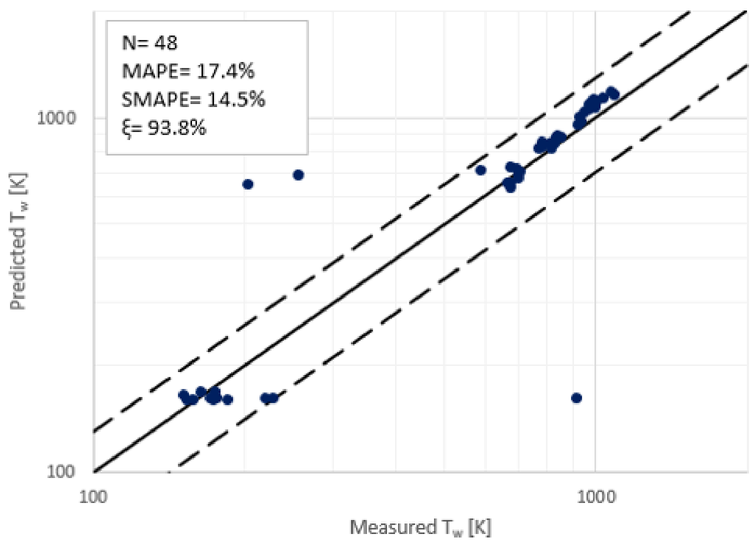
L = 31.97 in = 812 mm

Di = 0.345 in = 8.763 mm

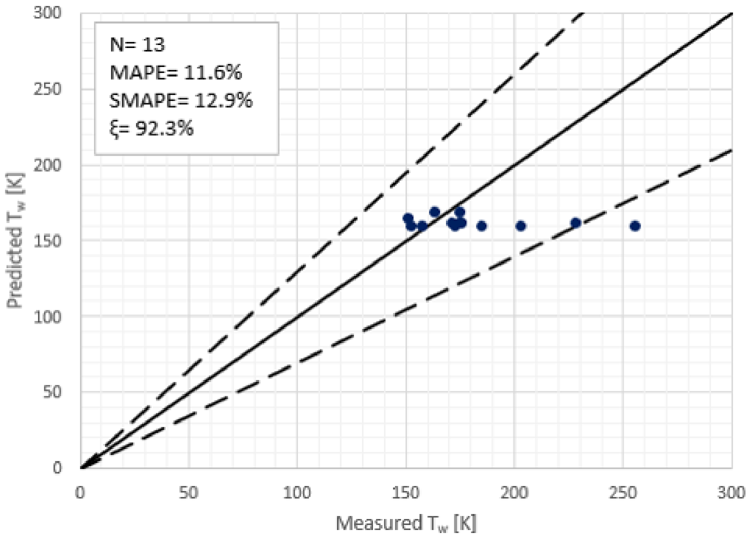
Two types of cases:

1. zCHF-predicted cases
2. zCHF-fixed cases (to ensure pre-CHF correlations are only applied to pre-CHF data points)

Results: Glickstein and Whitesides [1] CH_4



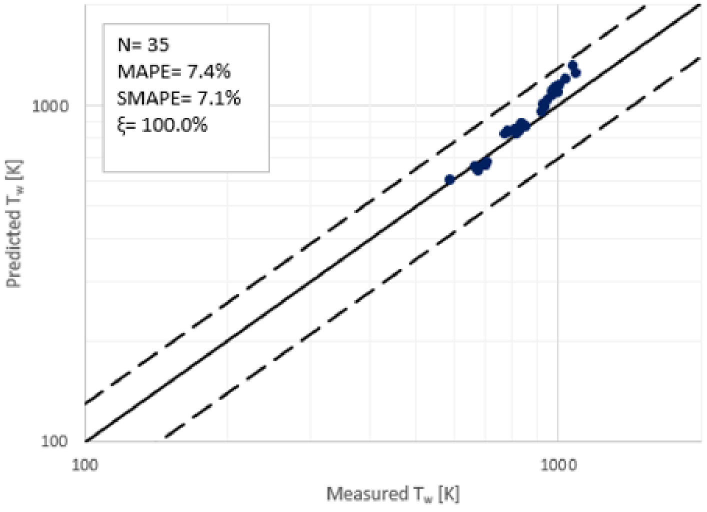
(a)



(b)

$$\text{MAPE} = \frac{1}{N}\sum_{i}^{N}\frac{|T_{\text{sim},i} - T_{\text{exp},i}|}{T_{\text{exp},i}}$$

