Modeling Cryogenic Chilldown of a Transfer Line with the Generalized Fluid System Simulation Program

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This paper describes a computational thermofluid model of the chilldown of a transfer line by a cryogenic fluid. Accurate modeling of the chilldown process is desirable to develop loading procedures that minimize propellant loss; however, accuracy has been impeded by uncertainty in boiling heat transfer correlations at cryogenic temperatures. The University of Florida has developed a new chilldown boiling correlation from a series of cryogenic experiments with liquid nitrogen and liquid hydrogen. This correlation has been coded as a Fortran user subroutine in the Generalized Fluid System Simulation Program, a general-purpose network flow analysis code. The model's predicted wall temperatures are compared to test data, as well as to predictions by other heat transfer correlations.

Nomenclature

LH2 = liquid hydrogen

LN2 = liquid nitrogen

Re = Reynolds number

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Introduction

WHEN starting cryogenic liquid propulsion system operations such as engine feed or tank-to-tank propellant transfer, the transfer lines must first be chilled down to cryogenic temperatures before steady flow rates can be achieved. Chilldown procedures can be optimized for time, or for minimum loss of useful propellant. The ability to accurately model the chilldown of transfer lines is vital for such optimization, but has been hampered by the uncertainty in boiling heat transfer correlations at cryogenic temperatures. Most boiling correlations in the literature are developed from experiments on room-temperature fluids, especially water. And most correlations are developed from steady-state heated-tube experiments, not from chilldown experiments.

This paper presents details of computational models of two series of chilldown experiments with liquid nitrogen (LN2) and liquid hydrogen (LH2) using the Generalized Fluid System Simulation Program (GFSSP). Both test series were well instrumented to provide sufficient data to develop a new boiling heat transfer correlation, the University of Florida (UF) Universal Chilldown Correlation [1]. The suitability of this correlation for chilldown modeling is studied in this paper, and compared to preexisting correlations from the literature. The calculated wall temperature profiles are compared to the experimentally measured chilldown curves.

Model Details

GFSSP is a 1-D network flow program developed at NASA Marshall Space Flight Center [2]. GFSSP models a thermofluid system as a network of nodes and branches. The conservation equations of mass and energy are solved in the nodes for pressures and temperatures. The momentum equation is solved in the branches to find flow rates. Conjugate heat transfer permits the addition of a network of solid nodes to represent the thermal mass of pipe walls and convection therefrom. The convection coefficient can be calculated by built-in correlations, or the user can program custom correlations in Fortran user subroutines. Fluid properties are calculated by the GASP package [3].

A primary focus of this modeling exercise was to evaluate a new set of boiling heat transfer correlations developed by UF, described in detail in Darr et al. [1]. The correlations cover the film, transition, and nucleate boiling regimes, and also include equations to calculate the rewet temperature, marking the beginning of transition boiling, and the critical heat flux at the start of nucleate boiling. The coefficients of the equations depend on the orientation of the flow: horizontal, vertical upward, or vertical downward.

For comparison with the predictions of the UF correlations, the models were also run with the Miropolski film boiling correlation [4]. In addition, the LH2 chilldown models were run with the Dittus-Boelter and Shah correlations [5].

Liquid Nitrogen Chilldown Experiments

The first set of experiments to be modeled are LN2 chilldown experiments conducted at UF in 2015 [6]. Figure 1 is a schematic of the test setup. Regulated high pressure nitrogen gas pressurizes an LN2 dewar to absolute pressures in the range 165–790 kPa (24–115 psia). The liquid is pushed from the dewar through a subcooler containing saturated LN2 at atmospheric pressure. A bypass valve allows the apparatus upstream of the test section to be prechilled before the start of the test. The test section is a 22.5-in SS304 tube with an inner diameter of 0.46 in, placed inside a vacuum chamber to minimize parasitic heat leak. Thermocouples measure the wall temperature at either end of the test section. A pressure control valve downstream of the test section can be partially closed to adjust the flow rate at a given driving pressure. Heat exchangers vaporize any liquid in the flow, the rate of which is measured by gas flow meters before the exit to ambient. The test section can be oriented horizontally, vertically upward, or vertically downward.

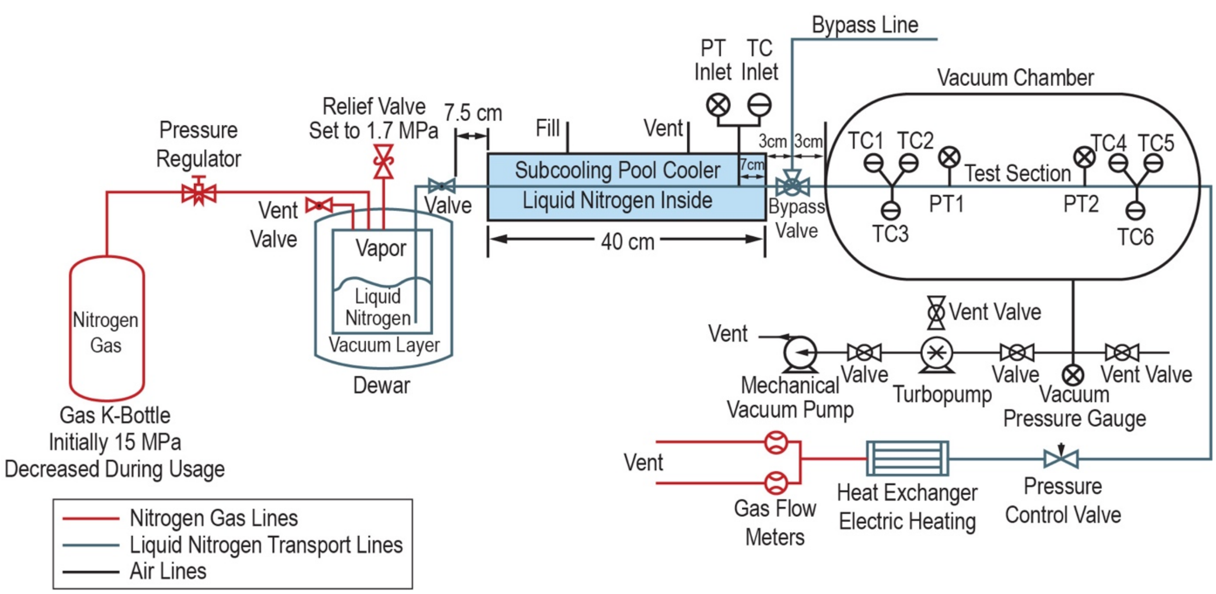

Fig. 1 Schematic of the UF LN2 chilldown experiment

Figure 2 is the GFSSP model of the LN2 chilldown experiment. The measured inlet pressure and temperature are fixed in boundary node 1. The test section is discretized into 20 pipe branches connected by 19 internal nodes. The 19 solid nodes represent the mass of the test section and are joined to the internal nodes by convection conductors. A small amount of heat is conducted axially through conductors 2526–4243. Boundary node 24 is set to ambient pressure. Branch 2223 is a flow regulator which adjusts its resistance so that the calculated flow rate will be forced to the measured flow rate, but note that until steady-state is reached, the flow rate in an individual branch upstream will not necessarily be equal to the flow regulator's flow rate.

