Matlab GUI for a Fluid Mixer

Sponsor ID NAG13-03006

Final Report – Grant Period February 2003 – February 2005
Including No-Cost Extension (August 2004-February 2005)

Submitted on April 6, 2005

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Abstract

The Test and Engineering Directorate at NASA John C. Stennis Space Center developed an interest to study the modeling, evaluation, and control of a liquid hydrogen (LH2) and gas hydrogen (GH2) mixer subsystem of a ground test facility. This facility carries out comprehensive ground-based testing and certification of liquid rocket engines including the Space Shuttle Main engine. A software simulation environment developed in MATLAB/SIMULINK (M/S) will allow NASA engineers to test rocket engine systems at relatively no cost. In the progress report submitted in February 2004, we described the development of two foundation programs, a reverse look-up application using various interpolation algorithms, a variety of search and return methods, and self-checking methods to reduce the error in returned search results to increase the functionality of the program. The results showed that these efforts were successful. To transfer this technology to engineers who are not familiar with the M/S environment, a four-module GUI was implemented allowing the user to evaluate the mixer model under open-loop and closed-loop conditions. The progress report was based on an udergraduate Honors Thesis by Ms. Jamie Granger Austin in the Department of Electrical Engineering and Computer Science at Tulane University, during January-May 2003, and her continued efforts during August-December 2003. In collaboration with Dr. Hanz Richter and Dr. Fernando Figueroa we published these results in a NASA Tech Brief due to appear this year. Although the original proposal in 2003 did not address other components of the test facility, we decided in the last few months to extend our research and consider a related pressurization tank component as well. This report summarizes the results obtained towards a Graphical User Interface (GUI) for the evaluation and control of the hydrogen mixer subsystem model and for the pressurization tank each taken individually. Further research would combine the two components – mixer and tank, for a more realistic simulation tool.

Summary

This report deals with efforts by the Test and Engineering Directorate at NASA John C. Stennis Space Center to develop a software simulation environment that captures the static and dynamic characteristics of modern and future rocket engine systems. At present, it is too costly to verify untried ideas because of the expensive fuels and man-hours required to ready the facility for testing. As a result, many potentially good ideas may go untested. As a solution, this proposed state-of-the-art simulation environment will allow NASA engineers to perform simulated testing exercises at fundamentally zero cost. Previous parts of this research have studied the small signal modeling and control of the hydrogen mixer [1] shown in Figure 1. The small signal model that was developed allowed for stability analysis of the system and the use of modern control simulation features. It additionally provided a method to study control authority or relegation. Studies were conducted that focused on the equilibrium point-to-point tracking control problem for the LH2 and GH2 mixer subsystem and its associated flow controllers [2].

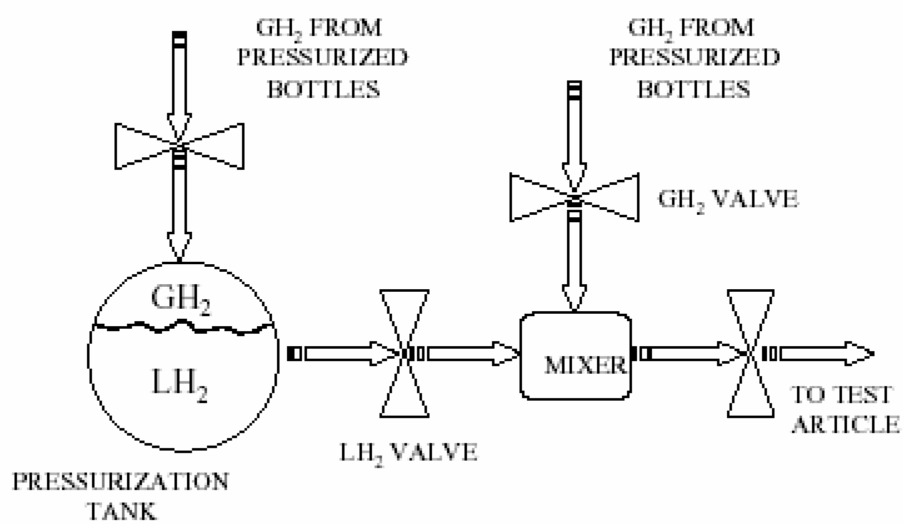


Figure 1: Diagram of HPH2 System.

