



# Mean Line Pump Flow Model in Rocket Engine System Simulation

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# MEAN LINE PUMP FLOW MODEL IN ROCKET ENGINE SYSTEM SIMULATION

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## ABSTRACT

A mean line pump flow modeling method has been developed to provide a fast capability for modeling turbopumps of rocket engines. Based on this method, a mean line pump flow code PUMPA has been written that can predict the performance of pumps at off-design operating conditions, given the loss of the diffusion system at the design point. The pump code can model axial flow inducers, mixed-flow and centrifugal pumps. The code can model multistage pumps in series. The code features rapid input setup and computer run time, and is an effective analysis and conceptual design tool. The map generation capability of the code provides the map information needed for interfacing with a rocket engine system modeling code. The off-design and multistage modeling capabilities of the code permit parametric design space exploration of candidate pump configurations and provide pump performance data for engine system evaluation. The PUMPA code has been integrated with the Numerical Propulsion System Simulation (NPSS) code and an expander rocket engine system has been simulated. The mean line pump flow code runs as an integral part of the NPSS rocket engine system simulation and provides key pump performance information directly to the system model at all operating conditions.

## INTRODUCTION

The mean line pump flow code PUMPA has been coupled to the Numerical Propulsion System Simulation (NPSS) system model of an expander cycle and has eliminated the need for pump maps in the model. The pump code also provides detailed pump flow information to the pump designer at all conditions along the rocket engine operating line. During the conceptual design of liquid propellant rocket engine systems, the performance of the propellant feed pumps at both the design and at several off-design operating conditions may be of equal importance. The operating range of the pump can be a design consideration that can influence the geometric design of the pump. By knowledge of the pump performance at off-design, or throttled engine conditions, the designer can optimize the pump geometric configuration to provide acceptable pump and system performance for a range of engine operating conditions. This ability to predict pump off-design performance is necessary for system evaluation of candidate pump configurations within rockets. A one-dimensional mean line flow modeling code for pumps PUMPA, has been written to provide a rapid evaluation of candidate pump design concepts and is described in detail in reference 1. Reference 1 contains a description of the capabilities of the PUMPA code and the model equations with the definition of the variables. Included in reference 1 are validation cases from cryogenic rocket engine pumps and research pumps that have been flow modeled with the PUMPA model during the computer code development and validation.

The pump code is based on the Euler equation coupled with empirical correlations for rotor efficiency. The code can estimate the off-design characteristic performance map. The match between the pump rotor and the diffusion system influences the shape and slope of the pump map and can effect the location of the stall and cavitation inception lines. The suction performance at off-design conditions is based on an empirical correlation to the suction performance at the design condition. The pump operating condition where the static pressure is equal to the vapor pressure, determines the cavitation inception point. Using the pump code in a design environment, the pump configuration can be quickly optimized by an experienced designer, to result in an acceptable system performance by the use of this multi-stage mean line flow modeling method. The flow path, blade inlet and exit angles and the number of stages can be manually varied by the designer until an acceptable configuration is achieved that will meet the overall rocket engine system requirements.



The pump code has been integrated into the NPSS engine system model in order to demonstrate its use in a system level design environment. An NPSS thermodynamic cycle model of an expander cycle pump-fed rocket engine has been created at NASA Glenn Research Center. This rocket engine has many similarities to the 16,500 Lbf thrust engine that was modeled in reference 2. The NPSS model uses the PUMPA mean line flow code to estimate the pump performance, instead of the traditional technique of representing a pump with head-flow-efficiency maps. In this method, the NPSS engine system model passes the pump inlet boundary conditions to the pump code, executes the pump code, and receives back the pump exit flow conditions required by the NPSS system model. Several iterations are required between the pump code and the system model of the rocket engine to reach convergence. Only the 0-dimensional information is passed to the NPSS model from the pump code at the operating point being modeled by the NPSS system model. The pump code calculates the exit pressure, temperature, and torque and passes it to the NPSS system model. In traditional system models, this information is obtained from the pump performance maps, which are usually part of the rocket engine system model. In addition to providing the required system level 0-dimensional data to the system model, the more detailed 1-dimensional flow conditions that include velocity vector data are also generated by the pump code and written to a detailed output listing. This more detailed output listing from the pump code provides the pump designer with the static and total fluid conditions of pressures and temperatures, absolute and relative velocity vectors and flow angles at key locations within the pump at the point of engine operation being modeled. The output listing enables the pump designer to gain further insight into the detailed performance of the pump at the actual engine operating condition being modeled.

