

Optimization of cryogenic chilldown and loading operation using SINDA/FLUINT

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Abstract

A cryogenic advanced propellant loading (APL) system is being developed at NASA. A wide range of applications and variety of loading regimes call for the development of computer assisted design and optimization methods that will reduce time and cost and improve the reliability of the APL performance. A key to the development of such methods is modeling and optimization of non-equilibrium two-phase cryogenic flow in the transfer line. Here we report on development of such optimization methods using a commercial SINDA/FLUINT software. The SINDA/FLUINT model is based on the solution of one-dimensional two-phase flow conservation equations and a full set of correlations for flow patterns, losses, and heat transfer in the pipes, valves, etc. We validate this model using experimental data obtained from chilldown and loading of a cryogenic testbed at NASA-KSC. We analyze sensitivity of the model with respect to the variation of key control parameters including pressure in the tanks, opening of the control valves, and insulation. We discuss the formulation of multi-objective optimization problem and provide an example of solution to one such problem.

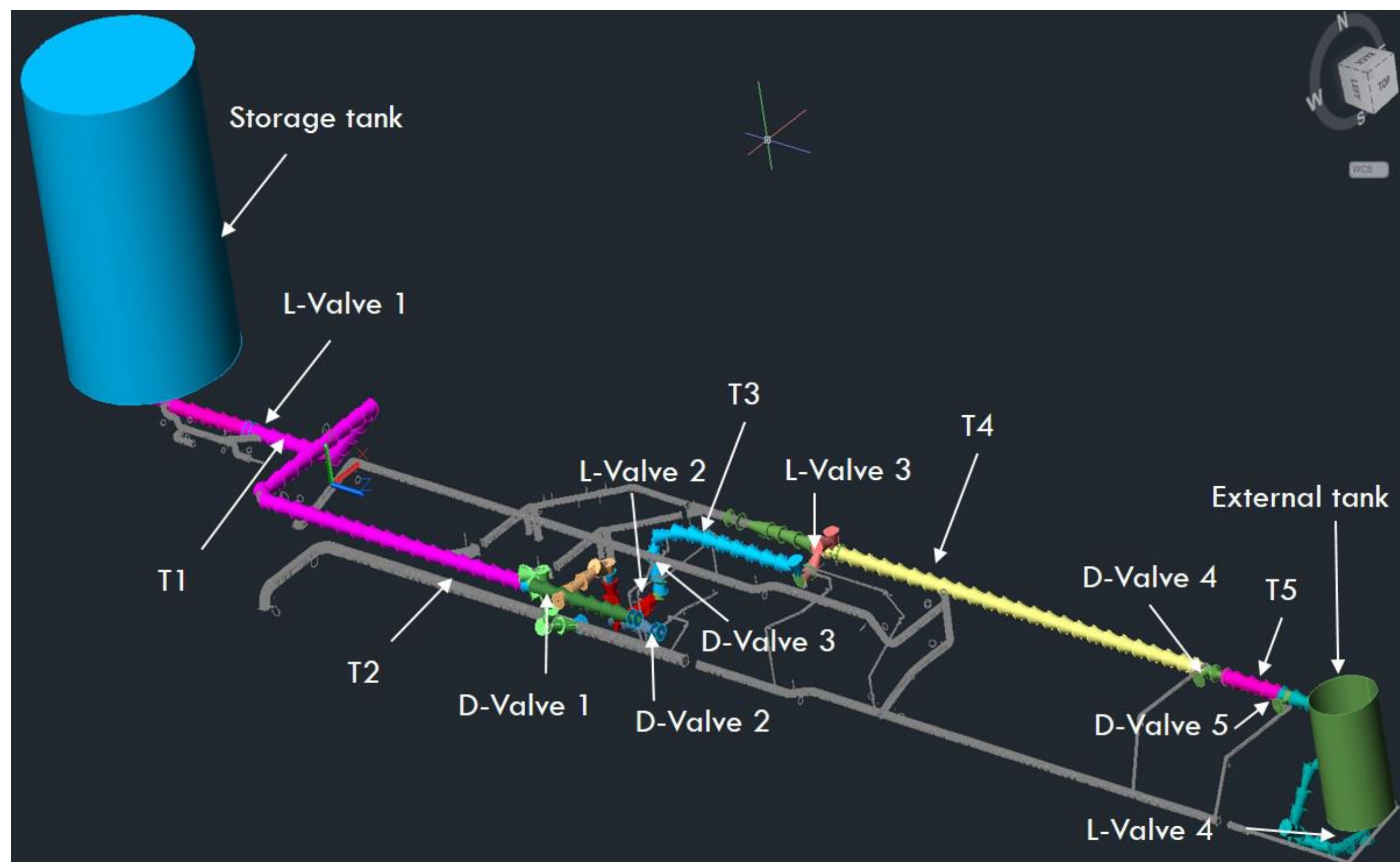


FIGURE 1. Figure 1. Schematic of the SINDA/FLUINT model of the cryogenic testbed at KSC. The locations of four in-line control valves (L-Valves), six dump valves (D-Valve), and temperature sensors (T1, ..., T5) are indicated by arrows.

