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# Science Article

# A Simulation Algorithm for Staged Combustion Cycle Liquid Propellant Rocket Engines

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*In order to reduce cost and time along with enhancing the safety issues, numerical computer modelling and simulations are widely used for analyzing complex systems such as launch vehicle or spacecraft propulsion system. The objective of this research is to obtain an algorithm for simulation of staged combustion cycle liquid propellant engines. For this purpose the space shuttle main engine (SSME), as one of the world's most complicated engines, is selected as a case study. A total of 34 elements is taken into account and using more than 100 linear/non-linear equations, the engine's steady state system model has been established in MATLAB SIMULINK software. The simulation method uses eleven nested loops for iteration. The algorithm is based on the known parameters at the inlet of engine main feed lines namely mass flow rate and pressure, similar to the known conditions during hot test of engine on test stand. The simulation is capable of predicting the engine's operation in wide range of thrust throttling levels from 69 percent to 109 percent of the nominal thrust. In order to validate the suggested method, SSME main component parameters, operating at 109 percent of rated thrust is presented. Simulation result mean error is less than 5 percent.*

***Keywords:*** *Cryogenic Propellant-Liquid Rocket Engines- Mathematical Modeling- Space Shuttle Main Engine.*

## Introduction

System Modeling and simulation for liquid propulsion systems is among one of the most important steps that can help designer and project managers to make effective decisions in early stages of design or enhancement phases. By employing a suitable model it is possible to reduce the program risks, refine the requirements, predict and improve the system performance in a repeated and traceable manner, validate the predictions before/after hot test with lower cost and time consume [1]. Therefore finding key parameters and major factors that their modification can lead to any valuable enhancement in system's performance and weight is an interest for engine designers. Considering the complexity of stage combustion cycle liquid propellant rocket engines shortly SCCLPRE, it is difficult to perform an integrated system modeling with considering most of the major elements into account.

Since 1970s, lots of contributions has been made for modelling and simulation of liquid propellant rocket engine (LPRE). In 1989, A. Duyar described the identification of linearized dynamic

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models for the SSME from the nonlinear dynamic simulation. The model could be used for control design process. For further studies the valve nonlinearities should have been added and the validity had to be checked with the full nonlinear engine model [2]. In 1990, J. D. De Abreu-Garcia; by combining three different methods namely Euler's method, Adams-Bashforth two step method and matrix stability region placement method obtained a faster simulation technique for simulating the valve dynamics of SSME [3]. In 1995, C. Goertz suggested a modular method of analysis for different liquid propellant engine cycles. In this concept the user assembles the desired cycle form choosing the basic components from a library that includes most important elements in engine. The developed platform was used for modelling SSME, RD-120 and RD-701 engine static performances [4]. In Goertz's article the equations and simulation algorithm are not explained in detail and the results are not compared with the experimental data. In 1995, M.P. Binder used the RL10A-3-3A expander cycle cryogenic rocket engine test data to create a transient model for government use which could work for a wide range of engine operating conditions, highly relying on the experimental data.
The engine results are said to have less than 10 percent error [5]. In 1998, P. C. Lozano-Tovar; focused on SSME to obtain dynamic models for liquid rocket engines. He used basic thermodynamic principles to obtain dynamic models for major elements of SSME [6].The work done has fairly good precision (less than 10 percent error) along the operating points for the components, but there is no system simulation done for the integrated model neither dynamic nor static. In 2011, F. D. Matteo et al. developed a transient model for RL-10 expander cycle cryogenic propellant engine (Centaur upper stage engine) for simulating the start-up process. They also used ESPSS, to build and analyze the model for the main subsystems [7]. In 2011, M. Chitsaz, E. Tahmasebi et al. proposed an algorithm for static simulation of stage combustion cycle cryogenic propellant engines focusing on a simplified model of RD-180 twin chamber engine as case study. The results are compared with the real engine data [8]. In 2013, M. Naderi, A.R.Jalali et al. developed a general software for modeling and simulation of liquid propellant engines. Their research mainly focused on open cycle LPRE [9].

In 2015, L. Wei et al. used the Modelica software to simulate general main engine component's transient start up and shutdown behavior with 0-D equations [10]. The simulation algorithm and validation for the published work is not presented in his work. In this paper, focusing on SSME as one of the most complicated, comprehensive and successful SCCLPRE built up to now, a simulation algorithm is suggested.