#### NUMERICAL PROPULSION SYSTEM SIMULATION (NPSS)

The NPSS Version 1 is a full-featured nonlinear engine system simulation package, developed through a cooperative effort between NASA and industry (refs. 3 to 5). The first application of the NPSS has been to air-breathing gas turbine engines, but work is currently underway to develop component models and thermodynamic packages to support rocket engine system simulation as well.

Because the NPSS was developed to provide complete modeling flexibility, no changes to the software framework are required to simulate space rocket engine propulsion systems. One of the first demonstrations of the NPSS rocket modeling capabilities was the expander cycle system illustrated in figure 1. The mean line PUMPA code is generally considered one-dimensional, while the NPSS cycle model is considered zero-dimensional. Since the PUMPA code is of higher fidelity than the NPSS cycle model, the output data has to be averaged, before being passed to the NPSS system model. The averaging is performed within the PUMPA code. The boundary condition data transfer between codes of different levels of fidelity is referred to as "zooming". The zooming linkage between NPSS and the PUMPA analysis code can be accomplished fairly easily. There were many methods the linkage between NPSS and the PUMPA code could have been accomplished. The first possible method was to use PUMPA to update the calculated design values that are used to modify maps. In this mode the cycle would be run in the design mode and the boundary conditions for the PUMPA model would have been determined by the NPSS system model. These values would be used by PUMPA to determine new design parameters. This method assumes that the pump map shape is more or less correct and that the main effects of a design change can be seen by changes in the design parameters. These parameters would then be used to determine a design scalar that would be used by the map at off-design operating conditions. The second method would be to use the PUMPA code to update both the design and off-design conditions. In this mode the cycle would be run to convergence in both the design and off-design modes. The PUMPA code would then be run with the converged conditions and map off-sets would be calculated to make the map data match. This method would be similar to a numerical data reduction. This method would probably work best when the higher order code (e.g., PUMPA code) takes a long time to run or produces numerically noisy results (the noise could cause solver convergence problems). Both of these issues could make it problematic to include a higher order simulation inside the NPSS solution loop. This method also assumes that the original map will not be modified too drastically. The third possible method, and the one that was used in this demonstration, is a straight substitution of the PUMPA analysis code for a map-based NPSS element. This is the most straight forward method of linking the two codes. It does not require the user to have a map already in place within the NPSS system model to use as a starting point. However, it does assume that PUMPA code runs quickly and boundary condition data



transfer is clean enough to be included in the solver iteration process. This method of linking (or zooming) of the two codes has the potential to eliminate the need for maps in the engine cycle simulation.

