Optimal Design and Test of Fuel-Rich Gas Generator

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Keywords: Liquid Rocket, Gas Generator, Optimal Design

Abstract

The optimal design and combustion analysis of the gas generator for Liquid Rocket Engine (LRE) were performed. A fuel-rich gas generator in open cycle turbopump system was designed for 10ton$_f$ in thrust with RP-1/Lox propellant. The optimal design was done for maximizing specific impulse of main combustion chamber with constraints of combustion temperature and power matching required by turbopump system. Design variables were selected as total mass flow rate to gas generator, O/F ratio in gas generator, turbine injection angle, partial admission ratio, and turbine rotational speed. Results of optimal design show the dimension of length, diameter, and contraction ratio of gas generator. Also, the combustion test was conducted to evaluate the performance of injector and combustion chamber. And the effect of the turbulence ring was investigated on the mixing enhancement in the chamber.

Style Guidelines

Feeding rocket propellants to the thrust chamber uses gas-pressurized feed system or turbopump feed system. Gas-pressurized system has an advantage of production and operation, but has the weight penalty to design the propellant tanks. In the meantime, for high thrust, long duration engines, the use of turbopump feed system usually decreases system weight and raises performance. Turbopump feed system requires relatively low pump inlet pressure, while the major portion of the pressure required at the thrust chamber inlet is supplied by pumps. Therefore, the application of turbopump system is essentially needed to improve the performance of larger LRE system [1, 2, 3].

Generally, delivered temperature out of gas generator has been held about 1000K by fuel-rich operation, which covers the combustion chamber of gas generator and turbine blades [2]. Due to fuel-rich operation, vaporization and temperature uniformity in gas generator become major issue of design and analysis.

Dennis, et al. [4] measured temperature uniformity and hot streak at downstream of gas generator varying length for NASA X-34 launch vehicle. Also the gas generator is the model which is used in soot formation as well as some ignition technique and combustion stability required to operation.

Mah [5] tested gas generator with turbulence ring to determine its operational length limits. The test was performed to verify the code that can calculate the product of fuel-rich combustion as well as measuring the drop-off point of c-star using O/F ratio, and chamber pressure of gas generator.

Since the chamber configuration with chamber length, chamber diameter and mass flow rate required for pump power output are of crucial importance in the design of GG, these parameters should be assessed and evaluated with proper method of analysis. In addition, radial temperature, and the possibility of hot spot formation in the flow should checked.

In this study, optimal design and combustion analysis of a fuel-rich gas generator in open cycle turbopump system was performed. Objective function is selected to maximize Isp of main combustor for a designed dimension of gas generator, mass flow rate, and O/F ratio. And, length of gas generator, radial temperature distribution, and mixing enhancement were investigated by combustion test when turbulence ring was installed.

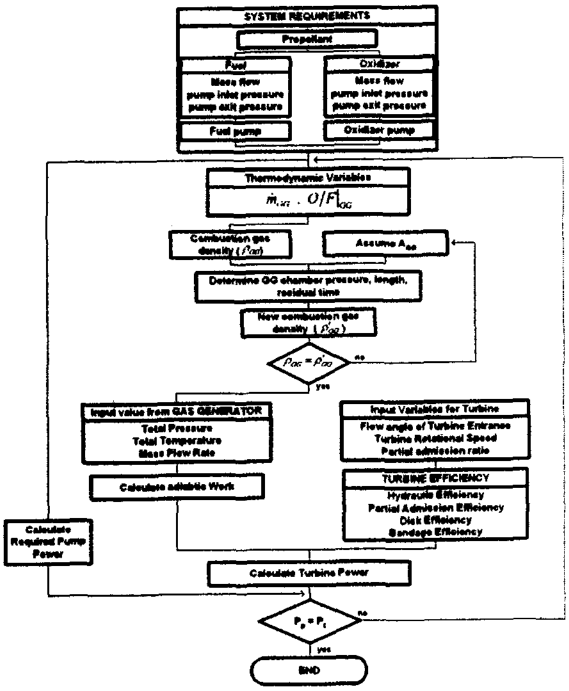

Fig. 1. Design Procedure of gas generator

Code Description

Figure 1 shows the schematic of flow chart for gas generator (GG) design. The gas generator is a component of turbopump system and is basically the same as a combustor without having divergent section of nozzle. In the design code, several variables are selected as performance parameters, such as chamber pressure, temperature, O/F ratio.