The studies referred to above rely on an accurate model of the hydrogen mixer subsystem, and to make the model evaluation and control more user-friendly, a graphical user interface would be most beneficial. The progress report submitted in February 2004 dealt with the mixer model and its GUI and was based on an udergraduate Honors Thesis by Ms. Jamie Granger Austin in the Department of Electrical Engineering and Computer Science at Tulane University [3].

In addition, we collaborated with Dr. Hanz Richter and Dr. Fernando Figueroa at NASA Stennis and published these results in a NASA Tech Brief due to appear in 2005 [4]. Other publications on the mixer modeling and control issues are [5-8].

A second component of interest to NASA engineers is a pressurization tank located upstream from the mixer and responsible for providing LH2 at specified thermodynamic properties in spite of many nonlinear variations in the system. The tank model is described by a set of four highly nonlinear differential equations that result from energy and mass balance equations. In this report, the variables $z_i(t)$, referred to as "states", are not be confused with the definition of the state of a system as described by its thermodynamic properties. Let $z_1(t)$ denote vapor density, $z_2(t)$ the vapor internal energy, $z_3(t)$ the liquid internal energy, $z_4(t)$ the vapor volume, ω_{vp} the vapor flow rate at the top of (or into) the tank, and ω_l the liquid flow rate at the bottom of (or out of) the tank. Then, the four dynamic equations are given by [9]

$$
\begin{aligned}
\dot{z}_1 &= \frac{1}{z_4}\omega_{vp} - \frac{1}{\rho_l}\frac{z_1}{z_4}\omega_l \\
\dot{z}_2 &= \frac{1}{z_1 z_4}\left(h_{vp} - z_2\right)\omega_{vp} - \frac{P_{vp}}{\rho_l}\frac{1}{z_1 z_4}\omega_l + \frac{1}{z_1 z_4}\dot{Q}_{vp} \\
\dot{z}_3 &= \frac{1}{\rho_l\left(V - z_4\right)}\left(z_3 - h_l + \frac{P_{vp}}{\rho_l}\right)\omega_l + \frac{1}{\rho_l\left(V - z_4\right)}\dot{Q}_l \\
\dot{z}_4 &= \frac{1}{\rho_l}\omega_l
\end{aligned}
$$

where V is the total tank volume assumed to remain constant; P_{vp} is the vapor pressure equal to the liquid pressure; ρ_l is the liquid density assumed to vary slowly with pressure; $\dot{Q}_{vp}$ and $\dot{Q}_l$ are heat transfer rates which are assumed to be negligible; and h_{vp}

and h_l are the vapor and liquid enthalpy, respectively. Thus, the dynamic model of the tank is a 4-state, 2-input system of nonlinear differential equations of the form

$$\begin{aligned}
\dot{z}_1 &= F_1\left(z_1, z_2, z_3, z_4, \omega_{vp}, \omega_l\right) \\
\dot{z}_2 &= F_2\left(z_1, z_2, z_3, z_4, \omega_{vp}, \omega_l\right) \\
\dot{z}_3 &= F_3\left(z_1, z_2, z_3, z_4, \omega_{vp}, \omega_l\right) \\
\dot{z}_4 &= F_4\left(z_1, z_2, z_3, z_4, \omega_{vp}, \omega_l\right)
\end{aligned}$$

where $F_i(\cdot)$ are nonlinear functions of the states and inputs.

For the remainder of this report, constant or equilibrium values of any variable are represented by an upper bar $\bar{(\cdot)}$. Given constant values for the vapor and liquid flows $\bar{\omega}_i = \left[\bar{\omega}_{vp} \quad \bar{\omega}_l\right]^T$ (superscript T denotes transposition) and constant fluid properties, the state of the model reaches an equilibrium point, $\bar{z}$. Perturbing the equilibrium by small signals x(t) and u(t) gives the equations

$$z(t) = \bar{z} + x(t) \text{ and } \omega_i(t) = \bar{\omega}_i(t) + u(t)$$

Then, performing a standard linearization results in the small signal model

$$\dot{x} = Ax + Bu$$

Where $x(t)$ is the error state vector, u(t) is the error control signal, and the four-by-four matrix A and four-by-two matrix B are given by