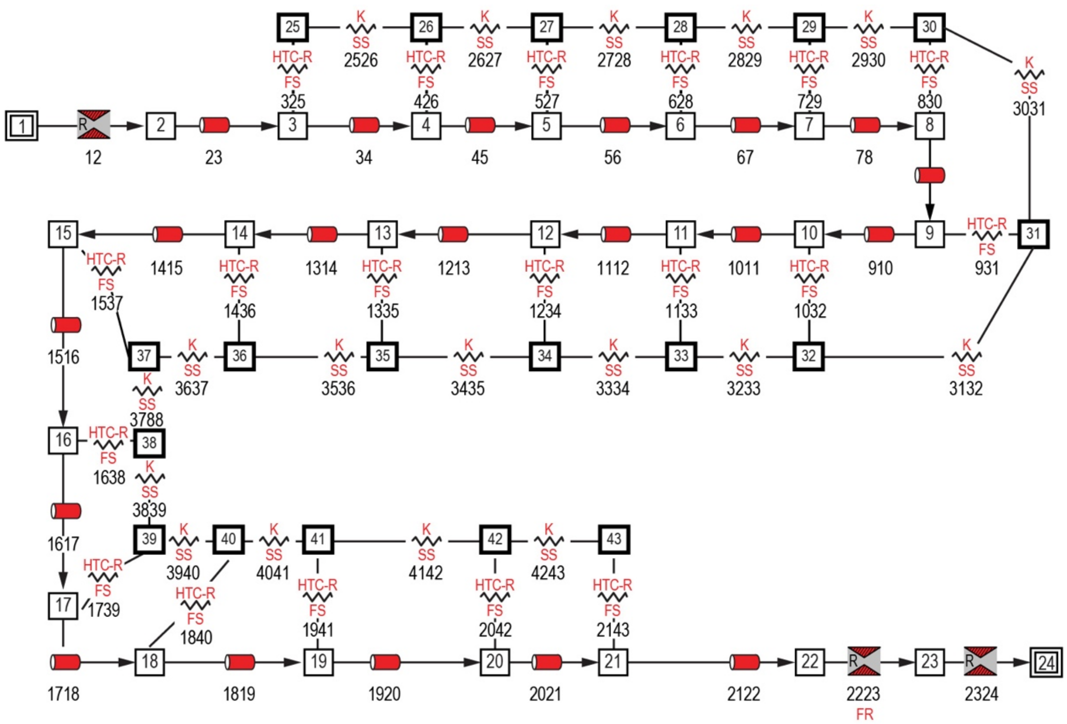

Fig. 2 GFSSP model of the UF LN2 chilldown experiment

Liquid Hydrogen Chilldown Experiments

The second set of experiments to be modeled are LH2 chilldown experiments conducted at NASA Glenn Research Center (GRC) in 2012 [7]. Figure 3 is a schematic of the test system, which is located inside a vacuum chamber. High pressure helium is used to pressurize and subcool a tank of LH2 in the range 20–24 K. The liquid flow rate, measured by a flow meter, is controlled by opening one of three valves. Two of the paths lead to flow control orifices for low and medium flow rates; the third path has no orifice and permits a steady flow rate up to 0.036 kg/s. The test section is an SS304 tube with inner diameter of 1.021 cm, placed above a dummy valve (valve 2). The total length of the stainless steel tubing is 2.14 m, followed by a 0.15-m Pyrex® sight glass. The test section is always oriented vertically upward. Silicon diodes (SD17, SD18, and SD19) measure the upstream and downstream wall temperatures. Pressure transducers (PT3 and PT4) measure the fluid pressures upstream and downstream.

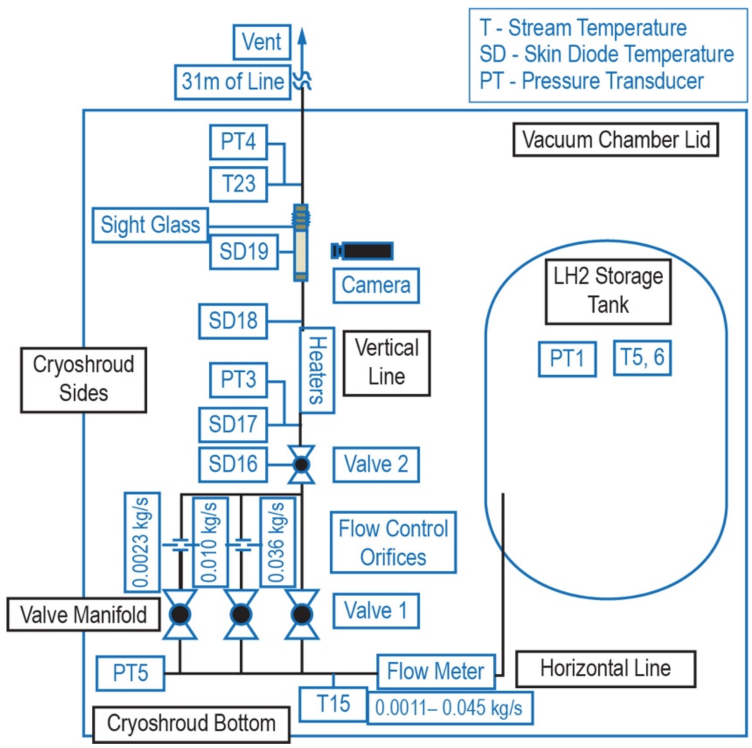

Fig. 3 Schematic of the NASA GRC LH2 chilldown experiment

Figure 4 is the GFSSP model of the LH2 chilldown experiment. It has the same general structure as the LN2 model. The inlet pressure at boundary node 1 is fixed to the measurement at PT3, 6.51 cm downstream of the dummy valve. Since there is no fluid temperature measurement at this location, the inlet temperature is set 0.2 °F below saturation to model pure liquid flow entering the test section. Pressure at outlet boundary node 36 is fixed to the measurement at PT4. Solid nodes 37–59 represent the mass of the stainless steel tubing, and solid nodes 60–64 represent the Pyrex sight glass. Restriction branch 23 acts as a flow regulator to force the incoming flow rate to match the test data.