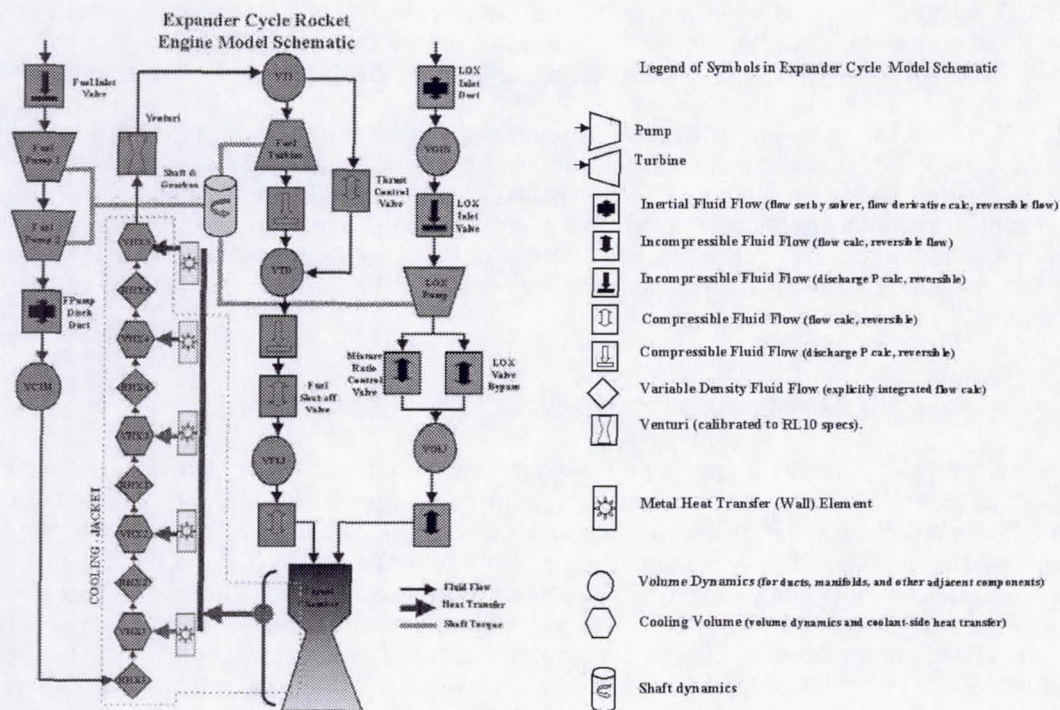


Figure 1.—Schematic illustrating an expander cycle rocket engine modeled with the NPSS system model. The fuel (liquid hydrogen) pumps 1 and 2 and the LOX (liquid oxygen) pumps are modeled with the PUMPA mean line pump flow code.

Initially the codes were linked together using the third method, a direct substitution. The NPSS code has its own programming language in which user commands and instructions are processed at run time and do not have to be compiled beforehand (interpreted language). Using the NPSS interpreted language it was easy to create a wrapper for the PUMPA code and include it as an element in the NPSS cycle code. In fact, this was done keeping PUMPA as a stand alone executable by having NPSS write out and read in PUMPA input and output files. However, when this was done the overall NPSS cycle model would not converge. Analysis of the resulting error terms showed that the cycle was able to get close to convergence since all but two of the error terms were within the prescribed tolerance and the last two were also close. This seems to indicate that the NPSS/PUMPA combination was too noisy for the NPSS solver. Further examination indicates that the problem is most likely that the NPSS code is not providing the inlet conditions it passes to the PUMPA code with enough significant figures during convergence, causing noise in the error terms. Although this problem will be addressed shortly, it could not be solved in time for this paper due to time constraints. However, this highlights an important fact mentioned above. When new tools are to be included inside the NPSS convergence loop, the result must not be noisy. For example, specifying the inlet pressure, temperature and flow rate to two decimal places is usually acceptable for a the stand-alone analysis code, but may not be adequate for the NPSS solver since it can cause noise during convergence.

The next method tried was the second method in which PUMPA was used to determine map adjustment factors. With this method the cycle was run with its original maps. The converged cycle data was then used to determine the input conditions for PUMPA. The PUMPA output conditions are then used to determine map adjustment values. The cycle is then rerun using the map adjustment values.

It is important to note that including PUMPA in the cycle is only part of the job. Once the combined system model was created, the cycle analyst had to work with the PUMPA code expert to reach



good results. Therefore, the combined NPSS/PUMPA system of codes did not eliminate the need for individual expertise. However, what the combined system did was make it much easier for the two experts to work together in a fast and seamless computing environment. The collaboration could now center on engineering issues completely and quickly without having to worry about computer science, data transfer, and other collaboration overhead issues. In addition, it eliminated the possibility of human error in the transfer of data between the higher fidelity component code and the thermodynamic engine system model.

The NPSS software continues to evolve. Its ultimate goals include integration of even higher fidelity codes than the PUMPA code, including two and three dimensional, as well as multidisciplinary analysis tools, in a common system simulation framework. The software is being designed to run on a distributed network of computers, taking full advantage of parallel processing for fast turn-around of results. These advanced computing capabilities hold great promise for accurate simulation of both air-breathing as well as space propulsion systems, and for reducing the design time of new aerospace propulsion systems.

