Validation of Heat Transfer Correlations in Line Chill-down Tests of Cryogenic Fluid in SINDA/FLUINT

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Introduction

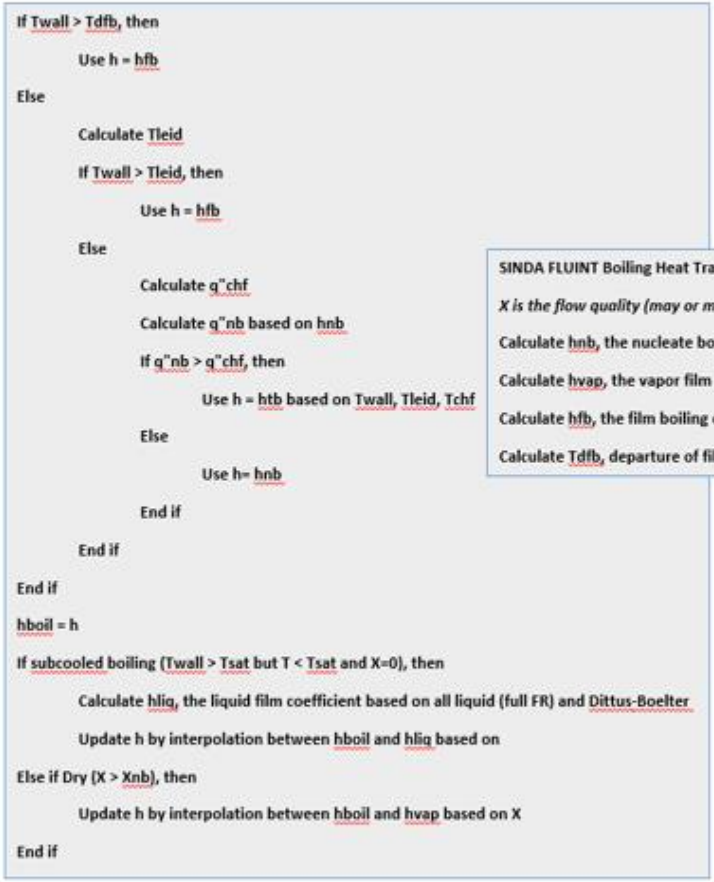
- Line chill-down is an important process in cryogenic tank propellant management, storage, and usage
- Complex flow dynamics during these processes:
  - boiling heat transfer (film, transition, and nucleate)
- Understanding boiling phenomena can lead to efficient line chill-down systems that use less propellant, propellant stored, reducing cost for space missions

Current Work

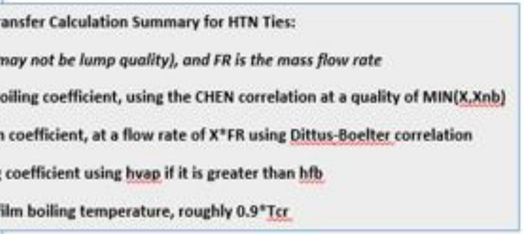
- Line Chill-down heat transfer was modelled using SINDA/FLUINT version 5.8 (SF)
- Multiple chill-down tests were modelled using:
  - heat transfer correlations readily available in SF using HTN/HTC TIES
  - heat transfer empiricisms developed by the University of Florida (UF) based on a series of liquid nitrogen chill-down tests using SF HTU TIES
- Chill-down tests modelled:
  - liquid nitrogen tests conducted by the University of Florida
    - horizontal flow, upward flow, and downward flow (Reynolds Numbers ranging 850 – 231,000)
  - liquid hydrogen tests conducted by NASA Glenn Research Center
    - vertical upward flow (Reynolds Number range of 18,400 – 433,000)

Heat Transfer

SF Heat Transfer Methodology



```
If Twall > Tdfb, then
    Use h = hfb
Else
    Calculate Tleid
    If Twall > Tleid, then
        Use h = hfb
    Else
        Calculate q"chf
        Calculate q"nb based on hnb
        If q"nb > q"chf, then
            Use h = htb based on Twall, Tleid, Tchf
        Else
            Use h= hnb
        End if
    End if
End if
hboil = h
If subcooled boiling (Twall > Tsat but T < Tsat and X=0), then
    Calculate hliq, the liquid film coefficient based on all liquid (full FR) and Dittus-Boelter
    Update h by interpolation between hboil and hliq based on
Else if Dry (X > Xnb), then
    Update h by interpolation between hboil and hvap based on X
End if
```



SINDA FLUINT Boiling Heat Transfer Calculation Summary for HTN Ties:

X is the flow quality (may or may not be lump quality), and FR is the mass flow rate

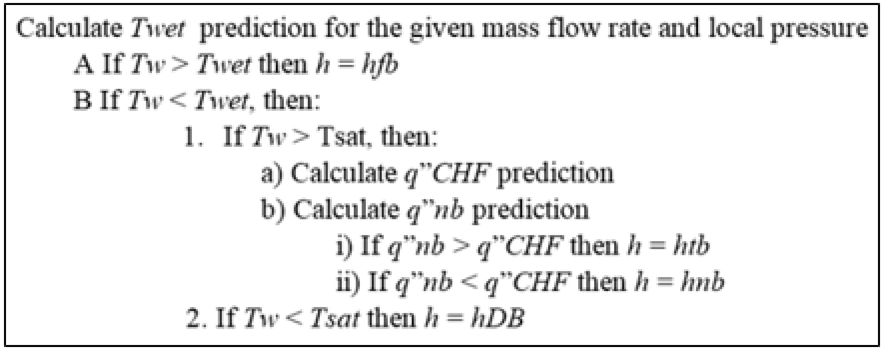
Calculate hnb, the nucleate boiling coefficient, using the CHEN correlation at a quality of MIN(X,Xnb)

Calculate hvap, the vapor film coefficient, at a flow rate of X*FR using Dittus-Boelter correlation

Calculate hfb, the film boiling coefficient using hvap if it is greater than hfb

Calculate Tdfb, departure of film boiling temperature, roughly 0.9*Tcr

UF Heat Transfer Methodology



```
Calculate $Twet$ prediction for the given mass flow rate and local pressure
    A If $Tw > Twet$ then $h = hfb$
    B If $Tw < Twet$, then:
        1. If $Tw >$ Tsat, then:
            a) Calculate $q''CHF$ prediction
            b) Calculate $q''nb$ prediction
                i) If $q''nb > q''CHF$ then $h = htb$
                ii) If $q''nb < q''CHF$ then $h = hnb$
        2. If $Tw < Tsat$ then $h = hDB$
```

Figure 1: Heat Transfer Methodology

Heat Transfer

UF Film Boiling Correlation:

$$Nu = c_1 \left[1 + \left(\frac{1}{\frac{L}{D} + 0.1} \right)^{c_2} \right] \left(\frac{GD}{\mu_v} \right)^{c_3} \mathrm{Pr}_v^{c_4}\, erf \left(\frac{X_E + 1}{\log_{c_5} \mathrm{Re}_v} \right)^{c_6} \left(\frac{\mu_v}{\mu_{v,\mathrm{wall}}} \right)^{c_7}$$

$$+ c_8 \left(\frac{k_l}{k_v} \right) \exp\left(- \left(\frac{L}{D} \right)^{c_9} \right) We_D^2 \left[\frac{h_{fg}}{c_{p,v}(T_w - T_{sat})} \right]$$

Weber number, $G^2 D / (\rho_l \sigma)$

SF film boiling uses a correlation by Bromley for low quality flows*:

$$U_{FB} = 0.62 \left[\frac{k_v^3 \rho_v g (\rho_l - \rho_v)(h_{fg} + 0.4 C_{p,v} \Delta T)}{L_h \cdot \mu_v \Delta T} \right]^{\frac{1}{4}}$$

Diameter for external flow
Or MIN (Diameter/2,hemholtz instability, L_h) for internal flow

$$L_{h,\max} = 8.646 \left[\frac{\sigma^4 \cdot h_{fg}^3 \cdot \mu_v^5}{\rho_v \cdot (\rho_l - \rho_v)^5 \cdot g \cdot k_v^3 \cdot \mu_v \cdot \Delta T^3} \right]^{\frac{1}{11}}$$

*For higher quality flows a correlation by Groeneveld is used making sure the minimum is a least vapor Dittus-Boelter

Heat Transfer

UF Nucleate Boiling Correlation:

$$h_{nb} = c_1 \mathrm{Pr}_l^{c_2} Ja^{c_3} We_D^{c_4} \left[\frac{\rho_l g (\rho_l - \rho_v) D^3}{\mu_l^2} \right]^{c_5} h_{sp,l}$$

$$h_{sp,l} = 0.023 \frac{k_l}{D} \mathrm{Re}_l^{0.8} \mathrm{Pr}_l^{0.4}$$

$$\dot{q}_{CHF} = c_1 G h_{fg} We_L^{-0.5} \left(\frac{\rho_l}{\rho_v} \right)^{-0.91} \left(\frac{L}{D} \right)^{0.48} \left(1 + 0.07 We_L^{0.35} \frac{\Delta h_{sub}}{h_{fg}} \right)$$

UF Transition Boiling Correlation:

$$h_{tp} = c_0 \mathrm{Pr}_l^{c_6} X h_{nb}$$

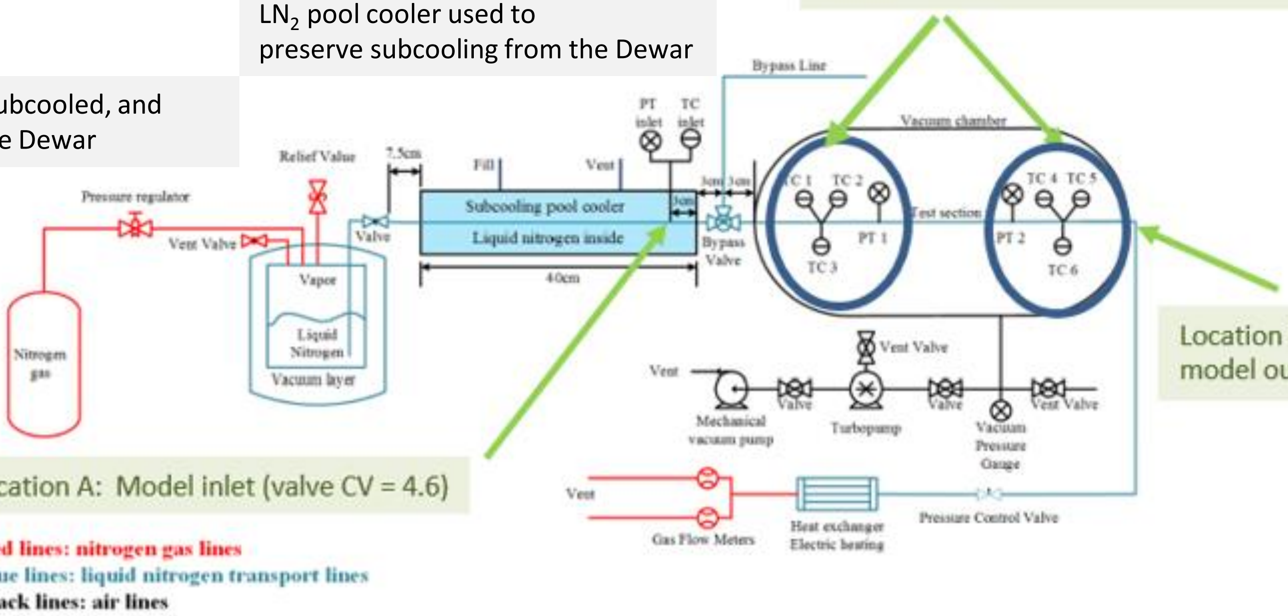
$$X = 10.37 - 36.93\theta + 47.49\theta^2 - 20.82\theta^3$$

$$\theta = \frac{T_w - T_{sat}}{T_{wet} - T_{sat}}$$

$$T_{wet} = \frac{27}{32} T_{cr} (1 + c_1 We_D^{c_8} Re_l^{c_9 Ja^{c_{10}}})$$

SF nucleate boiling uses the Chen correlation, and transition boiling is a nonlinear interpolation between nucleate and film boiling

Liquid Nitrogen Line Chill-down



Test section upstream and downstream wall temperature measurements

LN$_2$ pool cooler used to preserve subcooling from the Dewar

LN$_2$ was pressurized, subcooled, and supplied from a storage Dewar

Location A: Model inlet (valve CV = 4.6)

Location B: model outlet

Red lines: nitrogen gas lines
Blue lines: liquid nitrogen transport lines
Black lines: air lines

Figure 2: Liquid Nitrogen Chill-down Test Schematic

Liquid Nitrogen Line Chill-down

PIPE LENGTH	22.5 IN (57.2 CM)
PIPE OD	0.5 IN (1.27 CM)
PIPE ID	0.46 IN (1.168 CM)
WALL THICKNESS	0.02 IN (0.0508 CM)
WALL MASS	0.184 LBM (0.0836 KG)
MATERIAL	SS 304

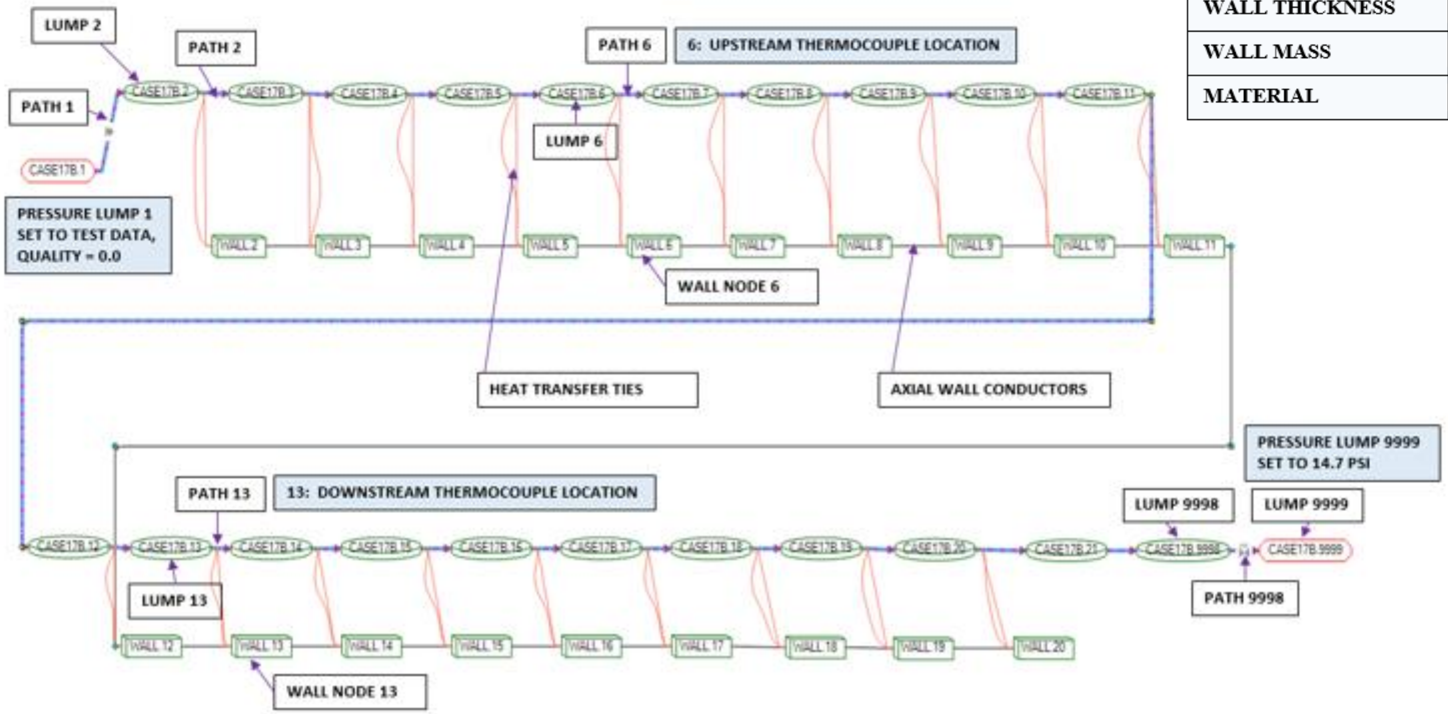


Figure 3: SINDA/FLUINT Flow Schematic of the Liquid Nitrogen Test Section Showing Fluid LUMPS, Flow PATHS, Wall NODES, Heat Transfer TIES, and Pipe Axial CONDUCTORS

Liquid Nitrogen Line Chill-down Model Assumptions

The flow rate was measured far downstream of the test section, near the system exit. Where to set the flow rate?

