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Optimization of the Startup Sequence of a Liquid-propellant Rocket Engine

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Abstract

The *engineering satisfactory startup sequence* is significant to the development of liquid-propellant rocket engine (LRE) that means the engine startup has been shifted to the steady-state as quick as possible without any harmful transition phenomena to the all subcomponents of engine. In this study, the overall design parameters of engine are divided into two categories - one is rigid-parameter like the hardware configuration and the other is flexible-parameter like the open time of shutoff valves. The flexible-parameters are chosen such as the open times of shutoff valves controlling the supply of propellants into the combustion chamber as the design parameters of optimization problem. The objective function is defined as the quick transition into the steady-state. For the stable engine startup sequence, the stable sequence has close correlation to each subcomponents of engine. For turbopump unit and combustion chamber, the excessive overshoot of rotational speed or pressure should be avoided and for the gas-generator, the temperature peak should be removed during the startup period. Using the developed numerical model, the startup sequence of an open-cycle rocket engine has been optimized by the method of response surface method and genetic algorithm. As a result, the open times of shutoff valves which guarantee the quick and stable startup sequence are obtained. The optimized startup transition curve has qualitatively similar characteristic of the LR87-AJ-11 engine's data.

1. Introduction

During the startup process of liquid-propellant rocket engine (LRE) system, most endeavors are used to be devoted to obtain the stable and the fast engine startup transient. The successful engine startup is able to satisfy two major significant factors. One is securing the reliable reproducibility of the safe ignition of combustion chamber and gas generator under safe range of turbopump rpm and combuster pressure. The other is to minimize the required time for the transition to steady state - full thrust mode from the start command. This provides to optimize fuel amount for full propulsion during the flight. Needless to say, these features should be obtained during firing test in the long run. However, the preceding analytic approach makes it possible to diminish the danger of test as well as the cost and the time to the final goal.

2. Scheme of engine and its startup

In this study, the optimization of engine startup focuses on an open type, bi-propellant liquid rocket engine. This engine type consist of relativly less components and high reliable. Moreover, the engine startup process for its engine type is simple so that most rocket engine has been developed in open type bi-propellant liquid rocket engine. Rocket eninges in u.s., H-1, MA-5, MB-3, LR87-AJ-11[1] are bi-propellant LRE and most recent falcon and merlin. In Russia, RD-0110, RD-107, RD-108 are also the same type of engines. Current rocket engine develpoment in Korea uses the open type bi-propellant liquid rocket engine.

The gas-generator cycle liquid rocket engine schematized in Figure 1 was chosen as the base of discussion. It is composed of Combustion Chamber (CC) for thrust ignited by hypergolic Triethylealuminium (TEA), Gas-Generator

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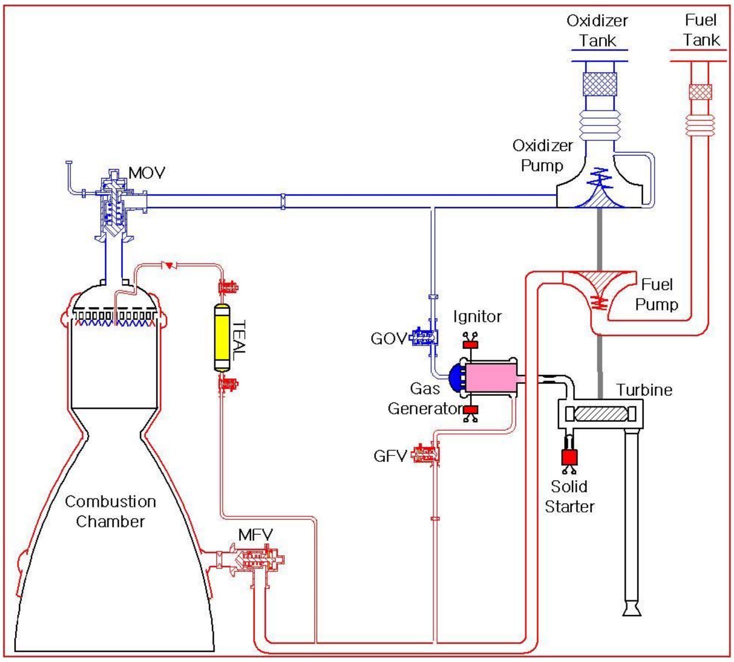
(GG) ignited by Pyro-Ignitor (PI), Turbopump (TP) initially driven by Pyrotechnics (PS), propellant fed pipelines, and shut-off valves of CC and GG, respectively. Kerosene and liquid oxygen are used for the fuel and oxidizer.

