SPACE SHUTTLE LOX BLEED SYSTEM ANALYSIS

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SPACE SHUTTLE LOX BLEED SYSTEM ANALYSIS

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ABSTRACT

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By Arash Firooznam

During the launch of the Space Shuttle, the External Tanks plays an important role in the success of the mission. The External Tanks, which store fuel and oxidizer have to be monitored for appropriate fuel levels and pressure to make every launch optimal. Small difference in the amount of fuel on-board can have great impact on payload weight and engine performance. The purpose of this study will be to improve the calculations for the oxidizer on-board the tanks at any time, which will then be used to properly pressurize the tanks before launch. The model will improve the calculations by better estimating oxidizer lost over-board through the LOX (Liquid Oxygen) Bleed System. The LOX Bleed System is an in integral part of the Space Shuttle System that allows the main engines of the Space Shuttle to be primed for launch. The goal will be to account for the steady state fluid flow through the LOX Bleed System as well as unsteady flow. Although the results of this study only showed small improvements in oxidizer levels, the effect to overall payload weight savings were significant.

ACKNOWLEDGEMENT

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1.0 INTRODUCTION

The Space Shuttle built by Rockwell International and operated by NASA (National Air and Space Agency) has been in service for over 20 years with over 100 successful missions. The concept of a reusable space vehicle with reusable solid rocket boosters has proven very useful for continuous access to space. Although the design of this space vehicle has stayed the same over the last two decades, new engineering techniques and technologies have improved its performance, reliability and safety.

One area where improvements can be made is in fluid dynamic calculations using modern computer programs. The use of new modern computers can allow for better refinement of solutions that were originally out of reach. During the propellant loading sequence of the space shuttle, LOX (Liquid Oxygen) is loaded into the external tanks. Once the LOX has filled the tank, a period of replenishing begins that allows the tank to continuously be topped-off be replacing the fluid that was lost from boiling off and the LOX lost through the LOX Bleed System. The amount of fluid boiled off is calculated based on environmental condition during the time of launch. The loss through the LOX Bleed System, a set of pipes that channels a small amount of LOX through the space shuttle main engines, is considered to be a constant. The operators of the shuttle have the responsibility of calculating the amount of LOX in the tanks during any phase of the mission. To make improvements to the replenishing phase the operators would like to gain more accuracy in calculating the amount of LOX lost through the LOX Bleed System.

The LOX Bleed System is a series of pipes and valves that directs a slow flow of LOX over the turbo pumps and other vital parts of the Space Shuttle Main Engines (SSME's) to thermally prepare these parts before the actual start of the engines. Preparing the SSME's is important for the prevention of thermal shock to the sensitive components. A diagram of the LOX Bleed System can be seen below in Figure 1.

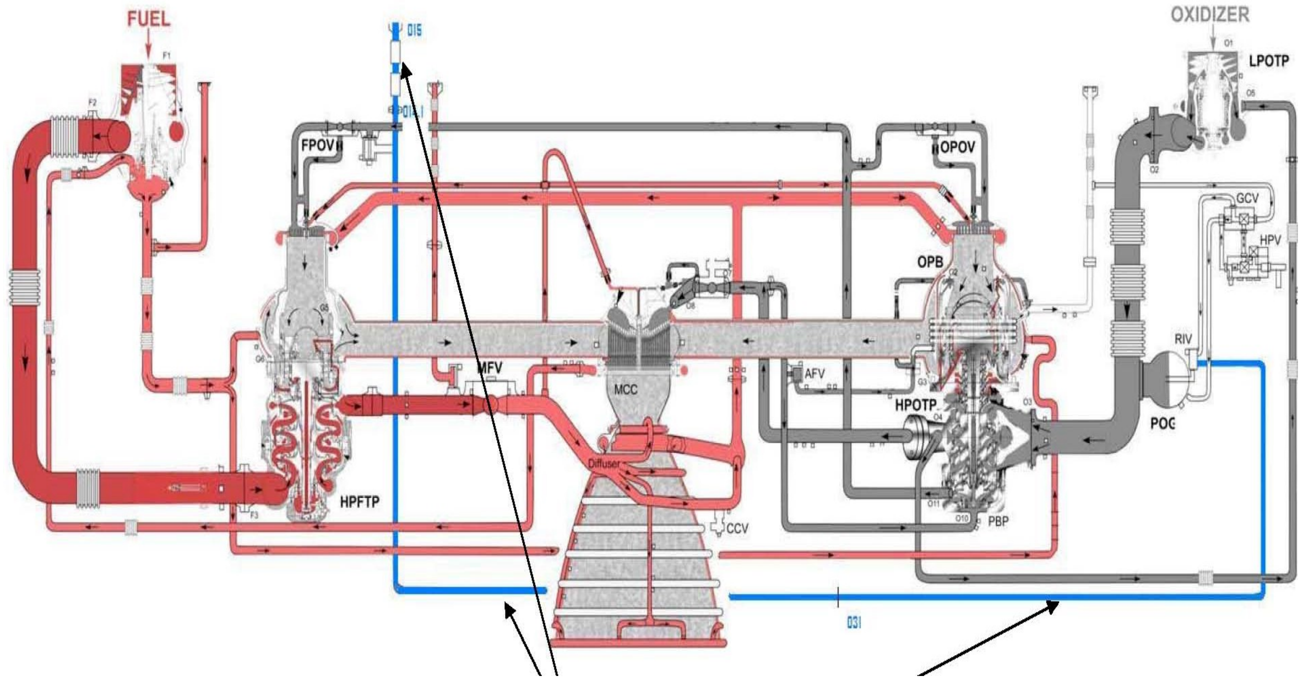


Figure 1: SSME Diagram

2.0 BACKGROUND

For the past 5 years the operators and engineers of the Space Shuttle Tank have been working with various dynamic flow problems to address the changes and needs of the Space Shuttle propellant system. These issues have included propellant budget, pressurization and fluid boil-off effects. In an effort to address these dynamic problems a wide range of in-house codes have been developed to calculate fluid properties and estimate flow through pipes. Some of the tools such as look-up tables and fluid properties calculators have been incorporated multiple times to address new issue. Some of these codes/algorithms have also been used for this project to create a new model that fits the needs of this current problem.

