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Research Article

Thermodynamic aspects of gas generator for application in military aircraft: Some considerations

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ABSTRACT

The importance of this research is that it mainly describes the various interesting areas of the thermodynamic aspects of a gas generator for application in aircraft. The gas generators are widely used for both civil and military applications. Thermodynamics is the branch of science that deals with energy being transformed into work and vice versa. The demand for gas generator and its applications continuously increases in the areas of aerospace and aeronautical technologies. Gas generating device involves creation of a high temperature and pressurised combustion of gas by burning propellant in cartridge. These devices are filled with energetic materials (EMs) and used to perform a critical operation in an emergency under adverse conditions by releasing energy very quickly in milliseconds. A data acquisition system (DAS) is used to verify the gas generator's performance parameters such as peak pressure (P_{max}) and time to maximum pressure (TP_{max}) generated in the closed vessel (CV). A double-base propellant consisting of fuel, oxidizer and other ingredients are used as the medium for gas generation. The main goal of this research paper is to establish various relationships and determine the various thermodynamic properties of a gas generator for application in aircraft. The experimental findings from this research show the specific heat of propellant is 0.3488 cal/g/°C, the calorimetric value to equal 925 cal/g, the force constant to be 1052 J/g, the co-volume to be 0.989 m^3/kmol and the flame temperature to be 2944 K. The thermodynamic analysis of a gas generator for military applications plays a significant role in the design and development phase.

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1. INTRODUCTION

Thermodynamics is a branch of science that pertains to certain laws of nature that are always obeyed and never observed to be violated. Thermodynamics relate to a classical and microscopic science. This study concerns to heat and work transfer, and the different energy interactions that bring out changes in the macroscopic properties of substances. These changes are observable and quantifiable. However, work and heat are path functions based on the processes that are adopted and their cumulative sum gives a non-zero number. The operational systems based on the thermodynamic cycle are used in a gas generator by burning a propellant. The operations of the gas generator depend on the combustion rate of the propellant, its heat and energy and the amount of generated gas that can be transformed into useful work.

This paper discusses the various aspects of thermodynamics related to a gas generator. Gas generators are mainly responsible for generating gases to operate different crucial mechanical system pertaining to aircraft. Basically,

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they are used in special applications such as seat ejection, catapults, parachute deployment, harnesses, signaling, short-term power supplies jet engine starting and launch tubes. Gas generators are designed to produce hot combustion gases and therefore have much slower burn rates by a factor of 5 to 6 and much lower combustion temperatures between 800K to 1600K. This allows these propellants to be used with un-insulated metals in applications such as launch tubes.

The novelty of this research article is how it determines the various thermodynamic properties of a gas generator when burning the propellant under the given conditions.

1.1. Defining the research problem

Gas generators are broadly used for military, space and civil applications to perform different roles such as thrusters, signaling, flares, seat ejections, cable cutting, bomb release, stage operation, flare and chaff. They are comprised of a propellant and a pyrotechnic component. The propellant works as the main source of energy for performing the various tasks after applying appropriate stimulus. Due to the propellants being ignited inside a cartridge case, an enormous amount of combusted products is generated. The propellant's behavior and thermodynamic aspects under given circumstances are very important for that particular application. The gas generator under study here is subjected to various testing and evaluation methods in the development phase. The gas generator described in this paper is used to save a life of the pilot in an emergency situation. This type of testing is performed using the gas generator to save the life of a pilot for various aircraft platforms. The thermodynamics of a gas generator involves science related to the transfer of energy and its results on the substances' physical properties. This is based on translating the observations of common experiences into thermodynamic laws and these laws preside over the principles of energy conversion.