An outlined procedure of the startup process of LRE is as follows (figure 2). At the beginning, oxidizer and fuel are filled up to the front of the shutoff valves of CC and GG; Main Oxidizer Valve (MOV), Main Fuel Valve (MFV), GG Oxidizer Valve (GOV), and GG Fuel Valve (GFV). Since there is no enough pressure sufficient to make successful atomization of propellants in the injector of GG combustion chamber initially, the turbine starter (PS) is used instead of driving the turbine by the gas produced from GG. In this study, the pyrotechnics was selected as turbine starter for its simplicity and lightness. If the discharge pressure of pump is developed sufficiently by PS, then open the GFV and GOV sequentially to ignite GG in the manner of fuel-leading ignition. Before the propellants are supplied to the combustion chamber of GG, there should be a source of ignition of GG. The Pyro-Igniter was used for this purpose. After GG is ignited successfully, the TP rotational speed and its discharge pressure increases as a result. In order to ignite CC, the TEA and oxidizer are supplied to the combustion chamber as a source of ignition, and then the Kerosene fuel follows later. PS is extinguished after the successful ignition of CC and GG, and TP goes into its nominal operation mode.

As the engine startup process (figure 3), the turbine starter and gas generator is started and worked at the same time if gas generator is ignited soon enough during turbine starter (PS) ignition for fast satrtup.



- Bi-propellant Gas-Generator(GG) Cycle
- Turbopump(TP) Fed Type
- Pyrotechnic Starter(PS) for Turbine
- Single Axis TP
- Triethylaluminum(TEAL) for Combustion Chamber(CC) Ignition
- Main Oxidizer Valve(MOV)
- Main Fuel Valve(MFV)
- GG Oxidizer Valve(GOV)
- GG Fuel Valve(GFV)
- Liquid oxygen and Kerosene

Figure 1: Typical Scheme of GG Cycle Engine

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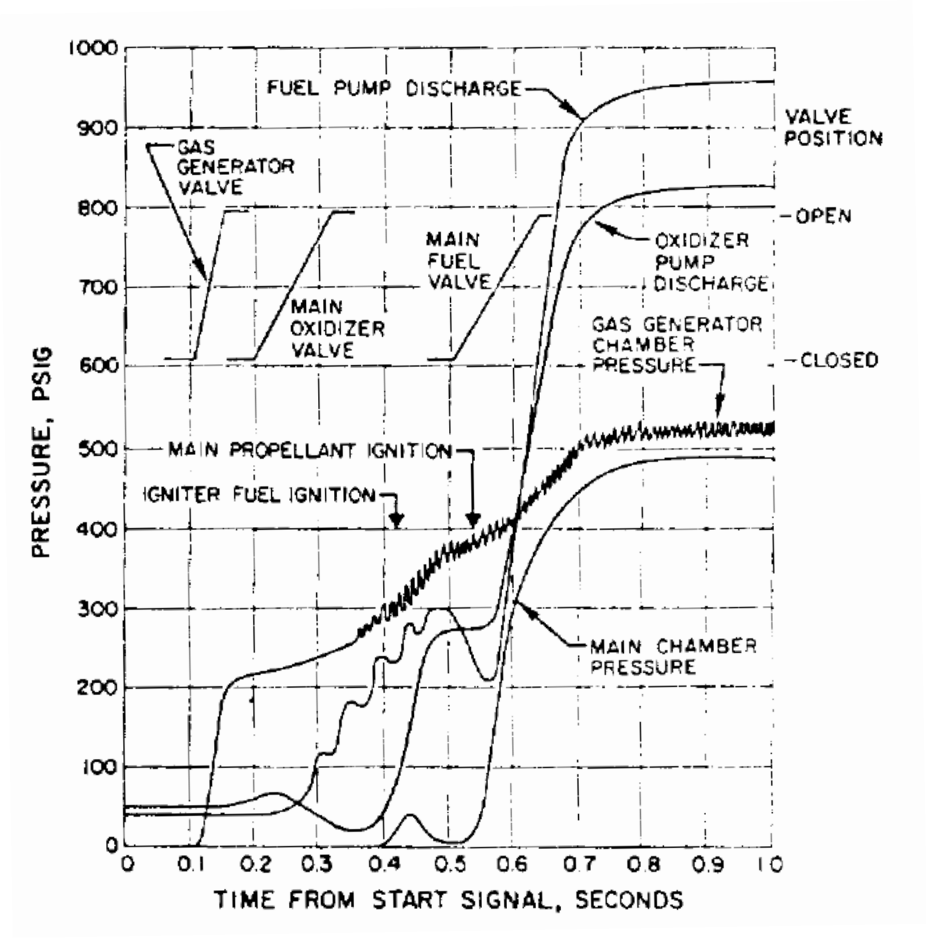