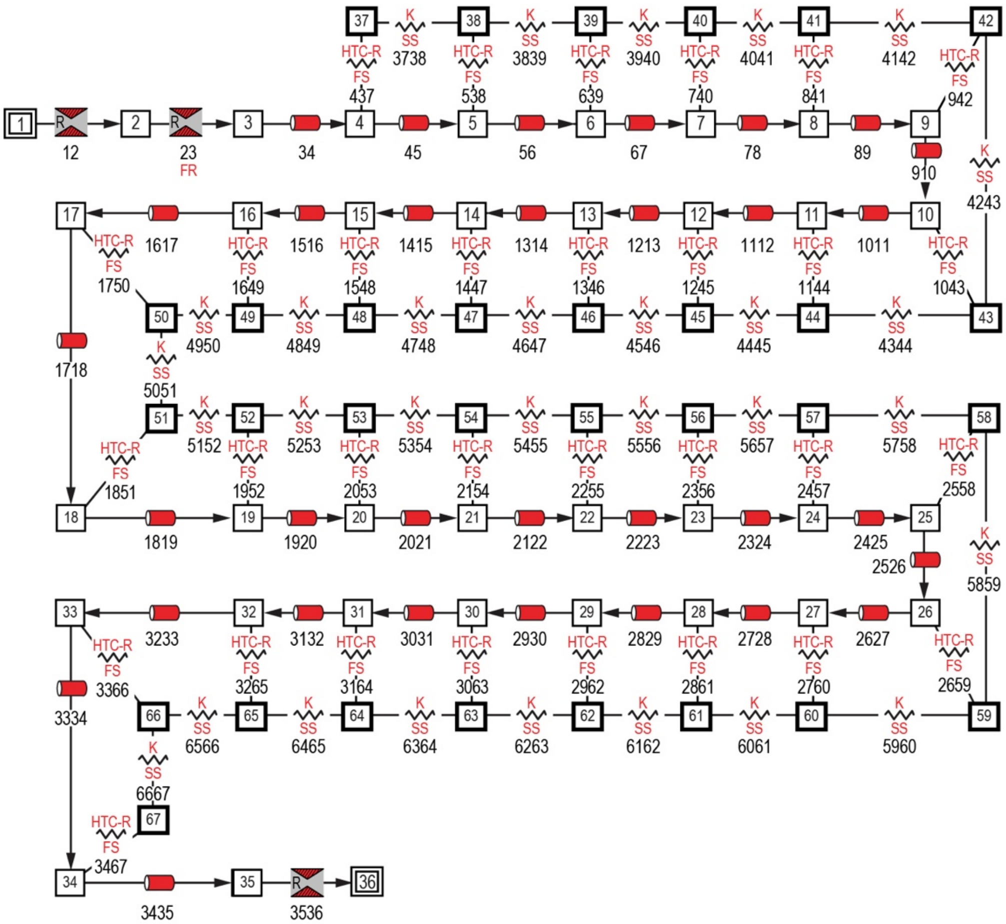

Fig. 4 GFSSP model of the NASA GRC LH2 chilldown experiment

Results

Liquid Nitrogen Chilldown Experiments

A total of 15 models were developed to simulate five LN2 chilldown tests in each of three orientations: horizontal, vertically upward, and vertically downward. Table 1 summarizes the five horizontal cases, with mean inlet Reynolds numbers (Re) ranging from 3,700 to 132,600. It is seen that the film boiling heat transfer coefficient, calculated by the UF correlation, increases with increasing Re. However, the maximum heat transfer coefficient, which occurs during transition and nucleate boiling, decreases with increasing Re.

Table 1 Summary of horizontal LN2 chilldown cases

Case	Re (Mean Inlet)	Approximate h_{film} (BTU/hr-ft^2-F)	Approximate h_{max} (BTU/hr-ft^2-F)
21B	3,700	7	3,600
17B	23,700	18	1,800
2B	46,700	25	1,100
40	68,200	36	680
26B	132,600	54	540

Figure 5 plots the upstream wall temperatures of the five LN2 horizontal runs. The test data are shown in orange, and the GFSSP prediction using the UF correlation is shown in green. The lowest Re cases take the longest to chill down and are on the right side of the plot. Figure 6 is a corresponding plot of the downstream wall temperatures for the five LN2 horizontal runs. It is observed that for the horizontal runs, the fit to the measured data is better for the upstream location.

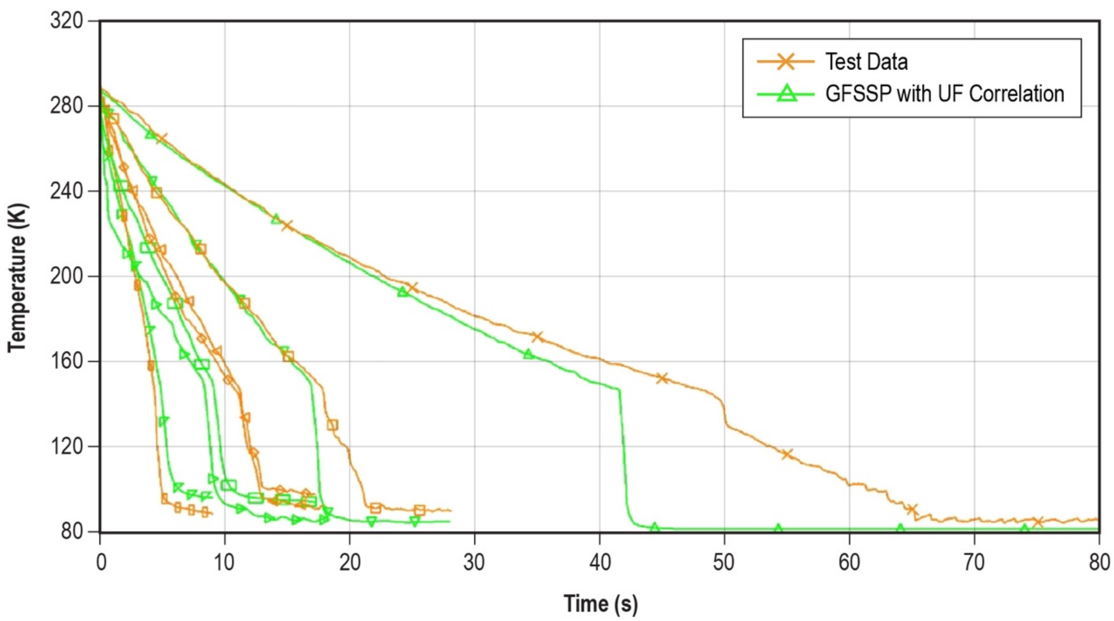

Fig. 5 Upstream wall temperature (K) vs. time (s) for horizontal LN2 chilldown runs