2. METHODOLOGY

2.1. Thermodynamic cycle

As far as the gas generator is concerned, fuel in the form of a propellant is already stored in the system. No oxygen is available for the gas generator as in the case of an internal combustion (IC) engine. The pictorial representation of the gas generators pressure vs. volume and temperature vs. entropy curves are illustrated in Figures 1 and 2 respectively (Shekar 2018). However, were one to consider the gas generator as an internal combustion (IC) engine, the process involves no intake stage. This is shown by the dotted line 1-2 in the figures. As the propellant is ignited, heat starts being added and equilibrium in pressure is attained. The heat addition is assumed to occur at a constant pressure and is shown by the line 2-3 in the figures. In many cases, the heat addition can occur at varying pressures. The combustion increases pressure initially and this transient phase can be treated as a compression stroke. The process is not isentropic and can not be represented properly by a single thermodynamic plane. This is shown as expansion stroke by the line 3-4 in the figures. However, the rise in pressure and temperature in the gas generator occurs in milliseconds (ms). Simultaneously, the combustion gases are expelled as a combination of both the expansion and heat ejection stages. Thus, the gas generator has only two valid processes on the thermodynamic plane. Another significant variation is that no cycle occurs once the propellant is initiated. After the propellant is completely burned the system returns to original state.

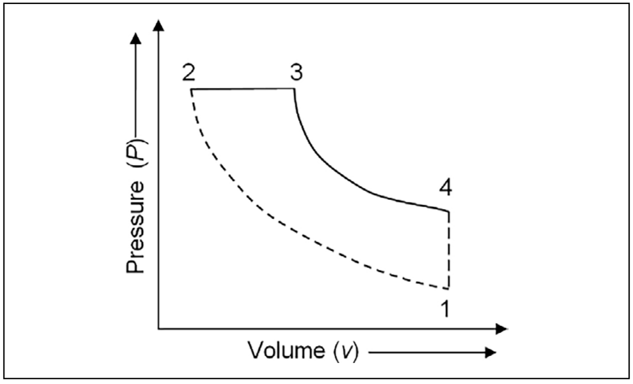

Figure 1. Pressure vs. volume.

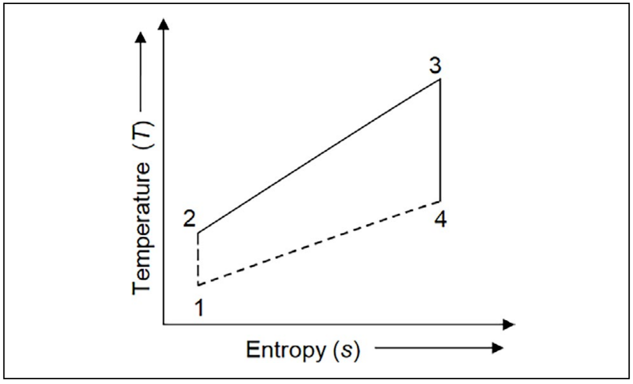

Figure 2. Temperature vs. entropy.

This indicates that the gas generator operates as a single stroke regarding thermodynamic cycle as the operation has no periodicity. A continuous generation of work occurs until the propellant (fuel) is fully consumed.

The gas generator device consists of a pyrotechnic component, the propellant and a means of initiation (Cumming, 2009). Using proper means of initiation, huge volume of gases can be generated due to the rapid chemical reactions that occur from burning the propellant. The gas generator consists of different ingredients such as oxidizing and reducing agents. Subjecting the propellant to testing involves evaluating different performance parameters such as heat of combustion, combustion temperature, specific volume, propellant force and burn rate in the test vessel. This article will outline the closed vessel (CV) firing of a gas generator and determine the various thermodynamic properties (Han, 2017). Martiosyan et al. (2009) have explained the design aspects and performance of nanoenergetic gas generator.

3. THERMODYNAMIC PROPERIES

After evaluating the gas, the various thermodynamic properties of the gas generator are then discussed as follows.