Equation (1) shows the chamber pressure that can be determined by the mass conservation through inlet and nozzle. And, we introduce the combustion efficiency (η_{GG}) to account for the deficiency associated with fuel-rich combustion in the gas generator. It should be also noted that combustion efficiency η_{GG} was unity in the design.

$$p_{GG} = \eta_{GG} \cdot \frac{\dot{m}_{GG}}{A_t} \sqrt{\frac{R \cdot T_{GG}}{\gamma}} \cdot \left(\frac{\gamma+1}{2}\right)^{\frac{\gamma+1}{2(\gamma-1)}} \qquad (1)$$

Chamber length can be determined by the relation of the mixing length of initial droplet size and injection velocity [7]. Also, the isentropic expansion flow was assumed from the gas generator to the inlet of turbine [8]. The flame temperature should be kept in the range of 800-1000K in order to avoid the blade from melting in fuel-rich combustion [2]. It should be, also, noted that the turbine is a of 100% impulse turbine

Formulation of Optimization

The optimal design of gas generator should be based on the overall performance of engine system and the design variables are pump inlet and exit pressure, propellant mass flow rate, O/F ratio and pump efficiency.

To this end, the object function is selected as the max specific impulse of engine system. Details of selected variables of optimization are shown below with (i)~(v).

Objective Function

$$f = \frac{F_c(x_i)}{g_e \cdot \dot{m}_c(x_i)} \qquad (2)$$

Constraints

$$c_1 = T_{GG}(x_i) \qquad (3)$$

$$c_2 = P_p(x_i) - P_t(x_i) \qquad (4)$$

Design Variables

i) Gas Generator O/F Ratio $0.3 \le x_1 \le 0.5$

ii) Gas Generator Mass Flow Rate $0 \le x_2 \le 5\%$ of total flow

iii) Turbine Nozzle Exit Angle $10° \le x_3 \le 20°$

iv) Partial Admission Ratio $0.25 \le x_4 \le 0.7$

v) Rotational Speed of Turbine Rotor $350 \le x_5 \le 450$ m/s

The mass flow rate into GG depends on the power requirement at turbine. So, the increase of turbine output requires more mass flow rate into GG. However it reduces the mass flow to main combustion chamber as well. Therefore, the mass flow rate to GG should be determined in the compromise between the turbine power and main chamber requirement. Generally, O/F ratio lies in the range of 0.3~0.5 although there is a variation in the ratio for the different O/F combination.

Equation (3) shows the constraint of the optimization and represents the total temperature. Equation (4) shows the power balance between turbine power and pump requirement. And no mechanical loss is accounted.

The optimization was done with commercially available DOT V4.01 SQP, and the objective function is simulated by 2[nd] order polynomial function with the constraint of 1[st] order function approximation. SQP seeks the optimal condition by the successive iteration of gradient linearization with the objective function and the constraints.

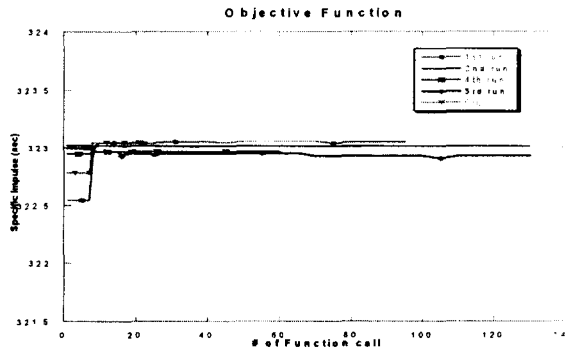

Fig 2. History of Objective Function in the Optimal Design

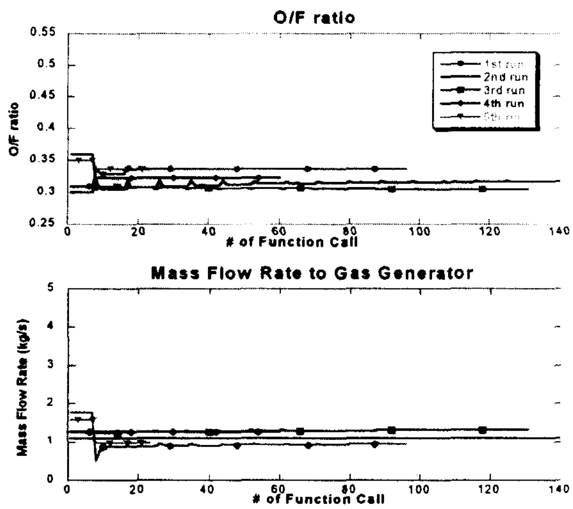

Fig 3. History of Design Variables in the Optimal Design

Optimal Design of Gas Generator

Optimal design the gas generator for 10ton$_f$ LRE was done to maximize Isp of main chamber. In the design calculation, main chamber pressure was assumed 2.0MPa and expansion ratio of 50. The pressure requirements of fuel and oxidizer at pump exit are 6.25MPa and 4.25MPa respectively [1].