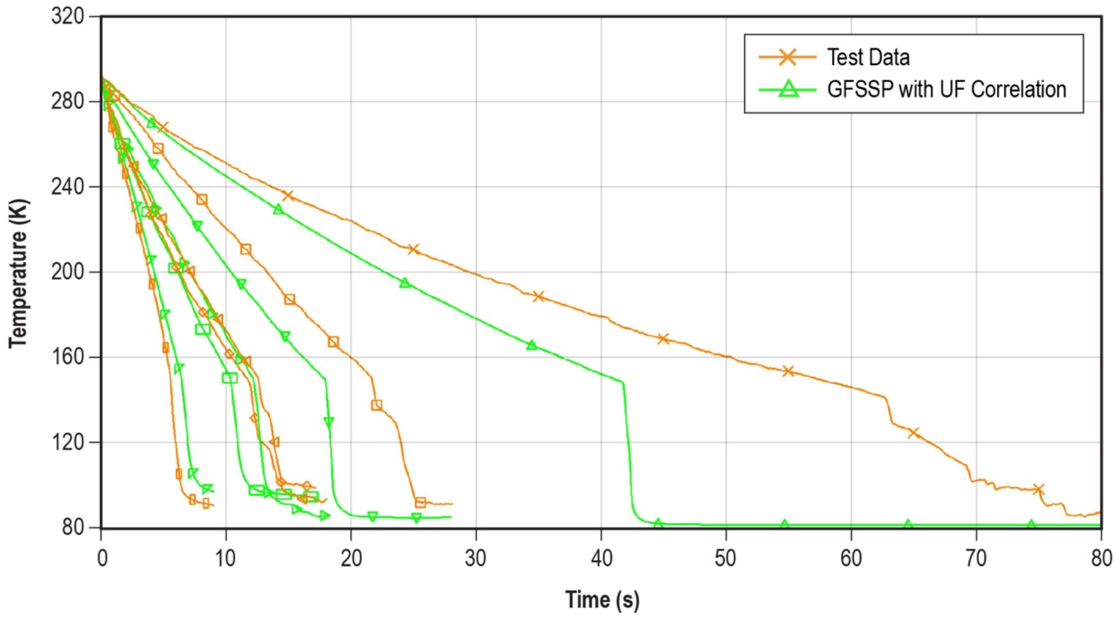

Fig. 6 Downstream wall temperature (K) vs. time (s) for horizontal LN2 chilldown runs

Figure 7 is a plot of the downstream wall temperature for case 40 (Re = 68,200). The test data are in orange, the GFSSP prediction with the UF correlation is in green, and the GFSSP prediction with the Miropolski correlation is in black. It is seen that the UF correlation fits the test data significantly better than the Miropolski correlation. This behavior was also seen in the other LN2 chilldown models. The Miropolski correlation tended to under-predict the heat transfer coefficient when the fluid was calculated to have nonzero quality (i.e., the fluid was a two-phase mixture); however, the correlation also over-predicted the heat transfer coefficient when the fluid was calculated to be pure liquid.

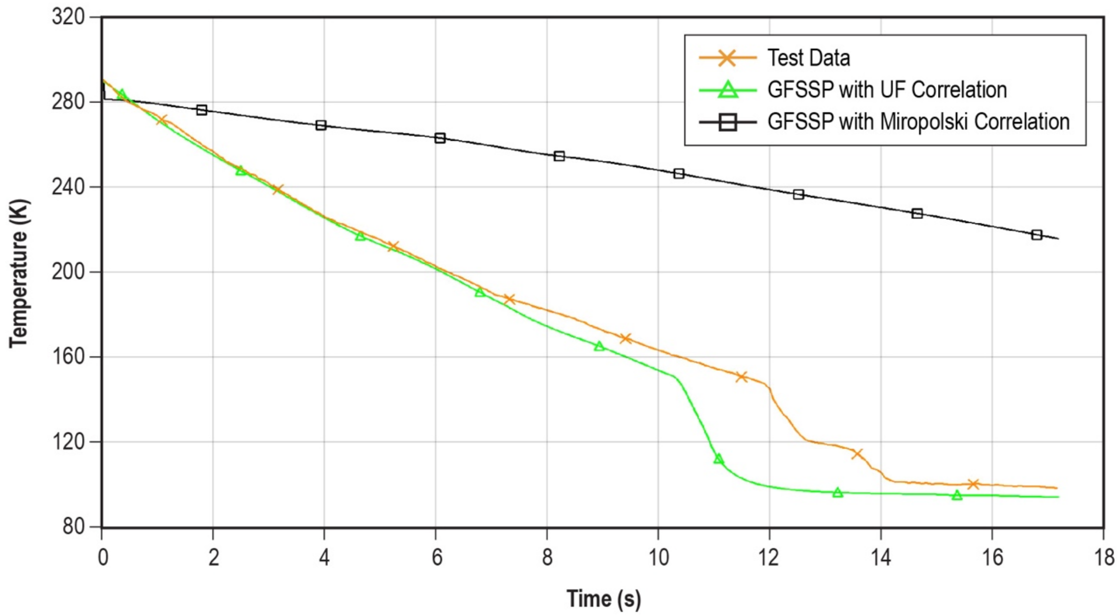

Fig. 7 Downstream wall temperature (K) vs. time (s) for LN2 case 40

Table 2 summarizes the five vertically upward cases, with mean inlet Re ranging from 3,500 to 186,400. There is a definite correlation between Re and the film boiling convection coefficient. However, unlike in the horizontal runs, the maximum predicted heat transfer coefficient does not have a strong correlation with Re.

