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Optimization of cryogenic chilldown and loading operation using SINDA/FLUINT

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Abstract. A cryogenic advanced propellant loading system is currently 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 aspect of development of such methods is modeling and optimization of non-equilibrium two-phase cryogenic flow in the transfer line. Here we report on the development of such optimization methods using commercial SINDA/FLUINT software. The model is based on the solution of two-phase flow conservation equations in one dimension and a full set of correlations for flow patterns, losses, and heat transfer in the pipes, valves, and other system components. We validate this model using experimental data obtained from chilldown and loading of a cryogenic testbed at NASA Kennedy Space Center. We analyze sensitivity of this model with respect to the variation of the key control parameters including pressure in the tanks, openings of the control and dump valves, and insulation. We discuss the formulation of multi-objective optimization problem and provide an example of the solution of such problem.

1. Introduction

The future of deep space exploration relies on autonomous operations [1] including autonomous control of cryogenic loading operations [2]. The ability to model and optimize non-equilibrium two-phase cryogenic flow is one of the key requirements for the development of autonomous cryogenic management. To meet this requirement we are currently developing and testing a hierarchy of models [3] ranging from quasi-steady homogeneous moving front model [4, 5] to separated model [6] cryogenic two-phase flow.

An important component of this hierarchy is the baseline model of the cryogenic transfer line developed in SINDA/FLUINT [7]. The SINDA/FLUINT model is used to verify [8] the performance of other models in the hierarchy and to analyze flow properties in various loading regimes. Here we report on the progress in development of the SINDA/FLUINT application to the optimization of the cryogenic loading operation. The discussion is limited to the optimization of the chilldown regime as the most nontrivial and challenging regime of cryogenic loading.

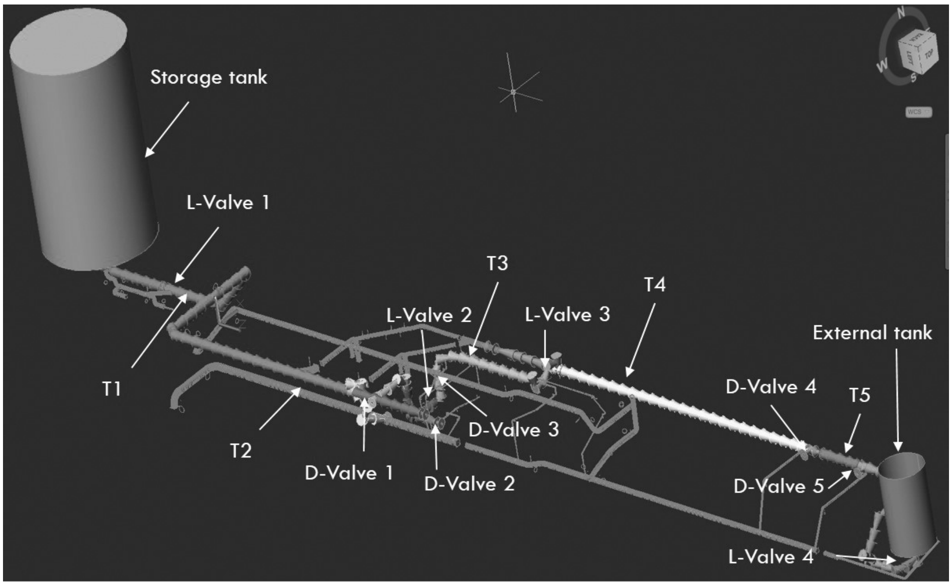

Figure 1: Schematics of the SINDA/FLUINT model of the cryogenic testbed at KSC. The locations for four in-line control valves (L-Valves), six dump valves (D-Valve), and five temperature sensors (T1,..., T5) are indicated by arrows.

First, we describe an experimental cryogenics transfer line built at KSC. Next, we discuss formulation of the optimization problem. We then analyze the system response to variation of the model parameters. Finally, we discuss an example of the chilldown optimization problem that can be formulated and solved within SINDA/FLUINT.