Table. 2 Design Results of Gas Generator of 10tonf LRE

		Optimal	Not Optimal
Turbine Power		160 kW	160 kW
Combustion Chamber	O/F Ratio	2.21	2.27
	Mass Flow Rate	32.1 kg/s	31.9 kg/s
	Isp	323.05 sec	322.9 sec
	Thrust	10.4ton$_f$	10.08ton$_f$
Gas Generator	O/F Ratio	0.337	0.31
	Total Pressure	1.93 MPa	1.71 MPa
	Total Temperature	920 K	880 K
	Mass Flow Rate	0.90 kg/s	1.25 kg/s
	Length/Diameter	29.3/5.2 cm	30.2/5.7 cm

Consequently, the total mass flow of fuel and oxidizer are 22.4kg/s, and 10.7kg/s respectively corresponding O/F ratio of 2.09. It should be noted that the same specifications of pump efficiency and angular velocity of turbine blade as that in [4,9] are used and a static pressure at turbine exit is fixed at 0.5MPa. By the analysis of requirements and operating conditions, pump power was calculated as 160KW

In the optimizing process, the randomly selected initial conditions are tried to avoid the local minimum. Fig 3 and 4 show the convergence trajectories of objective function and design variables, such as Isp, O/F ratio and mass flow of GG with the various initial conditions.

The optimization results show the converging Isp of 329.9-331.1sec after five iterations. And the corresponding mass flow is in the range of 0.9-1.3kg/sec equivalent to O/F ratio of 0.305-0.337. The results indicate design calculation did not converge to the same final value rather converging to a region. This may be due to the optimization method adopted in this study; gradient based technique. Table 2 shows the comparison of the design result with that in [10].

Thrust and turbine output meet the every requirements imposed in the design stage and the temperature in main chamber shows 920K that is 40K higher than that of non-optimized one [10]. Also the reduction of 28% in mass flow to GG is achieved without affecting the turbine power output. Thus, the optimization could improve the performance of GG by increasing thrust and decreasing mass flow.

It is, therefore, summarized that the optimization results of GG design correspond to the condition shows the combustion temperature of 920K, and 0.9kg/sec of inflow rate to GG. The physical dimension has 29.3cm in length and 5.2cm in diameter shown in Fig 4. However, it should be noted that chamber length can be further reduced if a turbulence ring is installed since turbulence ring can provide a better mixing in an even short distance

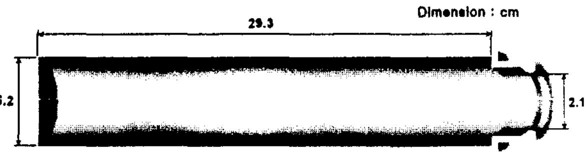

Fig. 4 Design Configuration of Gas Generator

Injector Design

Total mass flow rate to gas generator was calculated to be 0.9kg/s, which is approximately 2.7% of mass flow rate to main combustion chamber. Oxidizer flow occupies 0.23kg/s and fuel flow rate is 0.67kg/sec resulting in O/F ratio of 0.34 in gas generator.

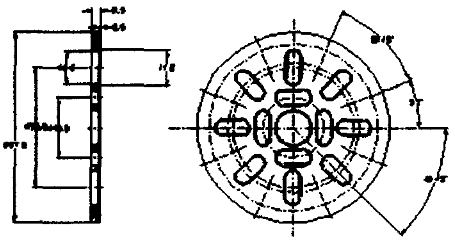
Figure 5. Configuration of Injector Plate

Injector type is of crucial importance in determining spray and the consequent combustion characteristics. A typical F-O-F impinging type was adopted for the baseline configuration of injector. Figure 5 shows the arrangement of injector elements on the plate. As seen in the figure, one element locates at the center surrounded by four elements in the first radial row. And the second row has eight elements locating perpendicular to the first row configuration. This arrangement has proven in many studies to have a good O/F ratio distribution over the entire injector plate and to be very effective in preventing or avoiding hot streaks and the detrimental damages on the plate. And C_D, discharge coefficient, is 0.75 for fuel and 0.78 for oxidizer [1].

Figure 6 shows the schematic of experimental set up for injector water tests. The mechanical patternator is the device for collecting spray droplets and located at 16~19cm from injector plate. The patternator used in the study has a total 300 cells (20x15). Each cell is rectangle of 8x8cm and the total collecting time is possible up to 60 seconds with this patternator.

