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# Experimental correction of combustion gas properties of AN-based composite solid propellants used for turbo-pump starter

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ABSTRACT

Solid propellant gas generators play a role as a turbo-pump starter in liquid propellant propulsion systems by supplying pressurized gas to power turbines for engine start. Among the required combustion gas properties provided by solid propellant gas generators, the combustion gas temperature should not exceed a certain temperature which may damage the turbine blades. For such purposes, phase stabilized ammonium nitrate (AN)-based propellants have been widely used with a low combustion temperature. However, gas generator propellants with ammonium nitrate have historically exhibited incomplete combustion resulting in increased flame temperatures differing significantly from equilibrium values. In consideration of design requirements, an engineering model of solid propellant gas generator was manufactured using the combustion gas properties calculated by a chemical equilibrium code and then hot-fire tests were performed. Procedures for the correction of $T_0$, $k$ and $M_w$ of the combustion gas from the experimental results are introduced and the following effects on the design of the solid propellant gas generator are presented. From the experimental correction of the combustion gas properties, it is found that the amount of the propellant could be reduced while providing the same amount of available power to the turbines and consequently, the size of the gas generator could also be decreased.

## 1. Introduction

A pump-fed system or a pressurized gas-fed system may be used depending on the design of the propellant feeding types for the liquid propellant engine system of launch vehicles. Pump-fed systems have usually been adopted for their high overall performance relative to the other propellant feeding systems [6]. As one of the gas devices in the pump-fed systems, solid propellant gas generators (SPGG) have been widely employed with its product gas to drive turbines for engine start [14]. For the protection of the turbine material from heat impact during the operation of the SPGG, a restriction on combustion temperature is generally imposed on solid propellants. For such purposes, phase stabilized ammonium nitrate (AN)-based propellants have been used with a low combustion temperature [4,7,8,10].

The combustion gas properties such as combustion temperature, specific heat ratio, and molecular weight are the main variables used to predict the amount of power produced by the SPGG. These gas properties are usually obtained by calculation with a chemical equilibrium code [7,8]. However, there could be a non-negligible discrepancy between the calculated values of combustion gas properties and experimentally observed values, because some thermodynamic data for the calculation are not available or the data available are obsolete for some possible products of combustion. Moreover the actual combustion reaction would not provide the chemical equilibrium composition. However, in the evaluation of the performance of solid propellants, the feasible error of the calculated combustion gas properties could be ignored by the term ‘efficiency’ of combustion, nozzle, and turbines.

Actually gas generator propellants oxidized with ammonium nitrate have historically exhibited incomplete combustion resulting in increased flame temperatures differing significantly from equilibrium values [3,13]. Products such as carbon black, polymer fragments, and unoxidized ammonia have been suggested as possibly being present. The unburned carbon and hydrogen-containing compounds permit the oxidation of additional CO to $CO_2$ and $H_2$ to $H_2O$ thereby increasing flame temperature. Sinditskii et al. [13] reported that the measured maximum temperature of burning appeared to be noticeably higher ($\sim 300$ K) than the calculated adiabatic temperature and this increase of flame temperature was explained by the nonequilibrium products formed during combustion.

In order to secure the precise operation of turbo-pumps as specified in the design and to guarantee the optimal design of the SPGG, it is important to accurately predict the amount of power produced by the SPGG. For example, if the actual combustion temperature is higher than the calculated one, the overall size of the SPGG could be reduced by decreasing the amount of the solid pro-

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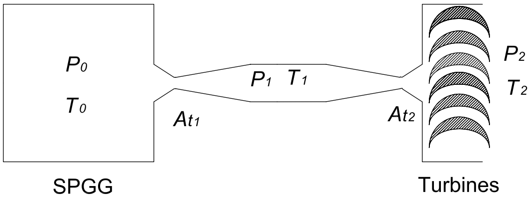
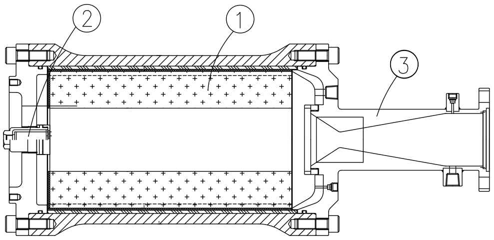


(a) SPGG/turbines systems



(b) SPGG sectional drawing

**Fig. 1.** Schematic layout of SPGG/turbines systems and SPGG sectional drawing (1. propellant, 2. igniter, 3. nozzle).

pellant while providing the same power to the turbines. Since the diminution of the SPGG case size is affected closely by the amount and the dimension of the charged propellants, the envelope and the weight of the SPGG could also be decreased. Therefore, it is significant to use the corrected combustion gas properties for the optimal design of the SPGG. On the contrary, the employment of uncorrected gas properties cannot secure the precise starting operation of the turbo-pump nor the optimized envelope and weight of the SPGG. In spite of the importance of combustion gas properties, there has not been any experimental evaluation of the combustion gas properties of AN-based propellants in the literature available in this area.