## A Brief Review on SSME

For better understanding a brief introduction to SSME is presented. The main engine of space shuttle known as RS-27, a fully cryogenic propellant engine burning liquid hydrogen and liquid oxygen generates a nominal sea level thrust of 1675 kN and 452s specific impulse in vacuum. SSME has throttling capability from 67% to 109% of the rated thrust, along with fail safe and fail operating controlling system. It is reusable up to 55 times [11]. For better understanding, consider Fig 1 .

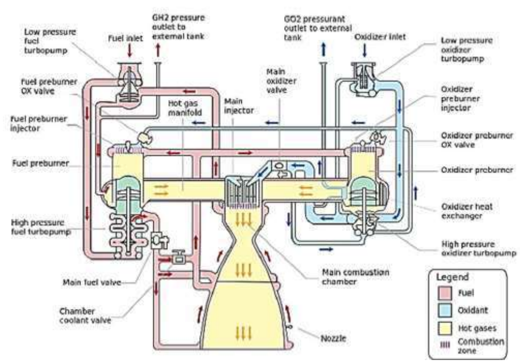

**Fig 1** SSME Flow Diagram [12]

According to the diagram the engine has four turbopump systems, two on each line. One for the low pressure and the other for the high pressure system. On the fuel line, liquid hydrogen is fed to the low pressure fuel turbopump (LPFTP) pump inlet by the force of tank pressure and also hydrostatic pressure. This pump is a single stage inducer type pump driven by single stage axial turbine which is driven by the high pressure hydrogen gas coming from the main chamber cooling jacket. The increased pressure liquid hydrogen from the inlet is now fed to the high pressure fuel turbopump (HPFTP) pump inlet. The LH2 enters the LPFTP pump inlet at an absolute pressure of 2 bar and it is pressurized up to nine times of the inlet pressure that is 17.2 bar. The rotor rotational speed is about 15000 rpm.

The HPFTP pump consists of three stage centrifugal type pump, rotating at 35000 rpm which would further increase up the inlet pressure to 414 bar. The HPFTP turbine is a two stage axial gas type turbine. At the exit of the main fuel pump, the normally closed main fuel valve is located after which the main fuel line is separated into two main paths at ratio of about one to four. About 80% of the HPFTP's pump outlet flow is directed to the preburners but firstly, this flow is divided into two parts. One part is used to cool the nozzle by flowing through fuel nozzle cooling by pass valve. The flow of is passage will finally merge and mix with the other part which directly goes to feed the preburners. The remaining 20% of the fuel flow would be used to cool the main chamber through its cooling jacket. Through this passage, the liquid hydrogen temperature is warmed up to -8 degree Celsius therefore it is gasified (at the inlet of the engine, fuel enters the engine at -253 degree Celsius). The high pressure gaseous hydrogen is now rooted to the LPFTP to drive the single stage impulse turbine. The gas needed to pressurize the fuel tank (about 0.32 kg/s), is branched from the exit of the LPFTP turbine and the rest of the gas is used to cool down the hot sections of the engine, mainly hot gas manifold, main injector baffles and faceplates prior to being injected to the main combustion chamber. On the oxidizer line, liquid oxygen enters the low pressure oxidizer turbopump (LPOTP) pump inlet at a pressure of 6.9 bar and by passing through an inducer rotating at 5000 rpm, its pressure is increased up to four times, that is 27.5 bar.

The turbine of the LPOTP is a six stage axial hydraulic turbine driven by liquid oxygen. The high pressure oxidizer turbopump (HPOTP) pump is constructed in a compact way. Dual inlet single stage centrifugal impeller (two impellers mounted back to back) is mounted on a single shaft, rotating at 30000 rpm which will cause the liquid oxygen pressure to be further increased to 310 bar. This is done by the torque produced by three stage axial type gaseous turbines.

Almost 90% of the discharged oxidizer flow from the main oxidizer pump is passed through the normally closed main oxidizer valve which is then fed to the main chamber oxidizer injector. The remaining 10% is branched for driving the LPOTP turbine (82 kg/s), feeding the HPOTP booster pump and a small amount (0.54 kg/s) for pressurizing the oxygen tank. The oxidizer booster pump is a single stage centrifugal impeller mounted on the same shaft of the HPOTP and is used to increase the liquid oxygen pressure up to 552 bar so that it can be injected to the preburners. This pressure will ensure the safe operation of controlling valves on the oxygen feeding lines prior to the preburners. These controlling valves include throttling valve on the oxygen line of the oxidizer preburner namely and mixture ratio controlling valve on the oxygen line of the fuel preburner. It should be noted that SSME has a total of five major valves [11].