Figure 2: Startup Trasient of Open-cycle Engine [2]

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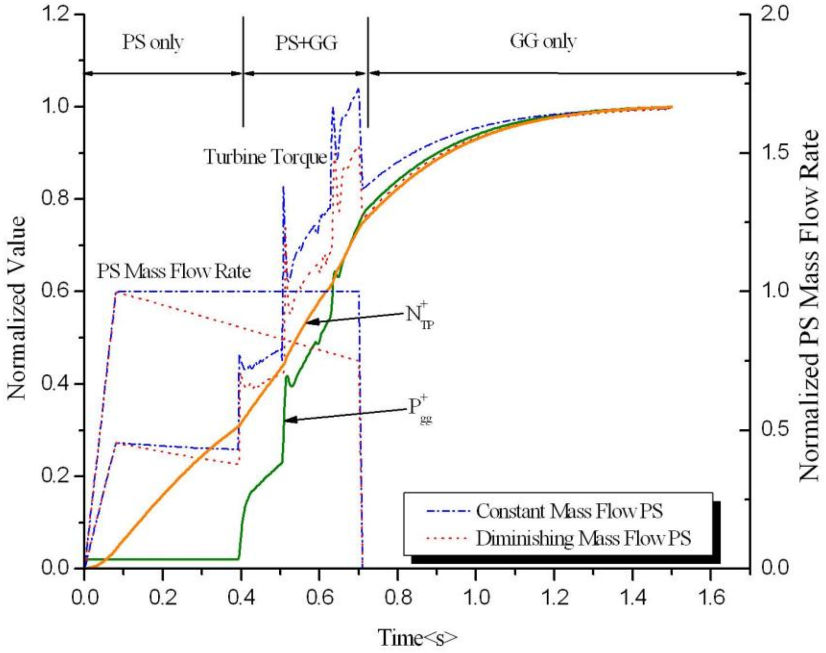
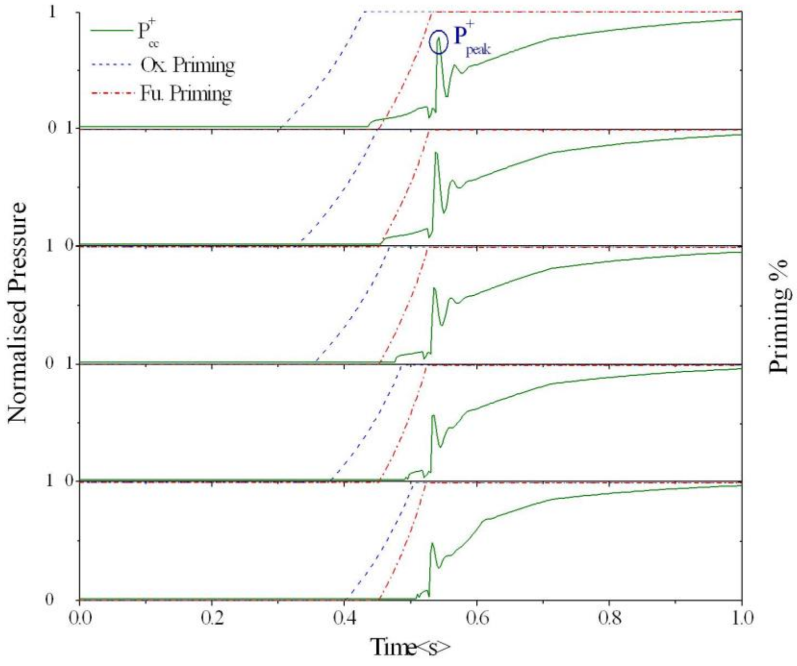