### LIQUID OXYGEN AND LIQUID HYDROGEN TURBOPUMPS

The rocket engine propellants are liquid oxygen and liquid hydrogen. The liquid oxygen is pumped with an inducer followed by a single stage centrifugal pump, as is illustrated in figure 2. Downstream of the centrifugal impeller there is a vaneless diffuser followed by a volute collector. Figure 2 also illustrates the head-flow-speed map of the oxygen pump that was generated using the PUMPA code (version 1.1). The pump map is only shown for illustration purposes, since as mentioned earlier, the current methodology implemented into the NPSS rocket engine system model does not use a map to define the characteristic performance of the pump components in the engine system. Instead, the NPSS engine code obtains the performance from the PUMPA code (version 1.3) at a point along the operating line that is being modeled by the system model. The PUMPA models of the oxygen pump have been successfully integrated with the NPSS rocket engine system model.

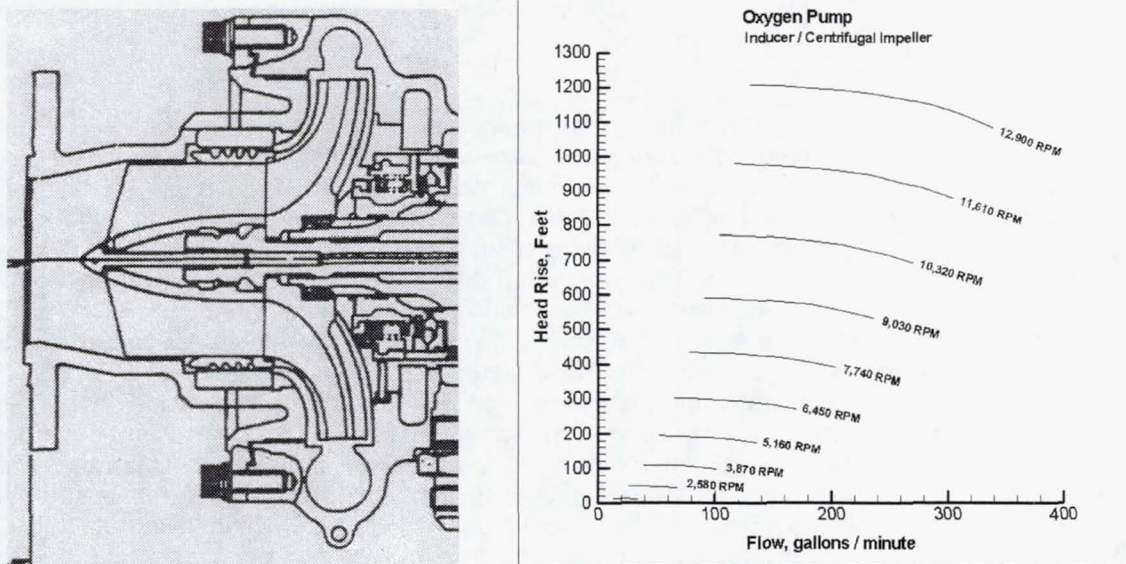


Figure 2.—Liquid oxygen pump featuring an inducer and a centrifugal impeller, and head-flow-speed performance map generated with the PUMPA model.

The pump map illustrates the characteristic performance map of the oxygen pump for a range of speeds and flows. Input parameters into the oxygen pump mean line model include the inlet and outlet radii and blade angles at the rotor inlet and outlet planes. The PUMPA code input and output requirements are described in detail in reference 1. Operating conditions of inlet pressure, temperature,



mass flow and shaft rotational speed for the pump are obtained from the NPSS system model. The PUMPA code is called from and executed by the NPSS system code to calculate the pump performance at each operating condition. The PUMPA code returns three key parameters to the NPSS system model: exit pressure, exit temperature and shaft power. Numerous other pump parameters are calculated by the PUMPA model at that operating condition and are printed to the detailed pump output file. The detailed output is for the benefit of pump designers to gain improved insight into the pump's performance and includes velocity triangles at the rotor inlet and exit, as well as local fluid conditions at key locations within the pump stage. Table 1 below is a summary of key performance parameters of the oxygen pump from the PUMPA model.