$$A = \begin{bmatrix} \frac{\delta F_1}{\delta z_1} & \frac{\delta F_1}{\delta z_2} & \frac{\delta F_1}{\delta z_3} & \frac{\delta F_1}{\delta z_4} \\ \frac{\delta F_2}{\delta z_1} & \frac{\delta F_2}{\delta z_2} & \frac{\delta F_2}{\delta z_3} & \frac{\delta F_2}{\delta z_4} \\ \frac{\delta F_3}{\delta z_1} & \frac{\delta F_3}{\delta z_2} & \frac{\delta F_3}{\delta z_3} & \frac{\delta F_3}{\delta z_4} \\ \frac{\delta F_4}{\delta z_1} & \frac{\delta F_4}{\delta z_2} & \frac{\delta F_4}{\delta z_3} & \frac{\delta F_4}{\delta z_4} \end{bmatrix} \quad ; \qquad B = \begin{bmatrix} \frac{\delta F_1}{\delta \omega_{vp}} & \frac{\delta F_1}{\delta \omega_l} \\ \frac{\delta F_2}{\delta \omega_{vp}} & \frac{\delta F_2}{\delta \omega_l} \\ \frac{\delta F_3}{\delta \omega_{vp}} & \frac{\delta F_3}{\delta \omega_l} \\ \frac{\delta F_4}{\delta \omega_{vp}} & \frac{\delta F_4}{\delta \omega_l} \end{bmatrix}$$

where the partial derivatives are evaluated at the equilibrium state $\bar{z}$ (arbitrarily chosen as 1 for each state) and constant flow values $\bar{\omega}_{vp}$ and $\bar{\omega}_l$ (both evaluated as 0).

The model, $\dot{x} = Ax + Bu$, describes the dynamics of the tank model in the vicinity of the equilibrium under consideration. Under ideal conditions the values of $x(t)$ and u(t) are zero. However, in practice, the state z(t) deviates from the desired state, $\bar{z}$ and therefore the corrective measure, u(t), is needed.

Mathematical models and modern controllers developed for the liquid/gas hydrogen mixer and tank in the MATLAB-SIMULINK programming environment were incorporated into a menu-driven graphical user interface (GUI). This GUI is designed to render the MATLAB-SIMULINK processing environment transparent to the user who is not familiar with the environment or to the control design principles.

Though all the modules have their unique functions, with the exception of the "High Pressure Hydrogen System Menu" module, they all have a set of common functions. Each module allows the user to enter model parameters. If the user does not wish to enter parameters then the module uses default values for the simulation. If the user enters non-numeric characters into any parameter input field an error message is generated and the parameter is usually set to zero. For the mixer model modules the user also has the option of introducing perturbations into the liquid flow, the gas flow, both, or neither.

The "Simulate" button passes the user-defined parameters or their default values to the base workspace and calls several MATLAB routines that set the parameters for the simulation. The simulation is run and after it completes a red indicator entitled "Simulation Finished" appears in the "Simulation Control" panel to notify the user of its completion. After the simulation is complete the "Plot" button can be used. The "Plot" button plots various simulation outputs against time. The plotted graphs vary between modules and will be discussed in each individual module's section of this report. The "Reset" button returns all parameters of the GUI to their default values and clears the "Simulation Finished" indicator.

High Pressure Hydrogen System Menu

The first module the user sees is the "High Pressure Hydrogen System Menu". From this menu the user can select from a variety of options including: Open Loop Evaluation, Open Loop Control, or PI Control of the Mixer Model, and Optimal Control of the Tank Model. A screenshot of this module can be seen in Figure 2. When the user selects one of the menu buttons the corresponding module is called and a new GUI window pops up.