2. SINDA/FLUINT model of the cryogenic transfer line

A sketch of the SINDA/FLUINT model of the cryogenic loading system developed at KSC for testing autonomous regimes of loading operation is shown in Fig. 1. The system consists of a 23 m^3 storage tank (left) and a 7.6 m^3 external tank (right) connected by a pipeline. A number of control valves and sensors can be seen along the loading path. The cryogenic fluid is nitrogen. The total length of the line is 45 m. The characteristic speed of sound is $\sim$ 200 m/sec in the gas phase and $\sim$ 700 m/sec in the liquid phase. The characteristic transient time of the pressure equilibration is less than 1 sec. The diameter D of the stainless pipe varies along the pipeline from 0.0254 m to 0.1524 m. The thickness d_w of the walls is approximately 3 mm. The total surface area of the pipe is $S_{tot} \approx 12.5\ m^2$ and the total volume is $\sim 0.4\ m^3$.

Temperature and pressure sensors located at several places along the system monitor the state of the fluid. 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 make current system a unique experimental testbed well suited for the development of autonomous loading operations.

The loading is driven by pressure difference between the storage and the vehicle tank. The loading process is accomplished in four main stages: pressurization of the storage tank, chilldown, fast fill, and replenish. The chilldown takes $\sim$ 25 min and consumes 565 kg of nitrogen. During the fast fill 1777 kg of liquid nitrogen is transferred to the vehicle tank in about 15 min. The replenish phase takes 22 minutes and consumes 977 kg of nitrogen.

2.1. Model Equations
The flow in the cryogenic system is modeled using mixture density and mixture enthalpy

$$\rho = \alpha_g \rho_g + \alpha_l \rho_l, \quad h = x_g h_g + x_l h_l, \tag{1}$$

where α_g is the void fraction and x_g is the mass fraction of the vapor and α_l is the void fraction and x_l is the mass fraction of the liquid.

The set of model equations representing conservation of mass, momentum, and energy [7, 9] has the form

$$\begin{aligned} &A\frac{\partial \rho}{\partial t} + \frac{\partial A\rho u}{\partial z} = 0, \\ &A\frac{\partial \rho u}{\partial t} + \frac{\partial A\rho u^2}{\partial z} = -A\frac{\partial p}{\partial z} - (\tau_w l_w)_{2\phi} - \rho A g \sin\theta, \\ &A\frac{\partial \rho E}{\partial t} + \frac{\partial A\rho u H}{\partial z} = H_w (T - T_w) l_w, \end{aligned} \tag{2}$$

where ρ is the density, u is the velocity, and p is the pressure of the fluid with specific energy $e = c_v T + \frac{u^2}{2}$ and specific enthalpy $h = e + \frac{p}{\rho}$ of the mixture. The no-slip condition $u = u_g = u_l$ (subscripts g and l indicate gas and liquid respectively) was assumed in derivation of eqns. (2). The cross-sectional area of the pipe is A, l_w is the perimeter, θ is the angle of the pipe axis with respect to the horizontal line, and z is the coordinate along the pipe.

The fluid dynamics is coupled to the energy conservation equation for the unit length of the wall via the heat exchange term

$$\rho_w c_w d_w \frac{\partial T_w}{\partial t} = H_w (T - T_w) l_w + H_{amb} (T_{amb} - T_w) l_o. \tag{3}$$

Here H_w is the heat transfer coefficient from vapor or liquid to the wall and H_{amb} is the heat transfer coefficient from the environment to the wall. T_w is the wall temperature, T is the mixture temperature, and ρ_w, c_w, and A_w are the wall material density, specific heat, and cross-section area respectively, l_o is external diameter of the pipe.

The set of model equations (2) and (3) is complete by adding the equation of state and the volume conservation equation

$$\rho_{(g,l)} = \rho_{(g,l)} \left(p, h_{(g,l)}\right), \qquad \alpha_g + \alpha_l = 1. \tag{4}$$

The source terms on the right hand side of the equations (2) are determined using multiple correlations.