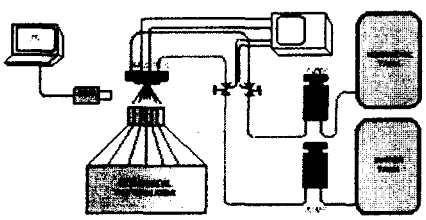
Figure 6. Experimental Set up for Cold Tests for Injector Element

A series of cold tests was done with various configurations of injection in order to finalize injector

$$MR = \frac{n_f}{n_{ox}} \frac{\rho_f}{\rho_{ox}} \left(\frac{d_f}{d_{ox}} \right)^2 (O/F)^2$$

element for gas generator. Test was designed to have the same momentum ratio between kerosene and water as in kerosene and liquid oxygen. Momentum ratio is defined by the equation below as;

Here n is a number of orifices and d is an orifice diameter and ρ represents a density of fluid. The baseline design O/F ratio was selected as 0.33 and a few variations of O/F ratio was selected and tested to find the performance characteristics at off design points as well.

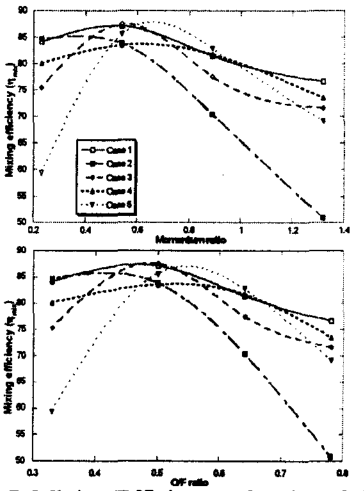

Figure 7. Mixing Efficiency of various Injector Elements

The extent of mixing was determined by measuring the mixture fraction of each component in each test tube. The ideal spray is one in which the local mixture is constant and equal to the input mixture ratio. By comparing the departure of the local mixture ratio of an actual spray with that of the ideal spray, the mixing efficiency can be defined to describe the degree of mixing in the impinging injectors. A mixing efficiency (η_{mix}) can measure the degree of mixing between fuel and oxidizer in collecting cell and can be used to determine the injector performance.

Figure 7 shows test results of mixing efficiency on various injectors. Also, figure 8 illustrates CCD photos for five cases of injector element. Each injector has a different injection angle from 30 degree to 45 and 60 degree

$$\eta_{mix} = 1 - \sum_{i=0}^{n} \frac{MF_i(R - r_i)}{R} - \sum_{i=0}^{m} \frac{\overline{MF_i}(R - \bar{r}_i)}{R - 1}$$

Combustion Efficiency

In the combustion analysis, the injector is chosen with impinging injection of 22.5°, F-O-F triplet impinging type. The turbulence ring is assumed at 5cm and 13cm from the injector plane, and the sonic nozzle is also attached to GG. The important things in the combustion analysis are the radial temperature distribution, characteristic velocity, and characteristic length. In addition, the possibility of the performance enhancement and the reduction of chamber length was checked in the experiments.

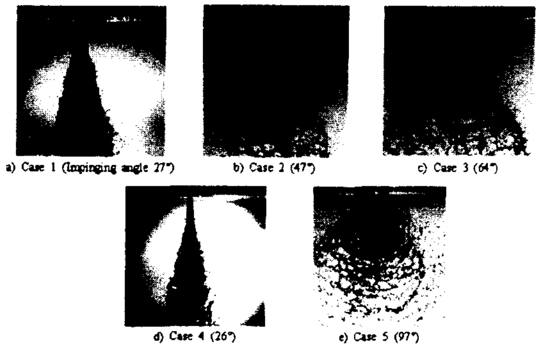

Fig. 8. CCD Photos for various test cases with different impinging angle

It is obvious from the results that turbulence generator can enhance the homogeneous distribution of temperature by avoiding hot spots in the radial flow field. Thus, a mixing enhancement and the reduction of chamber length are expected to occur in the GG chamber.

Summary

Configuration of fuel-rich gas generator for 10 ton$_f$ LRE was designed by optimal design code. The isentropic flow is assumed across the combustor. It is concluded that optimization results of GG design correspond to the condition of O/F ratio, and mass flow rate of GG. And, length of gas generator, radial temperature distribution, and mixing enhancement was investigated by combustion analysis when turbulence ring was installed.

Acknowledgement

This work was supported by financial grant of Ministry of Science and Technology with grant number M10138000012-02D0500-00810.

Nomenclature

O/F	Oxidizer to Fuel Ratio
Isp	Specific Impulse
T	Temperature
p	Pressure
P	Power
ρ	Density
u	Velocity
$\dot{m}$	Mass flow rate
ς	Drag
R	Gas constant
Cp	Specific Heat at Constant Pressure
γ	Specific heat ratio

η Efficiency
k Thermal Conductivity
A Area
L Length
r Radius
ε_c Contraction ratio

Subscript
GG Gas generator
t Turbine
p Pump
c Combustion chamber
i Inlet
e Exit
d Droplet
ℓ Liqid
o Stagnation property
f Fuel

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