Table 2 Summary of vertical upward LN2 chilldown cases

Case	Re (Mean Inlet)	Approximate h_{film} (BTU/hr-ft^2-F)	Approximate h_{max} (BTU/hr-ft^2-F)
50	3,500	9	900
7	42,000	29	580
29	98,000	54	500
11	118,400	54	500
3	186,400	110	540

Figure 8 plots the upstream wall temperatures of the five LN2 vertical upward runs, compared to the GFSSP predictions with the UF correlation. Figure 9 is a corresponding plot of the downstream wall temperatures. It is seen that for the vertical upward runs, the fit to the measured data is better for the downstream location.

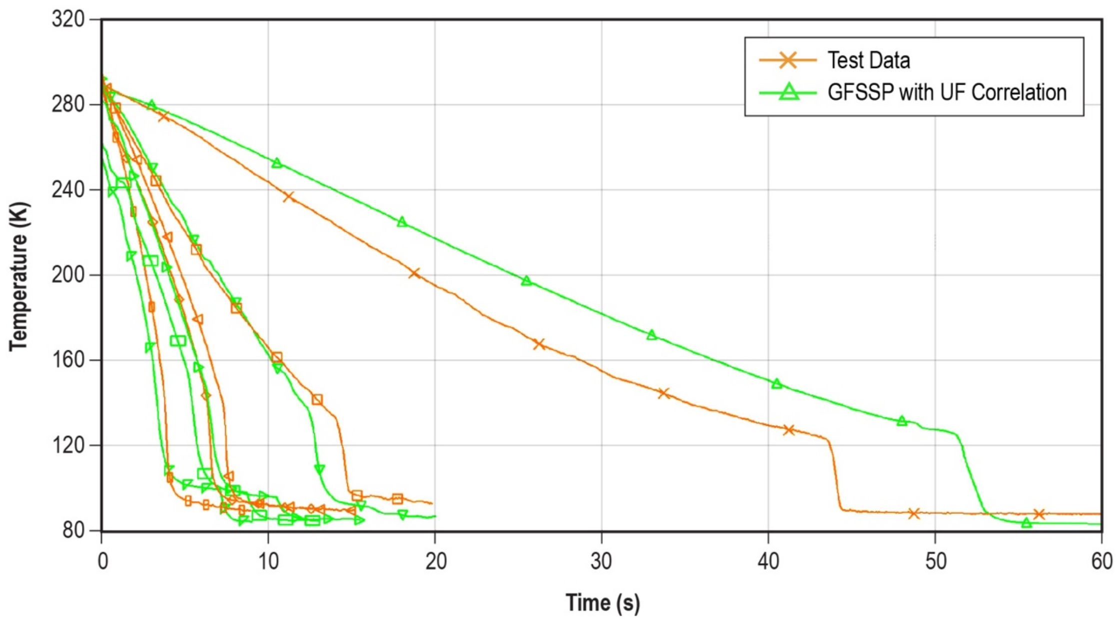

Fig. 8 Upstream wall temperature (K) vs. time (s) for vertical upward LN2 chilldown runs

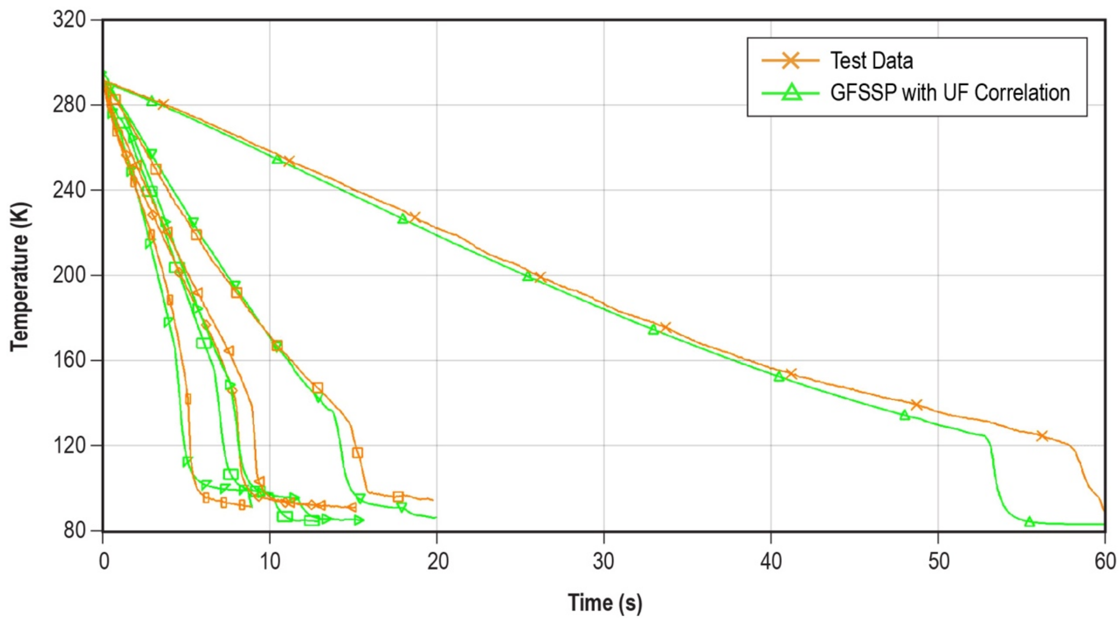

Fig. 9 Downstream wall temperature (K) vs. time (s) for vertical upward LN2 chilldown runs

Table 3 summarizes the five vertically downward cases, with mean inlet Re ranging from 4,200 to 126,400. Again, there is a definite correlation between Re and the film boiling convection coefficient. However, unlike in the horizontal runs and similar to the vertical upward runs, the maximum predicted heat transfer coefficient does not have a strong correlation with Re.

Table 3 Summary of vertical downward LN2 chilldown cases

Case	Re (Mean Inlet)	Approximate h_{film} (BTU/hr-ft^2-F)	Approximate h_{max} (BTU/hr-ft^2-F)
39	4,200	7	500
29	13,400	14	540
2	45,200	22	580
12	93,700	36	540
25	126,400	54	500

Figure 10 plots the upstream wall temperatures of the five LN2 vertical downward runs, compared to the GFSSP predictions with the UF correlation. Figure 11 is a corresponding plot of the downstream wall temperatures.