(a) Effect of Turbine Driving Power on the Engine Startup Transient



(b) Effect of Oxidizer Lead Time on the Ignition Pressure Peak of CC

Figure 3: Stability of Engine Startup Transient [3]

At PS+GG region in figure 3 (a), the high power exceeds turbopump rpm at nominal value and it causes increase of propellant (fuel) going into combustion chamber. This results in high pressure peak during combustion chamber ignition [2]. The high pressure peak causes harm in stability and safety of rocket engine and even the structure of rocket itself although faster engine startup is important and helps the efficiency of rocket system. As the oxidizer going into combustion chamber prior to charging fuel in CC, too much oxidizer that remains in combustion chamber causes also higher pressure peak as figure 3 (b) [3]. The optimization of engine startup is required to ignite open and close time fuel and oxidizer valves for stable and fast engine startup.

3. Objective Function and Its Evaluation

3.1 Design Variables

In LRE startup process, various representative parameters are required to decide engine startup characteristics as follows.

- Turbine stater (PS) power profile
- Turbopump rpm inertia (I_{zz}): the inertia of the rotational turbopump
- Ignition time for combustion chamber
- Ignition time for gas generator
- Head and efficiency of turbopump

Among these parameters, engine components (combustion chamber, gas generator, and turbopump etc) have already developed and met the previous requirement, then two timing of combustion chamber and gas generator ignition are main parameters to control and optimize engine system startup. Appropriate selection of the open time of the shut-off valve effects significantly on the total feature of startup of engine. The ignition time of GG and CC, pressure and temperature peak at the onset moment of ignition also dependent on the sequential order and timing of oxidizer and fuel supply into the chamber [5]. Moreover, the flow rate through the pump differs according to the state of CC shut-off valve. The main characteristic and safety of engine startup are determined by the settlement of open time of shut-off valves.

Ignition time for combustion chamber depends on MOV and MFV open time and ignition time for gas generator on GOV and GFV open time. Design variable for these valve open times (t_v^{open}) can control and optimize engine startup. However, the oxidizer and fuel supply time is relatively short to fill its manifold and cavity into combustion chamber after valve open for gas generator so that most LRE open GOV and GFV simultaneously. Finally, total 3 parameters, t_{gov}, t_{mov}, and t_{mfv} are chosen to be design variables.

3.2 Objective Function

Engine startup time, t_{ss} is chosen for fast engine startup. t_{ss} can be defined as steady state combustion pressure and calculated time to reach the steady state and converge to be 3 bar/sec (dP_{cc}/dt).

$$\left| d\,\mathrm{P}_{cc}/dt \right|_{t \geq t_{ss}} \leq 3\,bar\,/\,\mathrm{sec} \tag{1}$$