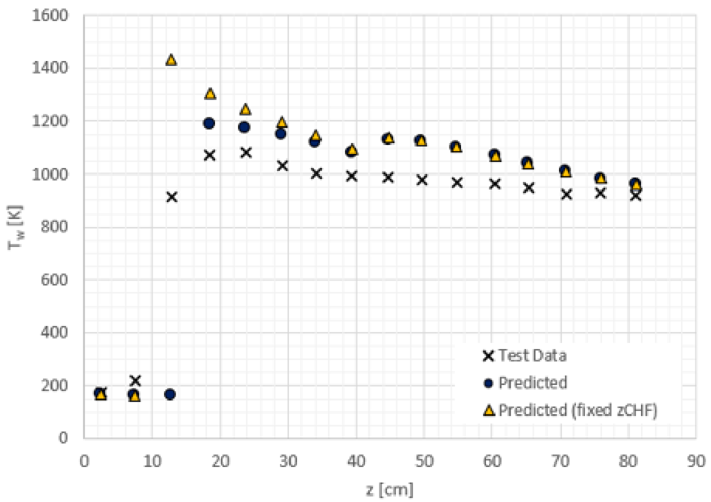
$$\text{SMAPE} = \frac{1}{N}\sum_{i}^{N}\frac{|T_{\text{sim},i} - T_{\text{exp},i}|}{\frac{1}{2}(T_{\text{sim},i} + T_{\text{exp},i})}$$



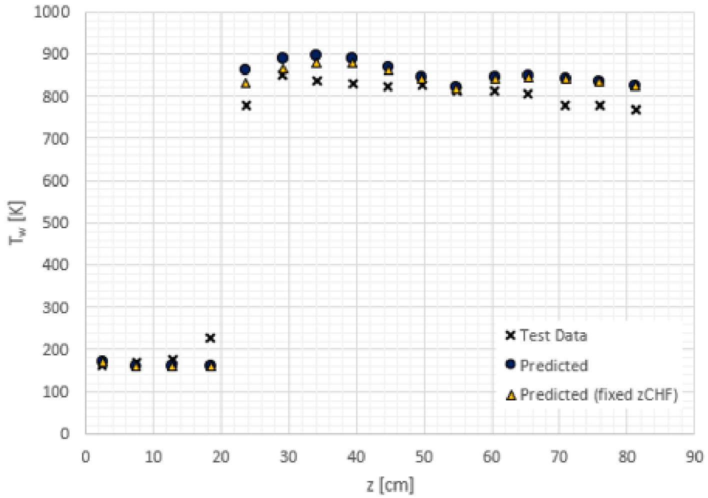
(c)

GFSSP vs. test data:
(a) Case 1 (all points)
(b) Case 2 (pre-CHF points only with fixed zCHF)
(c) Case 3 (post-CHF points only with fixed zCHF)

Results: Glickstein and Whitesides [1] CH_4

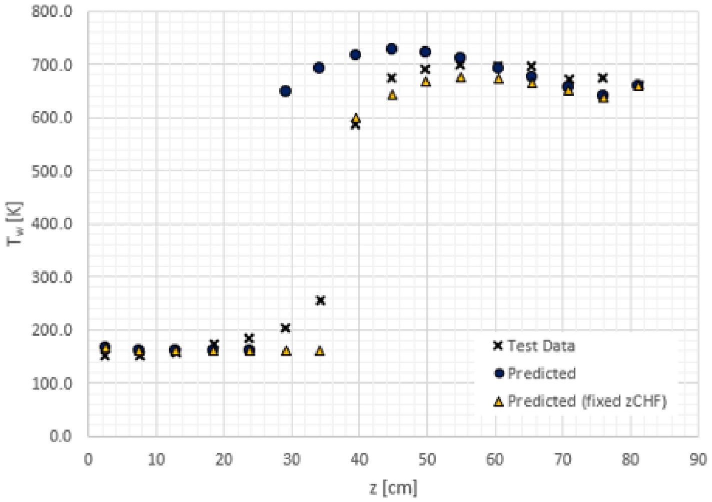


(a)



(b)