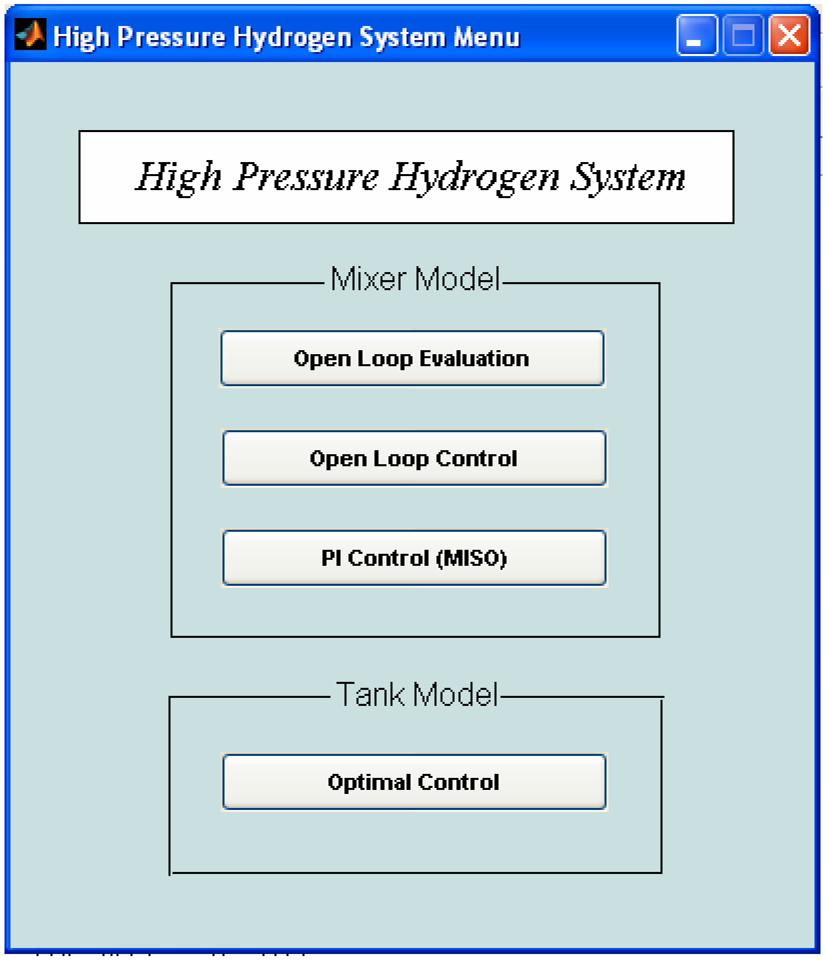


Figure 1: High Pressure Hydrogen System Menu

Mixer Model: Open Loop Evaluation

This module enables the user to run a simulation of the mixer model without detailed knowledge of the valve positions. Most of the valve configuration is embedded giving the user limited control over their functionality. The time that the valves stop opening or closing is the only valve parameter the user is allowed to enter. There is more flexibility, however, in describing the GH2 and LH2 supply, the mixer volume, exit conditions, and equilibrium points. The "Plot" button of this module plots the liquid, gas, and exit flows, the exit flow balance, the mixer energy, density, temperature, and pressure, and the valve positions. A screenshot of this module is displayed in Figure 3.