In this study, the first engineering model of the SPGG has been produced using the combustion gas properties calculated by a chemical equilibrium code, which could predict the thermodynamic properties of the product gas to meet the power requirement. The chemical equilibrium code played the role of a general guide for the propellant composition which may satisfy the design requirements. Then the engineering model has been put to several combustion tests in order to evaluate its performance. Based on the experimental results, the calculated combustion gas properties were evaluated and were corrected.

The importance of the combustion gas properties for the SPGG design and the theoretically calculated values are introduced in Section 2. In Section 3, procedures for the correction of combustion gas properties from the experimental results are presented and the consequent effects on the design of the SPGG by this correction are discussed.

## 2. Combustion gas properties

Fig. 1 shows the schematic layout of an SPGG/turbine system and the SPGG sectional drawing. The combustion gas produced by the SPGG is used to drive turbines for engine start [5]. The propellant of the SPGG is ignited by an igniter containing a pyrotechnic charge which is activated by an initiator. Once the propellant grain starts to burn, the pressure inside the SPGG casing rises in a controlled manner and then there is a mass flow output from the SPGG to the turbines through a nozzle. Usually the combustion gas should not contain corrosive constituents and the amount of solid particles should be as low as possible. Moreover the combustion temperature should not exceed a certain level, which may damage turbine material.

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

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

Here $\Delta h$ signifies the available enthalpy drop per unit mass flow. As seen in Eq. (1), $T_1$, $k$, $p_1$, $p_2$, $\dot{m}$, and $M_w$ (molecular weight) are design parameters to determine the amount of power for the SPGG to supply to the turbines. Among these design parameters, those related to the SPGG combustion gas are $T_1$, $k$, $p_1$, $\dot{m}$, and $M_w$.

The mass flow rate $\dot{m}$ can be calculated by the product of solid propellant density $\rho_p$, burning area $A_b$, and propellant burning rate $r$ [mm/s] as $A_b\rho_p r$ and the propellant burning rate $r$ may be expressed as $ap_0^n$ where $a$ and $n$ are 0.832 and 0.515 respectively and the unit of $p_0$ is MPa. By the mass flux equality at the combustion chamber and nozzle throat ($A_b\rho_p r = A_{t1}\rho_{t1}u_{t1} = \frac{p_0 A_{t1}}{c^*}$), the mass flow rate can be expressed with the characteristic velocity of the product gas $c^*$ as follows:

$$\dot{m} = \left[A_b\rho_p a \times \left(\frac{A_{t1}}{c^*}\right)^n\right]^{1/(1-n)} \tag{2}$$

where,

$$c^* = \frac{\sqrt{kRT_0}}{k\sqrt{[2/(k+1)]^{(k+1)/(k-1)}}} \tag{3}$$

Concerning the total temperature at the turbine inlet $T_1$, it could be obtained by convective heat transfer relation through a connection component as follows:

$$T_1 = T_0 - \frac{Q}{hA} \tag{4}$$

Here, $h$, $Q$, and $A$ are the convective heat transfer coefficient, the heat flux occurring between the SPGG and turbine assembly, and the heat transfer area respectively. The experimentally measured $T_1$ was lower than $T_0$ by about 100 K and then it could be assumed that $T_1 \approx 0.93 \times T_0$ by the heat transfer at the present feeding system between the SPGG and turbine assembly. Finally the total pressure at the turbine inlet $p_1$ could be calculated from the equality of mass flow rate at the two nozzle throats $A_{t1}$ and $A_{t2}$ for the isentropic flow gas dynamics:

$$\frac{p_0 A_{t1}}{\sqrt{RT_0}} f(k, M_1) = \frac{p_1 A_{t2}}{\sqrt{RT_1}} f(k, M_2)$$

where $f(k, M) = M\sqrt{k}(1+\frac{k-1}{k}M^2)^{(k+1)/(2-2k)}$. Because $M_1 = M_2 = 1$ by choking at the two nozzle throats, $p_1$ can be expressed as follows:

$$p_1 = p_0\frac{A_{t1}}{A_{t2}}\sqrt{\frac{T_1}{T_0}} = \left(\frac{A_b\rho_p a c^*}{A_{t1}}\right)^{1/(1-n)} \times \frac{A_{t1}}{A_{t2}}\sqrt{\frac{T_1}{T_0}} \tag{5}$$

From Eqs. (1), (2), (4), and (5), it is obvious that $T_0$, $k$, and $M_w$ are the main parameters to design an SPGG, especially to define the available power delivered by the SPGG. Geometries parameters such as $A_{t1}$ and $A_{t2}$ can be measured directly and the solid propellant density and the propellant burning rate can be also acquired easily. On the other hand, the values of $T_0$, $k$, and $M_w$ of the product gas are generally calculated by theoretical approaches based on chemical equilibrium compositions.