- SF was highly sensitive, and sometime unstable, setting the test flow rate downstream (the outlet) of the test section model and setting the test pressure upstream (the inlet) of the test section model
  - higher flow rate oscillations at the entrance of the model's test section
- SF was more stable setting the test flow rate upstream (than the downstream flow rate set case)
  - test pressure was used as an inlet (SF plenum) to set the thermodynamic state (temperature and quality) coming into the system
  - setting the appropriate downstream pressure was the unknown

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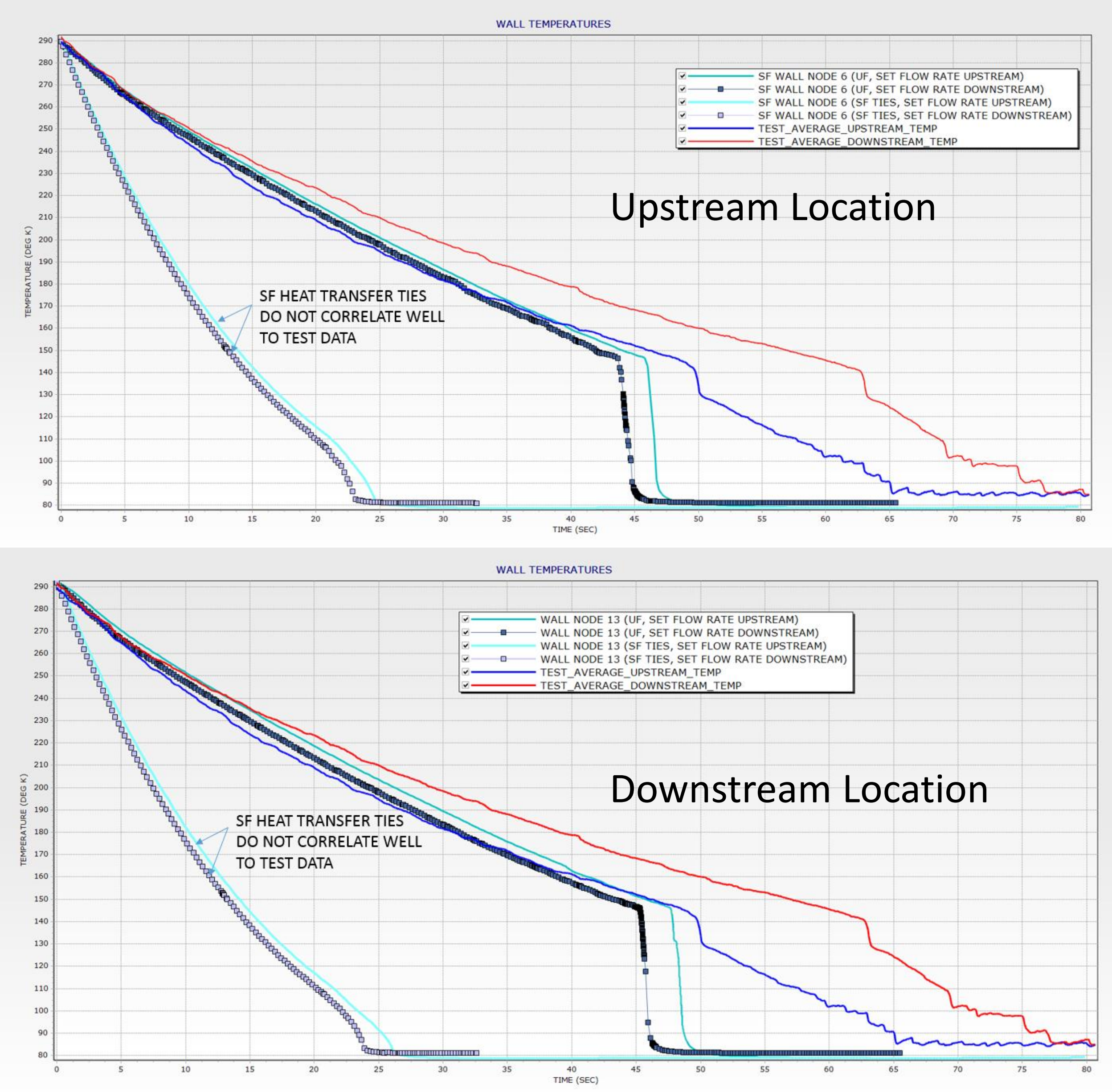
  - setting the appropriate downstream pressure was the unknown

Liquid Nitrogen Line Chill-down Model Assumptions

The pressure drops predicted by SF for the downstream set flow rate boundary condition were much smaller than test section measured pressure drops

- The multiphase pressure drop correlations used internally in SF may need to be adjusted
- Models with an upstream flow rate set assumed a pressure drop that was small

Liquid Nitrogen Line Chill-down Results (Horizontal Flow)



Upstream Location

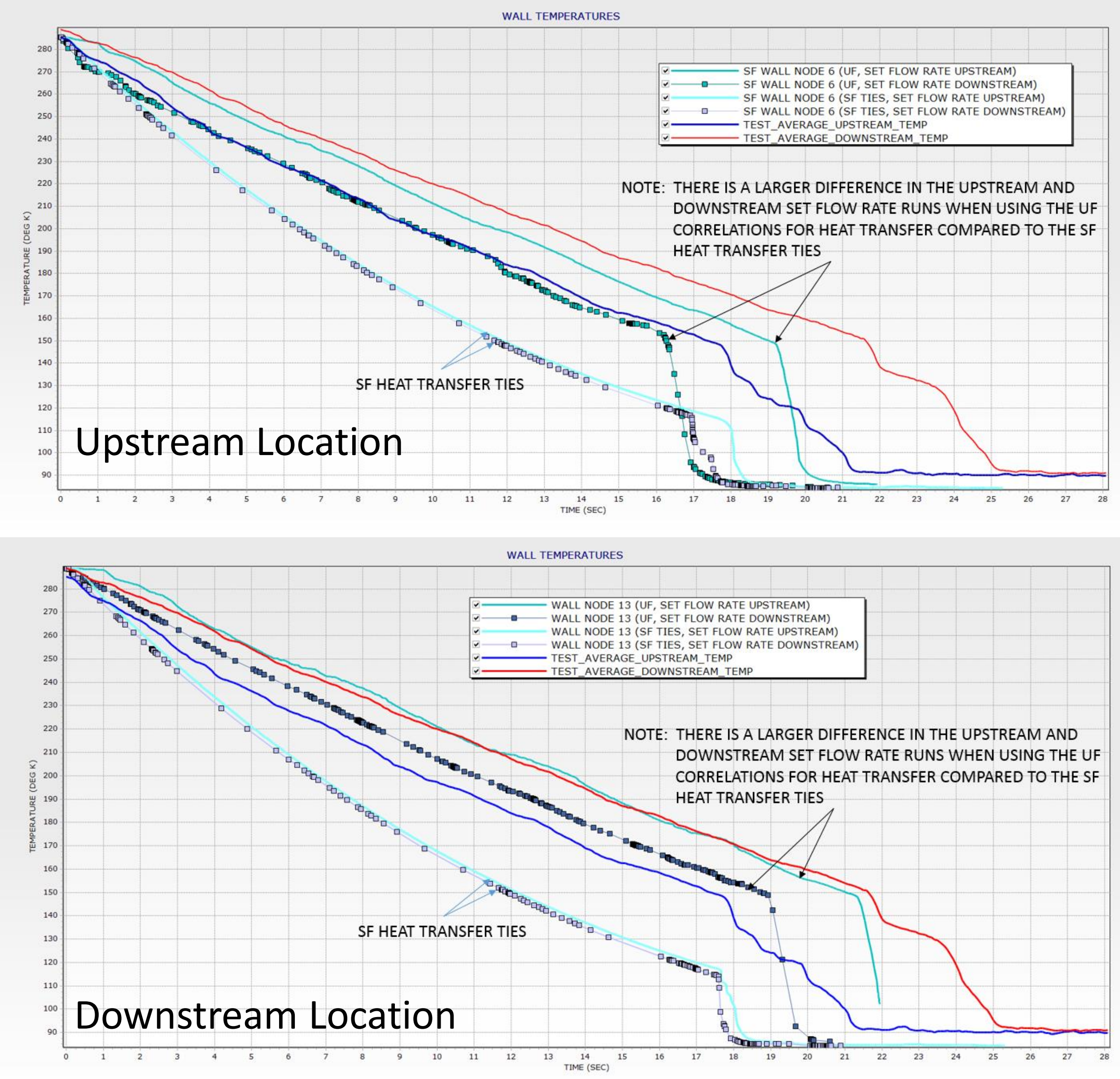
SF HEAT TRANSFER TIES DO NOT CORRELATE WELL TO TEST DATA

Downstream Location

SF HEAT TRANSFER TIES DO NOT CORRELATE WELL TO TEST DATA

Figure 4a-4b: Wall Temperatures for Liquid Nitrogen Horizontal Chill-down Test Case Reynolds Number = 3743

Liquid Nitrogen Line Chill-down Results (Horizontal Flow)



NOTE: THERE IS A LARGER DIFFERENCE IN THE UPSTREAM AND DOWNSTREAM SET FLOW RATE RUNS WHEN USING THE UF CORRELATIONS FOR HEAT TRANSFER COMPARED TO THE SF HEAT TRANSFER TIES

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Figure 5a-5b: Wall Temperatures for Liquid Nitrogen Horizontal Chill-down Test Case Reynolds Number = 23677

Liquid Nitrogen Line Chill-down Results (Horizontal Flow)

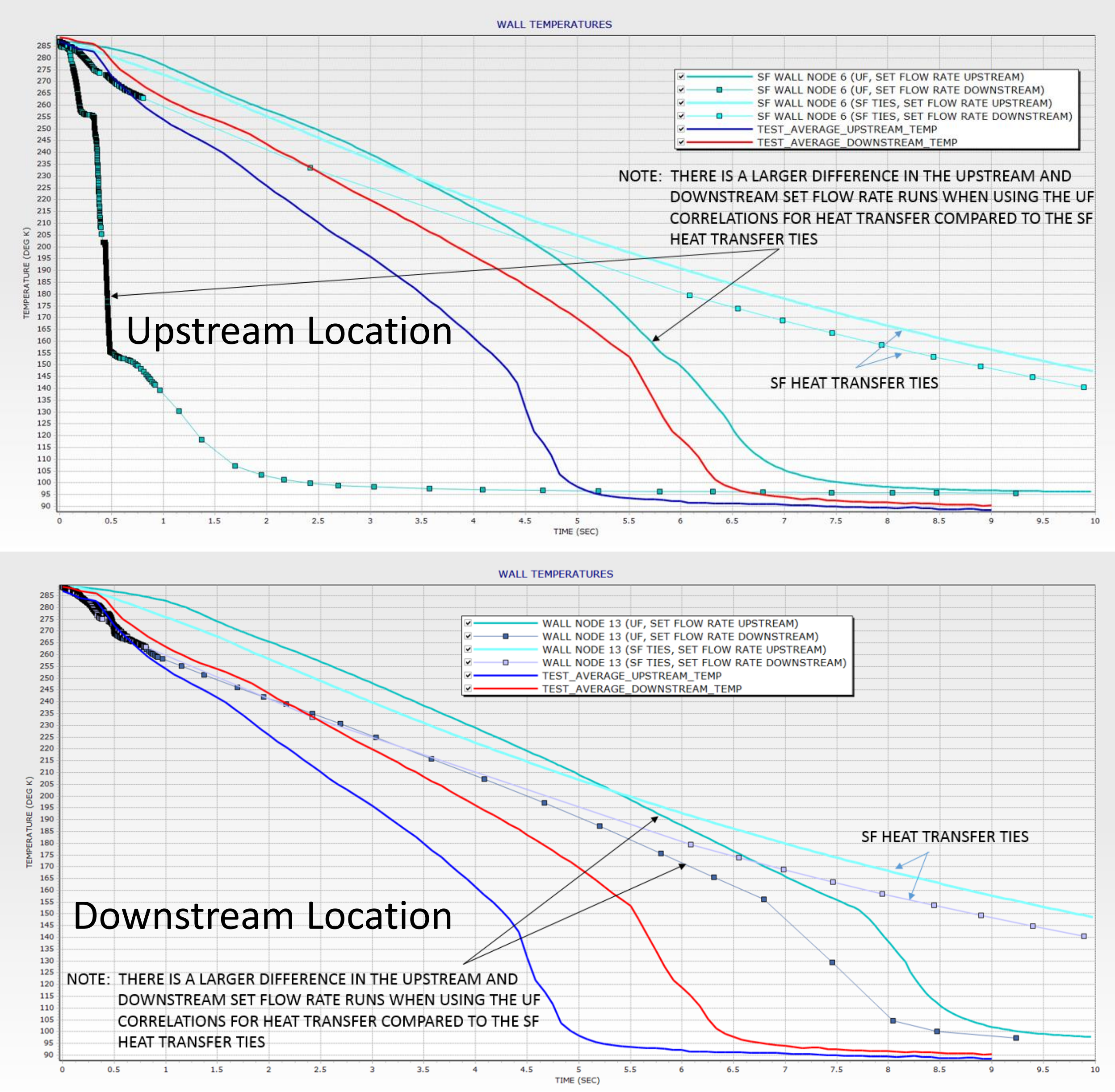

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Figure 6a-6b: Wall Temperatures for Liquid Nitrogen Horizontal Chill-down Test Case Reynolds Number = 132597

Liquid Nitrogen Line Chill-down Results (Horizontal Flow)