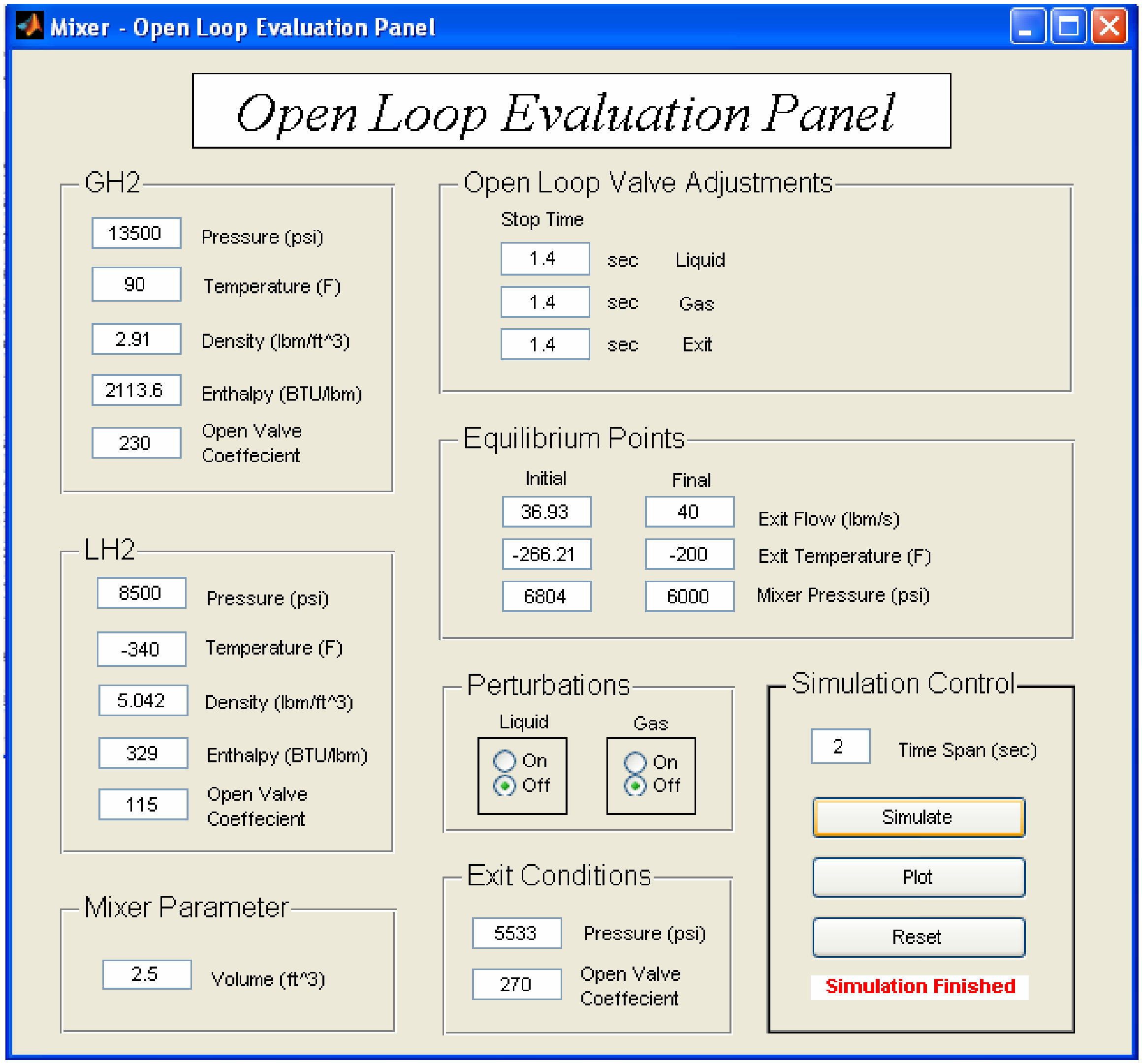


Figure 2: Mixer – Open Loop Evaluation Panel

Mixer Model: Open Loop Control

Contrary to the operation of the “Open Loop Evaluation” module, this module allows the user to perform a model simulation without set points but with detailed knowledge of the valve positions. In this case, the user has total control over the liquid, gas, and exit valves. They control the initial and final percentages of the valve openings, the time it starts to open or close, and the time it stops opening or closing. After the simulation is run, the module returns the set points that correspond to the mixer valve positions and the model outputs. The "Plot" button of this module plots the liquid, gas, and exit flows, the exit flow balance, the mixer energy, density, temperature, and pressure, and the valve positions. A screenshot of this module is displayed in Figure 4.