2.2. Correlation relations
The single phase frictional losses are calculated using Darcy friction factor. In turbulent regime the friction factor is calculated using Churchill approximation [10] to the Moody chart. In the two-phase region pressure drop is estimated using Chisholm approximation [11] of the Lockhard-Martinelli correlations.

The heat transfer values are based on the Nusselt number (Nu) correlations, which are chosen depending on the flow regime and the wall overheat temperature (the difference between wall temperature and saturation temperature T_s). In the single-phase region the value of Nu is a function of Reynolds number (Re). Nu is equal to 3.66 in the laminar regime ($Re < 1960$) and given by Dittus-Boelter [12] for $Re > 6420$. In the intermediate regime the Hausen [9] correlation is used.

In the two-phase flow two boiling flow regimes are considered: nucleate and film boiling. In the film boiling regime Dittus-Boelter [12] correlations are used with corrections to the mass fraction [9]. In the nucleate boiling regime Chen's [13] correlation is used.

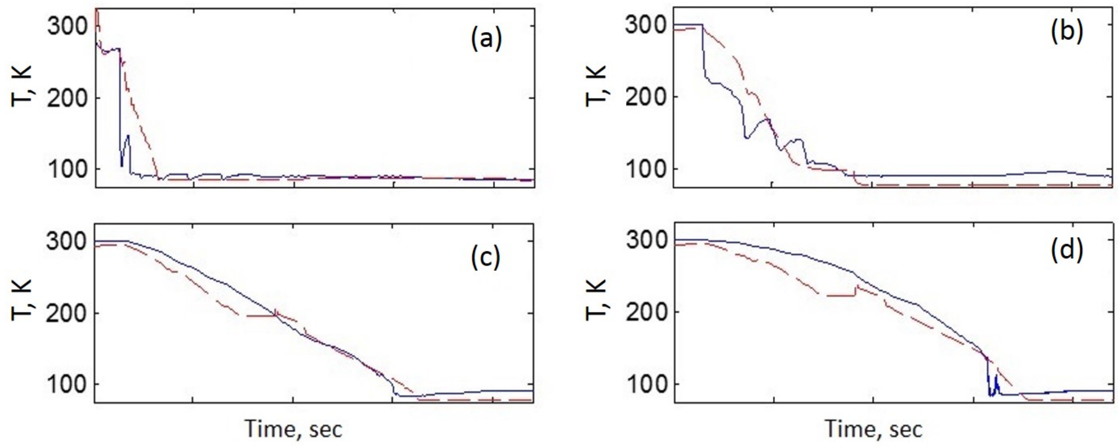

Figure 2: The comparison of the experimental time traces for the temperature (solid line) with the numerical predictions (dashed line) for four different locations along the line (see Fig. 1): (a) T1; (b) T2; (c) T3; (d) T5.

2.3. Model validation

The 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 model presented. 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. The external radiation is modeled explicitly. The valves are modeled as orifices with variable openings.

The model was validated by comparing its predictions with the experimental data obtained at NASA KSC (see [7] for further details) as shown in Fig. 2. It can be observed 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. Below we formulate the optimization problem in the context of cryogenic loading operation and report on the progress in developing solution of this problem using SINDA/FLUINT.

3. Optimization problem

Optimization of the cryogenic transfer systems may have multiple objectives. A knowledge of the amount of time and cryogenic fluid required to fill vehicle tank, maximum and minimum transfer rates for liquid and gas, optimal sensor placement, optimal component configuration and minimum redundancy, minimum cost, and safety requirements are examples of the valuable information [14] that can be obtained by solving the optimization problem. On the ground reliable guidelines for safe and effective cryogenic transfer can be drawn from prior experience and lessons learned. However, the role of modeling and numerical optimization becomes increasingly important once autonomous cryogenic fluid transfer is designed for 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 commercial SINDA/FLUINT software. The analysis is limited to the transient process of cooling the system to its equilibrium operating temperature since it is the most challenging regime of cryogenic transfer both from the point of view of modeling and safety.