3.1. Ratio of Specific heat (γ)

The specific heat of the gaseous product of combustion is basically a measure of temperature rise for a given heat input per unit mass of a given material. The given mass of material with a high specific heat results in a low temperature rise for a constant heat input. The reverse is true for materials with a low specific heat. Alternatively, a constant mass of a material with a high specific heat requires more heat input for a given rise in temperature. The difference in specific heats between specific heat at constant pressure and specific heat at constant volume is equal to the gas constant of the gas whose ratio is expressed by the Greek letter Gamma (γ) for ideal gases. This is also called the heat capacity ratio and adiabatic index and is basically an isentropic expansion factor. Thermodynamically, it also equals enthalpy (h) and the internal energy of the ideal gas (u). The value of γ is related to the degree of freedom available in the molecule (f) and is defined as $[1+(2/f)]$. However, the value of γ is reduced by the combustion gases containing traces of fuel. The reduction is dependent on the molecular weight of the combustion gases and their relative compressibility. The value of γ is taken as 1.2 for double-base propellant. The value of γ gets lower as temperature and pressure rise.

3.2. Mass generation rate (m_g)

This represents the rate at which the propellant is converted into gaseous form by combustion. It is given by the density of the propellant multiplied by the rate of volume consumption of the propellant. The rate of volume consumption is given by the product of the burning area (A) of the propellant and its burn rate (r) which is the consumption rate of the propellant grain or of the whole propellant mass at a constant pressure (P) per unit time. The volume of a grain consumed per unit time is the product of rate of regression (r) and the burning surface area (A). The rate of mass discharge is a function of pressure with higher pressures having higher discharge rates. This is the explosive mass consumed over a given unit of time. The expression for the mass generation rate due to propellant consumption is given below:

$$m_g=dm/dt = \rho\times A\times r \tag{1}$$

Using Vieille's equation for the mass burning rate

$$\frac{dm}{dt} = p^a\times k\times p \tag{2}$$

where k is a constant that consider the values of ρ, A and α.

The burning rate (r) plays an important role in the formulation of the propellant as it indicates the propellant's functional performance. The burn rate of the propellant is calculated from small slabs. In general, the burn rate is expressed either in mm/s or cm/s based on surface area (A) and pressure (P). This is expressed by the relation $r=\beta\ P^\alpha$ where α=pressure index and β=burning rate coefficient. Furthermore, this is also based on the propellant composition (fuel and oxidizer content of the propellant) and conditions prevailing inside the combustion chamber. The burn rate affects the gas pressure and gas velocity. This affects the rate of heat transfer from the hot gas into the propellant. If the initial propellant temperature is high, the burn rate also increases. The propellant having already gained the heat tends to burn faster due to the temperature gradient that drives the burning rate, the bulk temperature. Smaller the grain sizes for a particular propellant increase the total surface area per unit weight for burning. Because the propellant density is constant, decreases in grain size will increase in total surface area per unit volume. The surface area per unit volume is called the specific surface of propellant and is measured in cm^{-1} units.

3.3. Combustion heat (Q_v)

Combustion heat of substance is also known as the calorific value or the energy value. This can be defined as the amount of heat liberated when a given amount of the substance undergoes combustion. Usually, heat of combustion is considered to be a synonym of calorific value, which can be defined as the total amount of energy liberated when a given mass of a substance undergoes complete combustion in the presence of (an adequate quantity of) oxygen under standard conditions for temperature and pressure. The concept of the heat of combustion of a propellant is extremely important considering rocket, missile and power cartridge applications. The propellants used in these areas are often selected based on their calorific values (a value that denotes the heat of combustion of the fuel). The greater the heat of combustion of propellant, the greater the amount of power that can be produced from it inside combustion chamber. Combustion heat is determined as :

$$Q_v= Q_p+RT\times\Delta n \tag{3}$$

where Q_p=heat of combustion at constant pressure (kJ/mol), Q_v=heat produced at constant volume (kJ/mol), R=the gas constant (8.314 J/mol K), Δn=moles difference between reactant and products of one kg gas, and T is temperature (K).

3.4. Specific volume (v)

Specific volume is a property of materials, defined as the number of cubic meters occupied by one kilogram of a particular substance. Specific volume is determined as

$$v=22.4\sum n_i\ (g) \tag{4}$$

This is measured in (litere/kg) and $n_i(g)$ is the amount of substance for i^{th} gas products of one kg of combustion gas.