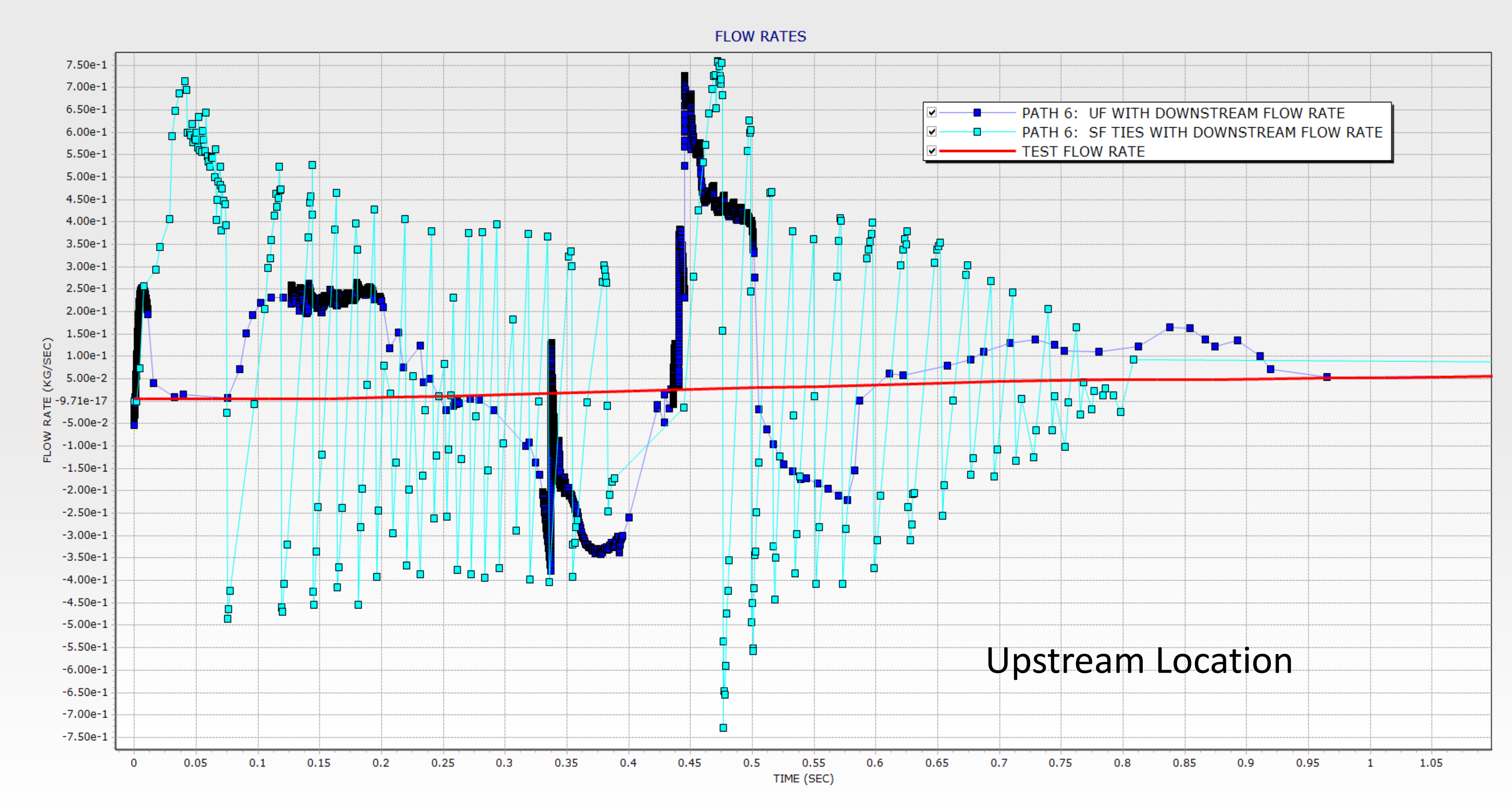
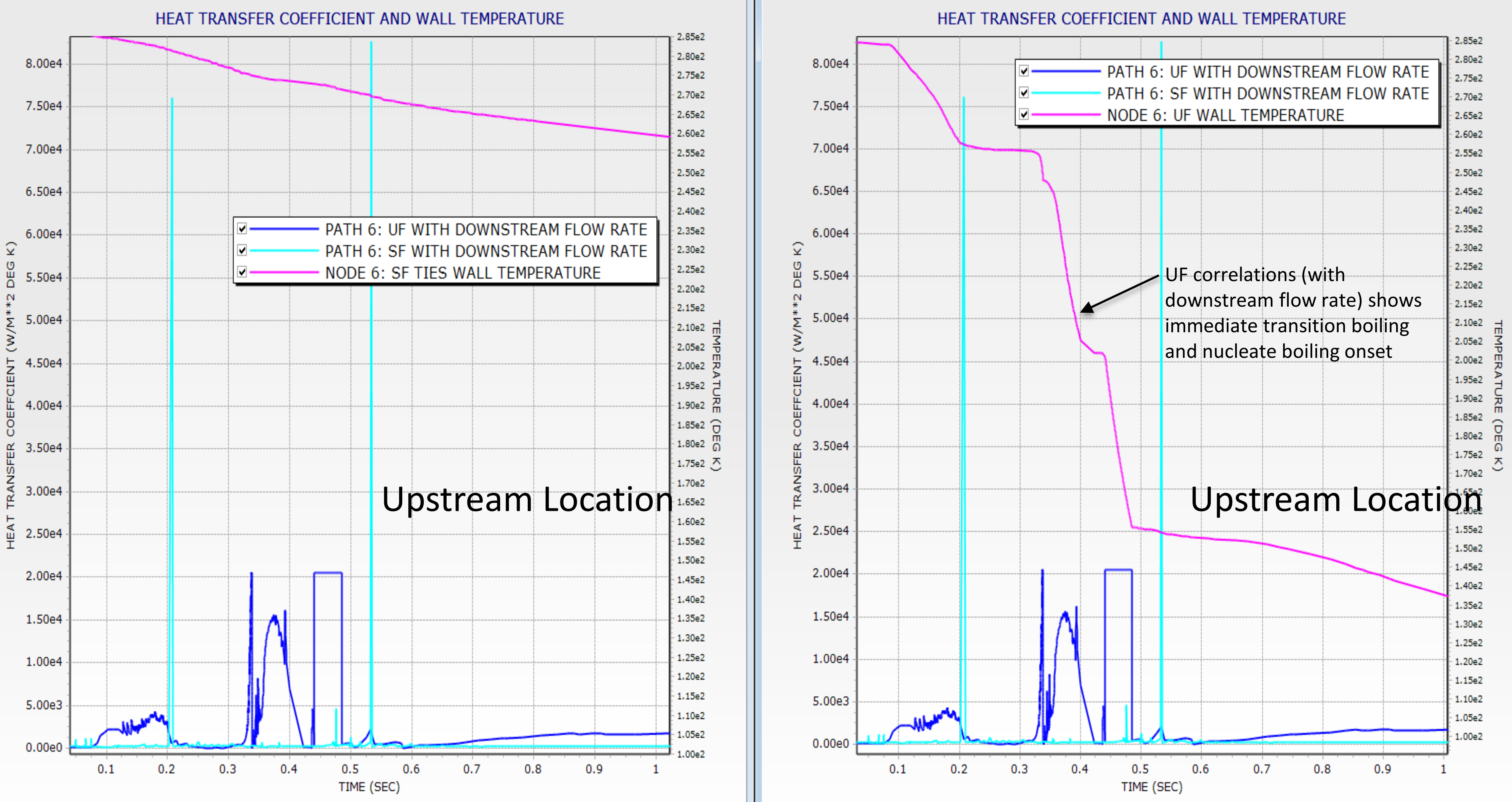


Figure 7: **Liquid Nitrogen Horizontal Chill-down Test Case Reynolds Number = 132597**

Liquid Nitrogen Line Chill-down Results (Horizontal Flow)



Upstream Location

UF correlations (with downstream flow rate) shows immediate transition boiling and nucleate boiling onset

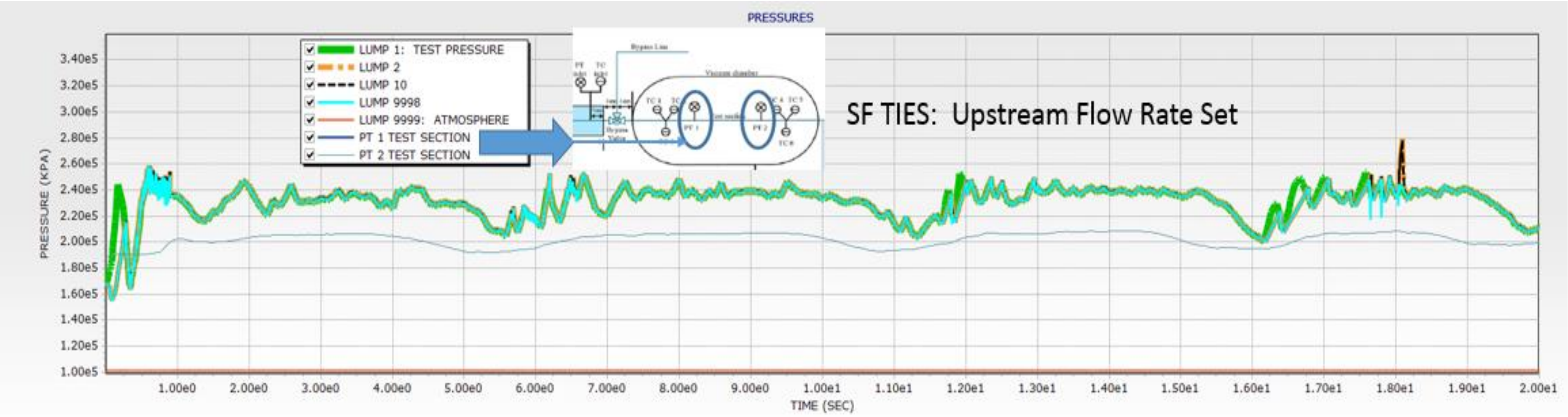
Upstream Location

Figure 8a-8b: Heat Transfer Coefficient and Wall Temperature for Liquid Nitrogen Horizontal Chill-down Test Case Reynolds Number = 132597

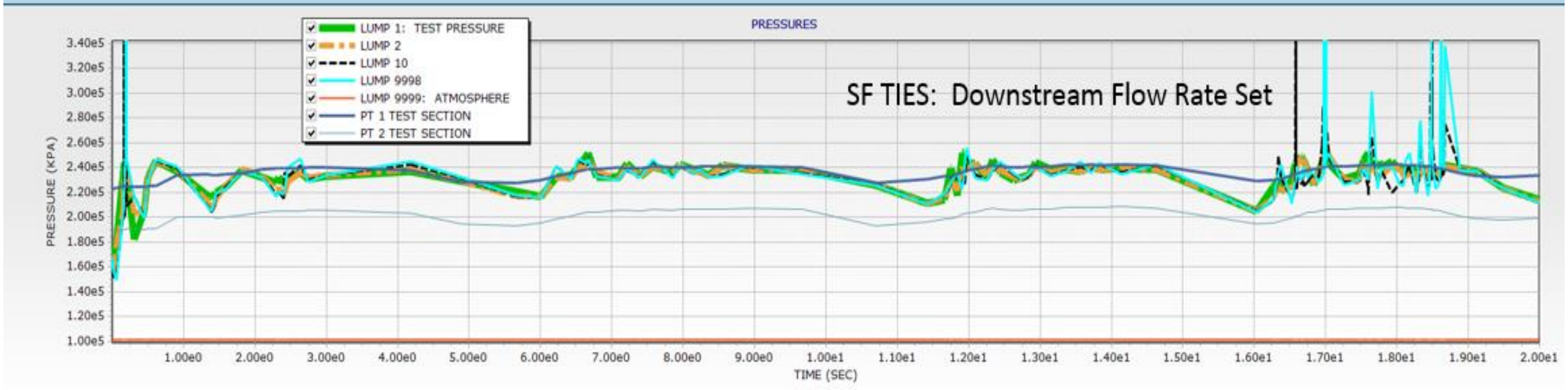
Liquid Nitrogen Line Chill-down Results (Horizontal Flow)

Figure 9a-9b: Pressures through the Test Section (Upstream and Downstream Flow Rate Boundaries) for Nitrogen Horizontal Chill-down Test Case Reynolds Number = 23677

Liquid Nitrogen Line Chill-down Results (Horizontal Flow)



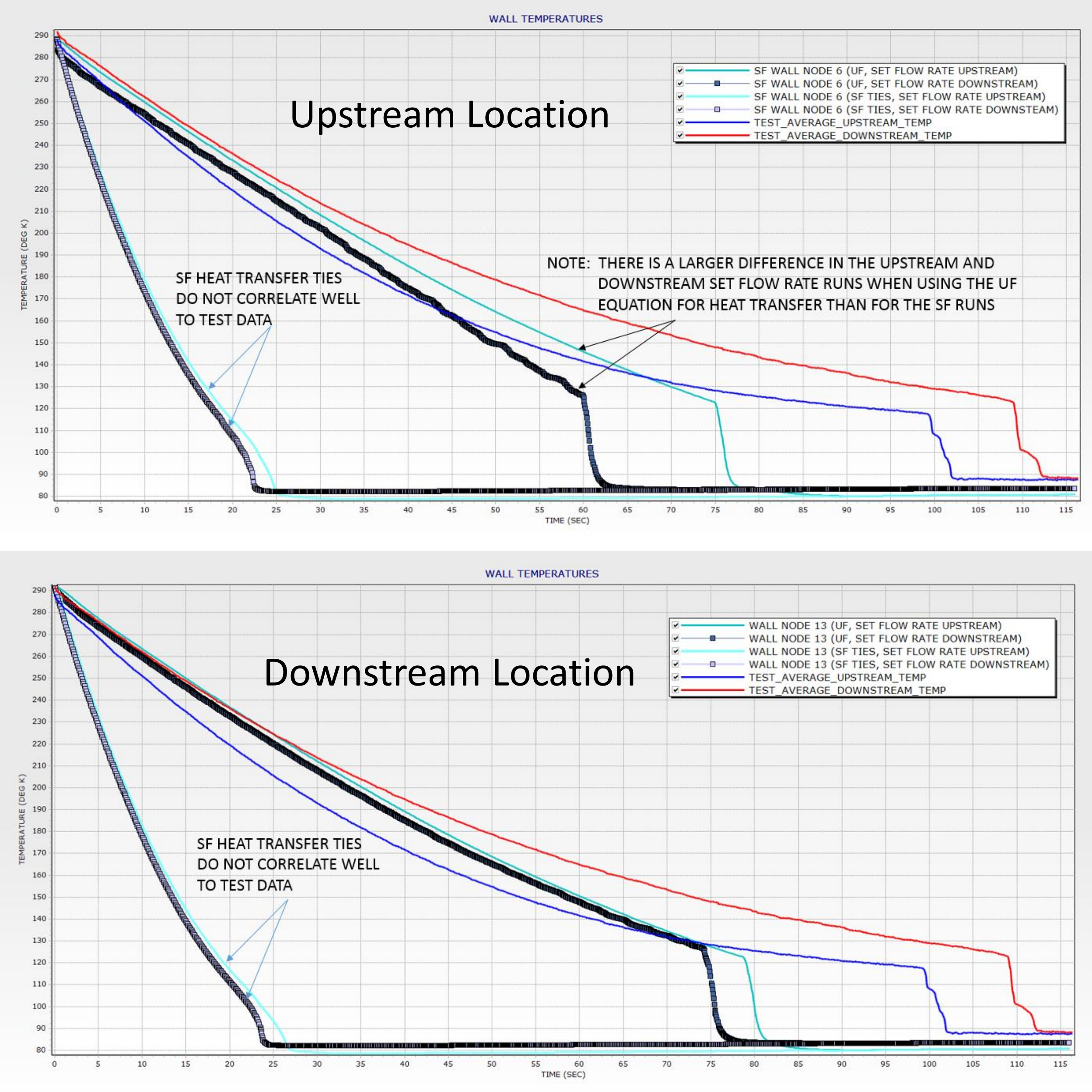
SF TIES: Upstream Flow Rate Set



SF TIES: Downstream Flow Rate Set

Figure 10: Pressures through the Test Section (Upstream and Downstream Flow Rate Boundaries) for Nitrogen Horizontal Chill-down Test Case Reynolds Number = 23677

Liquid Nitrogen Line Chill-down Results (Vertical Downward Flow)