Introduction

The future of deep space exploration relies on autonomous operations including autonomous control of cryogenic loading operations. The ability to model and optimize non-equilibrium two-phase cryogenic flow is one of the key ingredients required for the development of such autonomous cryogenic management. To meet this requirement we are currently developing and testing a hierarchy of models ranging from quasi-steady homogeneous moving front model to separated model cryogenic two-phase flow. One of the important components in this hierarchy is the baseline model of the cryogenic transfer line developed in SINDA/FLUINT. The model is used to verify the performance of other models in the hierarchy and to analyze flow properties in various loading regimes.

Introduction (Cont.)

A sketch of the model of the cryogenic loading system is shown in Fig. 1. The system consists of a 24000 liter storage tank (left) and an 8000 liter external tank (right). The tanks are connected by a pipeline. A number of control valves and sensors can be seen along the loading path. The cryogenic fluid used in the tests is nitrogen, which is used to simulate LO2 loading operations. The total length of the line is about 45 m. The characteristic speed of sound in the gas phase is ~ 200 m/sec and in liquid is ~ 700 m/sec. The transient time of pressure equilibration is less than 1 sec. The diameter of the stainless steel pipe varies along the pipeline from 0.0254 m to 0.1524 m. The thickness of the walls is ~ 3 mm. The total surface area of the pipes is approximately 12.5 m^2 and their total volume is around 400 liters.

Temperature and pressure sensors located at several locations along the system monitor the state of flow. Importantly, the temperature of the fluid is measured in the middle of the pipe. The real time accurate monitoring of complex nominal and off-nominal flow regimes during the loading and remote control of the flow by the valves makes the current system a unique experimental testbed well suited for the development of autonomous loading operations.

Model Development

Conservation equations for the mass and energy are solved by dividing the pipeline into a number of control volumes, which are called lumps. There are a total of 60 lumps in the present model. The lumps are connected by paths, which solve for the momentum conservation equation on a staggered grid. The heat transfer to the wall is modeled by introducing ties between the lumps and the wall control volumes. External radiation imposed on the pipes is modeled explicitly in RadCAD the radiation analysis component of the commercial software program Thermal Desktop. Thermal Desktop provides the user interface for the SINDA/FLUINT model as well. The valves are modeled as orifices with variable openings.

The model was validated by comparison of the model predictions with the experimental data obtained from the KSC testbed. The results of this comparison are shown in the Fig. 2. It can be seen from the figure that the model can accurately reproduce the key dynamical features of the system behavior during chilldown. Accurate predictions of the SINDA/FLUINT model pave the way for its application to the analysis of optimal loading regimes.

Optimization Problem

Optimization of the cryogenic transfer systems may have multiple objectives. A knowledge of the amount of time and cryogen required to fill the vehicle tank, the amount of hot liquid in the vehicle tank, maximum and minimum transfer rates for liquid and gas, optimal sensor placement, optimal fitting and minimum redundancy, minimum cost, and safety requirements are examples of the valuable information that can be obtained using optimization. On the ground reliable guidelines for safe and effective cryogenic transfer can be drawn from the prior experience and lessons learned. However, the role of modeling and numerical optimization becomes increasingly important once autonomous cryogenic fluid transfer is designed particularly in reduced gravity. In what follows we formulate an example of the optimization problem and discuss an approach to the solution of this problem that can be obtained using SINDA/FLUINT. The analysis is limited to the transient process of cooling the system to its equilibrium operating temperature because it is the most challenging regime of the cryogenic transfer both from the point of view of modeling and safety.