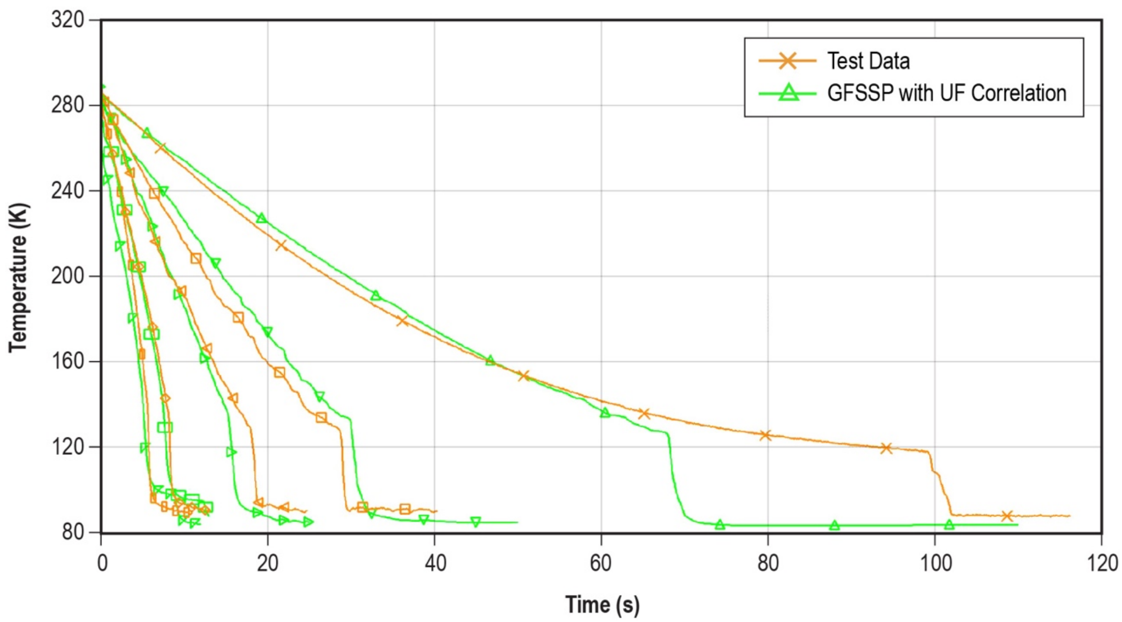

Fig. 10 Upstream wall temperature (K) vs. time (s) for vertical downward LN2 chilldown runs

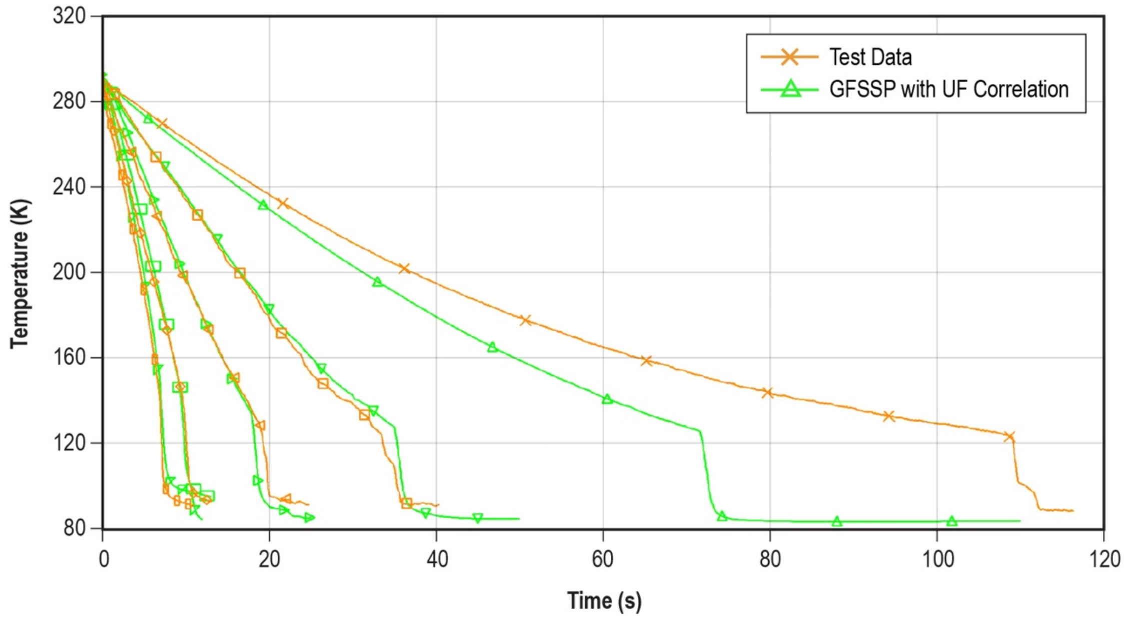

Fig. 11 Downstream wall temperature (K) vs. time (s) for vertical downward LN2 chilldown runs

Liquid Hydrogen Chilldown Experiments

Nine models were developed to simulate the vertically upward LH2 chilldown tests. Five of the runs used the medium flow rate path with a nominal steady flow rate of 0.010 kg/s, and four were at the high flow rate of 0.036 kg/s. Saturation temperatures ranged from 20.3–24.2 K. Tank driving pressures ranged from 207–345 kPa.

Figure 12 shows the upstream wall temperatures for test 22b. This test was conducted with a driving pressure of 345 kPa and initial saturation temperature of 20.3 K (corresponding to a saturation pressure of 101 kPa, so that the flow enters subcooled). Flow was directed through the medium flow-rate orifice. The time to chill down the stainless steel test section was approximately 15 seconds, during which the mean inlet Re was approximately 48,000. The test data are shown in orange. Although it is not a boiling heat transfer correlation, the Dittus-Boelter correlation (blue) fits the measured temperature the best, with a mean absolute error (MAE) of 17 K. The UF correlation (green) runs a distant second, with an MAE of 42 K. The fit of the Shah correlation (purple) is similar to UF, while the Miropolski correlation (black) significantly under-predicts the heat transfer coefficient.