Upstream Location

SF HEAT TRANSFER TIES DO NOT CORRELATE WELL TO TEST DATA

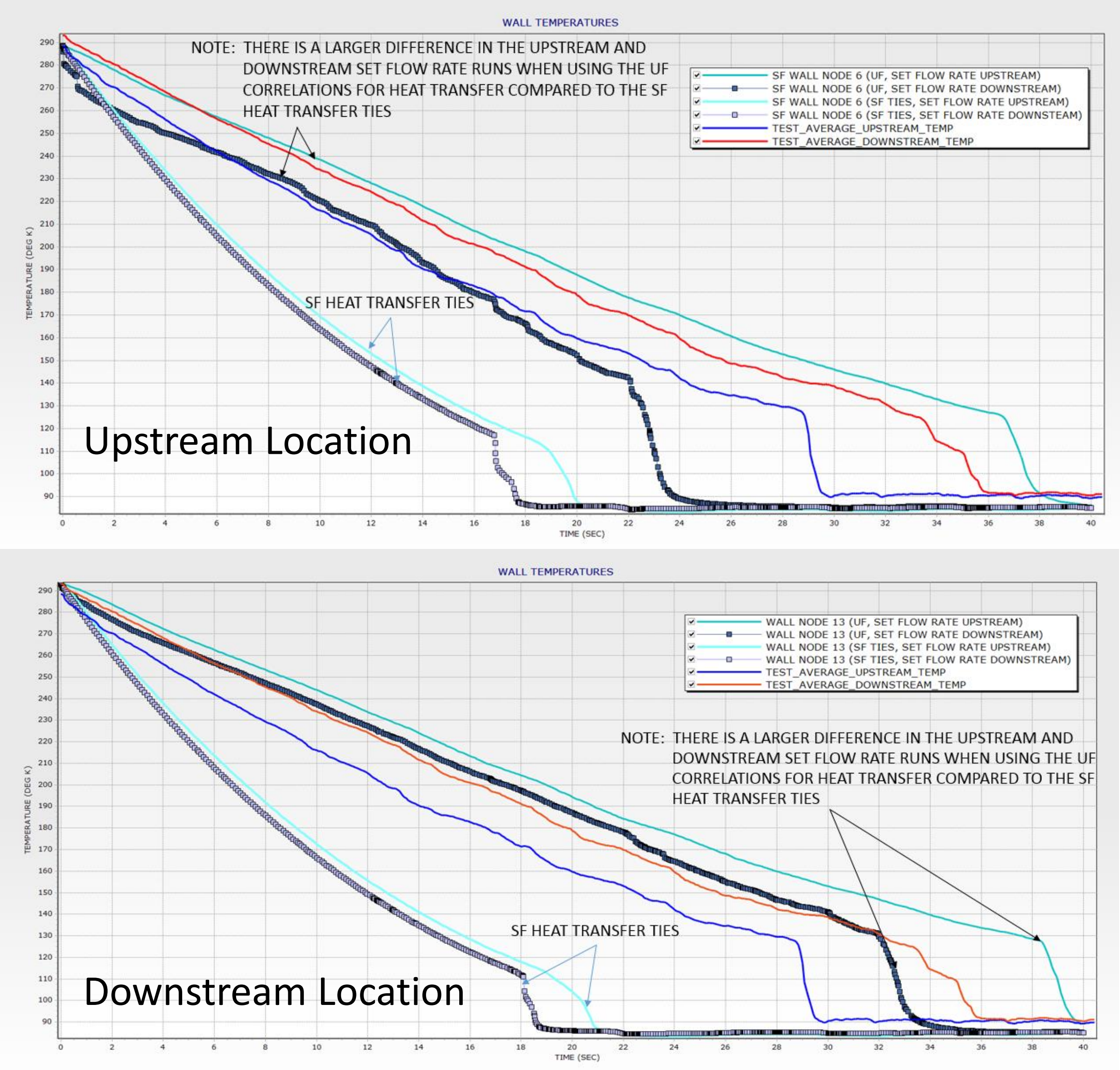
NOTE: THERE IS A LARGER DIFFERENCE IN THE UPSTREAM AND DOWNSTREAM SET FLOW RATE RUNS WHEN USING THE UF EQUATION FOR HEAT TRANSFER THAN FOR THE SF RUNS

Downstream Location

SF HEAT TRANSFER TIES DO NOT CORRELATE WELL TO TEST DATA

Figure 11a-11b: Wall Temperatures for Liquid Nitrogen Vertical Downward Chill-down Test Case Reynolds Number = 4164

Liquid Nitrogen Line Chill-down Results (Vertical Downward Flow)



NOTE: THERE IS A LARGER DIFFERENCE IN THE UPSTREAM AND DOWNSTREAM SET FLOW RATE RUNS WHEN USING THE UF CORRELATIONS FOR HEAT TRANSFER COMPARED TO THE SF HEAT TRANSFER TIES

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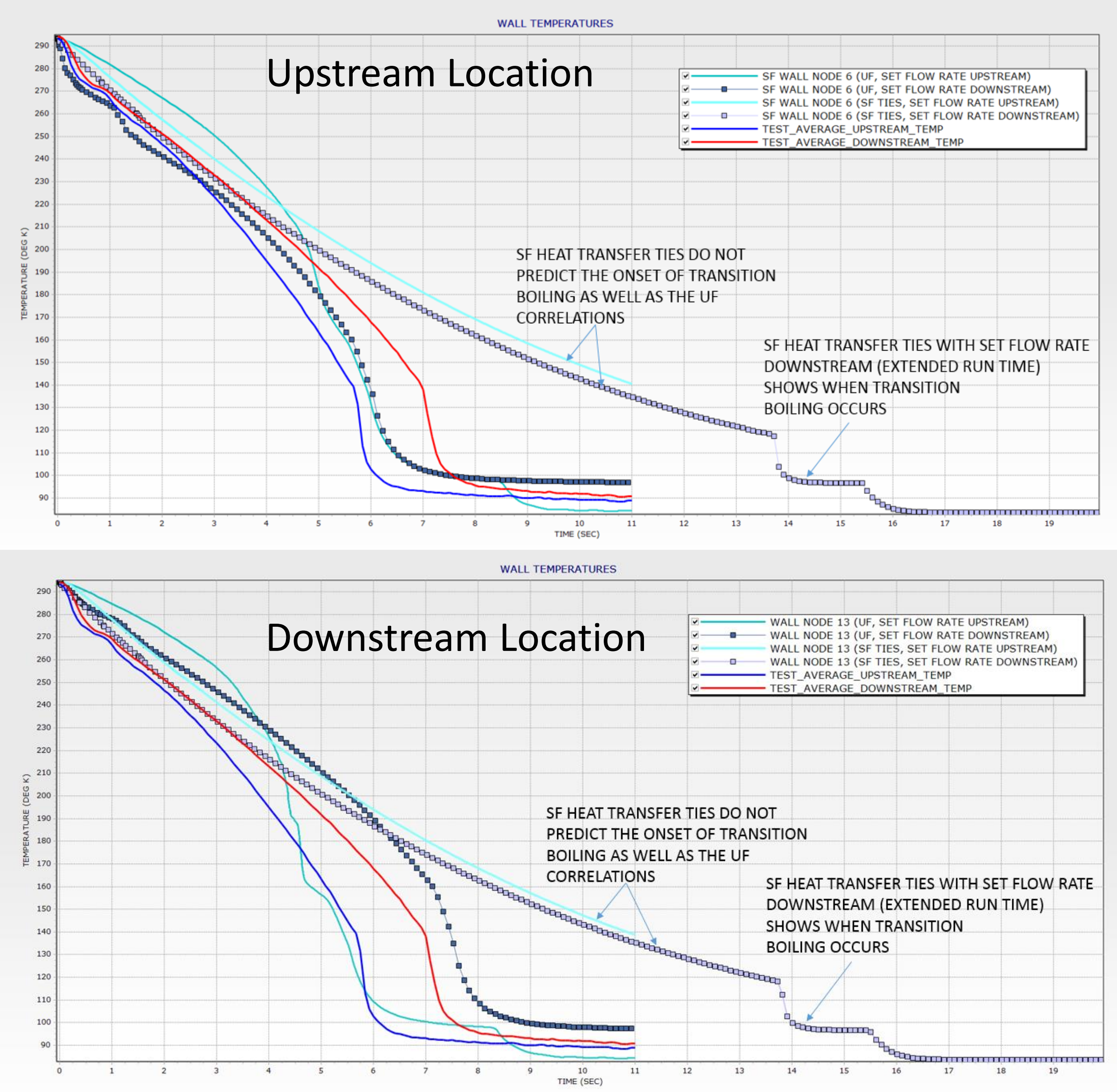
Figure 12a-b: Wall Temperatures for Liquid Nitrogen Horizontal Chill-down Test Case Reynolds Number = 13350

Liquid Nitrogen Line Chill-down Results (Vertical Downward Flow)



SF HEAT TRANSFER TIES DO NOT PREDICT THE ONSET OF TRANSITION BOILING AS WELL AS THE UF CORRELATIONS

SF HEAT TRANSFER TIES WITH SET FLOW RATE DOWNSTREAM (EXTENDED RUN TIME) SHOWS WHEN TRANSITION BOILING OCCURS

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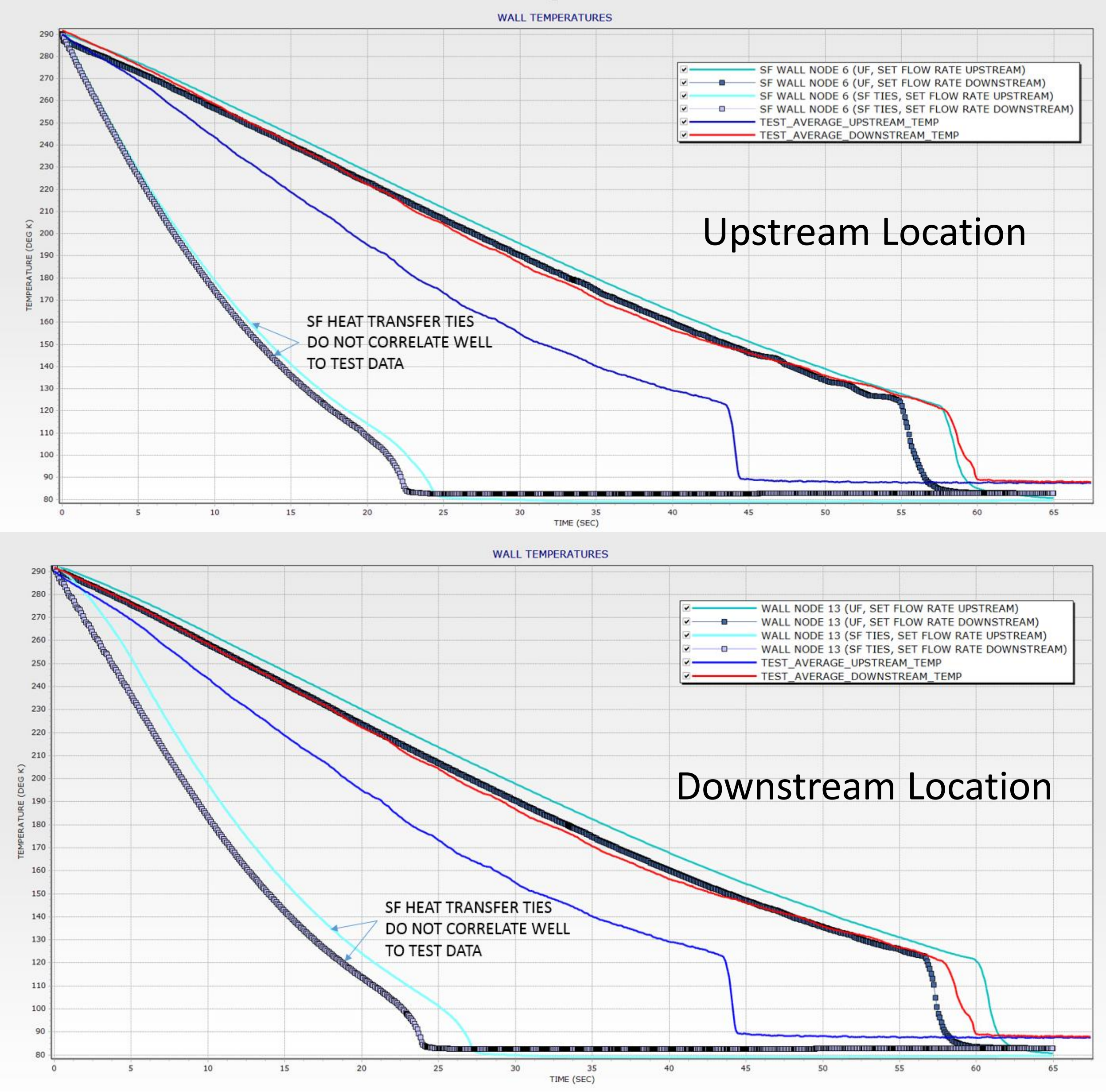
Figure 13a-b: Wall Temperatures for Liquid Nitrogen Vertical Downward Chill-down Test Case Reynolds Number = 126423

Liquid Nitrogen Line Chill-down Results (Vertical Upward Flow)



Upstream Location

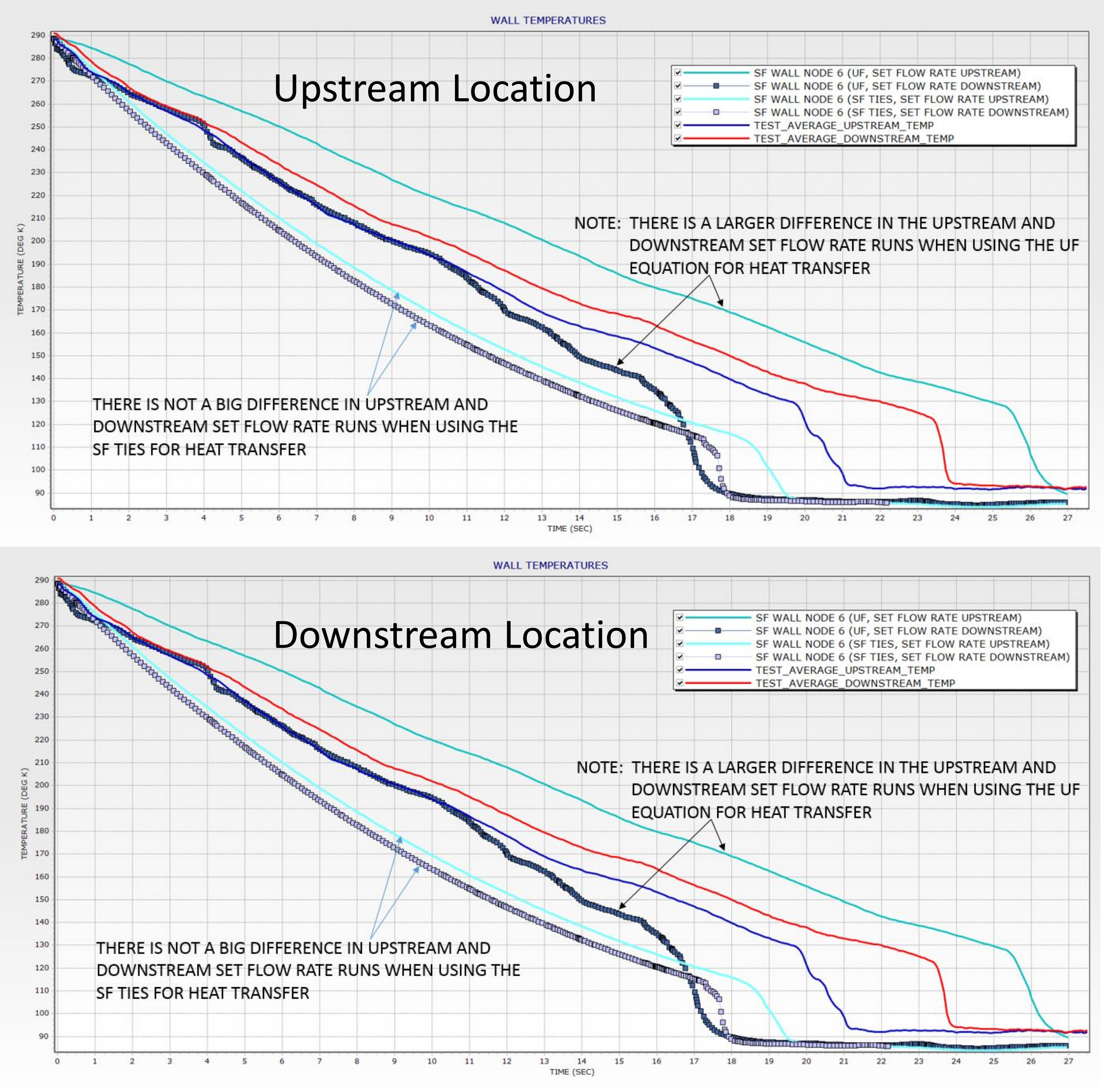
SF HEAT TRANSFER TIES
DO NOT CORRELATE WELL
TO TEST DATA

Downstream Location

SF HEAT TRANSFER TIES
DO NOT CORRELATE WELL
TO TEST DATA

Figure 14a-b: Wall Temperatures for Liquid Nitrogen Vertical Upward Chill-down Test Case Reynolds Number = 3454

