Cryogenic Line Cooldown

Comparison with Test Data

Revision 0; May 7, 2009

Reference: J. A. Brennan et al, "COOLDOWN OF CRYOGENIC TRANSFER LINES--AN EXPERIMENTAL REPORT," NBS (now NIST) Report 9264, November 7, 1966.

Purpose and Overview

The amount of liquid cryogen required to chill down lines, tanks, turbopumps, etc. from room temperature is often of significant importance. The physical phenomena involved can be complex, including film boiling and transition boiling, and two-phase pressure drops. Pressure surges can also be experienced when liquid, insulated by a layer of vapor film in the "inverted annular" regime, strikes a bend or obstruction downstream and boils explosively. However, the focus of this study is not on such hydrodynamic events, but rather on the longer time scale thermodynamic events: the time and liquid required to quench a line.

Simulations were made using SINDA/FLUINT V5.2, based in both the Sinaps© nongeometric (sketchpad) GUI and the Thermal Desktop© with FloCAD© geometric (CAD-based) GUI. Since all models are available for inspection and for use as a starting point or template, only brief descriptions are included in this document as general guidance. A basic understanding of SINDA/FLUINT modeling is assumed.

The primary purpose of this study was to ascertain the suitability of various SINDA/FLUINT assumptions and methods when applied to such cases, including a quantitative estimate of the uncertainties involved such that appropriate conservatism can be applied to the design. Typically, this conservatism takes the form of allocating additional cryogenic liquid as needed to assure the chilling and filling of the line despite the uncertainties involved.

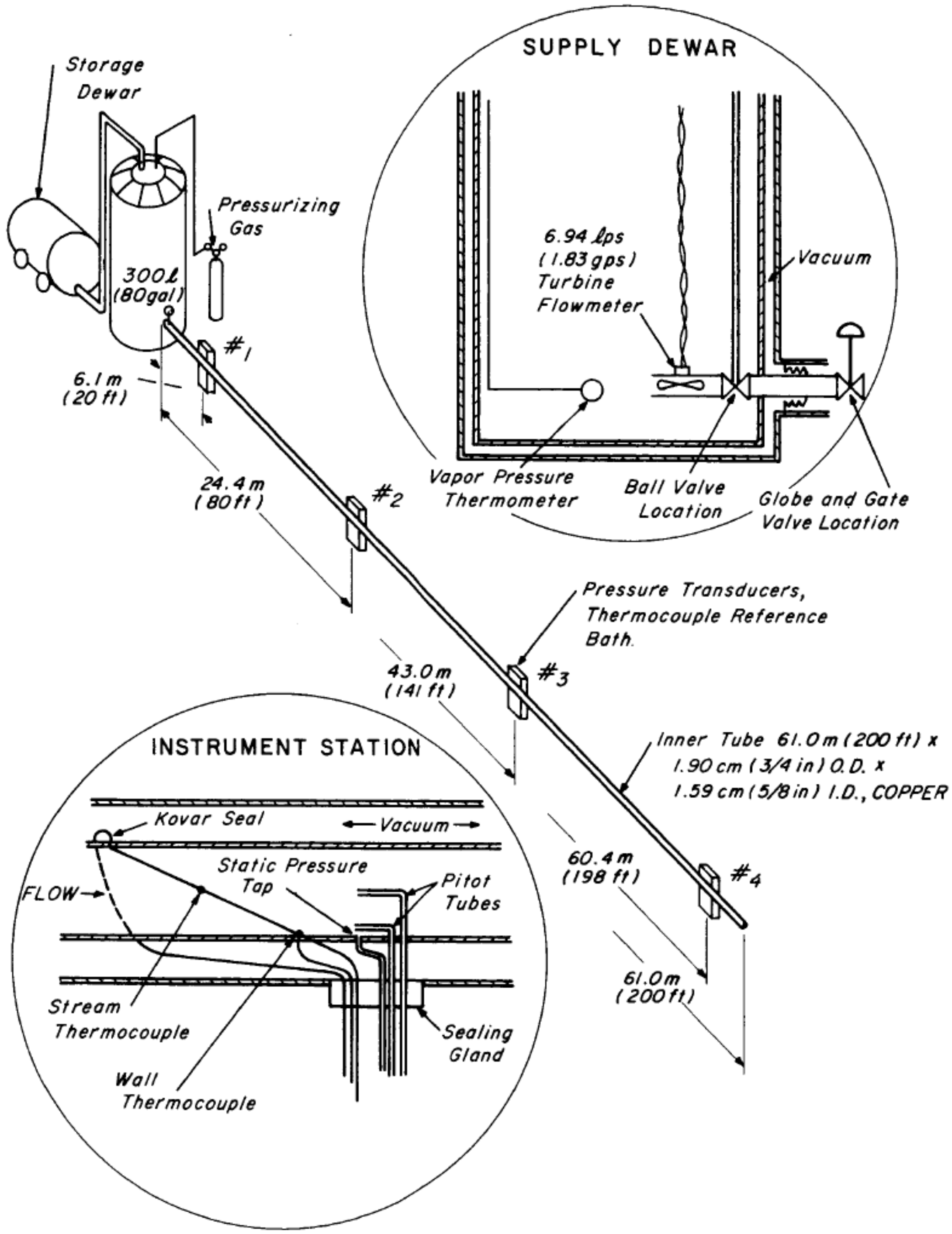
In particular, SINDA/FLUINT provides a set of default correlations for heat transfer and pressure drop that, being general-purpose and fluid-independent, may or may not be applicable to each new modeling need. While these correlations can be easily modified or replaced by the analyst, such extra effort is often neglected. One of the subpurposes of this study was to attempt to identify which if any defaults may be inappropriate for cryogenic quenching problems. Another subpurpose was to demonstrate the use of variational methods that are readily available within SINDA/FLUINT for exploring such uncertainties.