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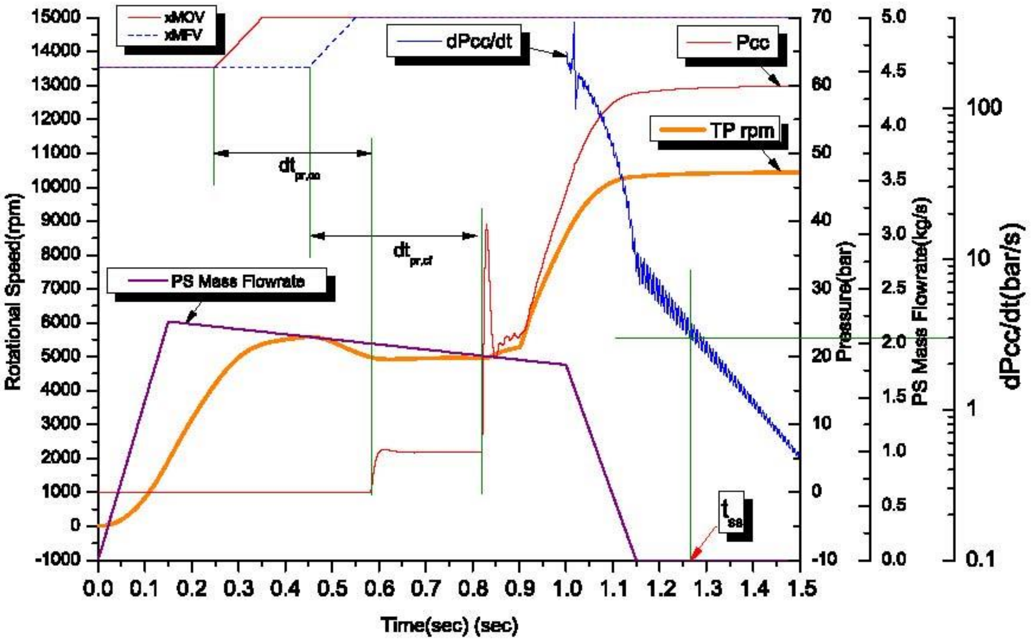

Figure 4: Definition of t_{ss}

3.3 Constraints

For stable engine startup, sequence parameters demands to be constraint in physical limit of engine startup. These parameter constraints are related to emergency engine stop algorism [6]. Maximum combustion chamber pressure peak, P_{cc}^{max} is affinitive relation to stable engine startup and maximum turbopump rotational speed, N_{tp}^{max} is limited for longer PS and GG overlapped time. The mixing process ratio of oxidizer and fuel in gas generator exceeds design value to be limited maximum gas generator temperature, T_{gg}^{max}. These 3 parameter constraints are defined as below (table 1).

Table 1: Description of Constraints

Constraints	Limit value	Physical meaning
$P_{cc}(t)\|t_v^{open}$	< 1.05 x P_{cc}^{nom}	No exceed pressure peak of hard start in ignition of CC
$N_{tp}(t)\|t_v^{open}$	< 1.05 x N_{tp}^{nom}	No exceed steady state design value of TP rpm
$T_{gg}(t)\|t_v^{open}$	< 1.05 x T_{gg}^{nom}	No exceed combustion gas temperature from GG

$$
\begin{aligned}
&\text{minimize} && t_{ss} \\
&\text{by varying} && \mathbf{t}_v^{open} = [t_{gov} \;\; t_{mov} \;\; t_{mfv}]^T \in \mathbf{R}^3 \\
&\text{subject to} && t_{min} \le \mathbf{t}_v^{open} \le t_{max}, \quad v = gov,\ mov,\ mfv \\
& && P_{cc} < P_{cc}^* \\
& && N_{tp} < N_{tp}^* \\
& && T_{gg} < T_{gg}^*
\end{aligned}
$$

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4. Response Surface Method

Using previous parameters and constraints, engine startup sequence is numerically calculated. To optimize engine startup sequence, the Genetic Algorithm (GA) using gradient-free method is appropriated for this purpose instead of using gradient-based method. The engine startup model uses Eulaer method to calculate integral with dt = 0.001 sec and takes 1.5 sec to reach steady state. Total calculation takes 1 min with one design variable. Therefore, the engine startup model is optimized with interpolation using Response surface method because of longer time to optimize using GA with calculating 3 variables. In this model, correlation model uses exponential as below [7],

$$R_j(\theta, d_j) = e^{(-\theta_j |d_j|} \tag{2}$$

In this case, $\theta_j = 0.2$ is applied considering stiffness of objective function. It is chosen to select the sampling point using Latin Hypercube Sampling method [4]. For 3 design variables, t_{gov}, t_{mov}, and t_{mfv}, each 10 sampling points are calculated 1000 times.

1. Each design variables (t_{gov}, t_{mov}, t_{mfv}), the engine startup model performs m(=10) division at the range of [*lub*, *upb*] = [0.1, 0.8]
2. Each division set one sampling point to be uniform distribution using *rand*() function
3. Each design variable, input vector is created with previous sampling point

Using this procedure, figure 5 shows sampling points.