### General Governing Equations

Due to page limitations and comprehensive governing equation for a complex SCCLPRE such as SSME, in this section only a summary of the final form of governing steady state equations for main engine components are introduced.

The SCCLPRE just like other LPRE is constructed of some major modules. These include connecting pipes, combustion chamber, pre-burner (or gas generator in open cycle LPRE), pumps, turbines and valves

## Pipes

The flow in pipes can be computed through the follwing equation based on the second law of Newton [13].

$$\left(\frac{L_p}{A_p}\right)\frac{d\dot{m}}{dt} = P_{out} - P_{in} - \frac{\lambda_p}{2\rho A_p^{\,2}}\dot{m}^2 \qquad (1)$$

In this equation , $A_p$ $L_p$ are the pipe cross sectional area, length and $\lambda_p$ is the pressure loss factor which can be obtained through published engine data according to the operating regime. For the steady state analysis, the left hand side of the above mentioned equation is omitted.

### Pre-burner and Combustion Chamber

The main equation for this component can be obtained using the governing equation for choked flows [14].

$$P = \dot{m}\frac{\sqrt{\gamma RT}}{A_t\gamma\sqrt{\left[2/(\gamma+1)\right]^{(\gamma+1)/(\gamma-1)}}} \qquad (2)$$

In this equation the gas properties can be obtained using equilibrium combustion analysis software such as CEA but may contain some error therfore another solution is through models presented by each company due to their own detailed model and experiments.

### Turbopump Assembly

For the turbine element working with gaseous fluid the final equation for calculating the torque is as folowing [15].

$$\tau_t = \lambda_t \dot{m}_t \sqrt{\Delta h_0}\,\Gamma(\nu_r) \tag{3}$$

$$\Gamma(\nu_r) = \chi \frac{\sqrt{\eta_{st}}}{\nu_r} \tag{4}$$

In these equations $\lambda_t, x$ are constants related to turbine geometry and efficiency, $\eta_{st}$ is the static efficiency, Γ is torque coefficient and is a function of velocity ratio $v_r$. Enthalpy change of the fluid crossing the turbine is presented as$\Delta h_0$. For hydraulic turbines the governing equation is different.

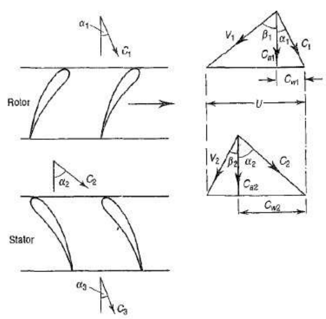


**Fig 2** Velocity Triangles for axial flow compressors [16]

$$\tau_t = n r_t^2 \dot{m}_t^2 \left(\frac{\tan\beta_1 + \tan\beta_2}{\rho r_t A_{aa}} - \phi_t\right) \Big/ g \tag{5}$$

$$\phi_t = \frac{\Omega_t}{\rho \dot{m}_t} \tag{6}$$

In this equation $n$ is the number of stages, $r_t$ is the rotor's disk mean radius, $\phi_t$ is the turbine flow coefficient and $\beta_1$, $\beta_2$ are related to flow angles depicted in Fig 2 and $A_{aa}$ is the turbine effective annular area.
The turbine mass flow for supersonic flow is calculated based on the pre-burner parameters, flow pressure ratio s across the blade and $C$ which is a function of shaft rotational speed.

$$\dot{m}_t = C \frac{P_{pb}}{\sqrt{T_{pb}}} \sqrt{\left(\sqrt{\sigma}^{\frac{2}{\gamma}} - \sqrt{\sigma}^{\frac{\gamma+1}{\gamma}}\right)} \tag{7}$$

When the flow speed is not supersonic the above mentioned equations cannot be used for mass flow rate calculation therefore

$$\dot{m}_t = \sqrt{\frac{2g\gamma\eta_{tot}}{\gamma - 1}\rho\Delta p} \tag{8}$$

The governing equations for centrifugal type pumps is as foillowing. In this equation, $f_b$ is the blockage factor due to blade thickness [16].

$$\tau_p = n r_p^2 \rho \phi_p \Omega_p^2 \left[1 - \phi_p \left(\frac{\tan\beta_p}{2\pi(1-f_b) r_p^2 B_p}\right)\right] \tag{9}$$