3.5. Peak pressure (P_{max})

Using the first-order approximation, the peak pressure generated inside the cartridge is obtained by assuming instantaneous propellant burning as:

$$P_{max}=\frac{m_p\ R\ T_f}{(\mathrm{V\text{-}b})}=\sum\frac{m_{pi}\ R_i\ T_{fi}}{(\mathrm{V\text{-}b_i})} \tag{5}$$

where m_p is mass of combustion product gases, P_{max} is peak pressure, R is the universal gas constant, R_i is the gas constant of i^{th} propellant product gases, T_{fi} is adiabatic flame temperature of the i^{th} propellant, b is co-volume of the i^{th} propellant product gases, and V is volume

The value of R is 8.31343 J/mole/K

At any given instance, the m_p generated by the propellant burning relates to the grain geometry of the propellant and can be expressed as a polynomial with powers of λ and dimensionless length, which characterizes the geometry of the propellant defined as a web.

$$m_p = m_{po} \sum_{j}^{n} k_j \lambda^i \tag{6}$$

where m_{po} is the initial mass of unburned propellant

The above relation is also known as a form function. The coefficients k_j are determined according to the propellant grain geometry. At each time frame, the combustion gases inside chamber are assumed to be in thermodynamic equilibrium with the pressure related to the equation of state for non-ideal gases.

3.6. Force constant (*F*)

This is one of the essential parameters of the propellant related to maximum work carried out by the propellant unit mass and is part of the utilizable energy in performing the work. The work done is expressed as product of distance covered and force. This energy is much lower than the heat from the explosion. Usually an important relationship exists between the propellant mass and maximum pressure. It is called impetus or the force constant and is denoted by F.

$$F = \frac{P_{max}(\text{V-b})}{m_p} \tag{7}$$

where F also equals T_f

The term n, is the number of moles of a gas per unit mass and is directly proportional to the gas volume (V) at standard temperature and pressure (STP). V can be substituted for n, and Q for T_f because the two are mutually proportional. In the expression

$$F = \text{Power} = T_f \times \alpha \times Q \times V \tag{8}$$

QV is known as the characteristic product of the propellant.

The closed vessel (CV) technique is generally used to determine various parameters such as co-volume and the force constant by burning the propellant at a 0.2 g/cc loading density. Maximum pressure and burning rate can be also determined. The propellant testing in a CV is more economical compared to the actual dynamic firing, as it only requires about 200 to 300 gram of propellant versus the several kilograms. Using F, the maximum energy (E) available from the propellant is estimated as

$$E = \frac{F\,C}{(\gamma\text{-}1)} \tag{9}$$

3.8. Thermodynamic relations

As per the first law of thermodynamics, the state of the gas in the system can be determined as (Nag, 2018)

$$Q = \Delta U + W \tag{10}$$

Here Q is the energy supplied to the system and ΔU is the change in internal energy, W is the work done by the system is expressed as:

$$\text{W} = \int \text{F.dx} \tag{11}$$

The right-hand side is the dot product of the two vectors and gives a scalar quantity.

Eq. 7 can also be rewritten as:

$$W = \int F\text{dx} \tag{12}$$

Using material mechanics

$$F = P \times A \tag{13}$$

where, F is the resultant force that is expressed as the product of average pressure P acting on the cross-sectional area A of the body.

Substituting this in Eq 12, gives

$$\text{W} = \int P \times A \times dx \tag{14}$$

where dx is the length displacement which means volume can be expressed as dv = A×dx. Putting this in Eq 14, gives

$$\text{W} = \int P \times dv \tag{15}$$

Here the gas compression is assumed to be adiabatic frictionless compression with no leakage. The combustion chamber possesses very little room for oxygen as it is filled with the propellant. The chamber is where the propellant combusts and has volume V_c which is given by

$$V_c = \frac{\pi d^2}{4} \tag{16}$$

According to the ideal gas law, the pressure P can be expressed as:

$$P = \frac{m_g \times R \times T}{V} \tag{17}$$

where, m_g is the mass of the gas, V is the specific volume of the gas, P is the gas pressure, R is the gas constant and T is the absolute gas temperature. Putting Eq 14 into Eq 12 gives

$$\text{W} = \int m_g \times R \times T \frac{dV}{V} \tag{18}$$

which shows that the work done by the gas on the projectile is a function of temperature and gas volume.