Liquid Nitrogen Line Chill-down Results (Vertical Upward Flow)



NOTE: THERE IS A LARGER DIFFERENCE IN THE UPSTREAM AND DOWNSTREAM SET FLOW RATE RUNS WHEN USING THE UF EQUATION FOR HEAT TRANSFER

THERE IS NOT A BIG DIFFERENCE IN UPSTREAM AND DOWNSTREAM SET FLOW RATE RUNS WHEN USING THE SF TIES FOR HEAT TRANSFER

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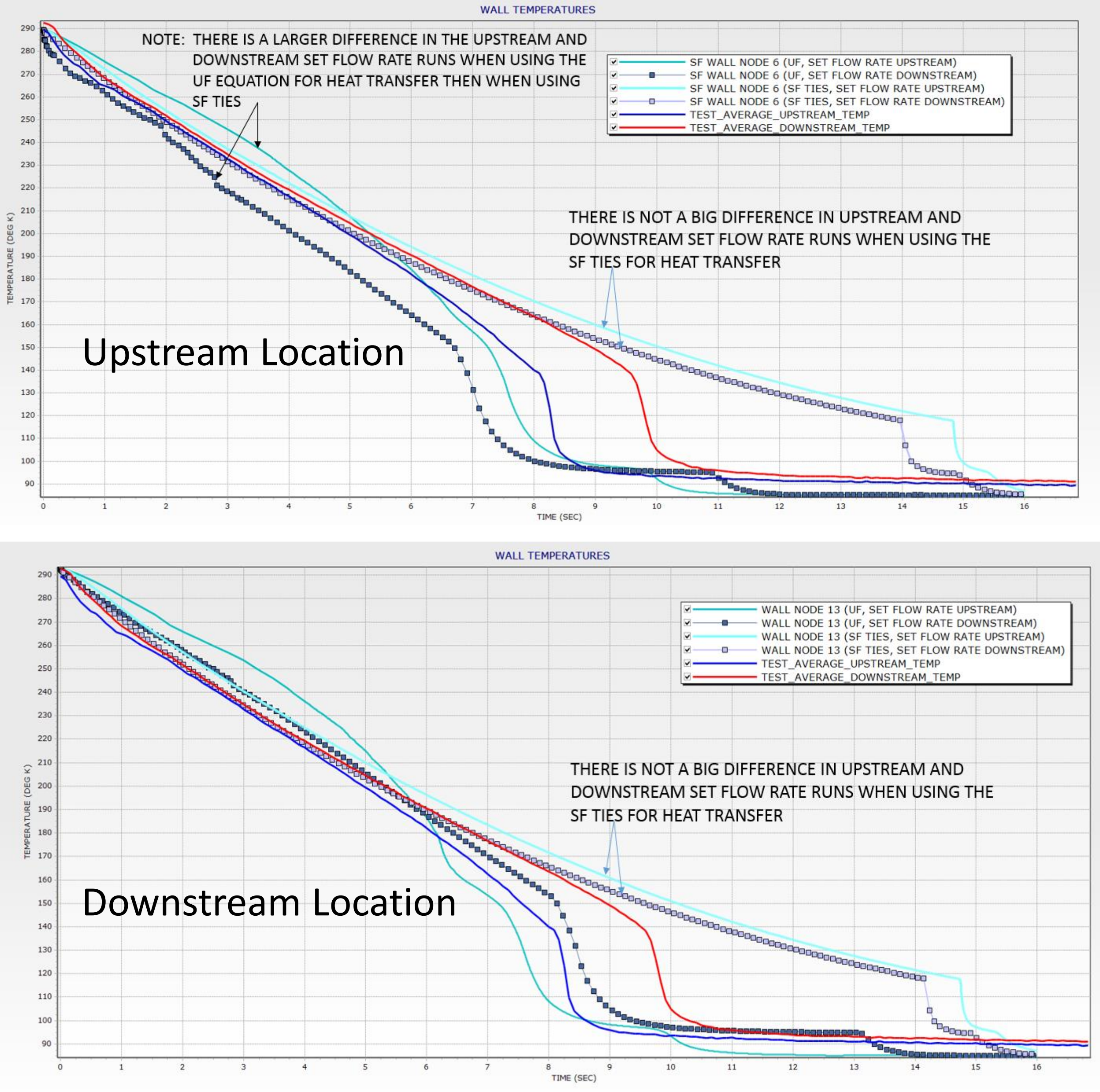
Figure 15a-b: Wall Temperatures for Liquid Nitrogen Vertical Upward Chill-down Test Case Reynolds Number = 14785

Liquid Nitrogen Line Chill-down Results (Vertical Upward Flow)



NOTE: THERE IS A LARGER DIFFERENCE IN THE UPSTREAM AND DOWNSTREAM SET FLOW RATE RUNS WHEN USING THE UF EQUATION FOR HEAT TRANSFER THEN WHEN USING SF TIES

THERE IS NOT A BIG DIFFERENCE IN UPSTREAM AND DOWNSTREAM SET FLOW RATE RUNS WHEN USING THE SF TIES FOR HEAT TRANSFER

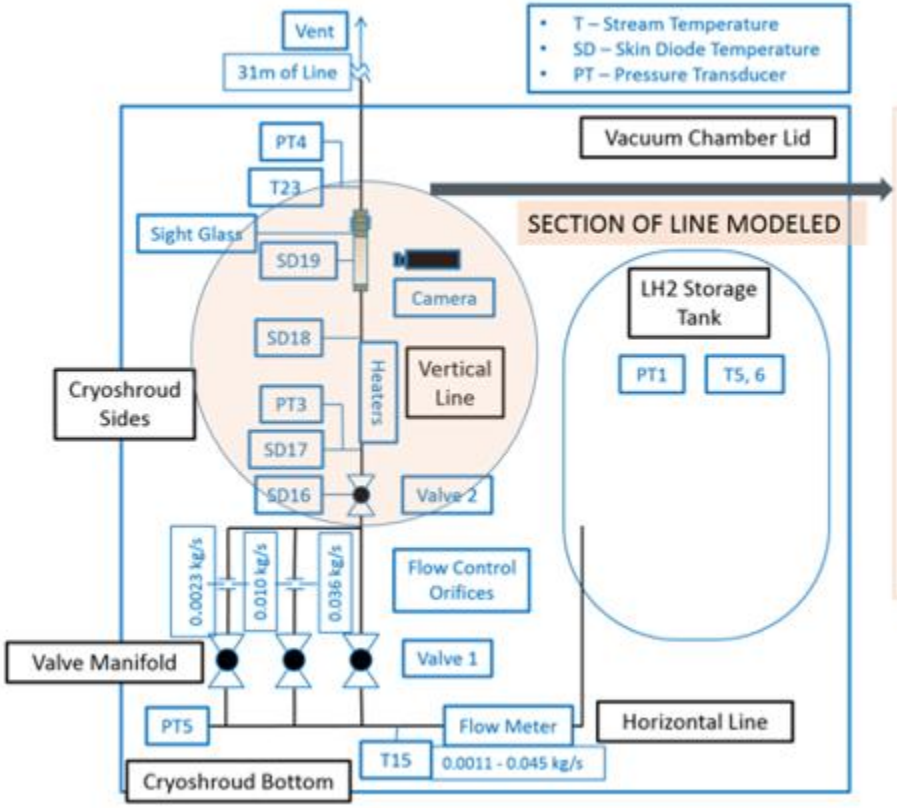
Upstream Location

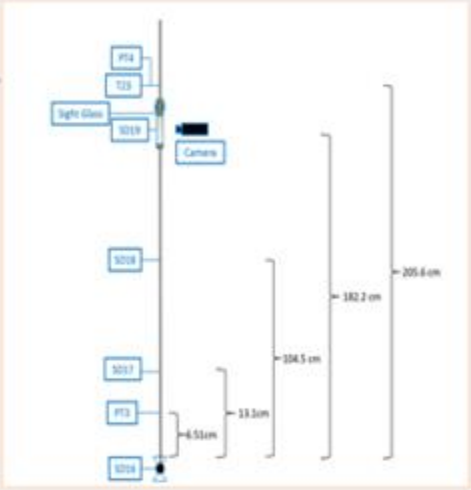
THERE IS NOT A BIG DIFFERENCE IN UPSTREAM AND DOWNSTREAM SET FLOW RATE RUNS WHEN USING THE SF TIES FOR HEAT TRANSFER

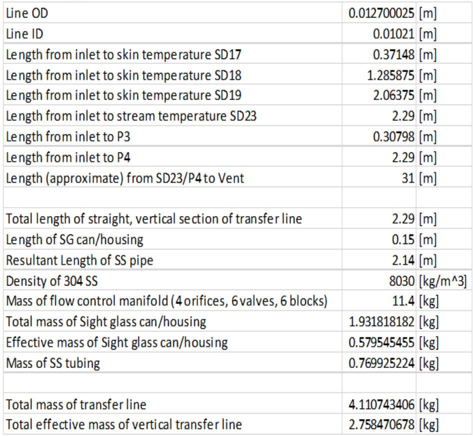
Downstream Location

Figure 16a-b: Wall Temperatures for Liquid Nitrogen Vertical Upward Chill-down Test Case Reynolds Number = 113303

Liquid Hydrogen Line Chill-down





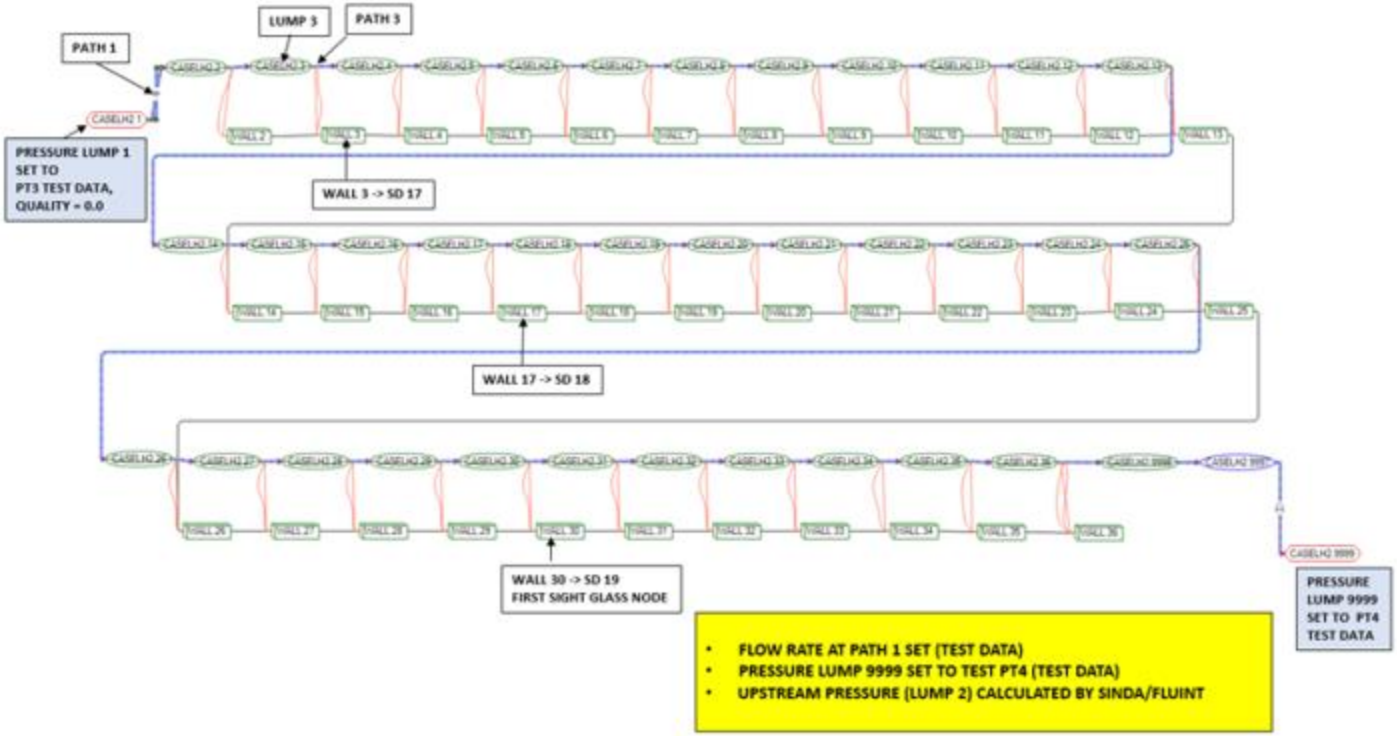


Line OD	0.012700025	[m]
Line ID	0.01021	[m]
Length from inlet to skin temperature SD17	0.37148	[m]
Length from inlet to skin temperature SD18	1.285875	[m]
Length from inlet to skin temperature SD19	2.06375	[m]
Length from inlet to stream temperature SD23	2.29	[m]
Length from inlet to P3	0.30798	[m]
Length from inlet to P4	2.29	[m]
Length (approximate) from SD23/P4 to Vent	31	[m]
Total length of straight, vertical section of transfer line	2.29	[m]
Length of SG can/housing	0.15	[m]
Resultant Length of SS pipe	2.14	[m]
Density of 304 SS	8030	[kg/m^3]
Mass of flow control manifold (4 orifices, 6 valves, 6 blocks)	11.4	[kg]
Total mass of Sight glass can/housing	1.931818182	[kg]
Effective mass of Sight glass can/housing	0.579545455	[kg]
Mass of SS tubing	0.769925224	[kg]
Total mass of transfer line	4.110743406	[kg]
Total effective mass of vertical transfer line	2.758470678	[kg]

- A set flow rate (from test data) at SD16
- No pressure data at SD16 so the inlet pressure was assumed to be the value taken at location PT3 where the pressure was measured
- Outlet location was PT4 (pressure from test data)
- Since a set inlet flow rate was specified as the boundary condition:
  - PT3 as well as the quality equal to zero were used to determine the thermodynamic state coming into the system