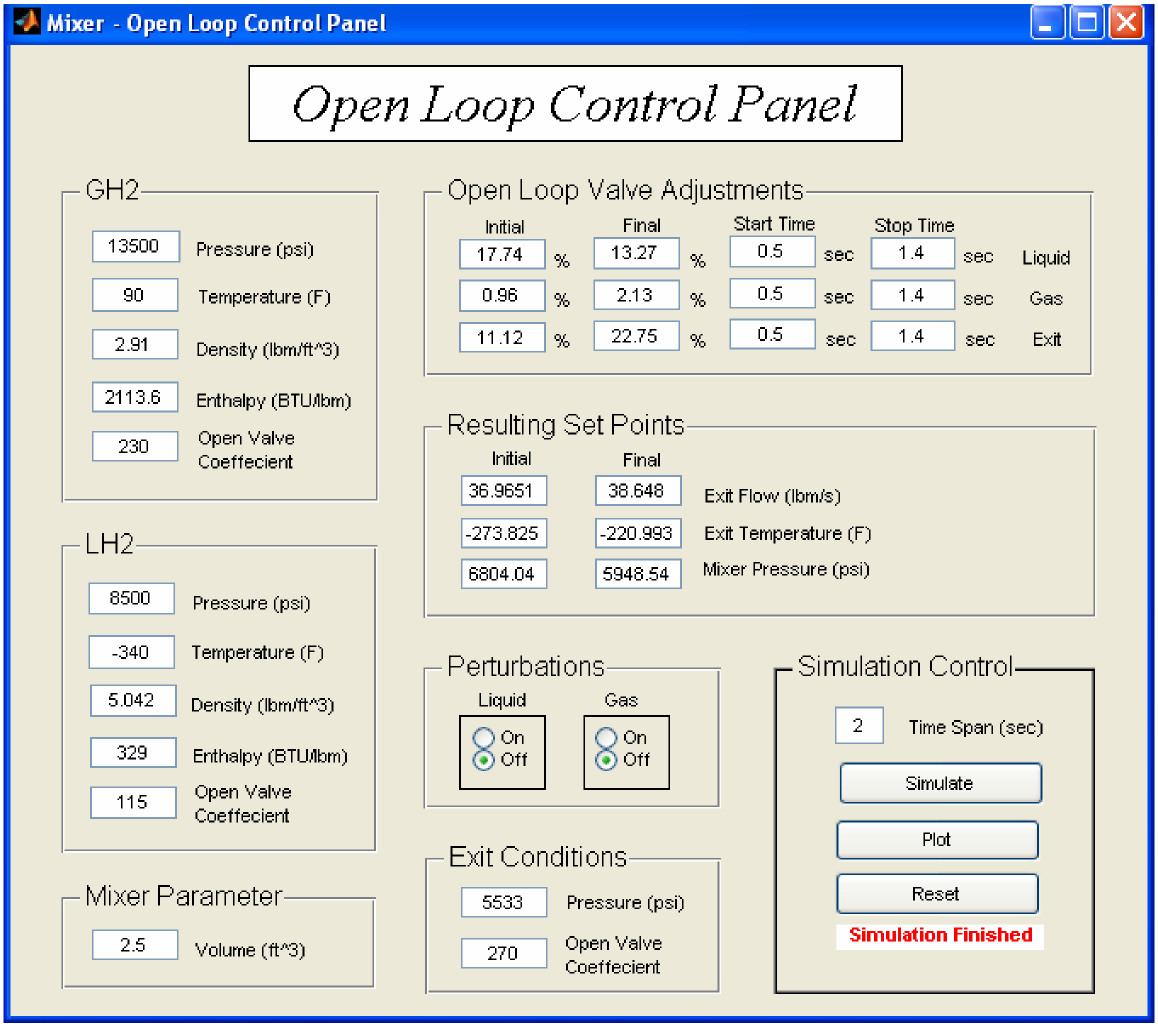