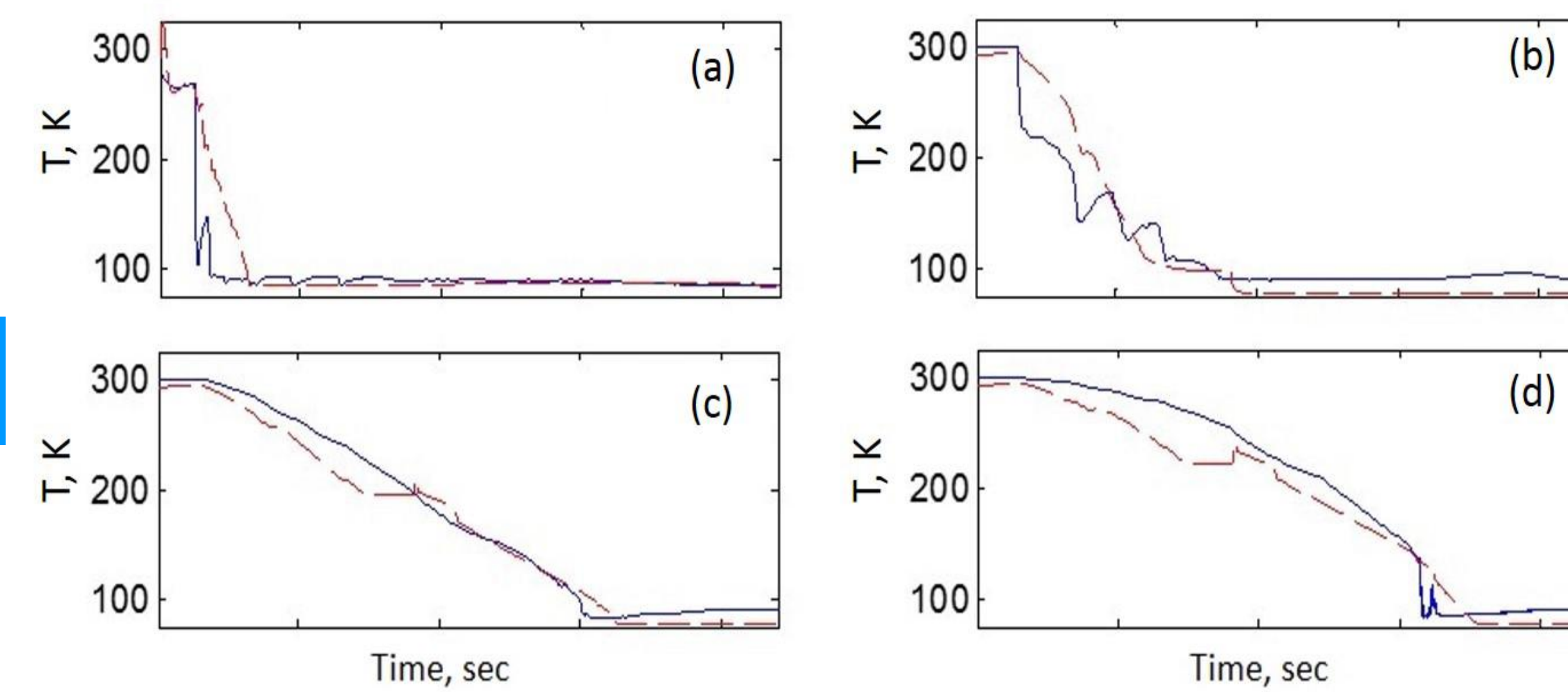


FIGURE 2. Comparison of the experimental time traces of temperature (solid line) with the numerical predictions (dashed line) for four different locations along the pipeline (see Fig. 1): (a) T1; (b) T2; (c) T3; (d) T5.

Next, we performed a sensitivity analysis of the system response to the variation of several model parameters. This analysis allows one to reduce the number of parameters involved in the optimization problem.

In the example presented here we performed sensitivity analysis of the chilldown of the first section of the transfer line, up to control valve L-Valve 3. We analyzed the dependence of the chilldown on the openings of two in-line and three dump valves and on the value of pressure in the storage tank. The dependence of chilldown on opening of the dump valve D-Valve 1 is shown in Fig. 3. It can be seen that reducing the opening of this valve to 25 % of its nominal value results in nearly two fold increase in chilldown time.

Optimization (Cont.)

