On the effect of filters for the design of solid propellant gas generators

Moongeun Hong† and Soo Yong Lee*

고체추진제 가스발생기 설계를 위한 필터 효과에 대한 고찰

홍문근 · 이수용

Key Words : Solid propellant gas generator(고체추진제 가스발생기), Turbopump starter(터보펌프 시동기), Filters(필터), Pressure loss coefficient(압력손실계수), Burning rate(연소속도)

Abstract

Solid propellant gas generators (SPGG) play a role as a turbopump starter in liquid propellant propulsion systems by supplying pressurized gas to power turbines for engine start. For such a purpose, the propellants should burn with a relative low flame temperature and the combustion gas should not contain corrosive constituents such as chlorine compounds. In accordance with these requirements, stabilized AN-based propellants have been usually used as the most appropriate oxidizer for propellant compositions. However, the burning area of the propellant intends to increase to satisfy the required mass flux because of its low burning rate. Consequently the burning area incensement brings on the SPGG size augmentation. A flow restriction such as filters is applied to decrease the SPGG size by rising up the combustion pressure resulting in increasing the burning rate. The feasibility of the size reduction of SPGG by the employment of filters have been studied. The preliminary results of this study show that the considerable reduction of SPGG size would be achievable just by installing a filter with relatively high pressure loss coefficient.

SYMBOLS

A_b : Burning area of the propellant grain (m^2)
A_t : Nozzle throat area (m^2)
a : Coefficient of pressure
c^* : Characteristic velocity (m/s)
n : Burning rate exponent
c_p : Specific heat at constant pressure (kJ/kg-K)
h : Enthalpy (kJ/kg)
K : Presure loss coeffient
k : Specific heat ratio
$\dot{m}$: Mass flow rate (kg/s)
M : Mach number

† Member, Launch Vehicle Future R&D Division, Korea Aerospace Research Institute
E-mail : conquet@kari.re.kr
TEL: (042)860-2585 FAX: (042)860-2214

* Korea Aerospace Research Institute

P_a : Available power delivered by SPGG (W)
p : Total pressure (Pa)
R : Gas constant (kJ/kg-K)
r : Propellant burning rate (mm/s)
T : Total temperature (K)
t_b : Propellant burning time (s)
u : Flow velocity (m/s)
ρ_p : Propellant density (kg/m^3)
ρ_g : Combustion gas density (kg/m^3)

Subscript
0 : SPGG Chamber conditions
0_1 : First nozzle throat inlet conditions
1: Turbine inlet conditions
2 : Turbine outlet conditions

1 Introduction

Pump-fed system or pressurized gas-fed system is used to pressurize propellants of launch vehicles depending on the design of propellant feeding types for liquid propellant rocket engine. Pump-fed system has been usually adopted for its high overall performance relative to the other propellant feeding system [1]. As one of the gas devices in the pump-fed system, a solid propellant gas generator (SPGG) has been widely employed with its product gas to drive turbine [3] for engine start.

In other words, SPGG plays a role as a turbopump starter in liquid propellant propulsion systems by supplying pressurized gas to power turbines for engine start. For such a purpose, the propellants should burn with a low flame temperature and combustion gases should not contain corrosive constituents such as chlorine compounds. In accordance with these requirements, stabilized AN-based propellants have been usually used as the most appropriate oxidizer for propellant compositions [2]. However, the burning area of the propellant intends to increase to satisfy the required mass flux because of its low burning rate. Consequently the burning area incensement brings on the SPGG size augmentation.

In the development of Korea Space Launch Vehicle (KSLV), SPGG is at the stage of development of AN-based solid propellant composition suitable to the engine starting system. A flow restriction such as filters is intended to be applied to decrease the SPGG size by rising up the combustion pressure resulting in increasing the burning rate. The feasibility of the size reduction of SPGG by the employment of filters have been studied.

Some simple equations, which ensure the relation between the pressure coefficient of a flow restriction and the solid propellant burning area, are introduced in section 2. In section 3, we have evaluated the feasibility of SPGG size diminution by employing filters at the inlet of a first nozzle throat.

2 A_b & K relation

Fig. 1 shows the schematic layout of SPGG-tubines systems. The combustion gas produced by a SPGG is used to drive turbines for engine start.

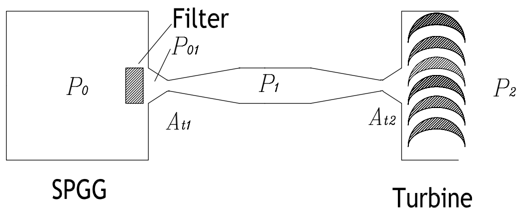


Figure 1: Schematic layout of SPGG/tubines systems.