And for axial type pump it is as below.

$$\tau_p = \frac{r_2^2 \rho \phi_p \Omega_p^2}{g}\left[1 - \left(\frac{\phi_p}{r_2 A_p}\right)\tan\beta_{p_2}\right] \tag{10}$$

The pressure rise of fluid passing through the pump is calculated by considering the Euler's equation in which $\zeta$ is a factor related to internal losses of the pump.

$$\Delta p = \frac{\zeta \tau_p}{\phi} \tag{11}$$

### Valves

The general governing equation for valves is as below [16].

$$P_{out} - P_{in} = f_v(\bar{A}_v)\dot{m}^2 \tag{12}$$

In this equation $f_v(\bar{A}_v)$ is the valve loss coefficient which is a function of nomalized area ratios, $\bar{A}_v$ . For each operating point of engine the value of valve normalized area ratio can be obtained form engine data depending on the valve position and adustment.

### Simulation Algorithm

According to the highly bonded equations of stage combustion cycle LPRE subsystems (here SSME), a different solution algorithm had to be thought for finding the order of solving the equations. The algorithm method chosen here is based on the known parameters at engine main feed lines namely liquid hydrogen and liquid oxygen mass flow rate and pressures at the engine inlet. Using these input parameters, the engine block is called and depending on the desired scheme and subsystem technical characteristics, the equations already discussed in previous sections are solved for the proposed engine. In brief, here the engine is a block, connected to propellant tanks from which we want to find out its performance relying on subsystem and total system analysis. Therefore, the known parameters and the required outputs, are similar to the case of testing the engine on test stand (consider Fig 3 ).

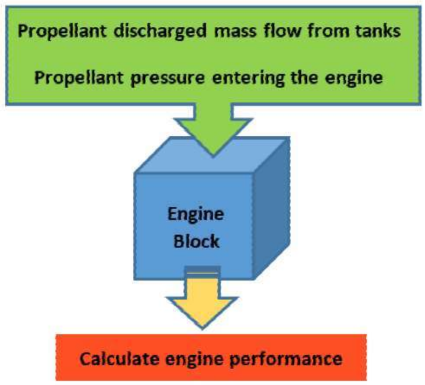


**Fig 3** Proposed simulation block diagram at system level

In this algorithm despite frequently used algorithms for steady state analysis [8], the chamber or preburner pressure is not known or not predetermined form the designer, but itself is a parameter required to be simulated. Based on these requirements the simulation process of the engine is divided to two main sections: The oxidizer line and fuel line. With a total of fourteen modules, containing more than one hundred equations, the system of equations are solved through nine initial guesses. These initial guesses are highly corrected through an iterative process using Newton Raphson method.

In fuel line, the flow diagram is categorized by five main modules: fuel preburner, HPFTP, LPFTP, valves, nozzle and CC cooling passage. Other feedline systems are considered within these modules. On the other line, the flow diagram is solved through a five segmented simulation process: Oxidizer preburner, HPOTP, LPOTP, preburner main supply lines and valve module.

As mentioned before this modularization is selected based on the dependent variables of component equations which are highly coupled together. By performing power and mass balance, the engine parameters are corrected at different stages. Finally using the calculated mass flow rate and pressure distribution on each line, the CC module is called and simulated. A brief presentation of the algorithm in system level is shown as a flowchart in Fig 4

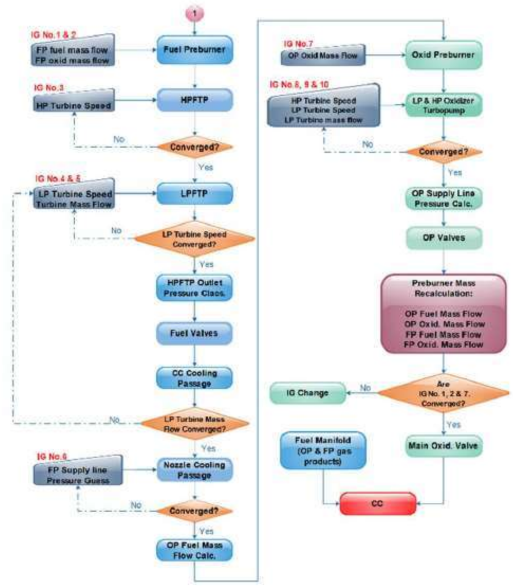


**Fig 4** SSME simulation algorithm (IG stands for Initial Guess)

## Results and Conclusion

For validating the suggested algorithm, SSME is used as a case study. For this purpose using the suggested algorithm presented at section 4 a system equation consisting of more than 100 linear/nonlinear equations has been formed in MATLAB SIMULINK.