3.0 IMPACT

In any rocket launch environment weight is the most important factor and most of the design parameters are based around minimizing it. This applies to the Space Shuttle as well. The LOX tanks in the space shuttle hold 1.375 million lbs of fuel and a small miscalculation in the amount of LOX in it can have a significant effect on the entire mission. Since there is no way to measure the weight of the LOX in the tanks, engineers must rely on software that estimates the amount of LOX lost in the system through boil-off and through the LOX bleed system. A better calculation of the LOX bleed system losses will help the replenishing process and bring the estimate of the LOX weight closer to the exact amount needed for launch. Currently the replenishing software uses a steady rate of LOX lost through the bleed system. The results of this analysis which also includes unsteady effects could further improve the accuracy of the total LOX loaded. Due to the large amount of LOX involved, even a small change of 0.1%, would amount to more than a 1300 lbs difference.

In addition, the amount of Oxidizer lost through the LOX Bleed System directly affects the Helium Pressurization system. During the last 5 minutes of the launch the replenishing of the oxidizer is stopped and the helium pressurization system is activated to maintain a proper amount of pressure in the tanks. The amount of injected helium is directly related to the volume of oxidizer in the tank. The correct amount of pressure in the tanks is critical for engine performance and the entire performance of the mission. Any increase in accuracy for these calculations would play an important part in future launches. (Need a bit of info about inlet delta psi vs. engine performance)

4.0 ANALYSIS APPROACH

The task of analyzing the flow for the LOX Bleed System can be a daunting task. The Bleed system shown in Figure 1 has variable line diameters and wall thicknesses that can have a significant impact on the flow model. The best way to approach the breakdown of the model is to start from the known data of the vehicle. This data includes pressure and temperature sensors placed at various points on the engines and bleed lines. Based on this information the bleed system can be modeled more simply as seen in Figure 2 below. The model begins with the node marked as “IN” , physically located at the beginning of the Low Pressure Oxidizer Turbo Pump (LPOTP), where the pressure and temperatures are known at all times. The last node in the model marked as “OUT” is physically located inside the nozzle of the respective engine where the conditions are considered to be at ambient.

Assumptions:
As mentioned before the LOX bleed system is a complex set of pipes, fitting and valves that can be very difficult to properly model. The best approach is to make some assumptions to be able to maximize the results without creating an unsolvable problem. Information used in the model is as follows and apply to each pipe section:

- Pipe length
- Pipe diameter (outer and inner)
- Pipe height (beginning and end)
- Pipe material
- Reductions in pipe
- Major bends in pipe

With these known parameters and the known pressures and temperatures at various locations in the bleed line a model can be created using the Conservation of Energy and Mass equations. The system, which includes all of the pipes can be set to an initial condition based on atmospheric conditions, which allows for fluid properties that can be calculated at each volume. Once the fluid properties are obtained, the Mass and Energy equations can be used to calculate the flow of mass and energy between the side-by-side volume elements through the node between them. This process can then be moved forward in time as the initial conditions of the inlet change and the change slowly propagates through the different volumes.

In addition the fluid flow between the volumes can change at any time depending on the current state of the fluid. Once the condition is updated in a particular volume element, it’s compared to saturations conditions to determine its state. This will then determine whether the flow out of that element is governed by liquid flow equations, gas flow equations or two phase flow equations.

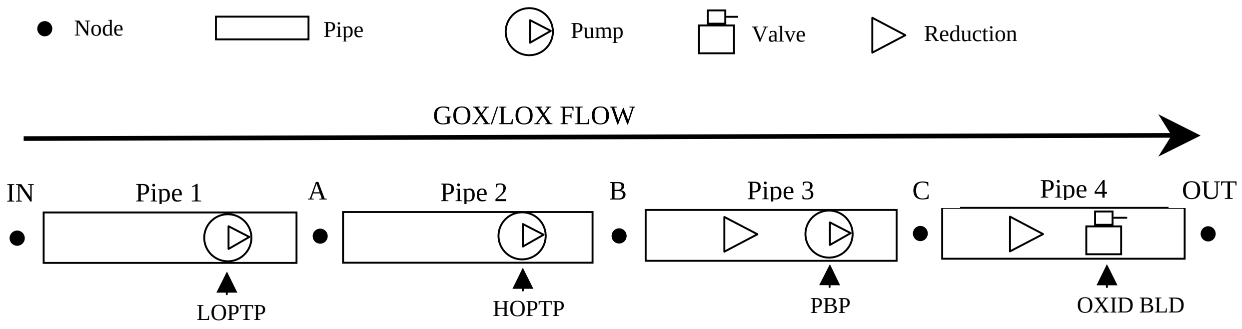


Figure 2: LOX Model Diagram

5.0 MODEL THEORY

The model begins with the initial conditions at the inlet, outlet and in each volume, A through C. Initially the volumes A through C are taken to be at ambient condition based on data provided by the shuttle vendor. The inlet where the flow begins the iteration process throughout the system is a table which provides actual measurement of pressures and temperatures. The outlet is also to taken to be at ambient conditions.

The top level program “arash.c” is initiated by reading the data file containing a table of pressures and temperatures vs. time. This data is taken into the 1st level program “fprop.c”. “fprop.c acts as a sorting program to keep tabs on all the data before it feeds the solutions back to the “arash.c”. Using the Pressure and temperature “fprop.c” calculates the density from a density subroutine. With the density known, any one of the fluid properties like internal energy, entropy and enthalpy can be calculated. A brief description for each subroutine used on this flow calculation can be seen as follows:

5.1 FLUID QUALITY FINDER

This program is designed to find the quality for a given fluid. The fluid quality is found based on temperature and density that must be provided. The quality is calculated by comparing the density of the liquid which is provided to the program and the density at saturated liquid and vapor conditions. The quality is calculated using the following equation.

$$Quality = \frac{(1/density) - (1/SatLiquidDensity)}{(1/SatVaporDensity) - (1/SatiquidDensity)}$$

5.2 OXYGEN PROPERTIES

This file is a common place where all properties can be calculated from. The file contains the 32 NIST coefficients for oxygen to calculate the equation of state.