4. GAS GENERATOR DESCRIPTION

All safety norms for the gas generator are strictly observed while filling so as to avoid any accidental initiation. This is achieved by selecting a proper explosive train for the initiator, booster, and propellant and is established by extensive trials carried out in the field. The most important test is the sensitivity test. It is carried out for each explosive item. The order of sensitivity decreases from initiator

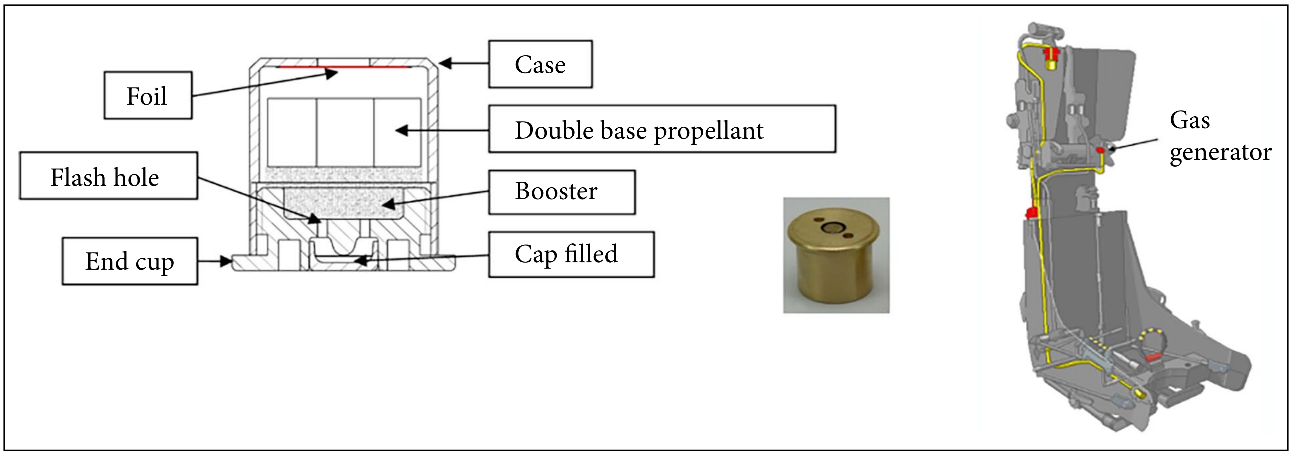

Figure 3. Schematic construction detail of the gas generator, its photo, and the seat of a fighter aircraft illustrating the location of the gas generator.

to booster and propellant. The amount of mass used in an explosive train increases from initiator, booster and propellant. The output of the explosive component increases from the initiator to booster and propellant. The initiator is the most sensitive and the propellant is the least sensitive. To bridge the gap between these two extremities, a booster is used in the explosive train. The highest order of safety is maintained while handling, storing and transporting these gas generators in this way. The cartridge is assembled with a case and foil assembly, and end cap. The cartridge case is designed so as to accommodate the propellant and booster. The necessary arrangements are made for initiating the gas generator. The case is made of brass and closed with copper foil with the other end being closed with an end cap. The foil ruptures as the high pressure and temperature of the gas act on it. The end cap is made of brass. The base of the end cap has a centrally located cap chamber at one end where the initiator is affixed. Arrangements are made for two flash holes in the cap chamber. The end cap is threaded and assembled with the cartridge case using thread sealant for proper hermetic sealing. The design aspect for the brass cartridge case using the bilinear kinematic hardening model is explained by Parate et al (2019). The schematic construction of the gas generator, its image and the seat of the fighter aircraft illustrating the location of gas generator are shown in Figure 3. The firing pin strikes the cap and generates the flash. This initiates the booster. The booster further ignites the propellant. The propellant gas so generated is used for operating the harness mechanism. This cartridge is responsible for the functioning of the harness system of the seat ejection.