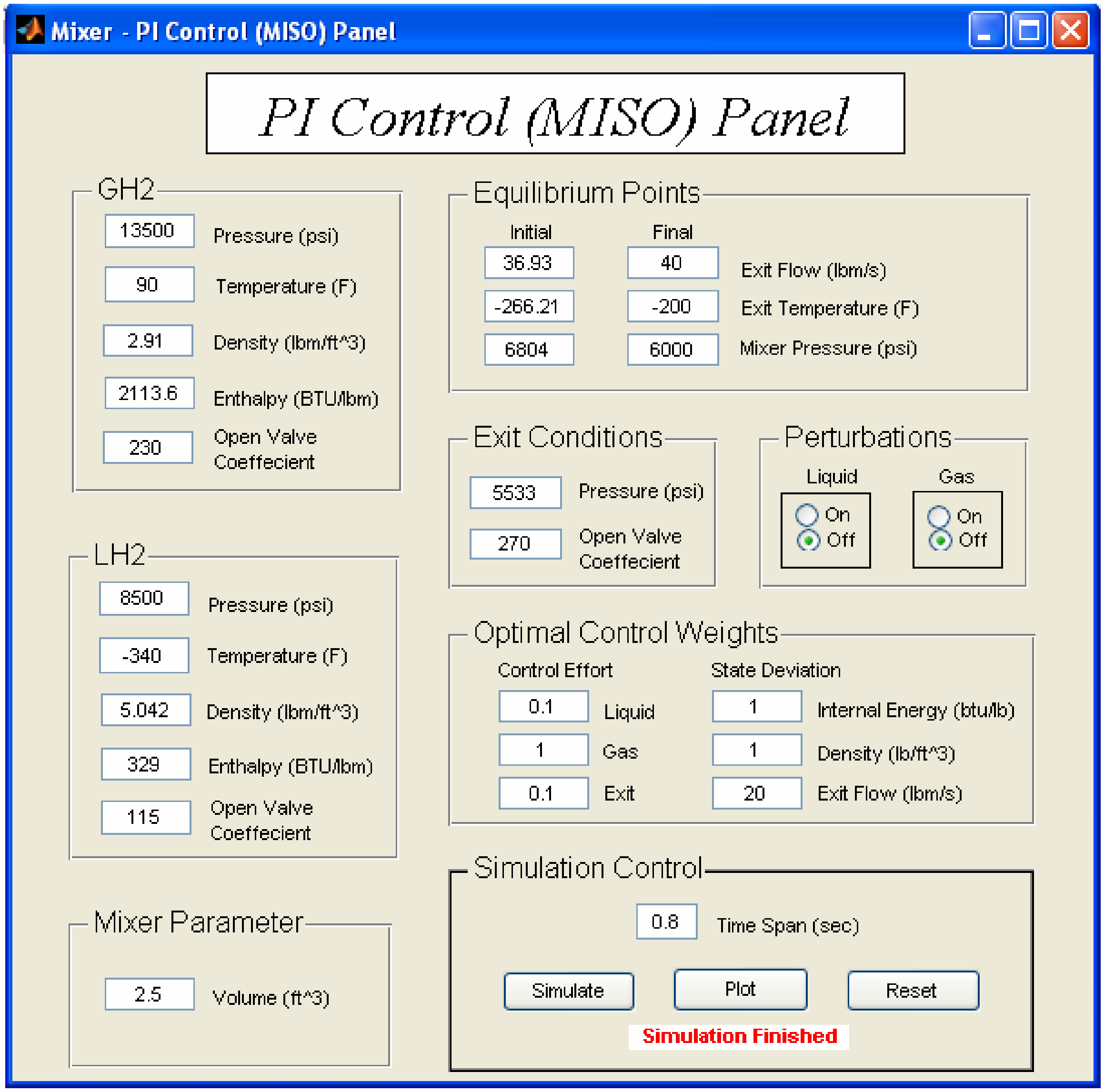