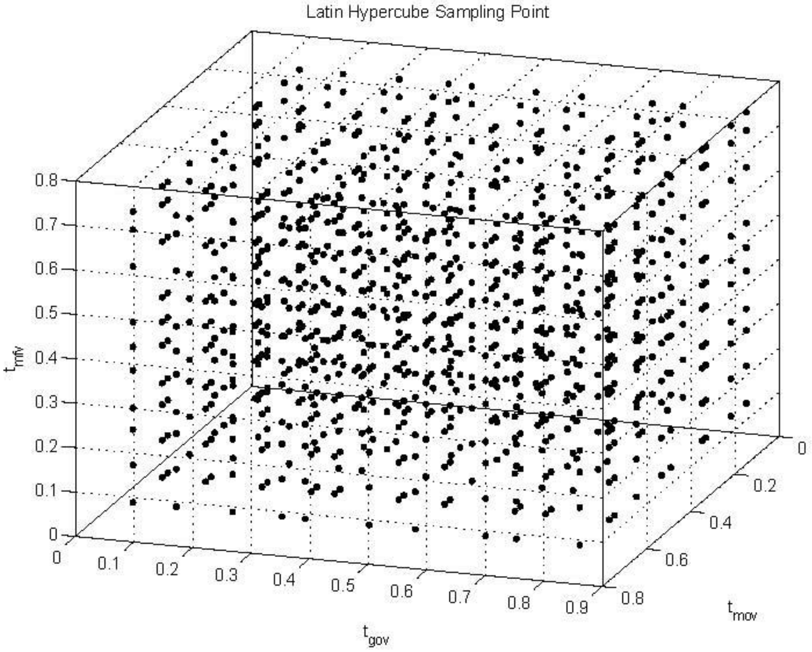

Figure 5: Sampling Points obtained by Latin Hypercube Method

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Table 2: GA processing

Generation	f-count	Best f(x)	Max constraint	Stall Generations
1	5300	1.1391	0	0
2	105000	1.13901	0	0
3	15700	1.13901	0	1
4	20900	1.13901	0	0
5	26100	1.13901	0	0