5. INGREDIENTS AND MATERIALS

5.1. Double-base propellant for gas generator

This study has chosen a propellant with a tubular shape, single-axial perforation without inhabitation, and neutral type burning due to this propellant being able to burn from inside to out and outside to in so that the burning surface area remains constant. The propellant used in harness purpose must be non-hygroscopic and compatible with the casing material in which it is to be loaded. Brass has been selected for the case material as it meets the obturation requirements. Based on the above requirements, a double-base propellant has been chosen consisting of nitro-glycerine (NG) and nitro-cellulose (NC) with other ingredients added to improve the properties. The percentage of the chemical contents and physical properties of the double-base propellant as used for this application are given in Table 1. The photo of the double-base propellant is given in Figure 4.

Diethyl phthalate (DEP) has the role of an inert plasticizer (non-energetic). The carbamite works as a stabilizer so as to increase the shelf life of the propellant and reduce the degradation of the NC. The candela wax acts as wear reducing agent. The propellant's chemical content in percentage dictates the total amount of thermal energy released by burning. The gas generator using the propellant has polymeric macro-molecules with oxidizer and fuel. The double-base propellant is a homogenous mixture of NG, NC and other additives. Upon ignition this propellant produces smokeless combustible products. These combustible

Table 1. Chemical content and the physical properties of double-base propellant (HEMRL, Propellant Specification 2018)

Chemical contents (percentages)		Dimensions of propellant grain	
NC (12 % N content)	59±1.5%	OD	14.1±0.2 mm (Nominal)
NG	32±0.5%	Web	5.10±0.15mm
DEP	6±0.5%	Length	6.5 mm (Nominal)
Carbamite	2±0.2%	Density	1.57 g/cc
Candela wax	1%	Shape	Tubular with single-axial perforation

NC: Nitro-cellulose; OD: Outer diameter; NG: Nitro-glycerine; DEP: Diethyl phthalate

Figure 4. Photo of the double-base propellant.

products are namely nitrogen oxides, water vapor and condensable gases. This propellant may react to provide a detonation velocity between 6-7 km/s when confined under specific circumstances. However, with proper compounding, it will undergo the deflagration phenomenon. Most of the propellant undergoes deflagration which is the main requirement for operating the harness mechanism.

6. EXPERIMENTAL PART OF THE CLOSED VESSEL (CV)

6.1. Pressure-time (P-t) profile of the gas generator

The CV is cylindrical in shape where the cartridge is loaded. This is to allow various performance parameters to be evaluated in the laboratory. The experimental firing procedure consists of the CV body, a gauge adapter, the cartridge, the firing mechanism, a copper washer and the closing plug. The firing mechanism is placed at one end and the closing plug at the opposite end. A copper washer is placed on the closing plug to avoid the combustion products from leaking after the propellant is burned. A Yokogawa scope corder and charge amplifier are used to record pressure. A gauge adapter with pressure sensor is fitted to the vessel body. The selected pressure sensor has a small size, fast response, durability, hermetically sealed construction, sensitivity to 0.39 *pC/psi*, a measurement range up to 15000 psi and a rise time of $\leq 1\ \mu s$. The vessel has been designed and fabricated for realizing the performance parameters (Parate et al 2019). The CV schematic is shown in Figure 5. The striker for the firing mechanism strikes the cap and indents it. This action crushes the sensitive composition between the cap and anvil in the base of the gas generator. The flash passes through the two flash holes to ignite booster and propellant. The pressure-time (*P-t*) profile produced after firing the cartridge in the CV is shown in Figure 6. The peak (i.e. maximum) pressure generated in the CV is 3.84 MPa and the corresponding time is 258.43 milliseconds. The methodology is similar for evaluating the performance parameters of the cartridge in the CV (Parate et al 2021).