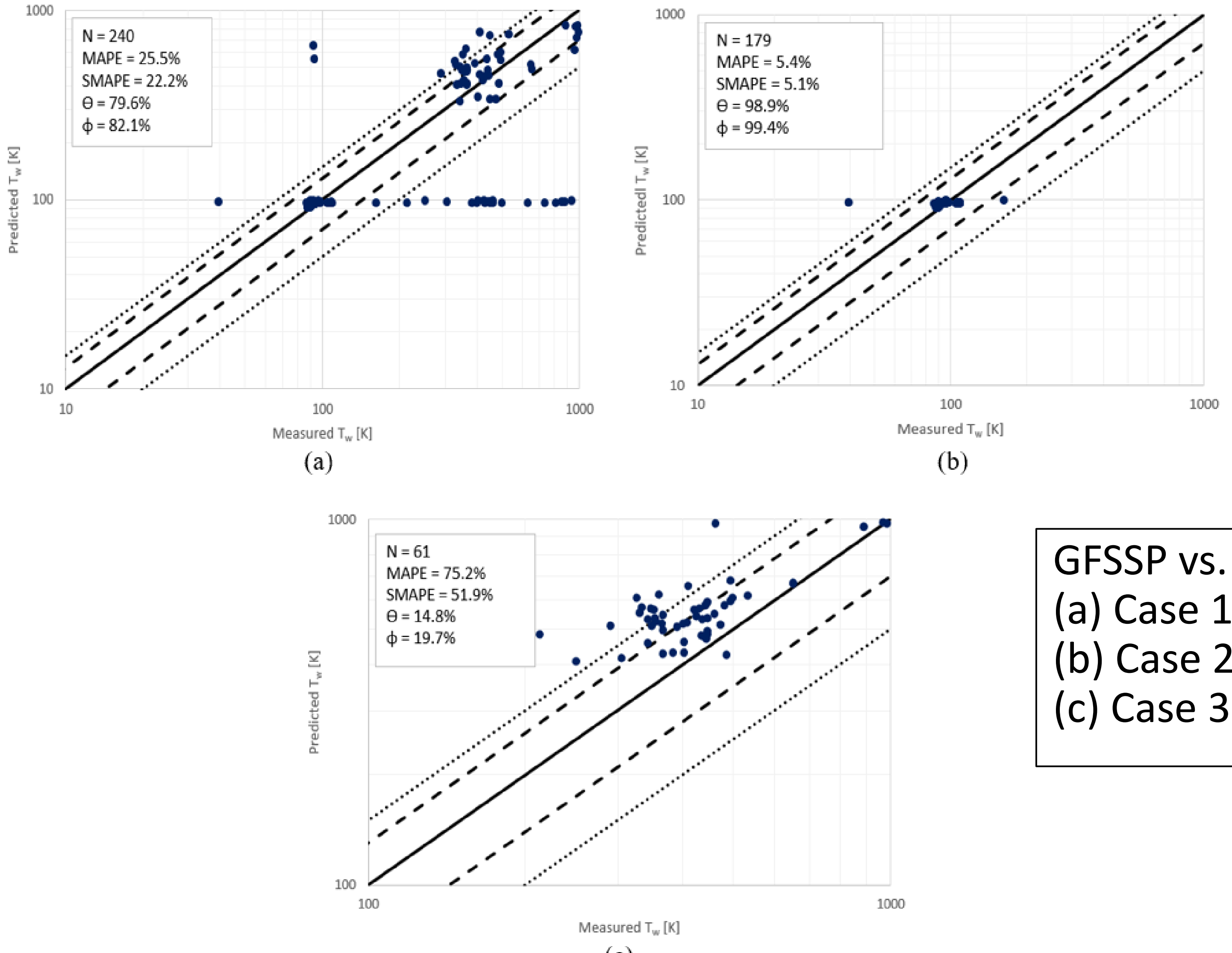
GFSSP vs. test data:
(a) Case 1 (high q’’)
(b) Case 2 (mid q’’)
(c) Case 3 (low q’’)



(c)

- Note points near CHF affected by axial conduction
- “Bump” in the post-CHF region occurs where flow become single-phase vapor

Results: Lewis et al. [2] N_2



(a)

(b)

(c)

$$\text{MAPE} = \frac{1}{N}\sum_{i}^{N}\frac{|T_{\text{sim},i} - T_{\text{exp},i}|}{T_{\text{exp},i}}$$