During chilldown the two main commodities are time and the amount of liquid required to cool the system. Their relative importance depends on the application. On the ground time may often be the key objective of the optimization, while on orbit the cost of propellant may become the primary concern.

3.1. Sensitivity study

As a first step towards the solution of the optimization problem we perform a sensitivity analysis of the system response to the variations of several model parameters. The goal of this study is to determine the key parameters of the system that allow for efficient control of the flow. This analysis also allows one to reduce the number of parameters involved in the solution of the optimization problem.

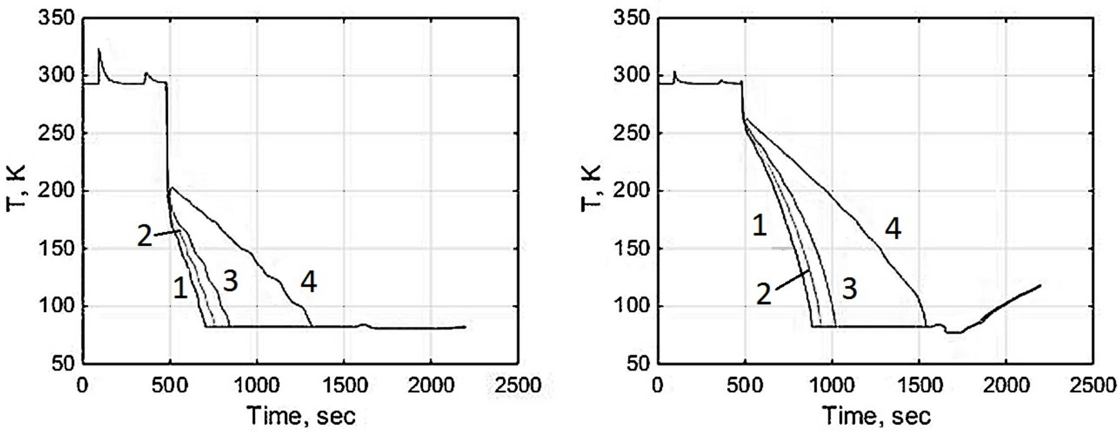

Figure 3: Temperature sensitivity to opening of dump valve D-Valve 1 predicted for two different sensors: T2 (left) and T3 (right). The different curves correspond to five different openings of the dump valve (left to right): (1) 1.25, (2) 1.0, (3) 0.75, and (4) 0.25 of the nominal opening.

In the particular example considered in this work we performed sensitivity analysis of the chilldown of the first section of the transfer line, up to the in-line 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 the chilldown in the opening of the dump valve D-Valve 1 is shown in the Fig. 3.

It can be seen from the figure that reducing the opening of this valve to 25 % of the nominal position results in a two-fold increase in the chilldown time. For the cases considered it was also noted that the pressure in the pipes was controlled by the pressure in the storage tank and sizing of the two in-line valves.

3.2. Optimization of the SINDA/FLUINT model

Dynamic calculations can be made from within SINDA/FLUINT. This enables parametric analyses, sensitivity studies, optimization, correlation, and reliability estimation. An example of the application of dynamical SINDA/FLUINT is the analysis of chilldown optimization.

Here the following problem was considered: find optimal openings of three dump valves (D-Valve 1, 2, and 3) that minimize commodity losses during chilldown under the constraint that chilldown time cannot be longer than 1500 sec. In this example no feedback control of the openings of the dump valves was imposed (i.e. the opening was constant during the whole chilldown operation).

The control 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.

Table 1: Results of the optimization of chilldown. First three columns show opening of the dump valves relative to the fully opened position. Fourth column shows total mass exiting the storage tank. Time in sec corresponds to the chilldown time. Mass in kg shows the commodity used for the chilldown of the pipes.