6.2. Energy balance equation

As the propellant burns inside the CV, its chemical energy is converted into gas energy resulting in high pressure and high temperature of the combustion products. During the burning, two assumptions are used (Parate et al 2018).

- The system is adiabatic (no heat transfer- due to the rapid burning process) where the propellant ignition takes place and
- The exothermic reaction within the CV is due to the decomposition

According to the first assumption, the solid (propellant+booster)→Gas+Energy

Using the first law of thermodynamics;

$$dQ=dW+dU \tag{19}$$

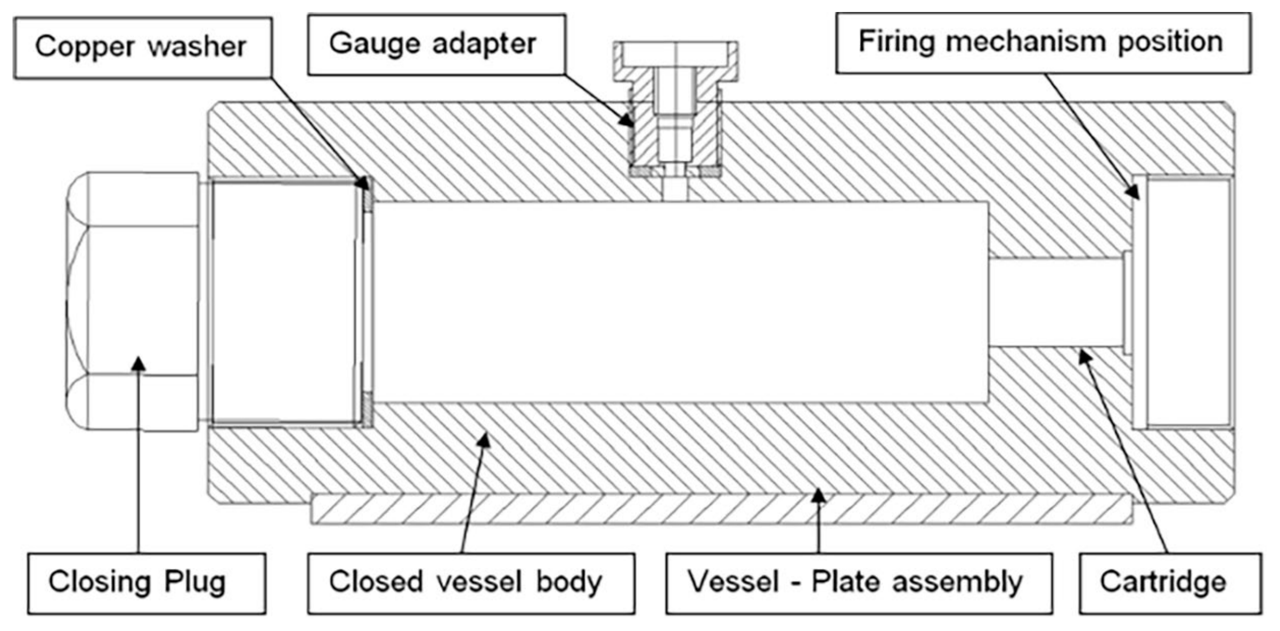

Figure 5. Engineering schematic of the CV.

CV: Closed vessel.

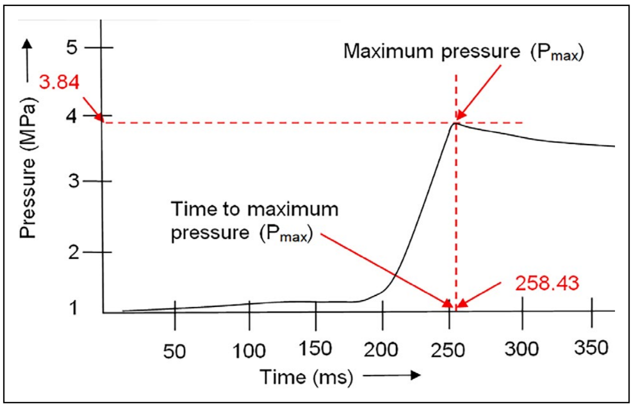

Figure 6. *P-t* profile in the CV.