The available power delivered by the SPGG can be expressed by mass flux $\dot{m}$, product gas properties at inlet of turbine (gas constant R, specific heat ratio k and total temperature T_1) and pressure ratio at inlet and outlet of turbine p_2/p_1 on the assumption of a perfect gas with constant specific heat c_p undergoing an isentropic process:

$$\begin{aligned} P_a &= \dot{m}\Delta h = \dot{m}c_p(T_1 - T_2) \\ &= \dot{m}T_1\left[1 - (p_2/p_1)^{(k-1)/k}\right] \end{aligned} \quad (1)$$

In eq. (1), mass flow rate $\dot{m}$ could be calculated from the equality of mass flow rate at two nozzle throats A_{t_1} and A_{t_2} for the isentropic flow in gas dynamics:

$$\dot{m} = \frac{p_{0_1}A_{t_1}}{\sqrt{RT_{0_1}}}f(k, M_{t_1}) = \frac{p_1 A_{t_2}}{\sqrt{RT_1}}f(k, M_{t_2}) \quad (2)$$

where, $f(k,M) = M\sqrt{k}\left(1 + \frac{k-1}{k}M^2\right)^{\frac{k+1}{2-2k}}$. Because $M_{t_1} = M_{t_2} = 1$ by chocking at two nozzle throats, p_1 can be expressed as follows:

$$p_1 = p_{0_1}\frac{A_{t_1}}{A_{t_2}}\sqrt{\frac{T_1}{T_0}} \simeq p_{0_1}\frac{A_{t_1}}{A_{t_2}} \quad (3)$$

The pressure p_{0_1} between a filter and a nozzle throat A_{t_1} can be expressed with the pressure loss coeffient K of the filter as follows:

$$p_{0_1} = p_0 - \Delta p = p_0 - K \times \frac{\rho_g u^2}{2} \quad (4)$$

The mass flow rate $\dot{m}$ also can be calculated by the product of solid propellant density ρ_p, burning area A_b and propellant burning rate r as $A_b\rho_p r$ and the propellant burning rate r may be expressed as ap_0^n (a and n are constant). By the mass flux equality at combustion chamber and nozzle throat, the mass flow rate can be expressed with the characteristic velocity of the product gas c^*, which is constant, as follows:

$$\begin{aligned} A_b \rho_p r &= A_b \rho_p a p_0^n \\ &= \frac{p_{0_1} A_{t_1}}{\sqrt{RT_{0_1}}} f(k,1) = \frac{p_{0_1} A_{t_1}}{c^*} \end{aligned} \quad (5)$$

therefore,

$$A_b = C_1 \frac{p_0^n}{p_{0_1}}, \quad C_1 = \frac{A_{t_1}}{\rho_p a c^*}$$

From the eq. (4), the relation between A_b and K could be obtained as follows:

$$A_b \propto \frac{\left(p_{0_1} - K \times \frac{\rho_g u^2}{2}\right)^n}{p_{0_1}} \quad (6)$$

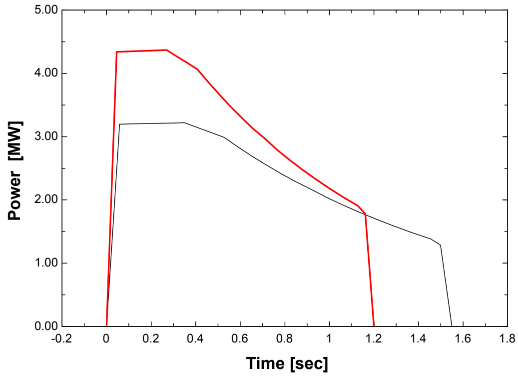
From the eq. (1), (2), and (3), p_1 and p_{0_1} should also stay constant on the condition that P_a should remain constant. In this case (for same P_a requirements), A_b could be reduced with a high value of K (see eq. (6)).

3 Preliminary results

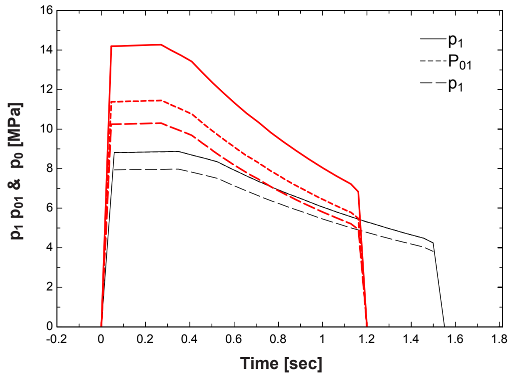
On the base of the idea, which is described in the previous section (see eq. (6)), preliminary analysis have been performed in order to verify the feasibility of SPGG size reduction by employing a flow restriction that could make the propellant burning area A_b decrease.