5.3 CPI FINDER

This subroutine has the ability to return specific heat, entropy or enthalpy. The input for this subroutine is temperature and a “k” value which designated what you need returned from the program.

5.4 FIND PRESSURE

This subroutine return pressure based on an input of temperature and density. First vapor pressure for the given temperature is calculated using another subroutine. Next the saturated vapor and liquid densities are calculated. The entered density is compared to the saturated values. Based on the state of the fluid, the density and temperature are sent to the props.h subroutine were the pressure is calculated and returned back.

5.5 PROPERTIES

This subroutine uses density and temperature as inputs to return a variety of different properties. Properties that can be calculated from this include pressure, change of pressure with respect to change in density, change in pressure with respect to change in temperature, entropy, enthalpy and CV. A simple integer designation will direct the subroutine as to which output to return.

5.6 FIND DENSITY

The find density subroutine finds the density of a fluid based on the pressure, temperature and the quality. The density can either be found at saturated or non-saturated conditions.

5.7 INTERNAL ENERGY

This is the fundamental subroutine for this program, which calculates the internal energy of the fluid at each time step. The input to this subroutine is temperature and density. The internal energy is calculated based on the quality of the fluid, being saturated or non-saturated.

5.8 LIQUID PIPE FLOW

This program is at the core of this analysis and is the program by which the flow properties are iterated through the different nodes. The program inputs are pressure, density, viscosity and enthalpy at the input node. Using the Bernoulli's equation and the conservation of mass, the same fluid properties can be calculated at the output node. A brief derivation of the equations for this program can be seen below:

Bernoulli's Equation [1]

$$\left(\frac{V_1{}^2}{2}\right)+\left(\frac{P_1G_c}{\rho_1}\right)+\left(G_rZ_1\right)=\left(\frac{V_2{}^2}{2}\right)+\left(\frac{P_2G_c}{\rho_2}\right)+\left(G_rZ_2\right)+Hl$$

Conservation of Mass

$$W=\rho VA=cons\tan t$$

Assumptions

$\rho_1=\rho_2=\rho$

$Area_1=Area_2=Area$

Then

$$G=\frac{W}{Area} \qquad V=\frac{G}{\rho}$$

Combining

$$\left[\frac{G^2}{2Gc\rho}+P_1+\frac{Gr}{Gc}\rho Z_1\right]=\left[\frac{r^2G^2}{2Gc\rho}+rP_2+\frac{Gr}{Gc}\rho Z_2\right]+\left[\frac{\rho}{Gc}\right]Hl \qquad \text{Eq.1}$$

Head loss defined by the Darcy Equation based on constant velocity [1] pp. 340

$$Hl = Kfac\frac{Vel^2}{2}$$

Applying earlier assumptions

$$Hl = \frac{KfacG^2}{2\rho}$$

Applying Equation 1 to above

$$((p_1-p_2))+\frac{Gr}{Gc}\rho(Z_1-Z_2)=\left[\frac{KfacG^2}{2Gc\rho}\right]$$

Now the term to calculate the effective delta pressure between the two nodes becomes as follows:

$$Dpeff = \frac{KfacG^2}{2Gc\rho}$$

5.9 GAS PIPE FLOW

Similar to the liquid pipe flow program, this program can calculate the gas flow between two volumes. The program uses steady-state, isentropic, adiabatic and constant-area conditions to calculate the flow for a perfect gas. The fundamental equation used is from our reference in “The Dynamics and Thermodynamics of Compressible Flow”:

$$F*\frac{L\max}{D}=\frac{1-M^2}{k*M^2}+\frac{k+1}{2*k}*Ln\frac{(k+1)*M^2}{2*(1+\frac{k-1}{2}*M^2)}$$

5.10 TWO PHASE FLOW FINDER

This program attempts to calculate the flow between two volumes under the condition of two phase flow. It’s a simple combination of the gas and liquid pipe flow subroutines, that checks for the percentage of gas vs. liquid content.

6.0 MODEL OPERATIONS

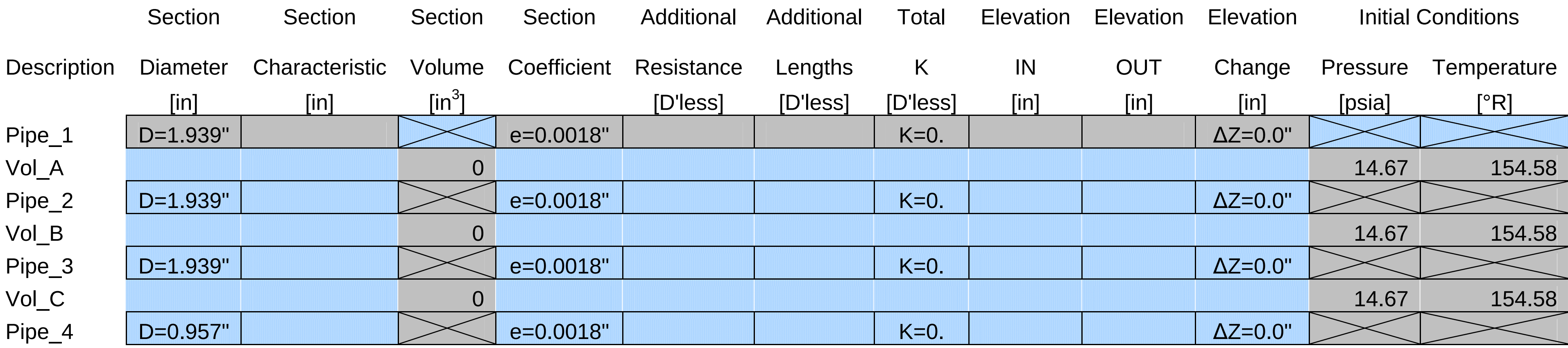
Working with the model starts with the input file shown below. As described previously the model is 3 volumes and 4 nodes. The characteristic length for the sections are entered along with the roughness coefficients and the pipe diameter. Then the elevation of the pipes are entered for both the inlet and outlet. If there are any additional lengths or resistances associated with a particular section, they can also be entered here. Section temperature and pressure are also entered but for all intensive purposes set to ambient.