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

At time $t \sim 500$ sec the dump valves D-Valve 1, 2, and 3 and the control valve L-Valve 2 are opened and remain opened until the end of the chilldown. The chilldown time is defined as the time when the fluid temperature approaches 83 K everywhere in the first half of the transfer line up to location of valve L-Valve 3.

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 [15] is used in SINDA/FLUINT [9] to solve this optimization problem. A subset of the solution results for nonzero ambient heat flux is shown in Table 1.

It can be seen from the table that there is a trade off between the amount of the cryogen and the time required to chill the system. Therefore the obtained results also provide solution to the following problem: find the minimum time required to chill down the system under the constraint that the amount of cryogen used does not exceed a predefined maximum value.

Table 2: Results of optimization of the chilldown with zero heat flux to the wall. First three columns show opening of the dump valves relative to the fully opened position. Fourth column shows total mass loss from the storage tank. Time in sec corresponds to the chilldown time. Mass in kg shows the commodity used for the chilldown of the pipe.

D-Valve 2	D-Valve 3	D-Valve 1	Total M, kg	Time, sec	M, kg
0.102	0.108	1.38	252.2	873	150
0.105	0.110	1.17	230.6	897	129
0.109	0.110	0.94	206.6	939	107
0.11	0.110	0.80	190.8	978	95.5

Similar results were obtained (see Table 2) for the case of zero ambient flux corresponding to the vacuum jacketed pipes. To understand the difference between the two cases, we note that total mass exiting the storage tank during the chilldown consists of two parts. The first part is exiting the dump valves and the second part remains in the pipe. The mass exiting via the dump valves can be considered as a loss and is shown in the last columns of both tables.

One can notice a consistent difference of ∼10 kg between losses in both cases. This difference corresponds approximately to the additional losses on evaporation that are required to compensate for external radiation in the first case. We also notice that the total mass is consistently larger in the vacuum jacketed case, indicating that larger amount of liquid is accumulated in the pipes in the end of chilldown when there is no external radiation. The time required to complete chilldown in this case is also shorter. All these changes are consistent with the intuitive physical picture that the external radiation causes additional evaporation losses and slows down the chilldown.

We note, however, that the minimum losses obtained for the vacuum jacketed case (∼95 kg) significantly exceeded the minimum possible losses (around 10 kg) required to cool the pipe wall from 300 K to 83 K. This result is most likely a consequence of no feedback simulations of the homogeneous model that allowed a significant amount of liquid to exit the pipes through the dump valves during the chilldown. To verify this conjecture we are currently performing simulations with the feedback control imposed on the valve openings.

4. Conclusions

To summarize, we extended our earlier results [7] on accurate predictions of pressure and temperature dynamics in cryogenic transfer line using SINDA/FLUINT by developing an efficient scheme for optimization of the cryogenic loading regime using its high level optimization solvers.

As an example we considered the problem of optimization of the dump valve openings that minimizes the amount of time and liquid required to chilldown the system. The obtained results demonstrate the existence of a trade-off between time and the propellant losses, i.e. the faster the chilldown the more propellant has to be used. We emphasize, however, that the obtained results are related to the case when no constraints were imposed on the valve openings.

In practice, the dump valve opening is often constraint by a feedback loop that closes the dump valve as soon as upstream temperature drops down below a certain value. Since the pressure in the pipes is usually constant during chilldown, the total mass flowing though the dump valves is proportional to the valve opening and adding feedback will further minimize commodity losses. The analysis of the corresponding optimization problem in the presence of feedback will be considered in the future.

In future the SINDA/FLUINT optimization solver will be used to verify the performance of fast optimization solvers based on hierarchy [3, 6, 4] of the two-phase models, which are under development. We are currently working on the application of these results to the optimization of loading regimes in the advanced propellant servicing system, which is under development at KSC. The obtained results can also be used to assess the performance of cryogenic transfer lines that will be developed for reduced gravity conditions.

Acknowledgments

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