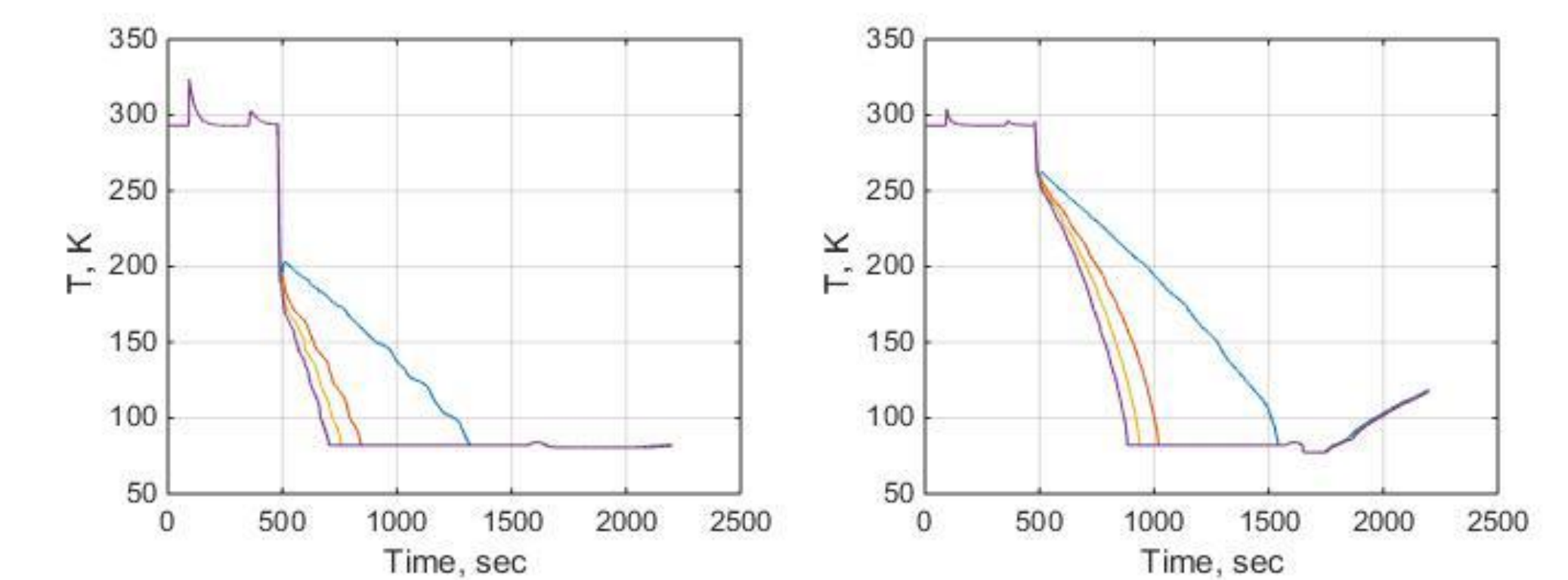


FIGURE 3. Temperature sensitivity to opening of the dump valve D-Valve 1 predicted for two different sensors: T2 (left) and T3 (right). The different curves correspond to opening of the dump valve (right to left): 0.25, 0.75, 1.0, and 1.25 of nominal opening.

Finally, we performed an optimization example of the chilldown of the cryogenic testbed. The problem considered was to find optimal openings of the three dump valves (D-Valve 1, 2, and 3) that minimize commodity losses during chilldown under the constraint that chilldown time not exceed 1500 sec. The input valve (L-Valve 1) was opened at 100 sec. One can observe a sharp peak in Fig. 3 at around 100 sec corresponding to the opening of this valve. It can also be seen from the figure that the temperature stays nearly constant until ~ 500 sec because the second in-line valve and the first two dump valves (D-Valve 1 and 2) remain closed until $t \sim 500$ sec.

The minimization of the total mass required to complete the chilldown before 1500 sec was set as the optimization objective. The default sequential linear method is used in SINDA/FLUINT to solve this problem. A subset of the solution results is shown in Table 1. It is noted that there is a trade off between the amount of cryogen and the time required to chill the system. Therefore the obtained results also provide solution to the following problem: find minimum time required to chill down the system under the constraint that the amount of the cryogen used does not exceed a predefined value.

TABLE 1. Results of optimization of the testbed chilldown. First three columns show opening of the dump valves relative to the fully opened position. Time in sec corresponds to the chilldown time. Mass in kg shows the total commodity used for the chilldown. The chilldown time is considered to be the time when the fluid temperature approaches 83 K everywhere in the first half of the transfer line.

D-Valve 2	D-Valve 3	D-Valve 1	Total M, kg	Time, sec	M, kg
0.102	0.108	1.40	232.4	886	160
0.105	0.110	1.24	212.6	902	141
0.109	0.110	0.98	185.7	954	118
0.117	0.110	0.80	165.3	1001	101

Summary

We have extended our earlier work on prediction of pressure and temperature dynamics in cryogenic transfer line using SINDA/FLUINT by developing a scheme for optimization of the cryogenic loading regime using SINDA/FLUINT high-level optimization solvers. As an example we considered problem of optimization of the dump valves openings that minimize the amount of time or cryogen required to chilldown the system. The results demonstrate the existence of a trade-off between time and propellant losses, i.e. the faster is the chilldown the more propellant has to be used.

Acknowledgements

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