In addition to the physical parameters in the input file, the excel file also has the following 4 tabs:

- Inlet Pressure
- Inlet Temperature
- Outlet Pressure
- Outlet Temperature

These 4 tabs in the input file simply contain the described parameter vs. time. The outlet parameters are considered to be at ambient based on the location of the LOX bleed system. The inlet is taken from known data provided by sensors on the vehicle.

Once the data has been entered and the code has been run, the output data is recoded in the output excel file output.xls. The data can then be sorted in any way the user sees fit. Some standard charts have been made such as pressure, temperature and mass flow. A sample of the input spreadsheet can be seen below in Figure 3.



	Section	Section	Section	Section	Additional	Additional	Total	Elevation	Elevation	Elevation	Initial Conditions	
Description	Diameter [in]	Characteristic [in]	Volume [in^3]	Coefficient	Resistance [D'less]	Lengths [D'less]	K [D'less]	IN [in]	OUT [in]	Change [in]	Pressure [psia]	Temperature [°R]
Pipe_1	D=1.939"		☒	e=0.0018"			K=0.			ΔZ=0.0"	☒	☒
Vol_A			0								14.67	154.58
Pipe_2	D=1.939"		☒	e=0.0018"			K=0.			ΔZ=0.0"	☒	☒
Vol_B			0								14.67	154.58
Pipe_3	D=1.939"		☒	e=0.0018"			K=0.			ΔZ=0.0"	☒	☒
Vol_C			0								14.67	154.58
Pipe_4	D=0.957"		☒	e=0.0018"			K=0.			ΔZ=0.0"	☒	☒

Figure 3: Excel Input Sheet

7.0 SOFTWARE FLOW DIAGRAM

The flow of the program can be summarized as follows in the diagram below:

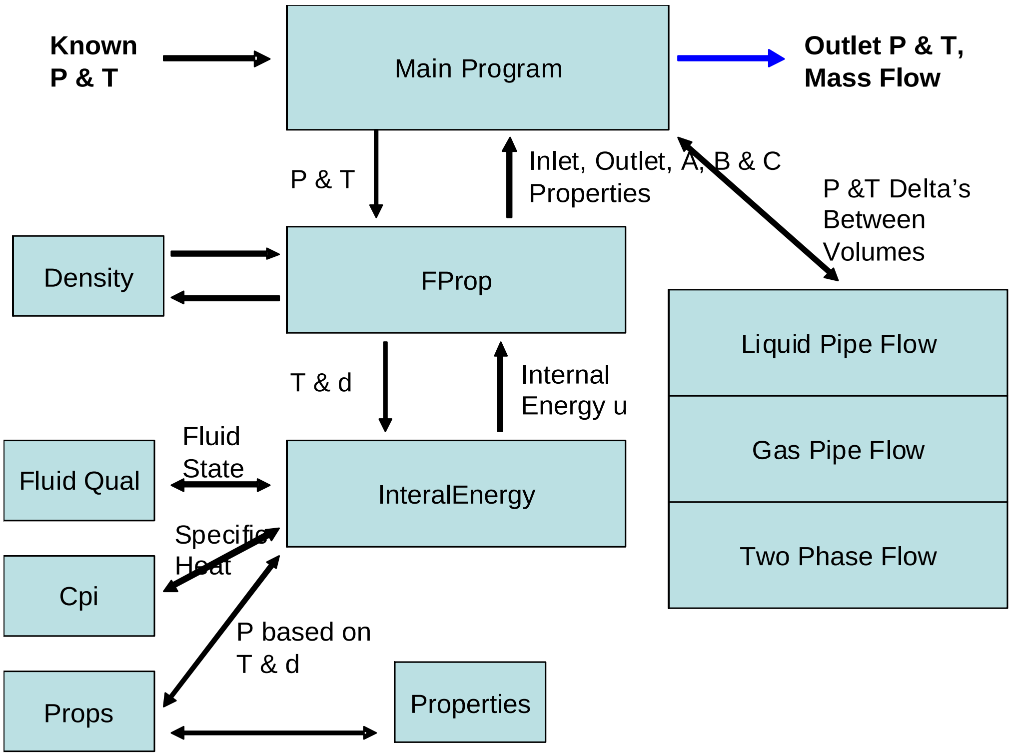


Figure 4: Model Program Flow

The Main Program "Arash.c" is what controls all of the input and output of the data. The known pressures and temperatures are entered for the initial node of the model. The program then initializes all of the other nodes at ambient conditions. As the pressure and temperature increase in the 1st node, a change in pressure and temperature causes flow between the first two nodes and consecutive nodes after that. The program then calculates the small flow between each node, based on this delta and iterates forward until the last node. The details of this program can be seen in appendix A

8.0 RESULTS AND DISCUSSION

The first few times that the program was run, many different problems were encountered, but were mostly due to coding issues and were easily fixed. The first official run of the program was for STS-117 which was launch in June 2007. Once the data from the on-board sensors had been entered the results were very similar to our bench mark data. The benchmark data was data we have been using from another fluid dynamic analysis group at the space shuttle vendor. The following figures show the mass flow and the pressure profile at the exit point of the LOX Bleed System.