Figure 3: Mixer – Open Loop Control Panel

Mixer Model: PI Control (MISO)

This module introduces an optimal multi-input/single-output proportional-integral (MISO-PI) controller to the mixer model and tracks the exit flow. Needless to say, the user no longer has direct control over the mixer valves. The user does, however, have the freedom to design the controller by entering the desired control effort and state deviation weights.

The “Plot” button of this module, in addition to the plots of the previous modules, also displays the exit flow error, a comparison of the exit flow values from the non-linear model and the linear model, and a phase-plane energy vs. density graph. A screenshot of this module is displayed in Figure 5.



Tank Model: Optimal Control

The “Optimal Control” module allows the user to provide control for the states of the tank model. These states are the GH2 density, the GH2 internal energy, the LH2 internal energy, and the GH2 volume. This module accepts the initial conditions of the tank model and the equilibrium point the user wants the tank model to reach. The user also defines the optimal controller by providing the desired control effort and state deviation weights. The “Plot” button of this module plots the gas density, internal energy, and volume, and the liquid internal energy. It also displays graphs of the gas and liquid flow rates. A screenshot of this module is displayed in Figure 6.

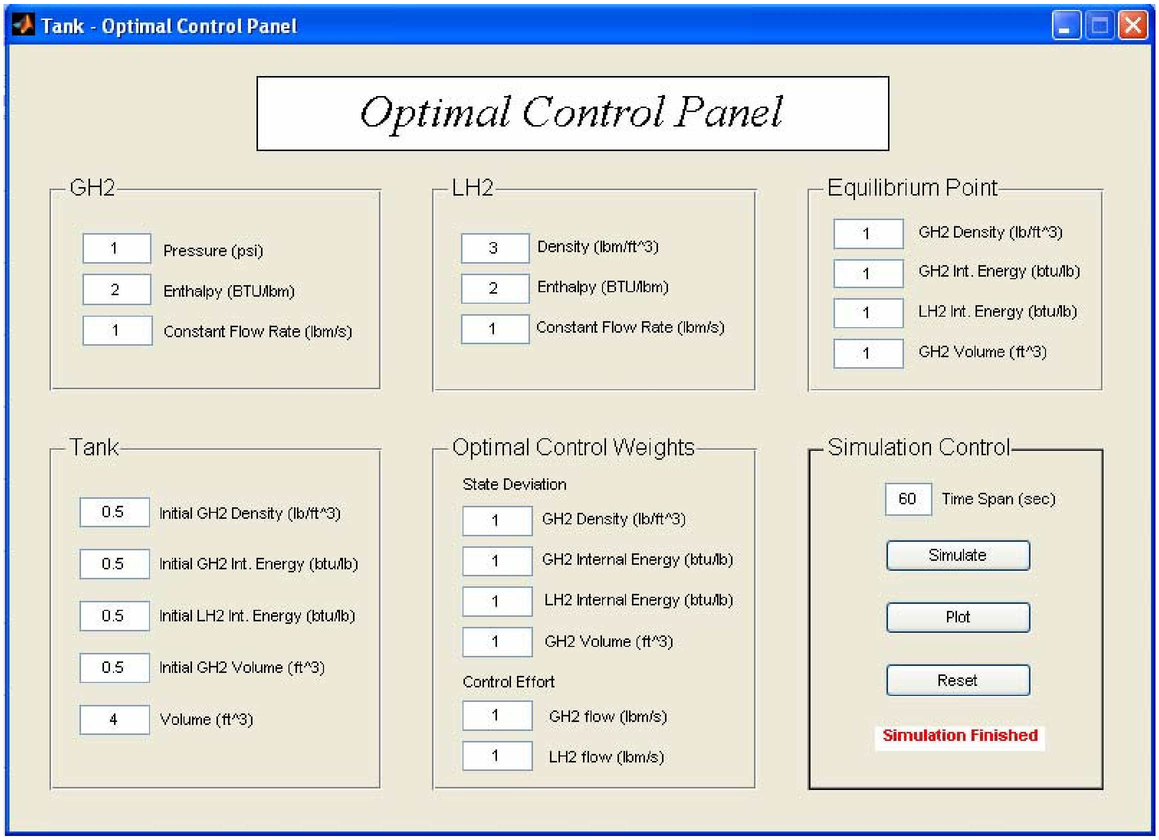


Figure 5: Tank – Optimal Control Panel

Attachment to this Report

A CD is included with this report that has the following files:

1. Electronic copy of this report in Word and in PDF.
2. User’s Manual in Word and PDF.
3. Listing of software code in Word and in PDF.
4. Matlab/SImulink and other files.

Conclusions and Further Research

The challenge of transferring model evaluation and control technology to NASA engineers who are unfamiliar with the MATLAB environment has been met. The GUI allows the user to evaluate and control the mixer or tank by simply entering the desired values, running the simulation, and viewing the results. This GUI development also takes us a step closer to the full software simulation environment that will allow NASA engineers to perform simulated testing exercises at fundamentally no cost. However, there is much more work to be done.

Topics for further research include:

- Allowing the user to design multi-input/multi-output controllers for the mixer and tank models
- Enabling the user to store simulation results for later use and analysis
- Enabling the user to determine whether or not the model is controllable
- Programming the GUI to inform the user when something has gone wrong in the simulation
- Programming a “Stop” button that will enable to user to have greater control over the model simulation
- Designing a GUI that controls the combined tank/mixer system

References

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