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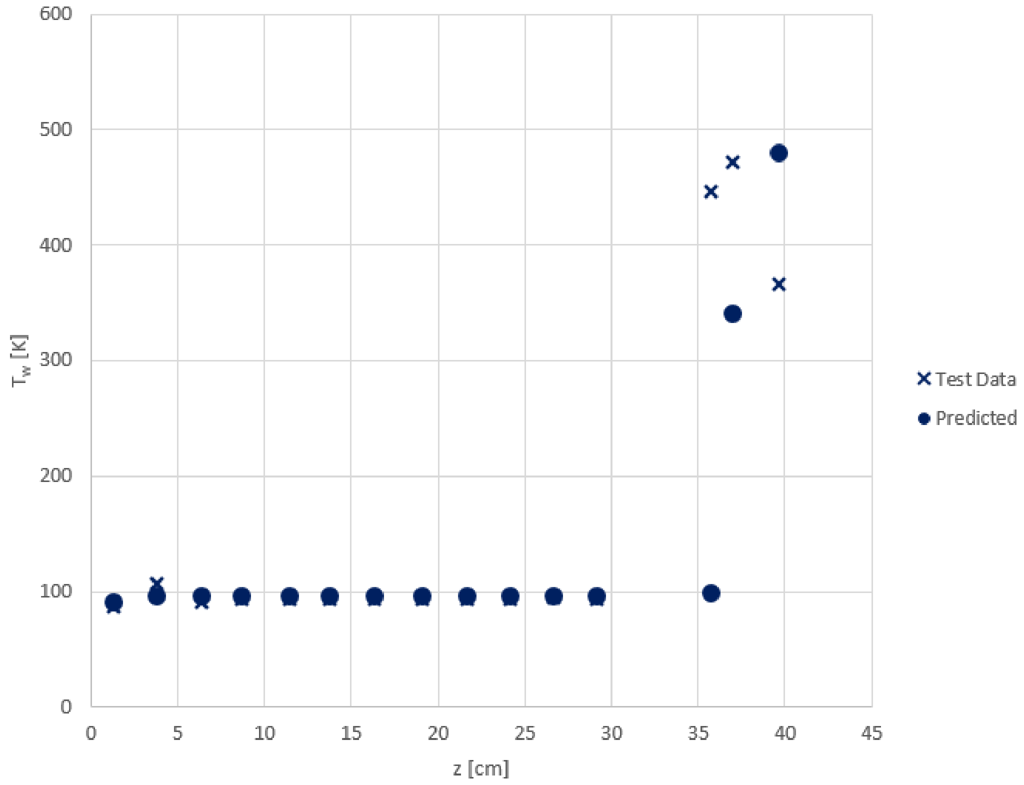
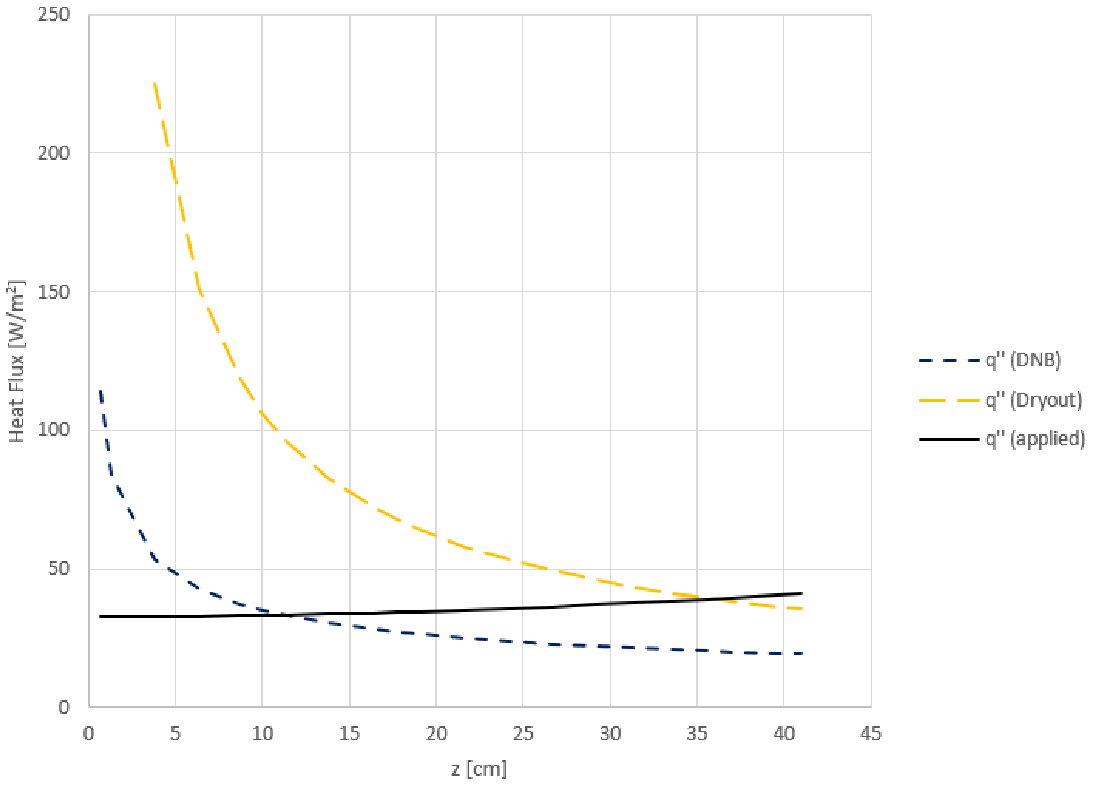
GFSSP vs. test data:
(a) Case 1 (all points)
(b) Case 2 (pre-CHF points only with fixed zCHF)
(c) Case 3 (post-CHF points only with fixed zCHF)

