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Gas Generator Pyrotechnics Using Gun Propellant Technology Methods

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***Abstract*—**This research article describes the gas generator pyro-cartridge using gun propellant technology methods for fighter aircraft application. The emphasis of this work is to design and develop a gas generating device with pyro-cartridge using double base (DB) propellant to generate a high temperature and pressure gas. This device is utilised for dropping empty fuel tank in an emergency from military aircraft. A data acquisition system (DAS) is used to record time to maximum pressure, maximum pressure and time to half maximum pressure generated in a vented vessel (VV) for gas generator. Pyro-cartridge as a part of the gas generator creates a maximum pressure and time in the closed vessel (CV). This article also covers the qualification testing of gas generator. The performance parameters of pyro-cartridge devices such as ignition delay and maximum pressure are experimentally presented through the CV tests.

***Keywords*—**Closed vessel, data acquisition, double base propellant, gas generator, ignition system, ignition delay, propellant, pyro-cartridge, pyrotechnics, vented vessel.

I. Introduction

A gas generator is one-shot device and highly reliable. It is a device for generating a gas by solid propellant grains and helps to keep the entire fleet in operational readiness [1]. Prior art was reported a series of gas generating devices used either a single base (SB) propellant or double base (DB) propellant for numerous military applications such as stage separation, propulsions, automobile industries to inflate the air bags to reduce a severity of crash and aerospace technology. Energetic materials (EM) are used in gas generator pyrotechnic devices that release the energy instantaneously by rapid chemical reaction process. The energy release is used to perform various operations such as releasing the bomb from the fighter aircraft, emergency brake application, cartridge actuated devices, control motors, impulse cartridges, launch vehicles, seat ejection, signalling, exploding bolts and cutting cable etc. The operation of a gas generator is based on the propellant combustions, its gas generation and the energy in the form of heat which is converted into useful work. Gas generator pyrotechnic device consisting of a series of components such as pyrotechnic composition and the propellant is referred to as “pyrotechnic gas generator” [2]. On suitable initiation, a huge amount of combustion products is developed. The gas generator comprises of various components and other chemicals in the form of reducing and oxidizing agents. Combustion heat and its rate, yield of gas generation and gas generator stability are based on the propellant grain geometry and its chemical constituents. Key performance factors of a gas generator consist of force constant of propellant, combustion heat and its temperature, specific volume, burn rate etc. This article addressees the outline for the CV firing of pyro-cartridge and a gas generator firing in the VV [3]. The performance parameters of pyro-cartridge and the gas generators are assessed in the respective test vessels [4]. The gas generator consists of the propellant that evolves the pressure and heat on burning upon initiation [5]. The selection of the propellant is dependent on its use and applications. A smart selection of propellant is highly desired. The propellant designer must select a correct type from a large variety of the propellants available. Those presently available will offer a wide range of densities, burning rates, mechanical, hazard properties and environmental capabilities. The above properties can be changed or modified depending on its applications. In general, the propellant selection considers satisfactory operation, performance, storage and handling and supply. Such properties are discussed below [6].

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a. Satisfactory Operation

- The temperature of combustion products should not exceed the melting point of cartridge case material.
- The propellants ingredients and their products of combustion should be compatible with the material of construction (MoC).
- Mechanical properties of the propellant should not lead to any mechanical deformation.
- The specific heat needs to be as high as possible if the propellant is used for cooling.
- The propellant should be easy to ignite.
- The propellant should give consistent and reliable performance under adverse conditions.
- To minimize temperature gradients, the thermal conductivity should be high so as to avoid the variations due to ambient temperature.

b. Performance

- The selected propellant must have low molecular weight that requires less energy to accelerate the gas molecules.
- It should possess a high density so that it will take less space or volume to give desired output (1.6 to 1.75 g/cc).
- It should have a low flame temperature (< 3500 K)
- It should have a low vulnerability.
- It should have continuous and constant burning.
- Combustion products should have a less effect on gun barrel surface.
- The propellant should possess a low specific heat ratio (γ) for combustion product.
- The propellant should possess a low vulnerability to heat,

shock, impact, bump, jolt etc.

- The propellant should possess a high force constant i.e., *F* (> 1000 J/g) to deliver more energy effectively.

c. Storage and Handling

- It should have non-toxic combustion products
- It should possess a small fire hazards and explosion.
- It should possess a no possibility for detonation.
- It should possess a long storage life.
- It should possess a non-hygroscopic property to avoid ingress of moisture.

d. Supply

- Propellant must be easily available
- Raw materials should be cheap and easily available
- Manufacturing process should be simple and safe.
- Propellants' cost should be a small considering total R&D costs.
- Propellants should be easy for transportation without affecting environment and health.

A. Aim of Research Paper

In this paper, the gas generator characteristics such as a maximum pressure, time and time for half maximum pressure are reported as an acceptance criterion. A gas generator generates the pressure in the range of 20 to 36.5 MPa in the VV whereas pyrotechnic generates the pressure in the range of 8 to 14 MPa in the CV with ignition delay less than 10 ms. A gas generator was designed and developed in the Laboratory which meets all the specifications of the user.