Figure 17: Liquid Hydrogen Chill-down Test Schematic

Liquid Hydrogen Line Chill-down



PATH 1

LUMP 3

PATH 3

PRESSURE LUMP 1
SET TO
PT3 TEST DATA,
QUALITY = 0.0

WALL 3 -> SD 17

WALL 17 -> SD 18

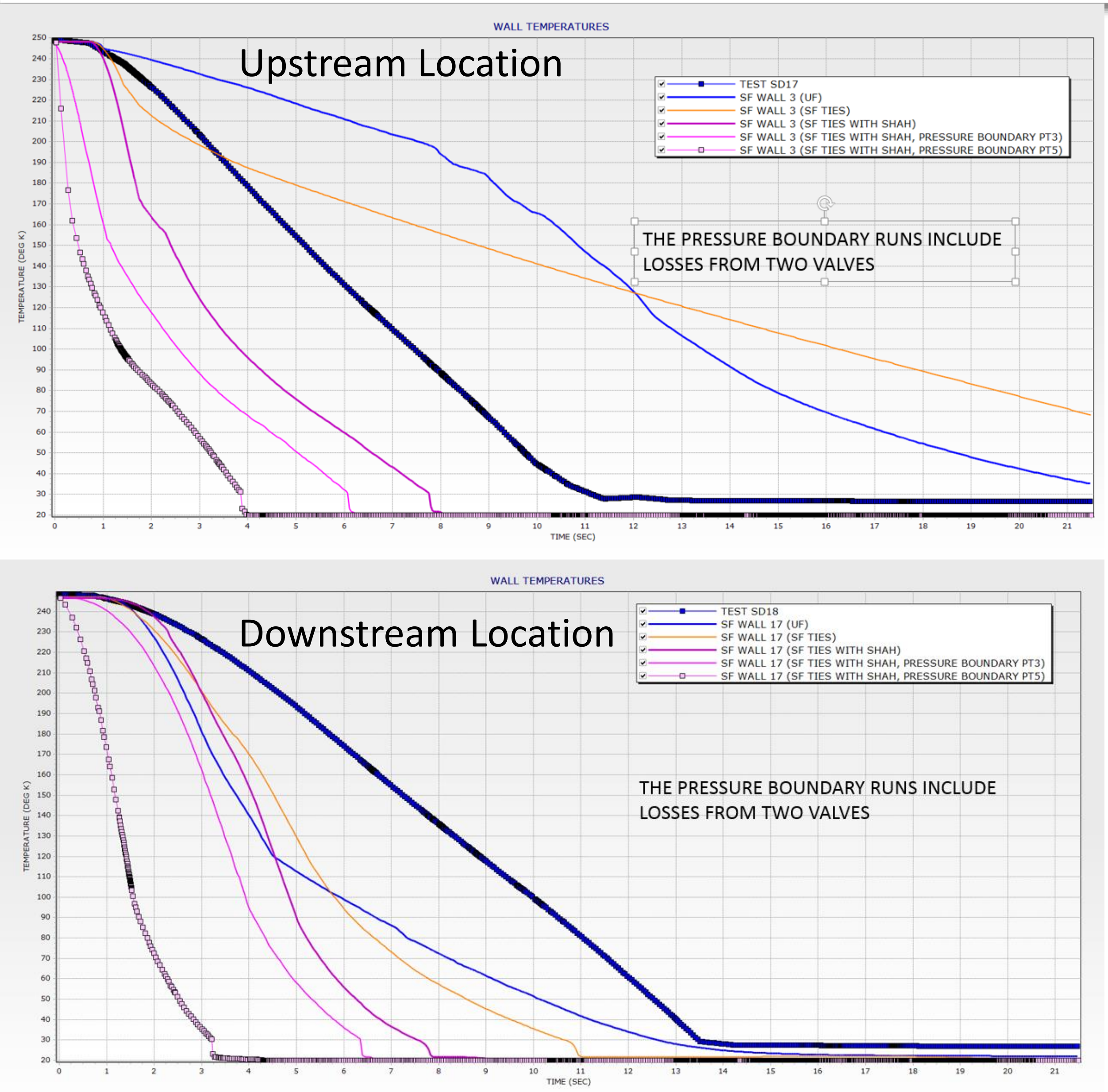
WALL 30 -> SD 19
FIRST SIGHT GLASS NODE

PRESSURE
LUMP 9999
SET TO PT4
TEST DATA

- FLOW RATE AT PATH 1 SET (TEST DATA)
- PRESSURE LUMP 9999 SET TO TEST PT4 (TEST DATA)
- UPSTREAM PRESSURE (LUMP 2) CALCULATED BY SINDA/FLUINT

Figure 18: SINDA/FLUINT Flow Schematic of the Liquid Hydrogen Test Section Showing Fluid LUMPS, Flow PATHS, Wall NODES, Heat Transfer TIES, and Pipe Axial CONDUCTORS

Liquid Hydrogen Line Chill-down Results (Vertical Upward Flow)



Upstream Location

THE PRESSURE BOUNDARY RUNS INCLUDE LOSSES FROM TWO VALVES

Downstream Location

THE PRESSURE BOUNDARY RUNS INCLUDE LOSSES FROM TWO VALVES

Figure 19a-b: Wall Temperatures for Liquid Hydrogen Vertical Upward Chill-down Test (Includes Shah Modification for SF TIES, and Pressure Inlet and Outlet Boundary

Nominal Tank Pressure kPa	T Sat Initial K	LH2 Flow Rate
207	21.4	HIGH

The Shah modification is used during film boiling on the default Dittus-Boelter correlation for gas convective heat transfer as a multiplication factor:

$$S = 0.046\, F\, (T_v/T_w)^{0.55}$$

$$F = 8.53\, (L/D)^{-0.63} \qquad L/D <= 30.0$$

$$F = 1.0 \qquad L/D >= 30.0$$

Liquid Hydrogen Line Chill-down Results (Vertical Upward Flow)

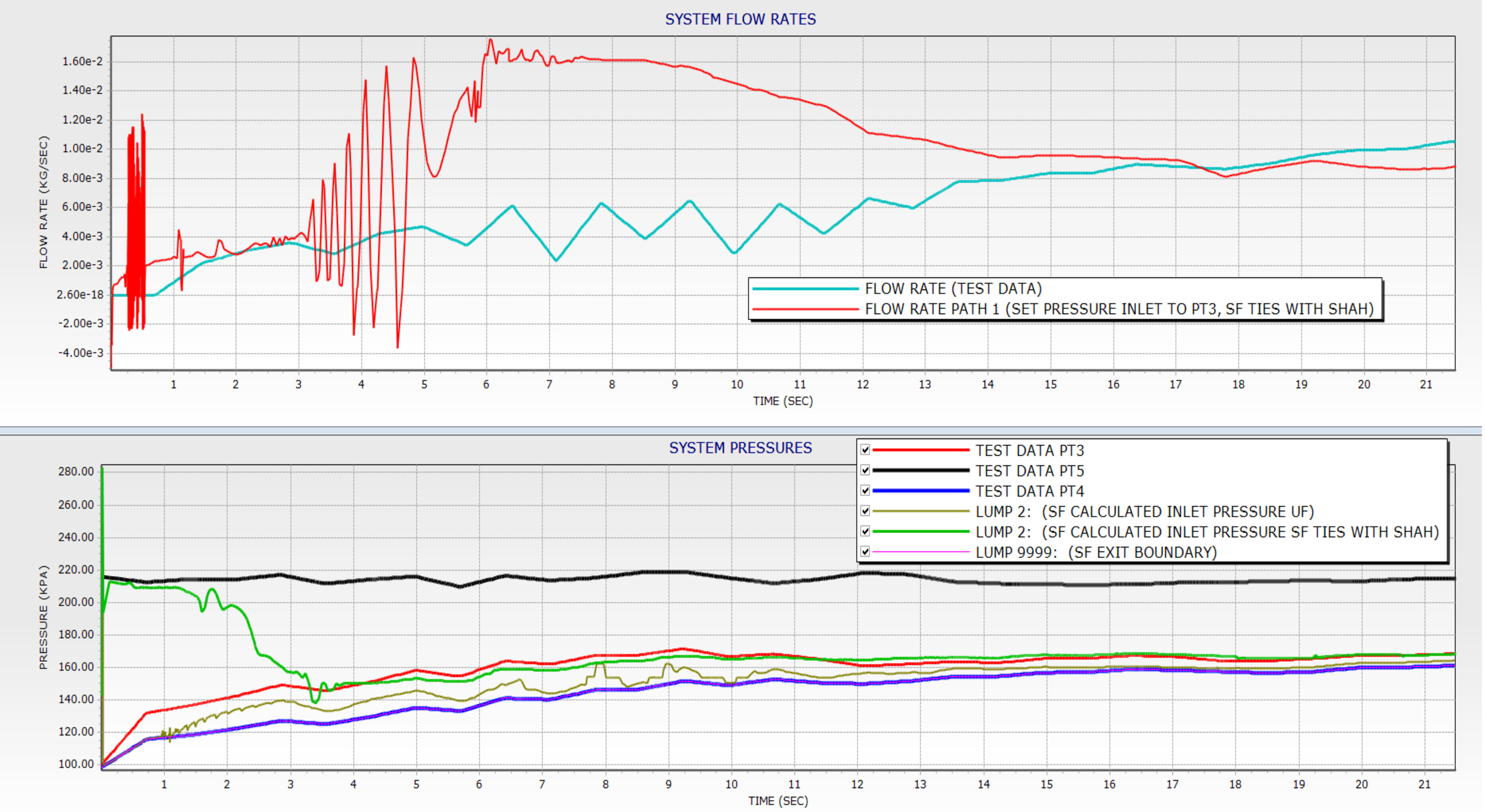
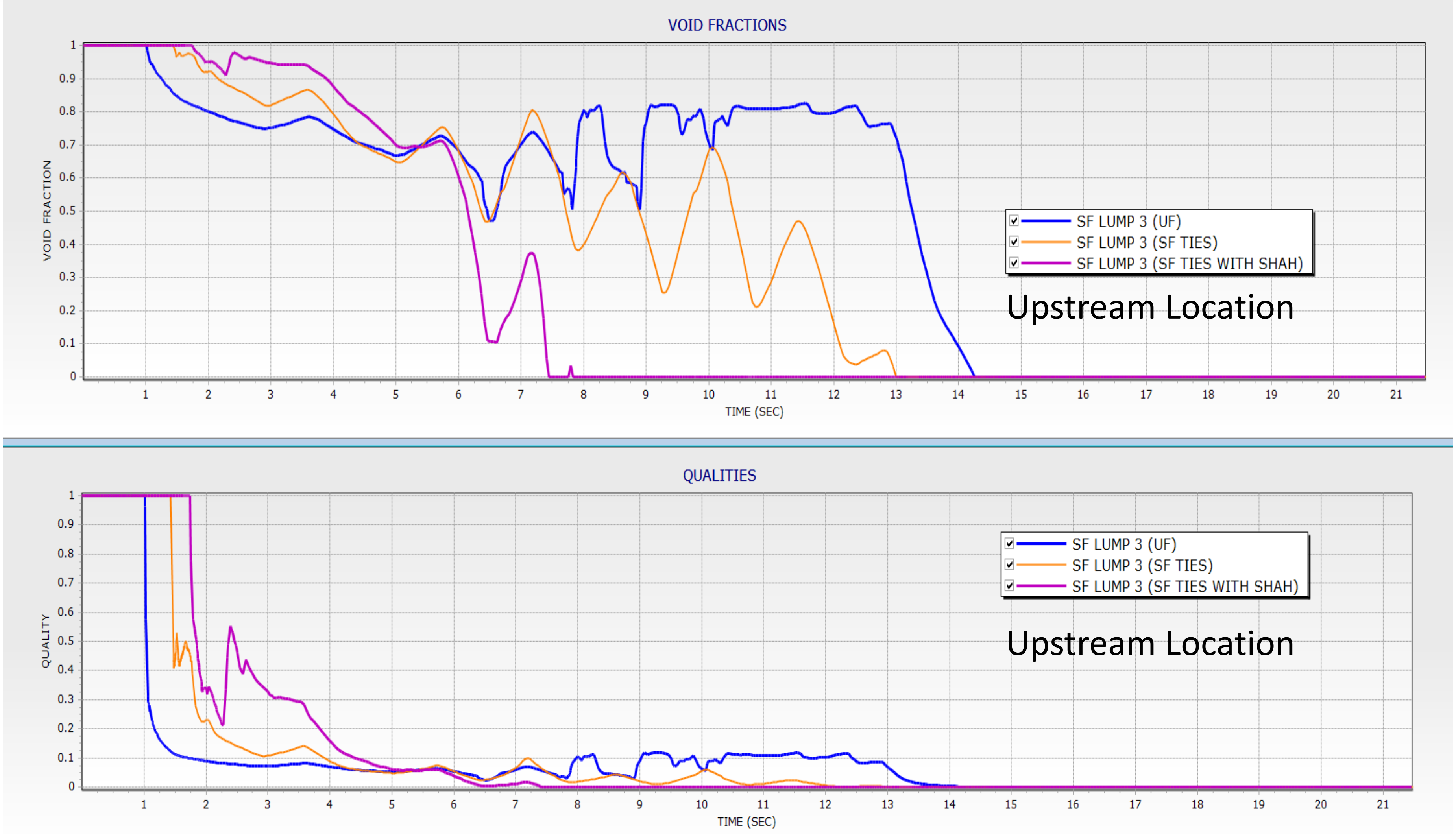


Figure 20: Flow Rates and Pressure for Liquid Hydrogen Vertical Upward Chill-down (Includes Pressure Inlet and Outlet Boundary)

Liquid Hydrogen Line Chill-down Results (Vertical Upward Flow)



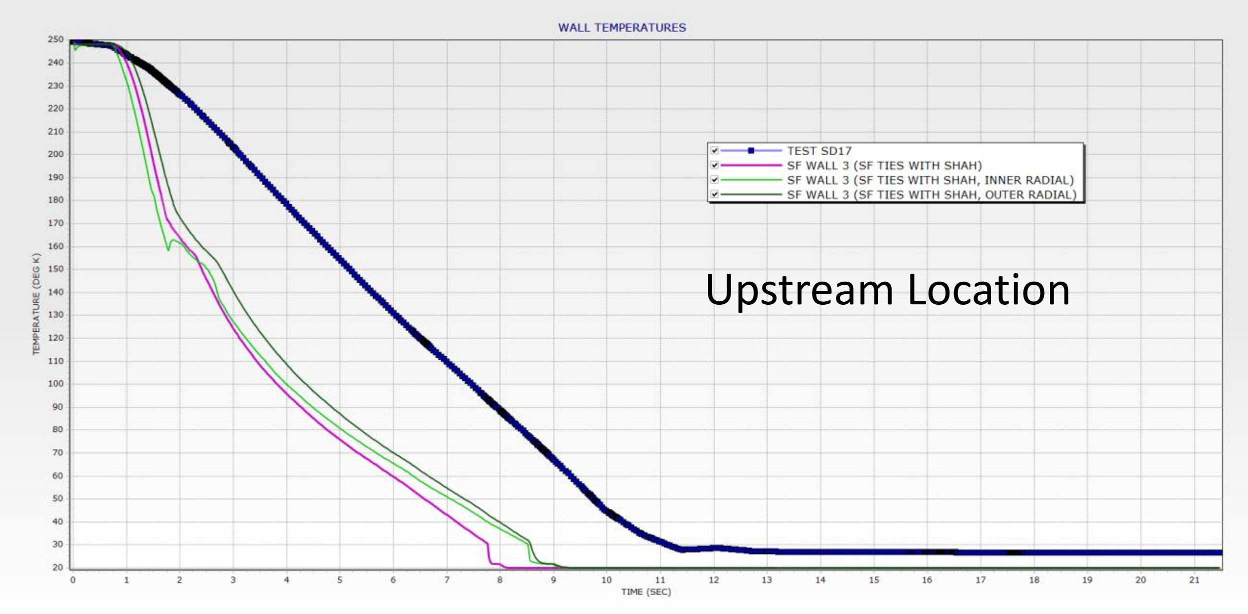
Upstream Location

Upstream Location

Figure 21: Void Fractions and Qualities for Liquid Hydrogen Vertical Upward Chill-down