Results: Lewis et al. [2] N_2 (Case 268)

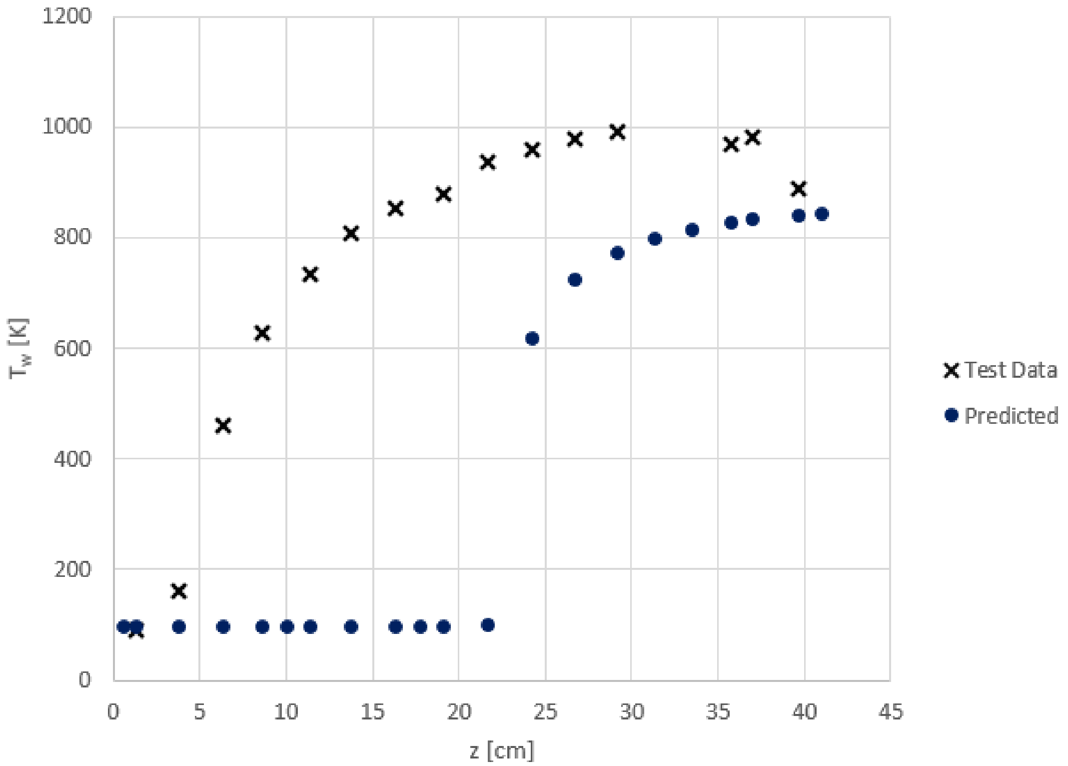


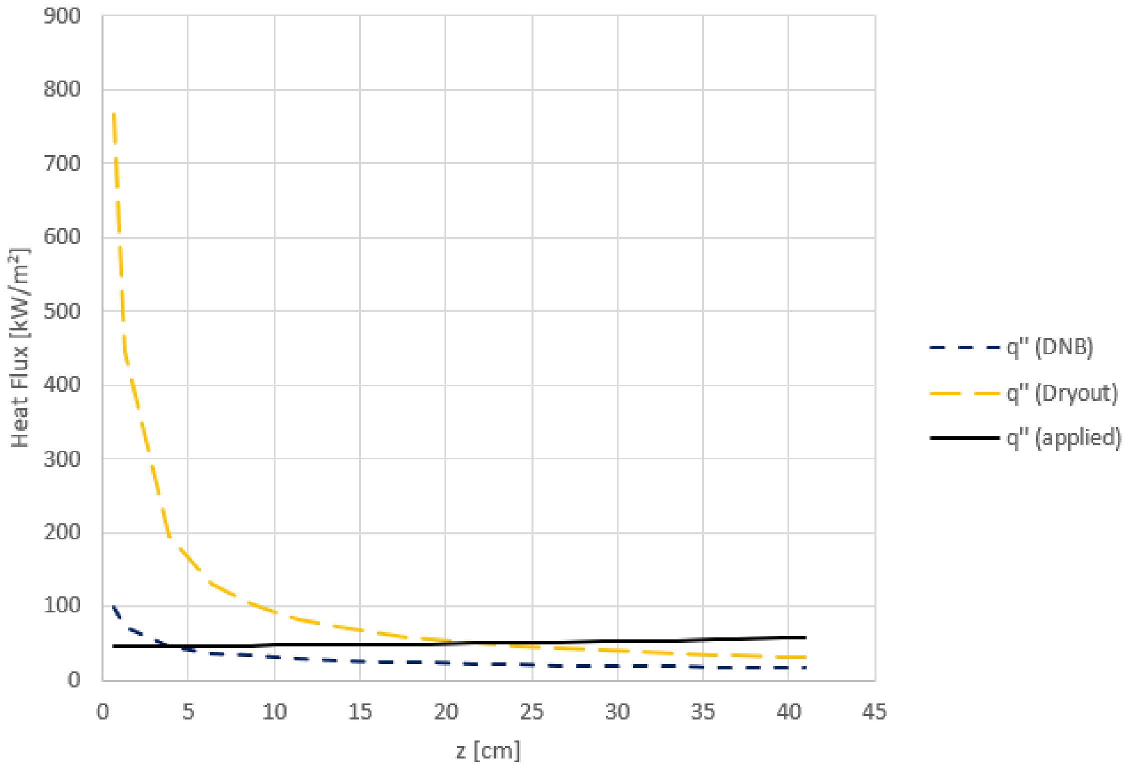


GFSSP overpredicted the location of CHF in 12 of the 16 cases considered (average error of 8.9% normalized by pipe length)

GFSSP underpredicted the location of CHF in 3 of the 