For the quantitative analysis, we utilize the practical values for the SPGG characteristics. For example, as a value of the burning rate exponent n we use 0.537 which has been measured by the strand burning test of the solid propellant of SPGG. In fig. 2, the effect of a filter is very clearly shown. P_a, pressures, and mass flux increase by the pressure loss of a filter. Moreover, the burning time decreases in supplying undesirable excess energy to the turbines in a very short duration.

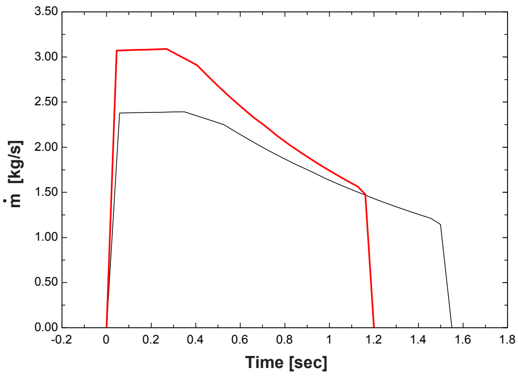
In fig. 3, it is shown that about 10% diminution of the burning area could be achievable just by employing a filter ($K = 3.0$) in satisfying the available power requirement profile. Even though it is indispensable to consider the potential incensement of SPGG case



(a) Power

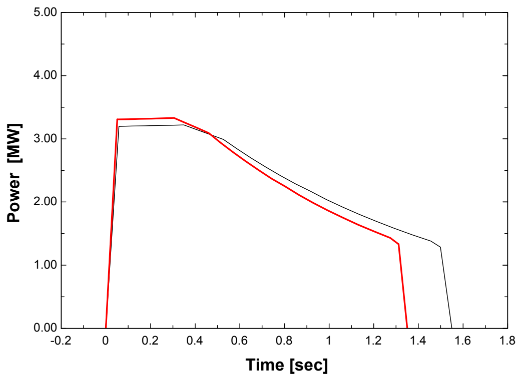


(b) Pressures

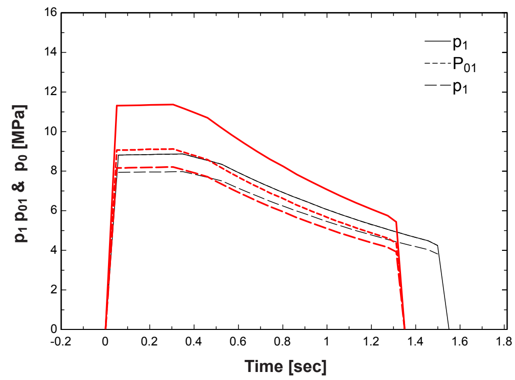


(c) Mass flux

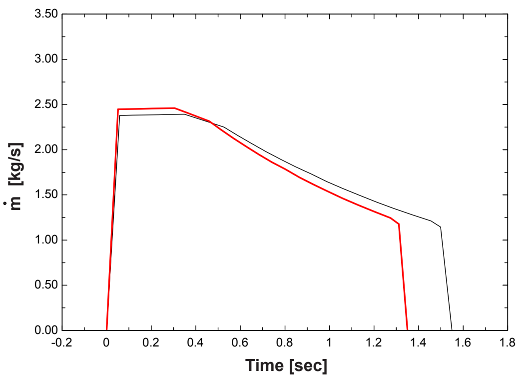
Figure 2: Predicted power, pressures, and mass flux evolution for the same grain geometry with/without a filter (black line: no filter, red line: with filter $K = 3.0$).



(a) Power



(b) Pressures



(c) Mass flux

Figure 3: Predicted power, pressures, and mass flux evolution for the different grain geometry with/without a filter (black line: no filter, red line: with filter $K = 3.0$ & 90% of A_b compared to the case without a filter).

wall thickness owing to the argumentation of the combustion pressure, 10% reduction of the SPGG case would be more favorable in the design of SPGG.

4 Conclusion

Stabilized AN-based propellants have been usually used as the most appropriate oxidizer for propellant compositions. However, the burning area of the propellant intends to increase to satisfy the required mass flux because of its low burning rate. Consequently the burning area incensement brings on the SPGG size augmentation. A flow restriction such as filters is applied to decrease the SPGG size by rising up the combustion pressure resulting in increasing the burning rate. The feasibility of the size reduction of SPGG by the employment of filters have been studied. The preliminary results of this study show that the considerable reduction of SPGG size would be achievable just by installing a filter with a relatively high pressure loss coefficient.

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