Nominal Tank Pressure	T Sat Initial	LH2 Flow
kPa	K	Rate
207	21.4	HIGH

Liquid Hydrogen Line Chill-down Results (Vertical Upward Flow)



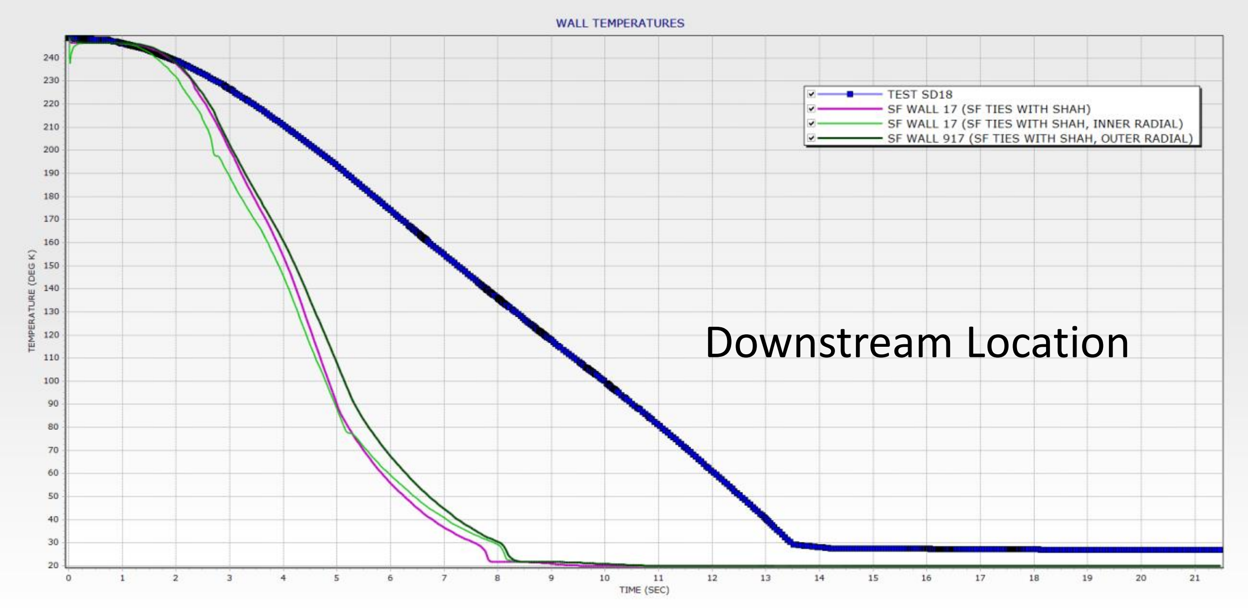
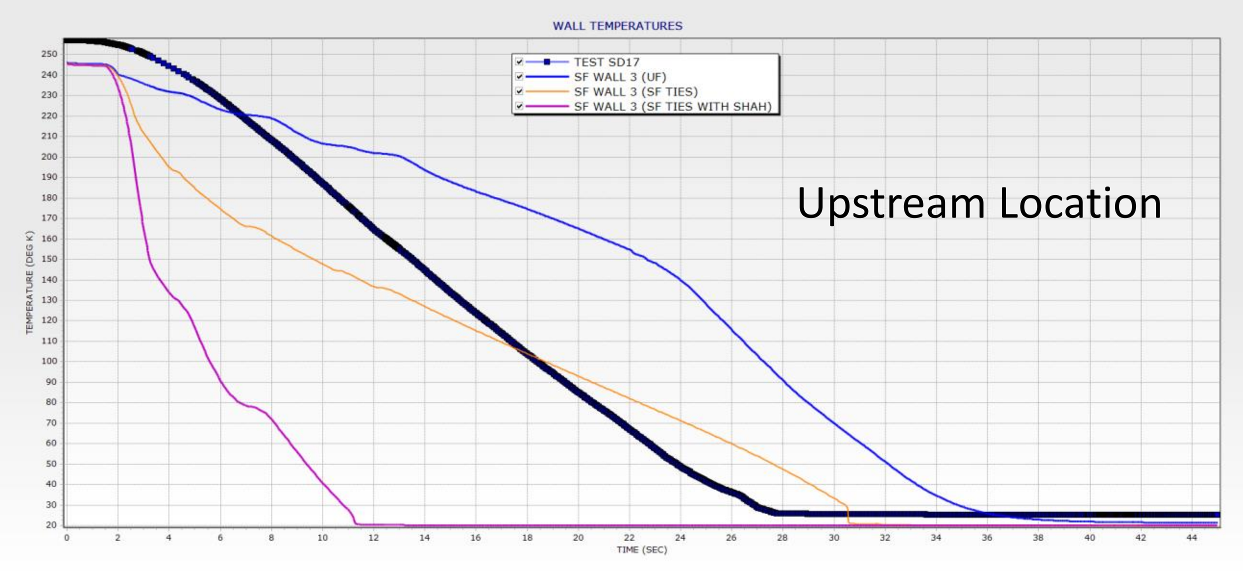


Figure 22a-b: Inner and Outer Wall Temperatures for Liquid Hydrogen Vertical Upward Chill-down Test (10 Radial Nodes)

Nominal Tank Pressure kPa	T Sat Initial K	LH2 Flow Rate
207	21.4	HIGH

Liquid Hydrogen Line Chill-down Results (Vertical Upward Flow)



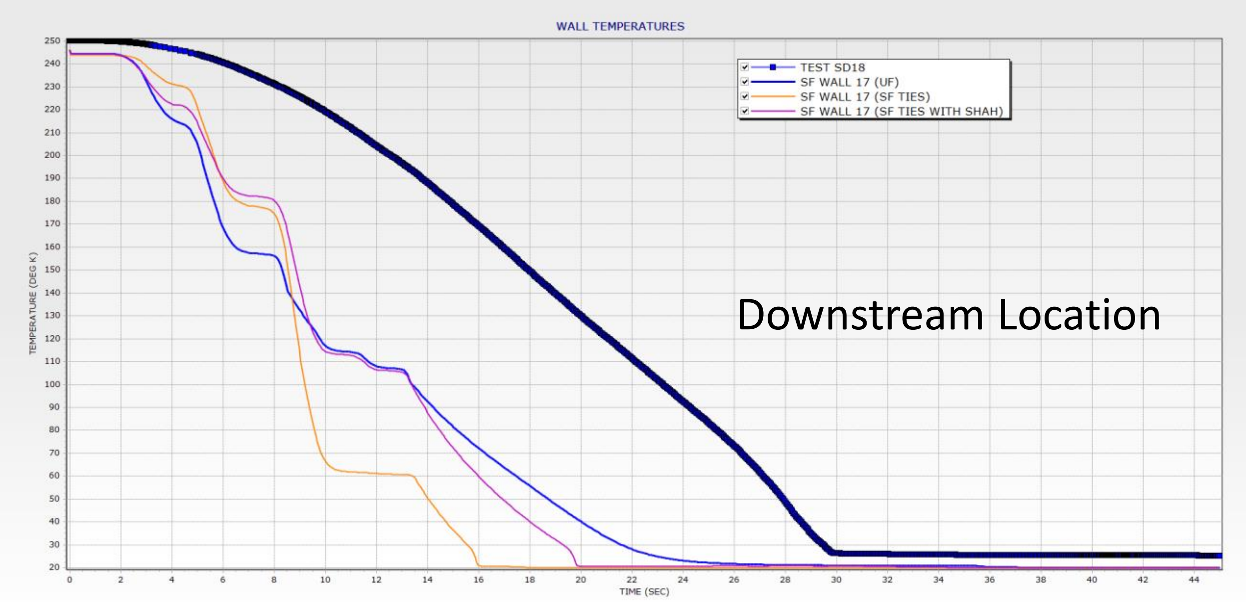


Figure 23a-b: Wall Temperatures for Liquid Hydrogen Vertical Upward Chill-down Test (Includes Shah Modification for SF TIES)

Nominal Tank Pressure kPa	T Sat Initial K	LH2 Flow Rate
207	21.4	MED

The Shah modification is used during film boiling on the default Dittus-Boelter correlation for gas convective heat transfer as a multiplication factor:

$$S = 0.046\ F\ (T_v/T_w)^{0.55}$$

$$F = 8.53\ (L/D)^{-0.63} \qquad L/D <= 30.0$$

$$F = 1.0 \qquad L/D >= 30.0$$

Liquid Hydrogen Line Chill-down Results (Vertical Upward Flow)

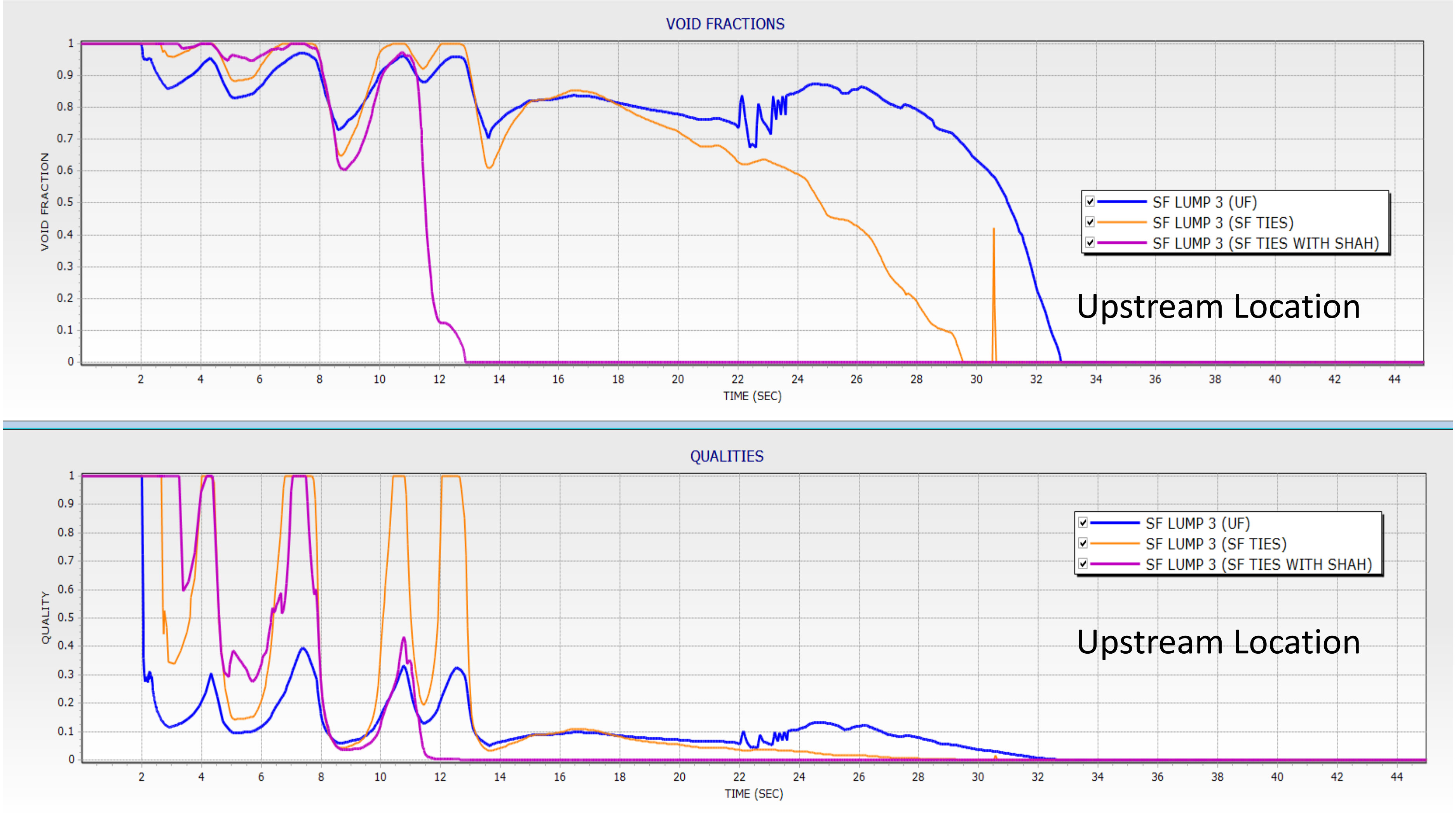


Figure 24: Void Fractions and Qualities for Liquid Hydrogen Vertical Upward Chill-down

Nominal Tank Pressure kPa	T Sat Initial K	LH2 Flow Rate
207	21.4	MED

Liquid Hydrogen Line Chill-down Results (Vertical Upward Flow)

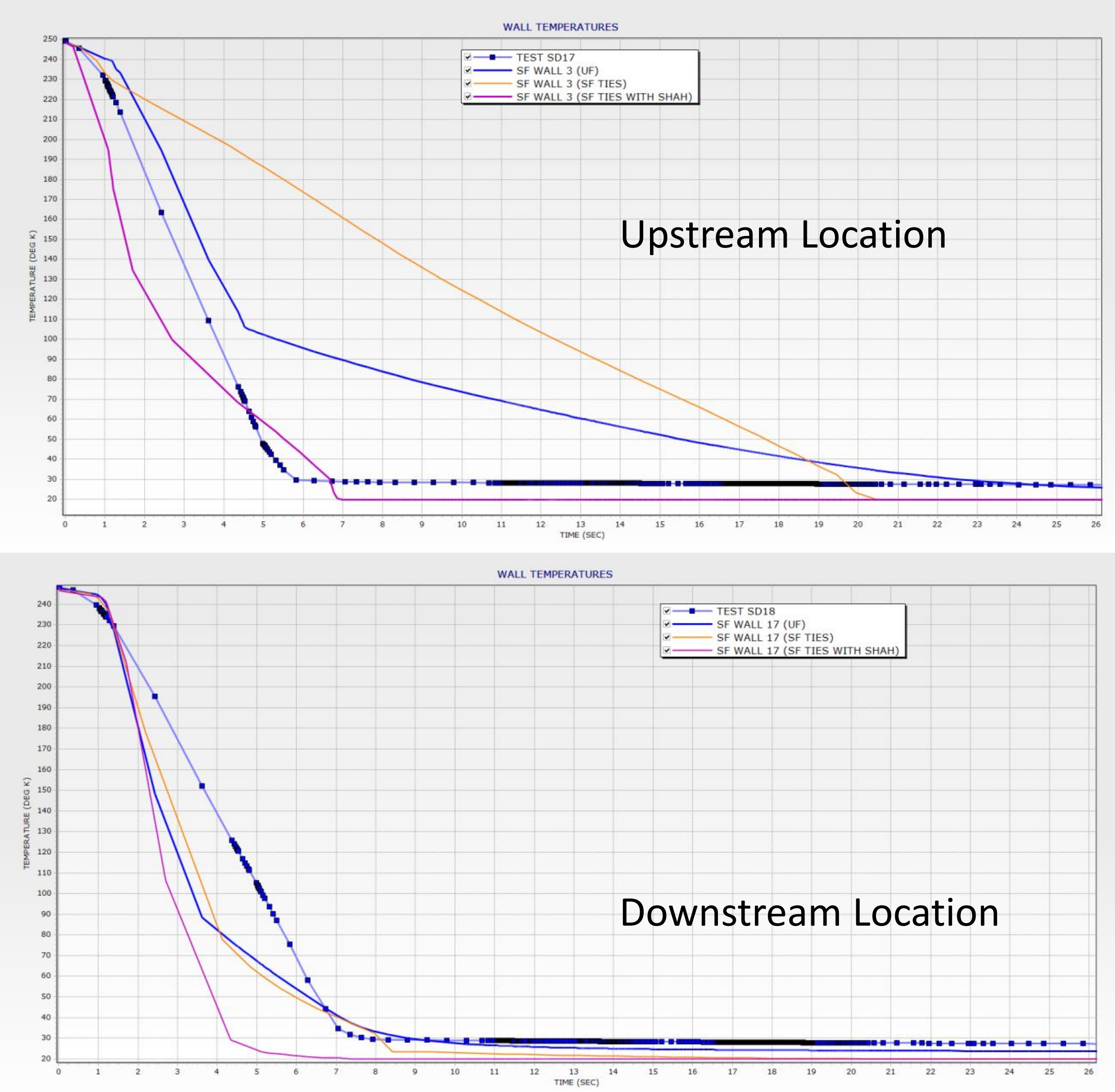


Figure 25a-b: Wall Temperatures for Liquid Hydrogen Vertical Upward Chill-down Test (Includes Shah Modification for SF TIES)