16 cases considered (average error of -7.0% normalized by pipe length)

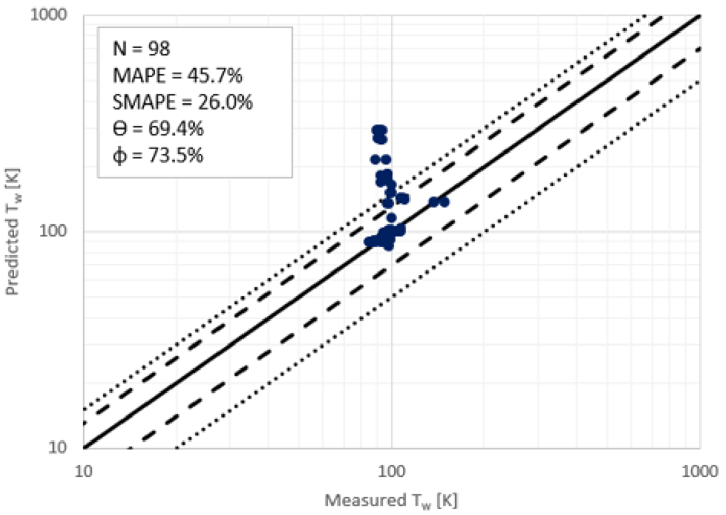
Results: Lewis et al. [2] N_2 (Case 327)



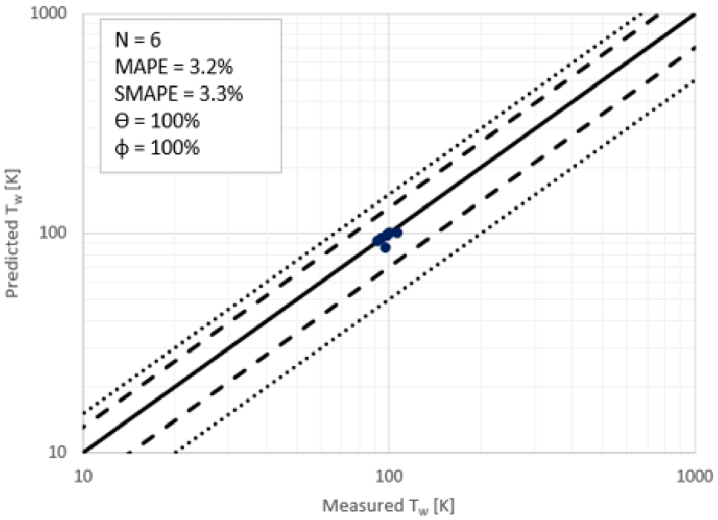


GFSSP incorrectly predicts the type of CHF in only one case

Results: Qi et al. [3] N_2



(a)



(b)