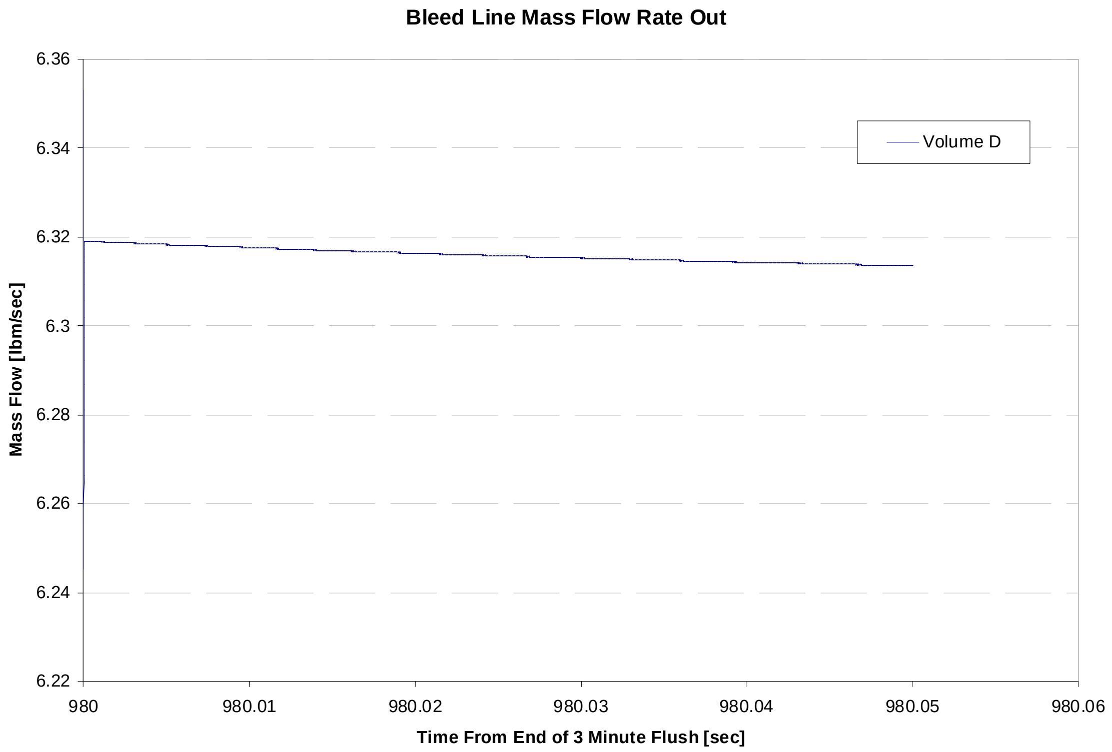


Figure 5: STS-117 LOX Bleed Mass Flow

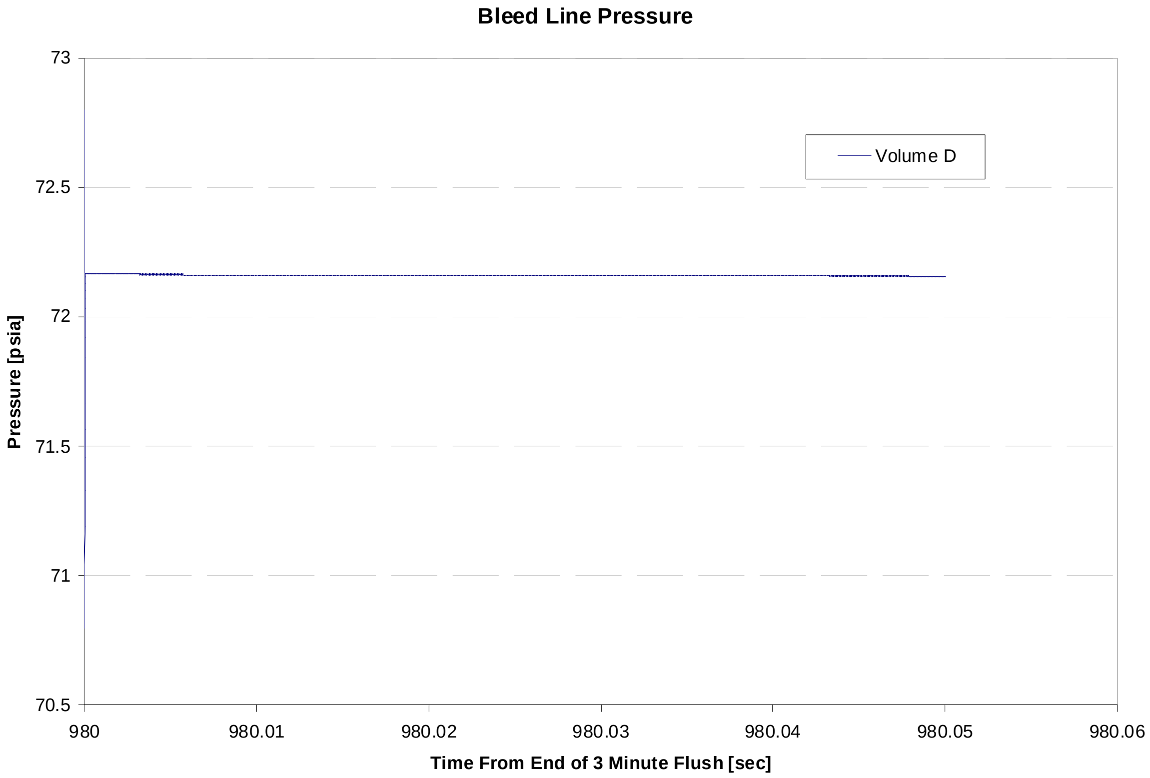


Figure 6: STS-117 LOX Bleed Exit Pressure Profile

Similar results can bee seen for the STS 123 launch, which had a similar pressure and mass flow profile ramp-up. The mass flow and pressure were lower in this run case, but as expected due to a 11 psi decrease in inlet pressure from the STS 117 case.