Table 1.—Oxygen pump key performance parameters obtained from the PUMPA model, and input parameters from the NPSS system model.

<i>Pump Inlet Conditions From the NPSS System Model:</i>				
Shaft Speed,	Rotations / Minute (RPM)			12900.00
Inlet Pressure,	Pounds Force / Square Inch Actual (PSIA)			40.00
Inlet Temperature,	Degrees Rankine (R)			175.00
Mass Flow,	Pounds Mass / Second (Lbm / Sec)			28.00
Flow,	Gallons / Minute (GPM)			182.22
<i>Pump Outlet Conditions Sent From the PUMPA code to the NPSS:</i>				
	Pressure (PSIA)	Head (Feet)	Temperature (R)	Horsepower (HP)
Oxygen Inducer	99.44	124.08	175.38	8.74
Oxygen Centrifugal	608.99	1063.96	179.05	75.67
Overall Oxygen Pump	608.99	1188.04	179.05	84.41

The liquid hydrogen pump consists of an axial flow inducer followed by two back-to-back centrifugal impellers (fig. 3). The inducer and the first centrifugal impeller are tightly coupled and act as one impeller with an axial inducer section. The second centrifugal stage has no axial inducer. Downstream of the centrifugal impellers there are vaneless diffusers followed by volute collectors.

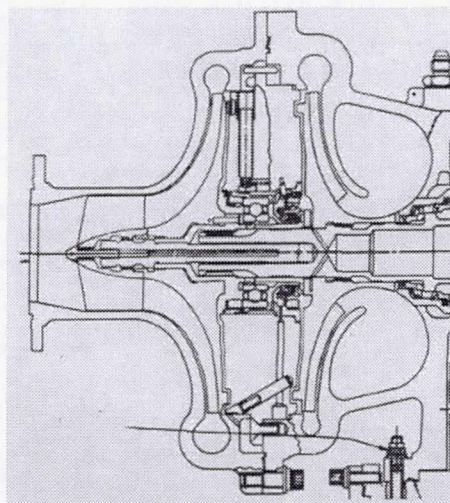


Figure 3.—Liquid hydrogen pump featuring an axial flow inducer and two centrifugal impellers with volutes.



The liquid hydrogen pump was modeled as two separate stages with the PUMPA code to facilitate modeling the inter-stage bleed with the NPSS system model. The first stage included the inducer and the first centrifugal impeller followed by a volute. The PUMPA code was run as part of the NPSS system simulation as two separate stages. As in the case of the oxygen pump, the inlet conditions for the first stage hydrogen pump were obtained from the NPSS system model. The pump code then solved for the exit conditions from the first hydrogen stage, and used these quantities as inlet conditions for the second stage hydrogen pump. Similarly, the exit conditions from the second stage hydrogen pump were calculated by the pump flow code, and transferred to the NPSS system model. These iterative steps were repeated numerous times, until convergence was reached in the NPSS system model. One of the convergence criteria in the NPSS model is the power balance between the pumps and the turbines, since these quantities have to be matched within an acceptable tolerance in order for the engine system to operate at a steady-state operating point. The performance maps that were generated (PUMPA version 1.1) for the two hydrogen stages are illustrated in figure 4. Table 2 below is a summary of key performance parameters of the hydrogen pump from the PUMPA (version 1.3) model.