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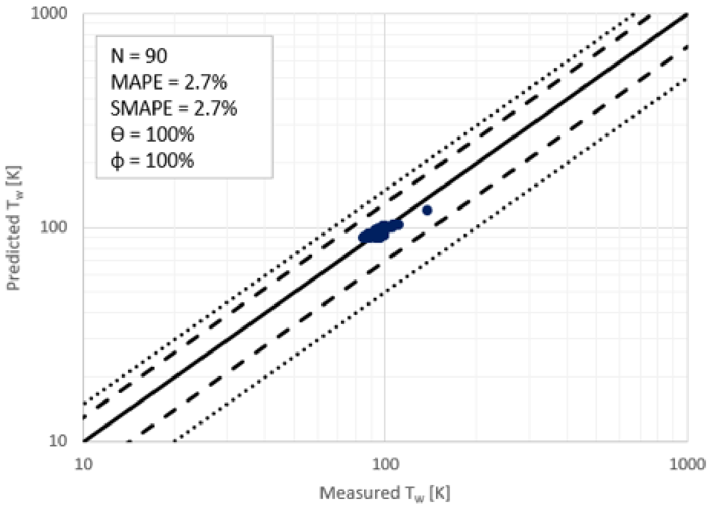
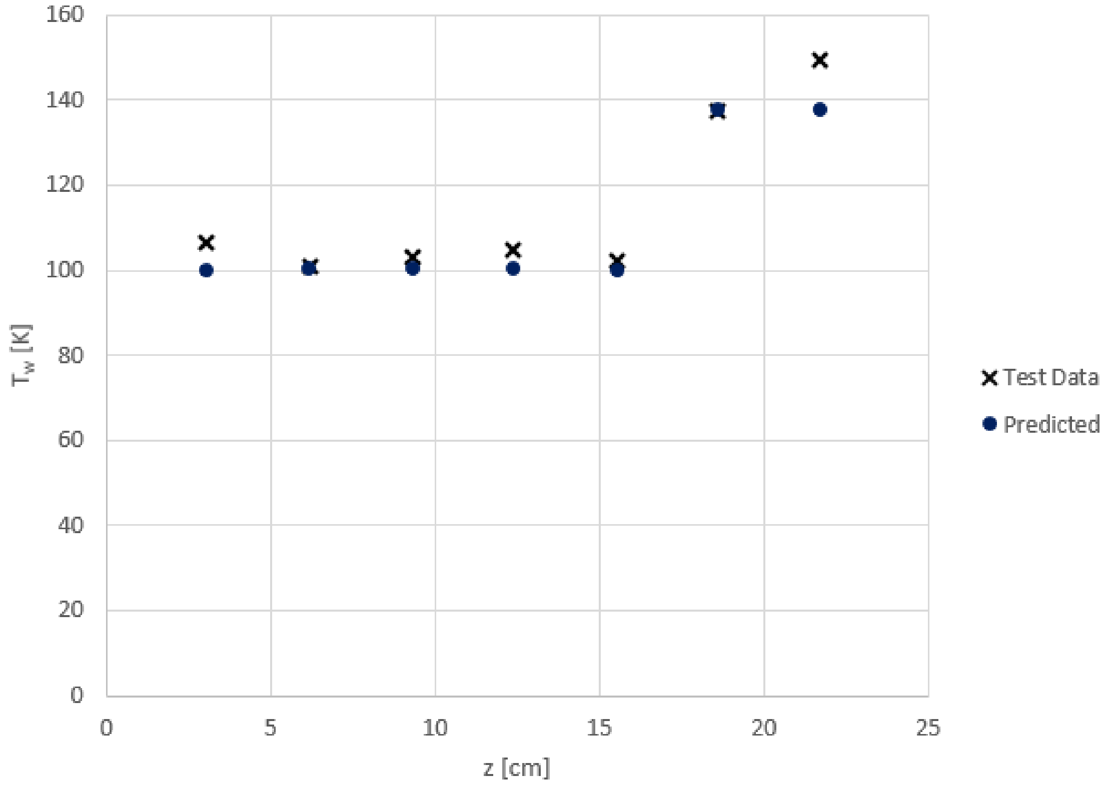
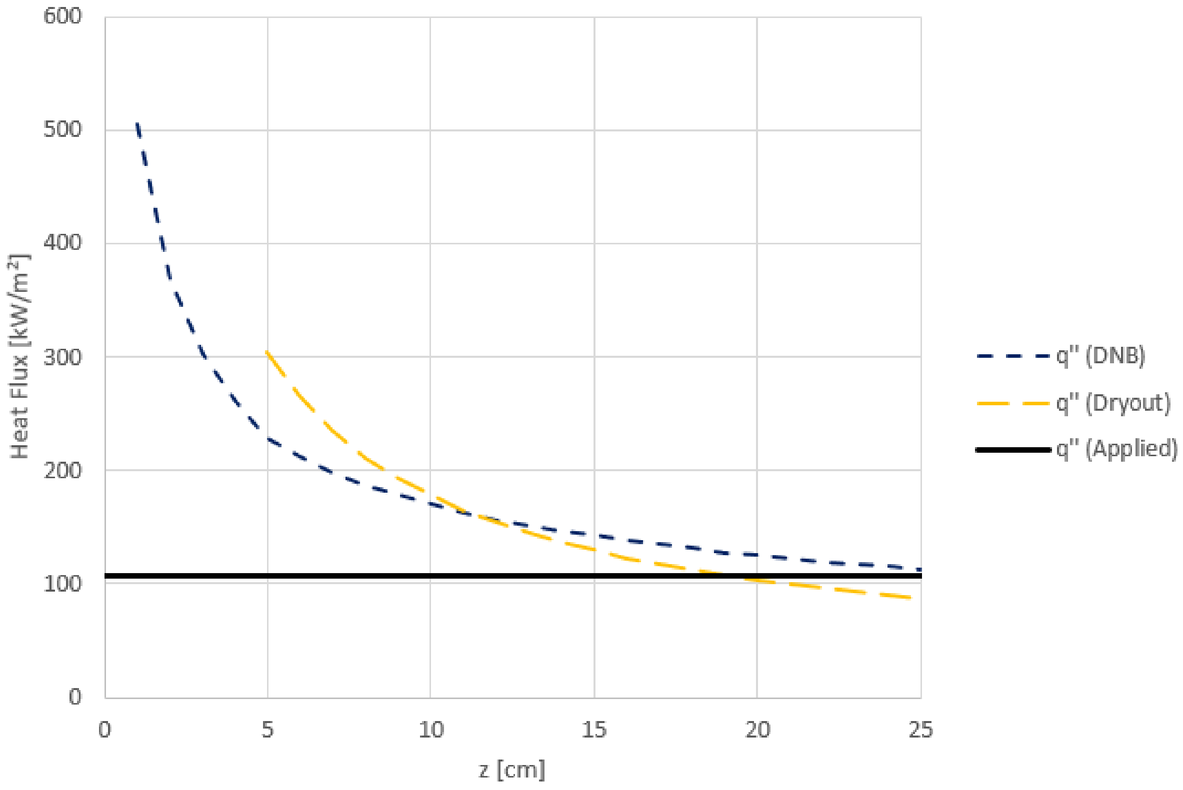