The steady state simulation is performed for SSME at 109 percent of nominal operation condition. The required system level input values can be found in Table 1.

**Table 1** SSME System input parameters atb109% thrust level

| Input Parameter | Value |
|---|---|
| Fuel tank discharge mass flow | 72.79 kg/s |
| Oxidizer tank discharge mass flow | 436.72 kg/s |
| Absolute pressure at the end of the fuel tank | 2.04 atm |
| Absolute pressure at the end of the oxidizer | 6.8 atm |

The simulation results can be found at Table 2. As it can be seen from the results, the governing equations used for turbopump system has leaded to fairly good accuracy. The rotational speed and the computed torque is a bit different for the LPFTP which is quiet expectable due to the lack of initial data for this element. The outlet pressure which is of course quiet dependable on the pump performance has been affected by the torque and speed, and the results seem to be following the expected trend. The turbine mass flow rate analysis which was highly based on initial guesses shows great convergence and the results are satisfactory. Here the LPFTP turbine also needs to be re-modified by introducing more accurate initial and geometrical data. The preburner pressure are precise which confirm the usage of the introduced equation sets for this element. For the preburner mass flow rate the errors can be improved by using better models for the controlling valves. For the combustion chamber, using CEA software for computing the gas product thermodynamic properties, the results do not show good precision but using the suggested equation for computing the gas properties by NASA, the simulation results for this element would be far better. Using

**Table 2** SSME simulation results

| Parameter | | Simulation | Reference [15] | Error% |
|---|---|---|---|---|
| Shaft rotational speed, $\Omega$ (rpm) | HPFTP | 36954.02 | 37354.67 | -1.07 |
| | HPOTP | 31497.53 | 31133.36 | 1.17 |
| | LPFTP | 15235.47 | 15806.83 | -3.61 |
| | LPOTP | 5505.54 | 5447.11 | 1.07 |
| Torque, $\tau$ (N.m) | HPFTP | 14389.05 | 14594.05 | -1.40 |
| | HPOTP | 6489.89 | 6350.64 | 2.19 |
| | HPOBTP | 449.72 | 438.58 | 2.54 |
| | LPFTP | 1238.39 | 1327.43 | -6.71 |
| | LPOTP | 2305.37 | 2271.32 | 1.50 |
| Pump outlet pressure (atm) | HPFTP | 463.92 | 476.61 | -2.66 |
| | HPOTP | 361.1 | 350.62 | 2.99 |
| | HPOBTP | 590.79 | 573.95 | 2.93 |
| | LPFTP | 16.05 | 17.63 | -8.96 |
| | LPOTP | 30.82 | 30.10 | 2.39 |
| Turbine mass flow rate, $\dot{m}_t$ (kg/s) | HPFTP | 72.79 | 73.32 | -0.72 |
| | HPOTP | 30.01 | 28.61 | 4.89 |
| | LPFTP | 15.1 | 15.73 | -4.01 |
| | LPOTP | 79.35 | 78.73 | 0.79 |
| Pb pressure (atm) | FP | 404.02 | 401.30 | 0.68 |
| | OP | 401.96 | 399.30 | 0.67 |
| Pb mass flow (kg/s) | FP | 76.86 | 73.33 | 4.81 |
| | OP | 26.47 | 29.38 | -9.90 |
| CC pressure (atm) | Exp. Gas prop. | 226.39 | 227.00 | -0.27 |
| | CEA | 280.96 | 227.00 | 23.77 |

## Conclusion

In this paper focusing on SCCLPRE and using the steady state mathematical governing equations for engine subsystems, a simulation algorithm based on engine input parameters at the inlet was considered. In the next step, an integrated system model was developed in MATLAB SIMULINK, capable of computing engine parameters. As case study and validation, SSME was selected and its working condition data on 109 percent of rated thrust level was used and given to the program as input. The simulation results for SSME main component parameters including fuel and oxidizer preburners, low and high pressure turbo pump assemblies and combustion chamber are shown to be in agreement with obtained data from [15]. The established platform based on the suggested algorithm can be used for performance analysis of SCCLPRE. As a future plan, the current model is can be further enhanced for covering engine dynamic conditions.

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