CV: Closed vessel.

where *dQ*, *dU*, and *dW* are the heat supplied to the system, the internal energy and the work performed. As the vessel experiences no heat transfer and no deformation, *dU=0*. However, in real practice heat loss will always occur from the vessel to the surroundings. This can be observed from the *P-t* profile as shown in Figure 6. Ideally the profile should be a straight line after attaining peak pressure. However, a pressure drop occurs after reaching maximum pressure. No system exists in the universe where heat loss doesn't occur. Heat loss can be minimized for maximum utilization of work.

7. RESULTS AND DISCUSSION

The performance evaluation of the gas generator is carried out in a specially designed test vessel (i.e. CV). The gas generator develops pressures between 2.7 to 5.3 MPa and a TP_{max} 216 within 332 ms in the CV under hot (45°C) and cold (-26°C) conditions and a volume of 150 cc. The cartridges filled with 1.5 g of propellant and 0.4 g booster for the CV firing. They are then conditioned for a minimum of six hours before firing. The performance characters (i.e. P_{max} and TP_{max}) of the gas generator have been experimentally evaluated in a suitable test vessel designed and fabricated for that application (de Oliveira et al. 2005; Parate et al. 2021). This is explained in Section 5. The various thermodynamic parameters of the gas generator such as co-volume, flame temperature, force constant, calorific value, and maximum pressure have been obtained experimentally by burning the propellant inside the closed vessel within laboratory facilities are enumerated in Table 2.

The burn rate and calorimetric value of the propellant is determined using strand burner and bomb calorimeter instruments. The other parameters of flame temperature and force constant are obtained by burning the propellant in a CV at loading density of 0.2 g/cc. A differential scanning calorimeter (DSC) is used to determine the specific heat. The specific heat of the propellant gas has been determined as 0.3488 cal/g/°C depending on the propellant composition. This paper has addressed all the goals and an objective has been met in a full-scale test demonstration of a gas generator for aircraft application.

Table 2. Thermodynamic properties of the gas generator

Thermodynamic properties	Values
Mean molecular weight	23.27 g /mole
No. of moles of gas	0.04542 mole/g
Combustion heat of propellant	531.32 cal/g
Ratio of Specific heat (Gamma)	1.2448
Flame temperature	2944 K
Internal energy of product gases	830 cal/g
Specific heat	0.3488 cal/g/°C
Gas volume	962.75 cc
Co-volume	0.989 m^3/kmol
Force constant	1052 J/g
Calorimetric value	925 cal/g
Specific heat of the propellant gas	0.3488 cal/g/°C
Maximum pressure at 0.2 loading density	260 MPa

6. CONCLUSION

The work that is present in this paper summarized the different thermodynamic aspects for evaluating the various properties of a gas generator for aircraft application. The major parameters of the gas generator are dependent on volumetric loading, pressure time profile, propellant grain configuration, and chemical contents. This paper also explains the performance characteristics of a gas generator in a CV. These data will help ballistic studies, serviceability, safety and propellant life before induction into actual use in the development phase. All calculations have generally been made with through applicability of the ideal gas law and in terms of temperature and pressure. When predicting and assessing the results, the various assumptions needed to be kept in mind. This type of a gas generator has to meet various design qualification tests during development phase before getting inducted into service. The author has brought out the essence of recently published papers of interest from open available sources.

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DATA AVAILABILITY STATEMENT

The published publication includes all graphics and data collected or developed during the study.

CONFLICT OF INTEREST

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

FINANCIAL DISCLOSURE

The authors declared that this study has received no financial support.

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