(c)

GFSSP vs. test data:
(a) Case 1 (all points)
(b) Case 2 (pre-ONB points only)
(c) Case 3 (post-ONB and pre-CHF points only with fixed zCHF)

Results Qi et al. [3] N_2 (Sample Case)





GFSSP correctly predicted the occurrence of CHF in the one case it was observed.

Conclusions

- Using GFSSP with universal Purdue University cryogenic flow boiling correlations:
  - Glickstein and Whitesides [1] CH_4 has SMAPE of 14.5%
  - Lewis et al. [2] N_2 has SMAPE of 22.2%
  - Qi et al. [3] N_2 has SMAPE of 26.0%
- When predictive errors occur, the chief culprit is the type and location of the CHF
  - CHF predictions are excellent for Glickstein and Whitesides [1]
  - CHF predictions are excellent for Lewis et al. [2] (only one mis-prediction of CHF type)
  - For Qi et al. [3] CHF is usually predicted but not observed.

References

- [1] GLICKSTEIN, MR, and RH WHITESIDES. "Forced-convection nucleate and film boiling of several aliphatic hydrocarbons(Heat transfer characteristics of several aliphatic hydrocarbons in nucleate and film boiling during forced flow in heated tubes)." (1967).
- [2] Lewis, James P., Jack H. Goodykoontz, and John F. Kline. *Boiling heat transfer to liquid hydrogen and nitrogen in forced flow*. National Aeronautics and Space Administration, 1962.
- [3] Qi, S. L., et al. "Flow boiling of liquid nitrogen in micro-tubes: Part II–Heat transfer characteristics and critical heat flux." *International journal of heat and mass transfer* 50.25-26 (2007): 5017-5030.
- [4] Sherley, Joan E. "Nucleate boiling heat-transfer data for liquid hydrogen at standard and zero gravity." *Advances in Cryogenic Engineering: Proceedings of the 1962 Cryogenic Engineering Conference University of California Los Angeles, California August 14–16, 1962*. Springer US, 1963.
- [5] Mercado, Mariano, Nathaniel Wong, and Jason Hartwig. "Assessment of two-phase heat transfer coefficient and critical heat flux correlations for cryogenic flow boiling in pipe heating experiments." *International Journal of Heat and Mass Transfer* 133 (2019): 295-315.