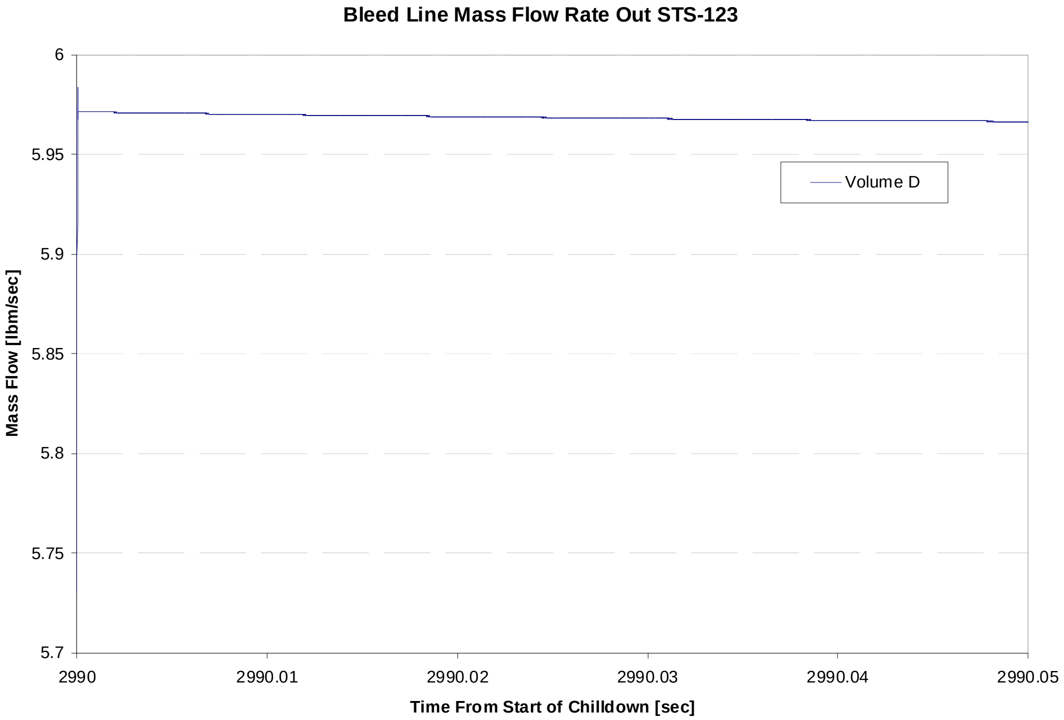


Figure 7: STS-123 LOX Bleed Mass Flow

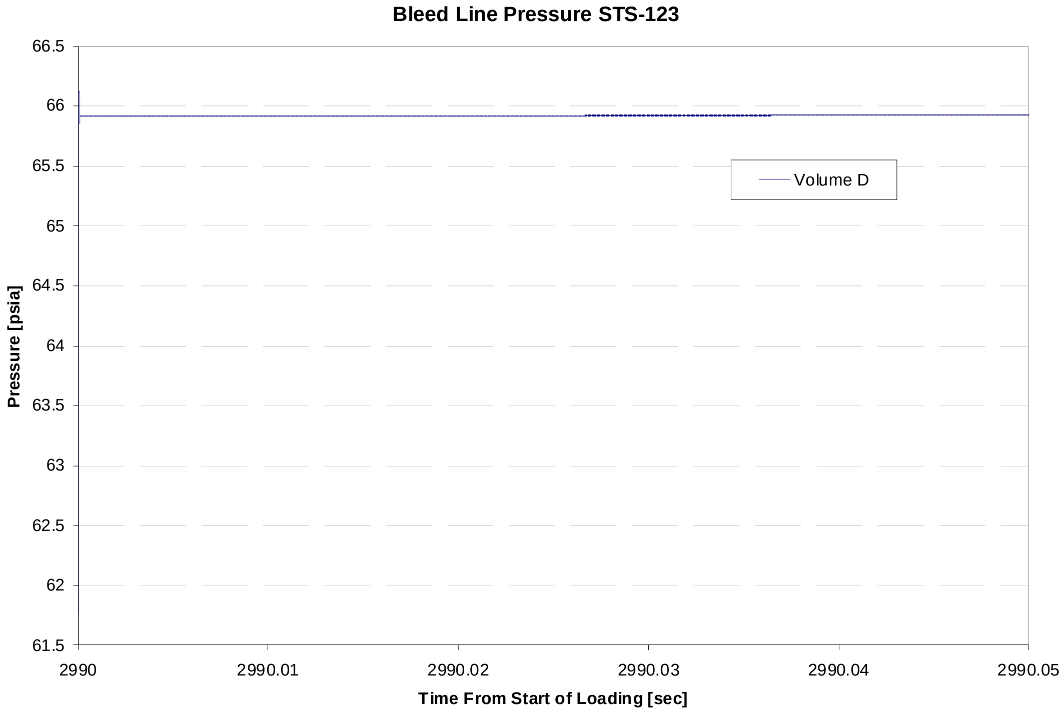


Figure 8: STS-123 LOX Bleed Exit Pressure Profile

The next case was the STS-122 launch which again produced similar results to the previous two cases. This time the mass flow rate settled back to about 6.3 lbm/sec, which was similar to the values from STS-117. Both STS-122 and STS-117 had very similar inlet pressures and thus produced similar mass flow rates.