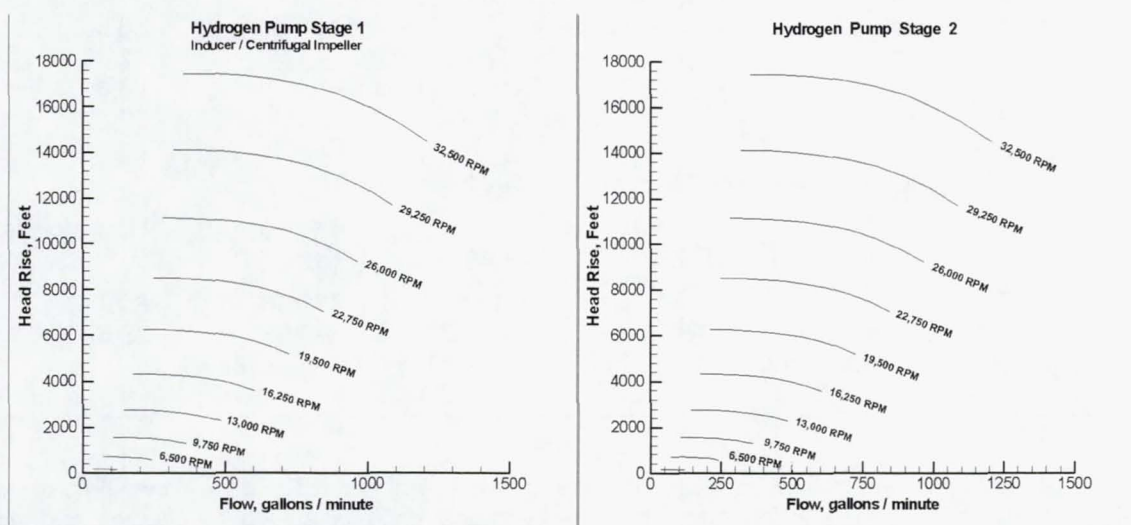


Figure 4.—Liquid hydrogen pumps 1 and 2. Head-flow-speed performance map generated with the mean line PUMPA version 1.1 model.

Table 2.—Hydrogen pump key performance parameters obtained from the PUMPA model, and input parameters from the NPSS system model.

<i>Pump Inlet Conditions From the NPSS System Model:</i>				
Shaft Speed,	Rotations / Minute (RPM)			32500.00
Inlet Pressure,	Pounds Force / Square Inch Actual (PSIA)			28.00
Inlet Temperature,	Degrees Rankine (R)			38.00
Mass Flow,	Pounds Mass / Second (Lbm / Sec)			8.63
Flow,	Gallons / Minute (GPM)			887.92
<i>Pump Outlet Conditions Sent From the PUMPA code to the NPSS:</i>				
	Pressure (PSIA)	Head (Feet)	Temperature (R)	Horsepower (HP)
Hydrogen Inducer	37.93	327.96	38.17	11.86
Hydrogen Centrifugal 1	495.38	15221.10	46.94	404.94
Hydrogen Centrifugal 2	984.25	16494.41	55.71	441.60
Overall Hydrogen Pump	984.25	32043.48	55.71	858.40



Current efforts to successfully integrate the PUMPA models of the hydrogen pumps into the NPSS system model are continuing. The first attempt at integration of the pump code directly under the NPSS solver resulted in nonconvergence due to numerical instability. This appears to be due to the accuracy of the boundary condition data transferred between the PUMPA code and the NPSS code. This is being addressed by increasing the number of significant digits of the data being transferred between the two codes. The integration of the hydrogen pump models into the NPSS system model is continuing and it is anticipated that the convergence issue will be resolved as the number of significant digits of the boundary condition data is increased.

## CONCLUDING REMARKS

A mean line method for flow modeling of pumps has been successfully accomplished for a variety of cryogenic rocket engine turbopumps and research pumps. This mean line flow analysis method has been programmed into the PUMPA code. The flow code can be used in the conceptual design phase of new pumps since it requires minimal input and has fast setup and computer run times. The performance of candidate pump configurations can be assessed to within reasonable accuracy with the mean line flow code in a rocket engine system model environment. In addition to assessing the design point performance, the code can predict the shape of the pump head-flow characteristic performance map and can provide pump performance for system evaluation of the complete rocket engine. Version 1.3 of the PUMPA code has been successfully linked to the Numerical Propulsion System Simulation (NPSS) code in order to demonstrate rocket engine simulation capabilities of the NPSS code. This direct coupling method enables instant transfer of key pump performance parameters from the pump code to the NPSS model, thereby eliminating the need for pump maps in the NPSS model. This method will be refined in the future to improve convergence by increasing the number of significant digits of the boundary conditions being passed between the NPSS and the PUMPA codes, in order to reduce the noise currently encountered during convergence. The coupled NPSS/PUMPA capability will enable designers to quickly evaluate the detailed performance parameters within pump configurations in a rocket engine system environment. It is anticipated that when fully developed, the NPSS system modeling capability will reduce the design time required for rocket engines.

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