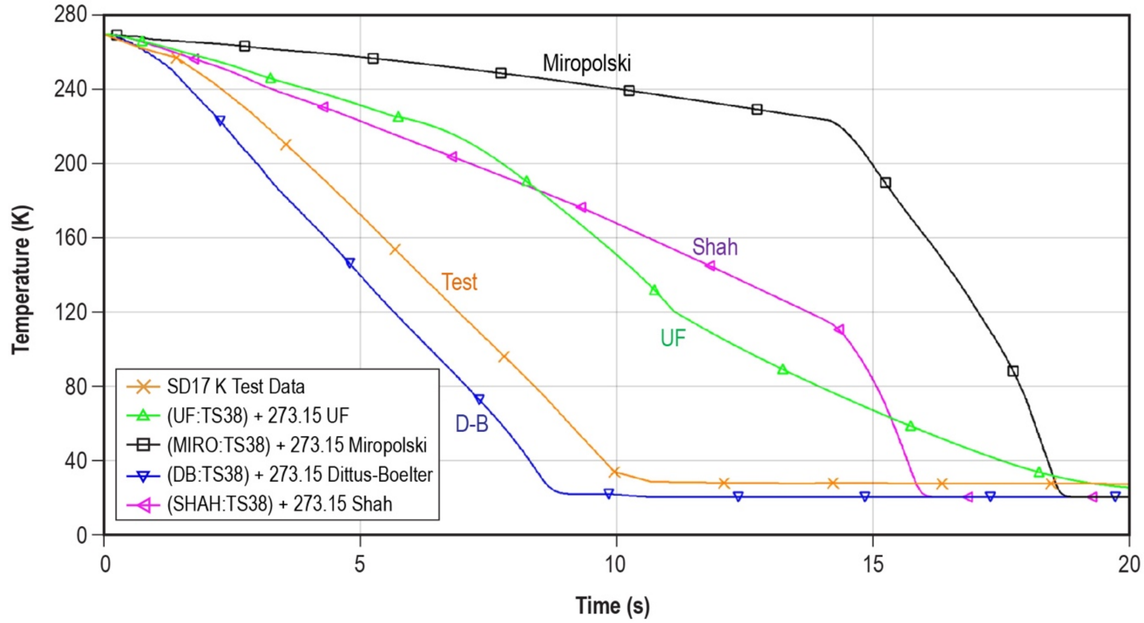

Fig. 12 Upstream wall temperature (K) vs. time (s) for LH2 test 22b

Downstream wall temperatures for test 22b are shown in Figure 13. There is much less variation in the predicted wall temperature than is seen at the upstream location. The UF correlation provides the best fit, with an MAE of 31 K.

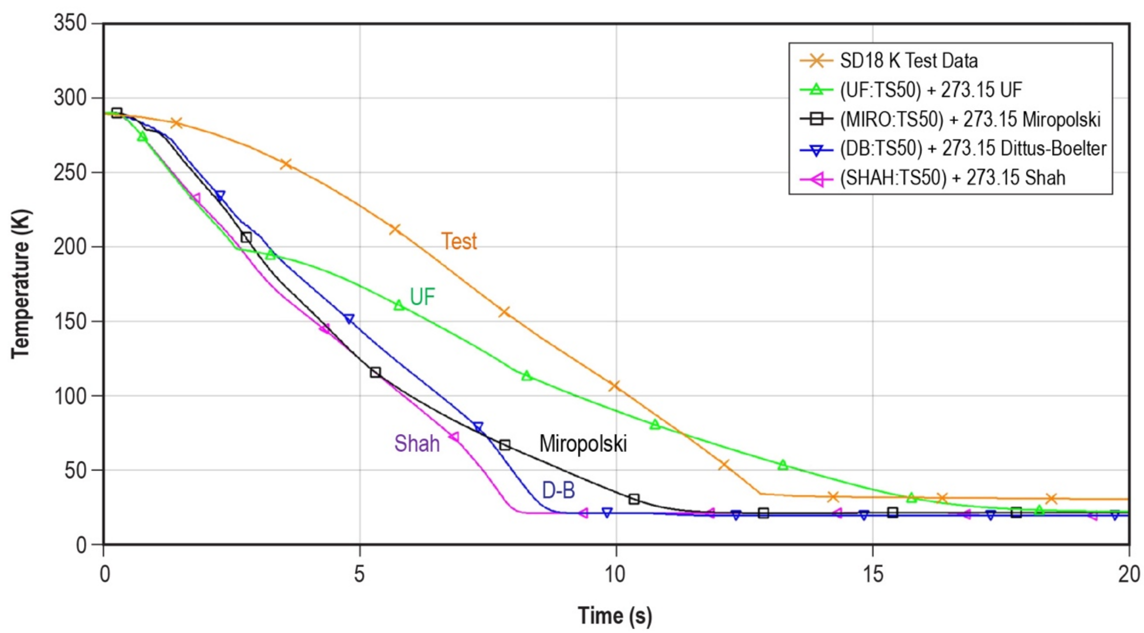

Fig. 13 Downstream wall temperature (K) vs. time (s) for LH2 test 22b

Figure 14 shows the upstream wall temperatures for test 3b. This test was conducted with a driving pressure of 207 kPa and initial saturation temperature of 21.4 K (corresponding to a saturation pressure of 138 kPa, so that the flow enters slightly subcooled). Flow was directed through the high flow-rate valve. The time to chill down the stainless steel test section was approximately 13 seconds, during which the mean inlet Re was approximately 50,000. The test data are shown in orange. The Dittus-Boelter correlation (blue) fits the measured temperature the best, with an MAE of 17 K. Again, the UF correlation (green) runs a distant second, with an MAE of 46 K.