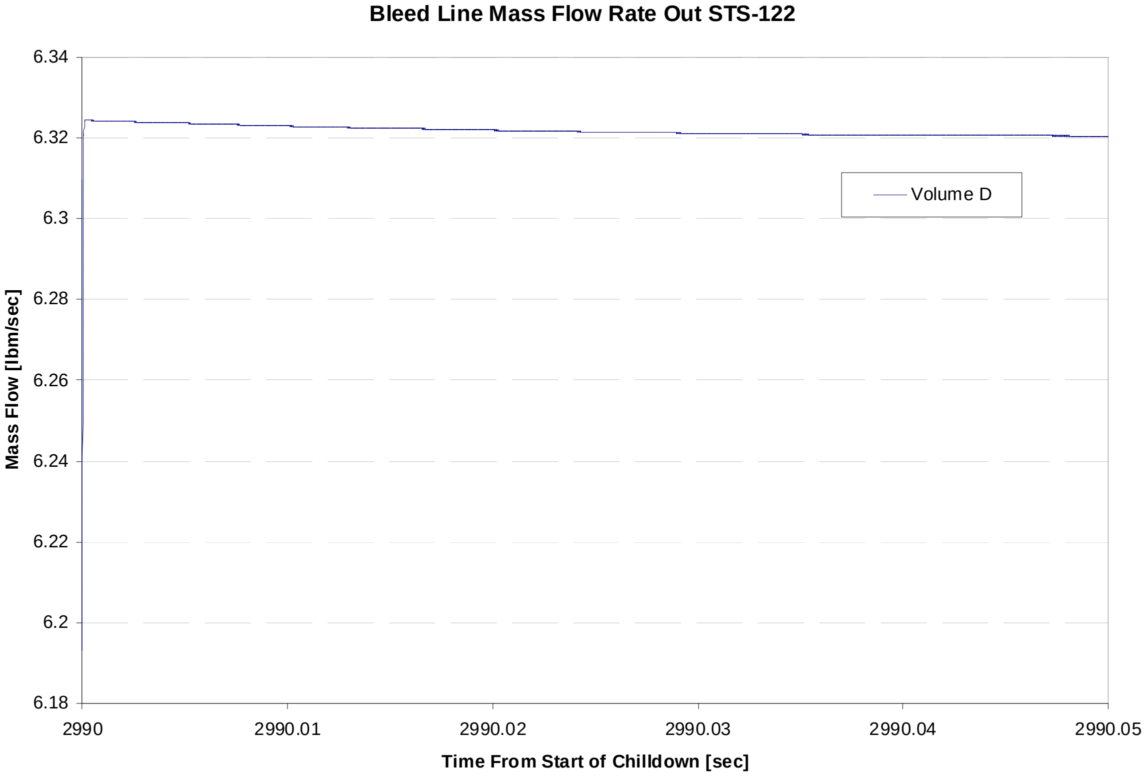


Figure 9: STS-122 LOX Bleed Mass Flow

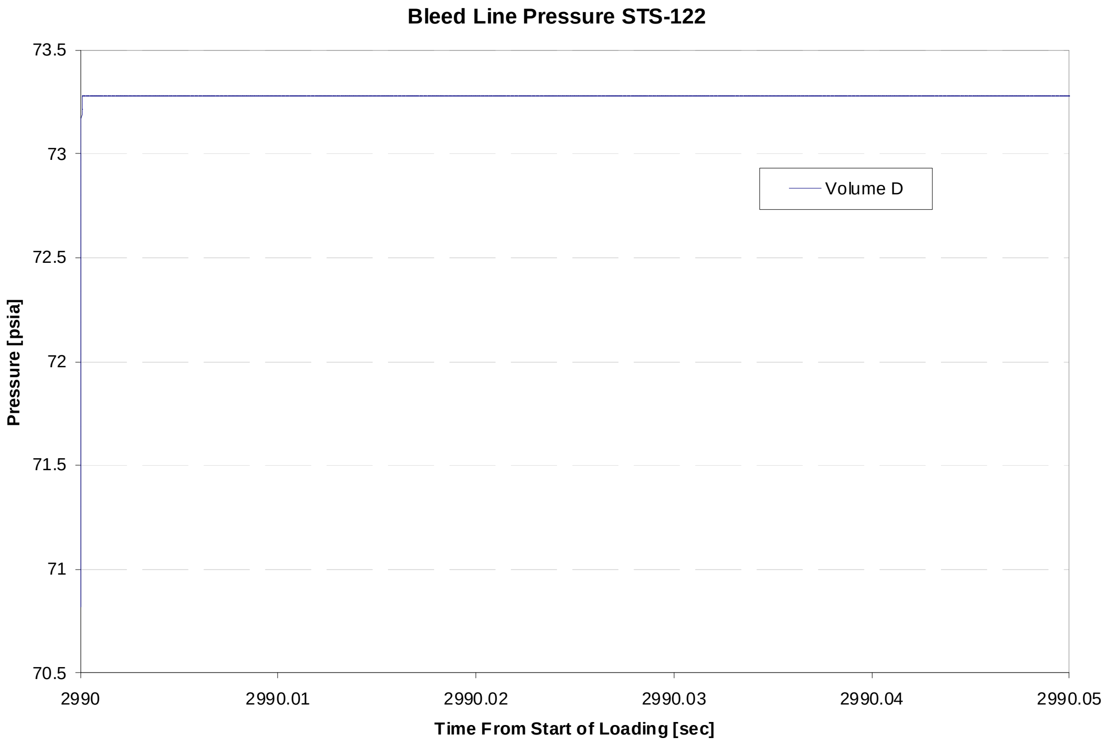


Figure 10: STS-122 LOX Bleed Exit Pressure Profile

The last case, STS-120 was similar to STS-123 with a lower mass flow rate of about 5.8 lbm/sec. This again is as expected given the lower inlet pressure for this case. The profile also looks different due to the time when the model was initiated. As a check of the fidelity of the model the starting point was advanced by 20 seconds, when pressure in the inlet has already built up to the maximum value. This created a larger mass flow estimate at the starting point, which was later corrected for, in 3-4 iterations, settling to an expected value.