Nominal Tank Pressure kPa	T Sat Initial K	LH2 Flow Rate
345	24.2	HIGH

The Shah modification is used during film boiling on the default Dittus-Boelter correlation for gas convective heat transfer as a multiplication factor:

$$S = 0.046\, F\, (T_v/T_w)^{0.55}$$

$$F = 8.53\, (L/D)^{-0.63} \qquad L/D <= 30.0$$

$$F = 1.0 \qquad L/D >= 30.0$$

Liquid Hydrogen Line Chill-down Results (Vertical Upward Flow)

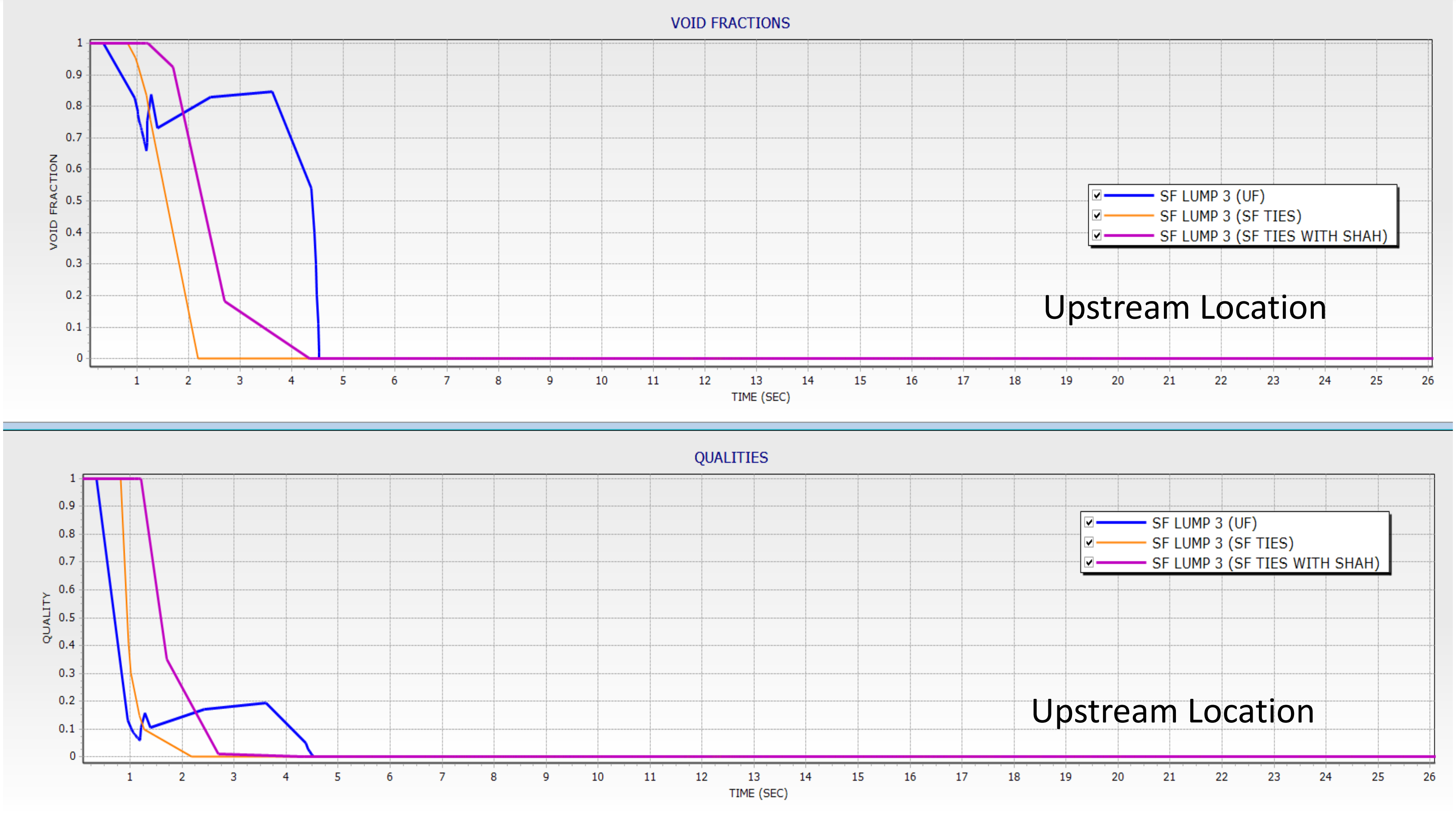
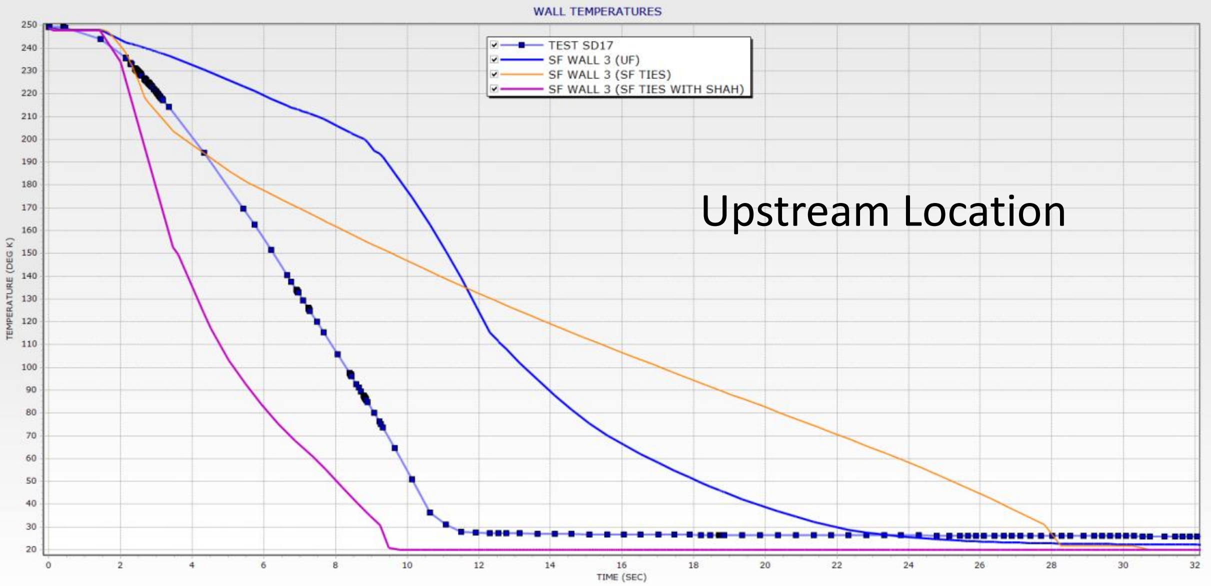


Figure 26: Void Fractions and Qualities for Liquid Hydrogen Vertical Upward Chill-down

Nominal Tank Pressure kPa	T Sat Initial K	LH2 Flow Rate
345	24.2	HIGH

Liquid Hydrogen Line Chill-down Results (Vertical Upward Flow)



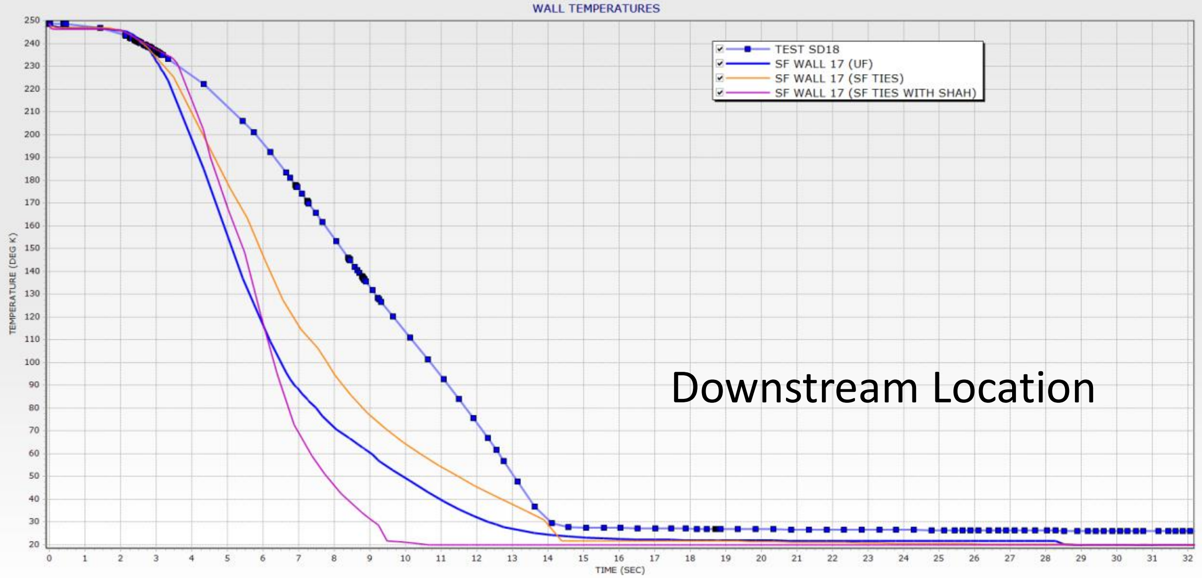


Figure 27a-b: Wall Temperatures for Liquid Hydrogen Vertical Upward Chill-down Test (Includes Shah Modification for SF TIES)

Nominal Tank Pressure kPa	T Sat Initial K	LH2 Flow Rate
345	24.2	MED

The Shah modification is used during film boiling on the default Dittus-Boelter correlation for gas convective heat transfer as a multiplication factor:

$$S = 0.046\ F\ (T_w/T_w)^{0.55}$$

$$F = 8.53\ (L/D)^{-0.63} \qquad L/D <= 30.0$$

$$F = 1.0 \qquad L/D >= 30.0$$

Liquid Hydrogen Line Chill-down Results (Vertical Upward Flow)

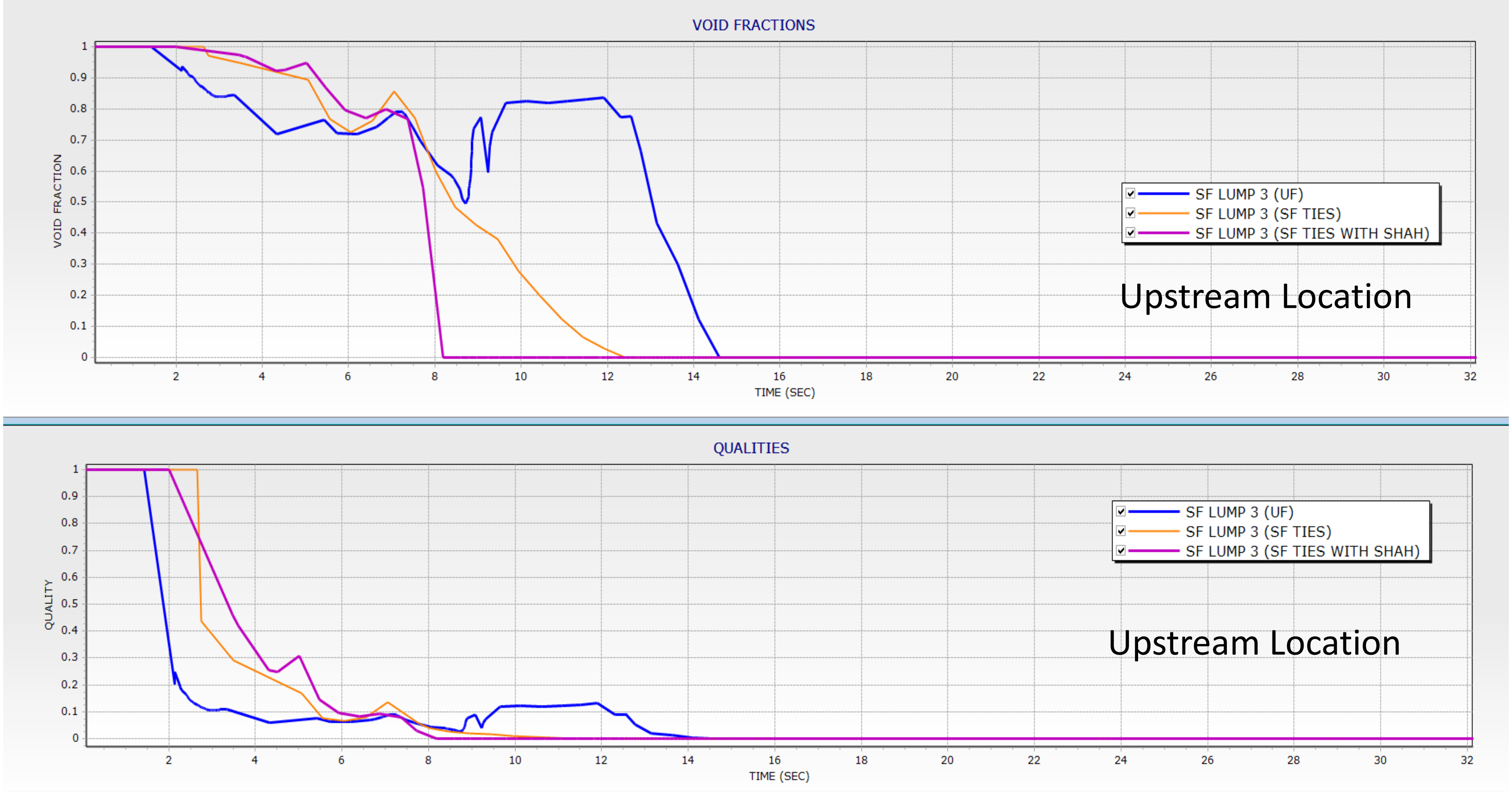


Figure 28: Void Fractions and Qualities for Liquid Hydrogen Vertical Upward Chill-down

Nominal Tank Pressure kPa	T Sat Initial K	LH2 Flow Rate
345	24.2	MED

Results Conclusions

- University of Florida’s film boiling correlation can over predict heat transfer to the wall due to flow rate oscillations
- SINDA/FLUINT’s correlations can either over predict or under predict the film boiling heat transfer to the wall, but is less sensitive to flow rate oscillations
  - high Reynolds numbers under predict film boiling (~ 100000)
  - low Reynolds numbers over predict film boiling (~ 5000)
  - Reynolds number (~ 10000) “just about right”
- Along with heat transfer correlations for multiphase flow, pressure drop correlations need to be addressed and/or modified since the pressure drops in all the cases did not correlate to test data, whether upstream or downstream set flow rates were employed

Results Conclusions

- Test cases with hydrogen showed that radially discretizing the wall did not significantly impact the model temperature results
- Sometime SINDA/FLUINT did better, other times the UF correlations faired better