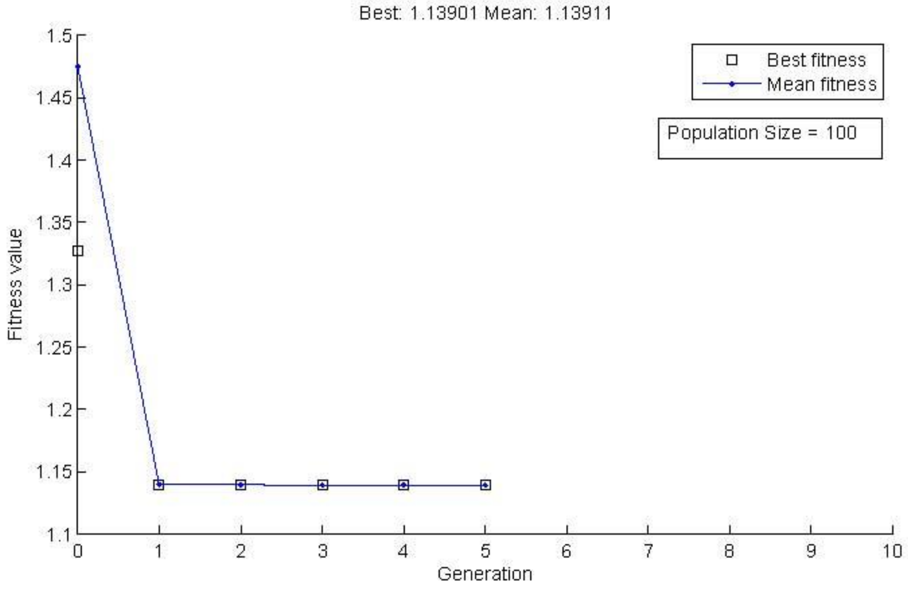


Figure 6: Genetic Algorithm Convergence

5. Optimization and Results

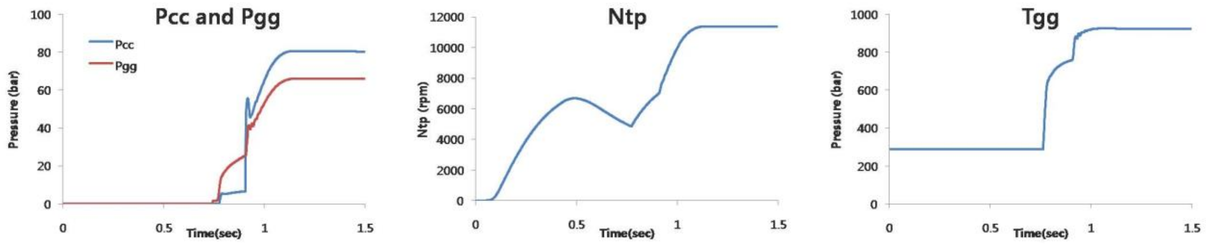
The optimization from approximation using engine startup analysis and response surface method results in table 2. Total population is to be 100 and convergence condition to be *function tolerance* < 1.0e-16 and *Nonlinear constraint tolerance* < 1.0e-16. The final optimization converges in 5th generation using Genetic Algorithm (figure 6). The result shows that $t_{ss,min}$ is 1.139 sec and the design variables are

$$t_{gov} = 0.70$$

$$t_{mov} = 0.541$$

$$t_{mfv} = 0.439$$

With these variables, the optimized engine startup results in figure 7. The pressure peak for ignition of combustion chamber and gas generator shows lower than design values and the rotational speed for turbopump stays stable without causing overshoot. The temperature for combustion gas from gas generator also develops under steady state value.

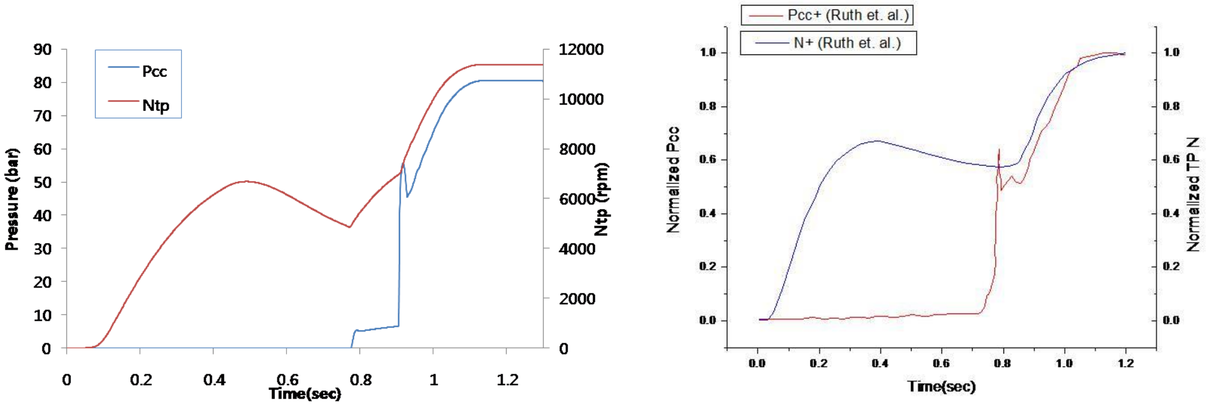


(a) Pcc and Pgg (b) Ntp (c) Tgg

Figure 7: Calculated Optimized Cycloram of Engine Startup Transient

5. Discussion

In figure 8, the calculated results from the pressure of combustion chamber and the rotational speed for turbopump are compared with results from Titan IV rocket engine. As the result shows, the optimization from valve operation with time and order in engine startup results the similar to the actual engine startup process. Especially, the ignition time of combustion chamber and the slope trend of pressure and rotational speed have the similarity between the results. Using engine startup cyclogram, the optimized calculation can be driven from a numerical analysis without actual conducting many attempts of engine startup process in development of liquid-propellant rocket engine.



(a) Calculated results (b) LR87-AJ-11 Engine

Figure 8: Existing Startup Transient of Engine (Titan IV 1st stage engine)

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