Summary of the NBS Report 9264

A PDF scan of the original report is available. Therefore, this section provides only a brief summary.

A series of cooldown tests was conducted whose focus was the investigation of pressure surges within a room temperature line when liquid cryogen is injected into it from one end. The line was a copper vacuum-jacketed pipe: 1.59cm ID and 1.90cm OD, 61m long. The source was a 300 liter tank that was filled with either liquid hydrogen or liquid nitrogen. The opposite end of the line was open to the atmosphere (approx. 0.82 atmosphere in Boulder, Colorado). At time zero a valve was opened, allowing liquid to flow into the line. Pressure and temperature histories were recorded at 4 stations along the line (6.1m, 24.4m, 43m, and 60.4m from the supply tank).

The figure below was extracted from Figure 1 of the NBS report.



The fluid within the supply dewar was either (1) pressurized and allowed to come to approximate thermal equilibrium at that pressure ("saturated"), or was (2) quickly pressurized from saturation at atmospheric pressure ("subcooled").

Some of the ambiguities or uncertainties in the report, and their relative importance, are discussed below:

1. The initial temperature of the liquid is unknown, despite the declaration of "saturated" or "subcooled." However, a reasonable value can be guessed from the test data, and the results are not very sensitive to this uncertainty.
2. The nature of the pressurizing gas, though presumed to be helium, is unknown, as is the hold time. Dissolution/evolution of the gas is therefore neglected, and the consistent trend between saturated and subcooled runs (at least for hydrogen) is taken as an indication that this effect is indeed negligible. (The presumption here is that the subcooled runs should be nearly free of dissolved gas since the hold times must have been very short.)
3. The type of valve used for each test is unknown. However, since the focus of this study is on longer time-scale events, and since the results were insensitive to the small magnitude of pressure losses associated with each valve, this unknown is not important. A ball valve (very low resistance) was assumed for most analyses reported. Valve opening times were assumed instantaneous.
4. The nature of the vacuum-jacketed shield is unknown, but the results are largely insensitive to variations in the model of this insulation.
5. The material specification for the copper line is missing. While the thermal conductivity of various alloys is highly variable, that particular property does not have much effect on results. More important is the specific heat, but fortunately variations between alloys are relatively small: on the order of 5% or less. OFHC copper was used as a baseline (even though it would have likely been unavailable in drawn tubing) and uncertainties in the specific heat were explored analytically.
6. The accuracy of the supply pressure and the line temperature measurements is unknown. There are clear indications of problems in the thermistry based on inconsistent results. (This is noted in the NBS report.[1])
7. The amount of initial fill of liquid in the supply tank is uncertain, and pressures can drop during the run due to depletion (expansion of the ullage). The volume of the line is 12 liters compared to 300 liters in the supply tank, but it can take perhaps 30-50 liters of liquid hydrogen to accomplish the cooldown event. This effect (i.e., the added uncertainty in the supply pressure) is more important for hydrogen runs than for nitrogen runs, since the amount of liquid nitrogen required is much less (about 15-20 liters).

---

[1] The crossing of lines at cold temperatures was noted in the NBS report as an indication of measurement error. For example, station 3 often stayed warmer than station 4, which was downstream of it. Interestingly, some of this discrepancy actually has a physical explanation that the NBS authors did not appear to consider. In saturated runs, or in downstream sections, the liquid continues to flash as the pressure drops. This means that while both stations 3 and 4 might contain mostly liquid, they are at different pressures, and so different saturation conditions. Therefore, station 4 *should* be colder since it is nearer the exit (and so at a lower pressure than is station 3).

8. The relative amount of para versus ortho hydrogen is unknown. This turns out to be a cause of significant uncertainty in the results for hydrogen cases, as will be explained in detail below.
9. The ID and roughness of the tube are uncertain. The classification of the tube is not known, and the dimensions do not correspond to currently available off-the-shelf options. While the roughness uncertainty is not significant, one percent uncertainty (i.e., on the order the manufacturing tolerance) in the ID makes a very big difference in the results.

The curves from various figures in the NBS report were converted into digital data so that the results could be plotted together with SINDA/FLUINT predictions, and also so that numerical measurements of goodness of fit (e.g., root-mean-square or RMS error) could be calculated. The NIST plots include sparse data markers with lines drawn between them. It is not clear whether this treatment was used because only a few data points were available, or because only representative points were depicted. In other words, it is not clear how faithfully one should attempt to represent the drawn curves versus the data points. For example, is the frequency of the oscillation in the data of station 1 in Figure 14 accurate, or a is it a result of sampling error? Fortunately, this uncertainty is not critical.

More importantly, some of the traces begin late (long after time zero) or stop short (before the end of other data). However, in order to compare numerically, data for each station for the entire event is required, so some effort was made to extrapolate the data in the plots. Also, it is clear from some plots (e.g., Figure 6) that the valve was opened a second or two before time zero: data needed to be shifted to the right slightly in order to be compared with analysis. None of these adjustments was made with intent to alter the comparison with analysis results. The digitized data, in the form of SINDA arrays, is available along with the models for inspection or comparison with the original hardcopy plots in the NBS report.

A summary of the tests used for comparison are listed below. The NBS figure number is used for naming run cases and files.

Figure	Fluid	Pressure (atm.)	State
2	hydrogen	5.1	saturated
3	"	2.5	subcooled
4	"	4.2	subcooled
5	"	5.9	subcooled
6	"	7.6	subcooled
7	"	11	subcooled
10	nitrogen	2.5	saturated
11	"	3.4	saturated
12	"	5.9	saturated
13	"	4.2	subcooled
14	"	5.9	subcooled