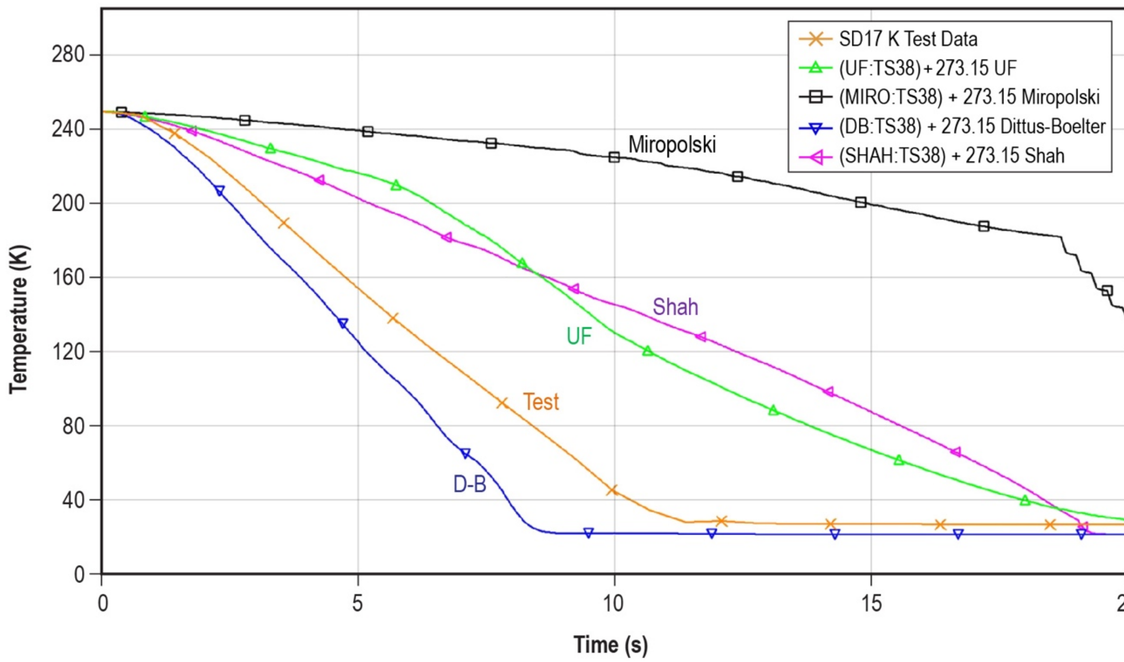

Fig. 14 Upstream wall temperature (K) vs. time (s) for LH2 test 3b

Downstream wall temperatures for test 3b are shown in Figure 15. There is much less variation in the predicted wall temperature than is seen at the upstream location. The UF correlation provides the best fit, with an MAE of 16 K.

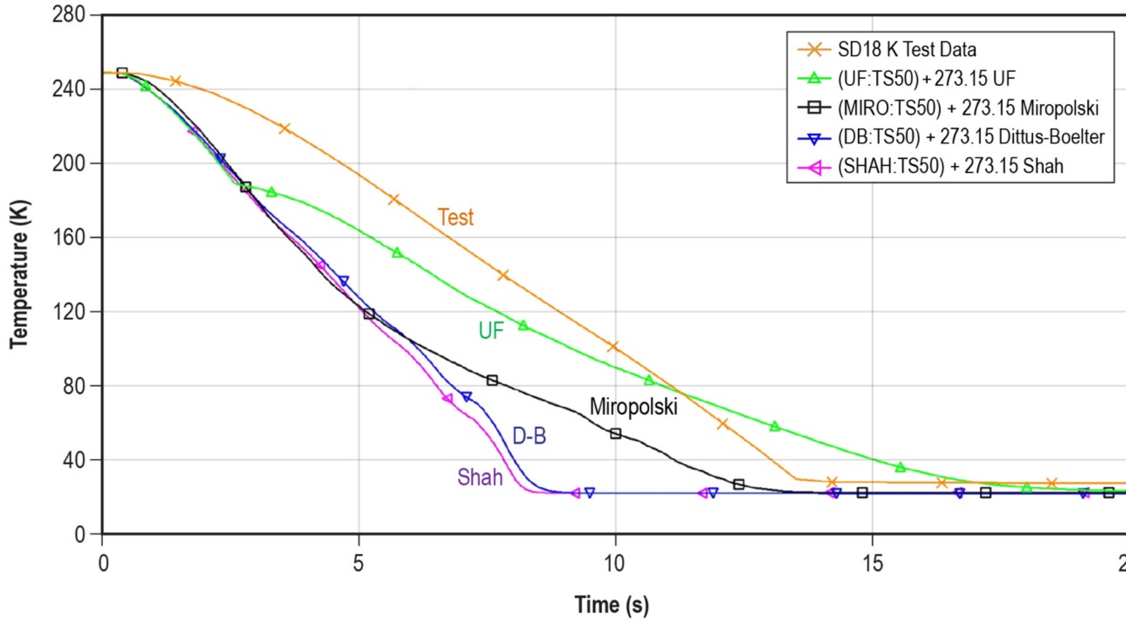

Fig. 15 Downstream wall temperature (K) vs. time (s) for LH2 test 3b

The MAEs of the four correlations are shown in Tables 4 and 5 for the upstream and downstream locations, respectively. For each case, the lowest MAE is highlighted in green, and the second-lowest is highlighted in yellow. At the upstream location, for all but the lowest Re, the Dittus-Boelter correlation provided the best fit to the data, with the UF correlation a distant second. At the downstream location, the UF correlation provided the best fit at all but the lowest Re, with the Miropolski correlation usually performing second-best.

Table 4 Mean absolute errors (K) for LH2 chilldown tests at upstream location

Test	Re (Mean Inlet)	University of Florida	Miropolski	Dittus-Boelter	Shah
1b	18,000	16	103	30	100
12b	34,000	60	112	11	103
22b	48,000	42	112	17	108
6b	48,000	65	124	8	114
17b	48,000	66	127	10	117
7b	51,000	45	103	15	98
3b	50,000	46	124	17	51
15b	80,000	40	123	8	101
8b	121,000	29	102	8	68

Table 5 Mean absolute errors (K) for LH2 chilldown tests at downstream location

Test	Re (Mean Inlet)	University of Florida	Miropolski	Dittus-Boelter	Shah
1b	18,000	55	58	61	46
12b	34,000	18	31	36	41
22b	48,000	31	44	45	51
6b	48,000	12	25	26	30
17b	48,000	18	33	30	37
7b	51,000	14	29	39	36
3b	50,000	16	30	38	40
15b	80,000	9	19	22	24
8b	121,000	7	14	15	16

Conclusion

Comparison of the predicted and measured wall temperatures points to several broad conclusions about the new UF chilldown correlation. In the models of all fifteen LN2 tests, the UF correlation provided far superior fit to the measured data than the Miropolski film boiling correlation, suggesting that the UF correlation is to be preferred for chilldown modeling of short transfer lines. Previous modeling of chilldown experiments with a 200-ft pipeline [8] showed that the Miropolski correlation provided acceptable predictions of chilldown time; this suggests that the correlation is best reserved for cases when most of the nodes in two-phase flow have a high vapor mass fraction (i.e. quality close to 1.0).

Conclusions from modeling the nine LH2 chilldown tests are less clear. At the upstream measurement location, the Dittus-Boelter correlation generally showed the least MAE, despite not being a boiling correlation. The UF correlation was second best, and the Miropolski and Shah correlations were the worst. At the downstream location, the UF correlation generally showed the least error, with Miropolski slightly outperforming the Dittus-Boelter and Shah correlations.

It is recommended that modeling work continue as new experimental data sets of cryogenic chilldown become available.

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