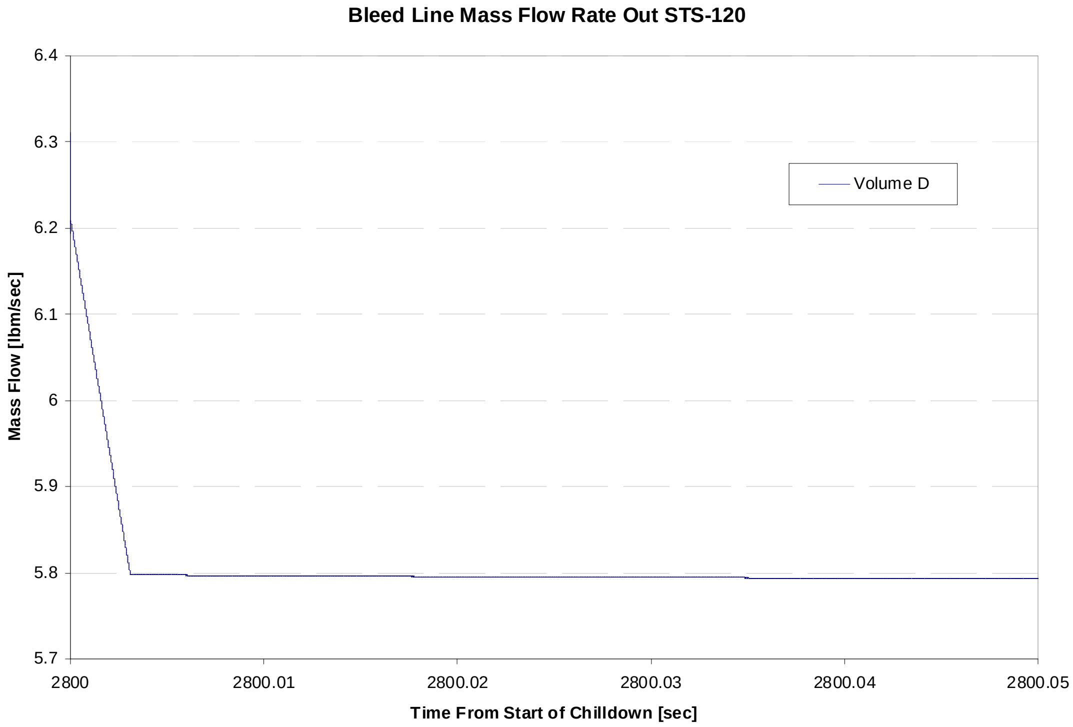


Figure 11: STS-120 LOX Bleed Mass Flow

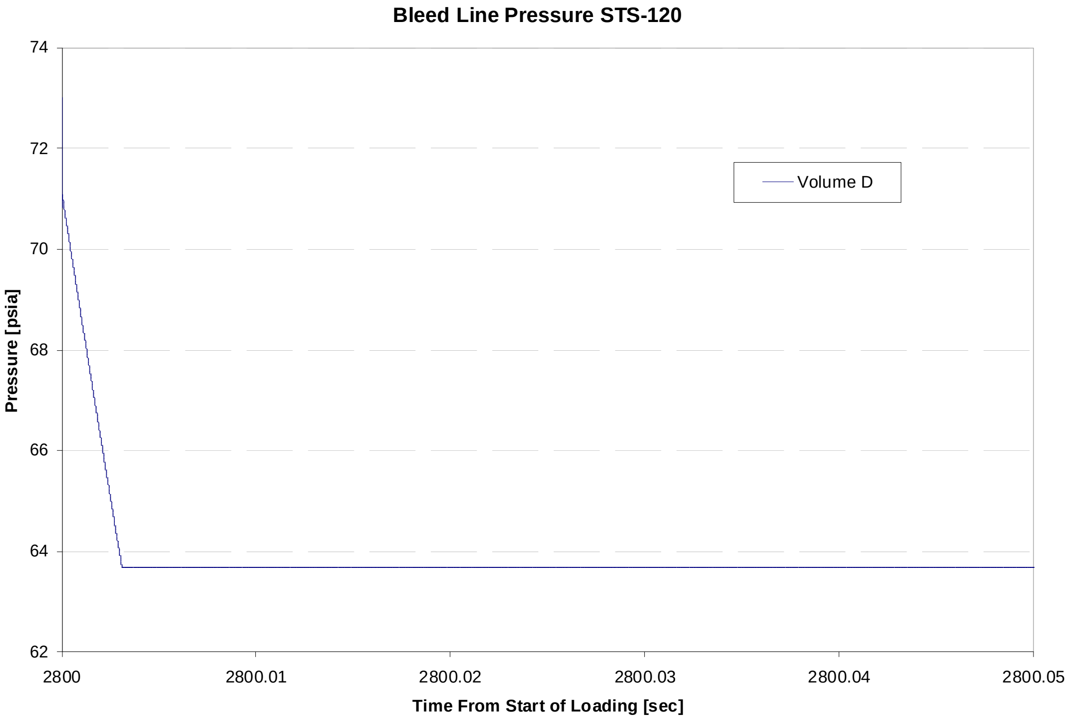


Figure 12: STS-120 LOX Bleed Exit Pressure

9.0 CONCLUSION

As we can see after running 4 cases, the results show that the model is consistent and produces results that are consistent with the benchmark program. The original mass flow that was used ,20 lbm/sec can now be replaced with individual data flow rates that are more appropriate for each launch. This new data will allow engineers to better calculate the mass of the LOX tank at any time as well as be able to better estimate the amount of helium required to pressurize the system during the last few minutes before launch. The consistency in the data gives us confidence that the model is operating properly. In addition the correlation between the inlet pressure profile and the mass flow at the exit, gives us confidence that the model can accurately respond to small changes in input.

Despite the models advancement at this early stages of development, there is more work requires. As we can see during the starting phase of fluid flow at the exit point, the mass flow seems to instantaneously jump to a value close to steady state. Based on engineering intuition we can guess that the amount of piping in the LOX system would take a few seconds to fill up and reach steady state. This means that we have more work to do to improve the models fidelity during the unsteady phase. This could include de-bugging the program and looking into splitting the model into more nodes and elemental volumes. Altogether this was a good first iteration for the model which has produced useful results and can be used as a stepping stone for more accurate modeling of the LOX Bleed System.

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