B. Description of Gas Generator

The gas generator consists of case material; i.e., brass, the bottom of which is closed with a pyro-cartridge assembly for initiation. The other end of the cartridge is closed by a brass closing disc having a rubber washer positioned on the disc. The cartridge comprises of rubber washer, closing disc, spring ring, grid, DB propellant, case, igniter pellet, pyro-cartridge and protective cap. The casing material of gas generator has to withstand both a high pressure and hot combustion gases generated by the burning of the propellant. The strength of casing material at high temperature is an important criterion for material selection. The design aspect for the brass cartridge case is based on thin cylinder theory [7]. The pyro-cartridge consists of six pin molded plug assembly and the main filling of pyro-cartridge is lead styphnate and gun powder. The initiation of the propellant needs external heat flux, which is given by pyrotechnic. This is initiated by a squib inside pyro-cartridge using a power supply bank from the aircraft. The pyro-cartridge produces the hot combustion products for initial pressurization of the propellant inside the cartridge case and bringing the surface temperature of the propellant to an auto-ignition temperature to establish self-sustained combustion. The quantity of igniter composition and its design are important factors for efficient pyro-cartridge. The schematic construction detail of the gas generator with pyro-cartridge is shown in Fig. 1. With the passage of an electric current through the pins and bridge, pyro-composition gets initiated and the gun powder gets ignited, which further ignites the main propellant. On supply of electrical pulse, combustion gases travel the entire surface of the propellant, heating its surface and pressurising the available empty free volume. The gas pressure generated after the deflagration of the propellant is just sufficient to puncture/rupture the closing disc. The propellant gases developed by the gas generator acts on the piston which produces the force. This is responsible for the functioning of the jettison system of the wing drop tank.

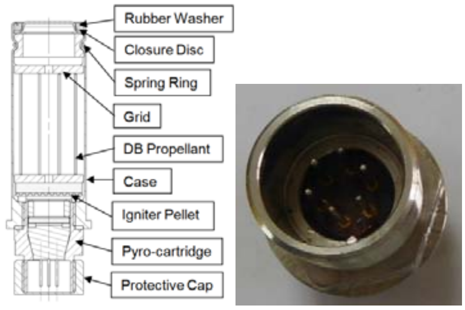

Fig. 1 The schematic construction detail of gas generator with pyro-cartridge

C. Types of Gas Generators

Based on the gas yield and its temperature, gas generators are classified as

- *Hot gas generators:* Generally, the gas temperature for the hot gas generators is more than 1200 K. The applications of these devices are primarily to initiate the seat ejection system, thrusters, alternators, and separators etc. for secondary propulsion [8].
- *Cold gas generators:* In this case, the gas temperature is less than 600 K (or 400 K in some cases). Such types of gas generators are frequently used in either inflating or pressurizing systems. They are used in automobile airbags, fire extinguishers, inflatable life rafts, escape slides where high gas temperatures are not suitable.

D. Gas Generator Requirements

Based on the applications, gas generators have to satisfy a series of exhaustive test requirements. Each gas generator has its own specific requirements with respect to safety and reliability. The requirements of gas generator are listed below:

- pyro-cartridge is to be fired and used to excite the explosive train of the gas generator
- it should possess a good performance reliability, easy and reliable ignition
- it is to be designed for ruggedness, consistency and safety
- it should generate steady gas flow rate which depends on the form function of the propellant
- it should give enough burning rate which calculates the flow rate of released gas
- it should generate a sufficient vivacity related to pressure rise per unit time inside the combustion chamber
- it should generate high yield of gases that implies a reduction of weight required for gas generator
- it should have mechanical strength of cartridge case which may not change during handling, storage or

transport (cracks may not take place)

- it should generate high-quality propellant ageing properties, so that prolong storage does not cause any deterioration
- it should possess a low manufacturing and processing cost
- it should be easy for disposal and recycling
- case materials should be compatible with the propellants and pyrotechnic materials
- the packaging should meet the desired envelope requirements

These are the basic requirements of gas generator. These requirements are often conflicting and selected with certain compromises depending on the end use and energy released by the propellant. Gas generators used for aerospace applications has many advantages, such as small volume, low weight, and high inflation rate.

II. Materials and Methods

A. Pyrotechnic for Pyro-Cartridge

The complete pyro-cartridge consists of a molded plug with the pin, copper cup, the distance piece, celluloid foil, washer and squib plug. It is filled with 90 mg of lead styphnate and covered with a celluloid foil. Gun powder, 450 mg is poured over the foil. The copper cup is placed over gun powder. The combined resistance of all three bridges in parallel is 1 to 1.5 Ω.

B. DB Propellant for Gas Generator

The propellant will be selected with known characteristics, preferably neutral type of burning, so as to achieve build up of pressure. The propellant so selected should be compatible with case material and non-hygroscopic in nature. Based on the above requirements, DB propellant type is selected which consist of nitro-cellulose (NC), nitro-glycerine (NG) and other additives. The basic chemical composition and physical properties of DB propellant that is used for the CV firings are indicated in Table I.

TABLE I
Basic Chemical Composition and Physical Properties of DB Propellant [7]

Chemical Composition		Dimensions of the propellant grain	
NC (12 + 0.1 % N2 content)	58 ± 1%	OD	5.71 mm (Nominal)
		Web	1.82 ± 0.03 mm
Nitro-glycerin (NG)	27 ± 0.1%	Length	31.8 mm (Nominal)
Dinitrotoluene (DNT)	8 ± 0.5%	Density	1.54 g/cc
Carbamite	3 ± 0.2%	Shape	Tubular
Di-butyl Phathalate	4 ± 0.2%	Flame temperature	2220 K

Fig. 2 The photo of DB propellant

Various ingredients are incorporated in the propellants to achieve the desired properties:

- Nitro-cellulose (NC): NC plays as an oxidizer and fuel also. This is main ingredient used with either single or DB propellant. Further it helps to improve the propellant properties.
- Nitro-glycerin (NG): It is used to plasticize the high molecular weight NC to yield thermoplastic materials. NG reduces smoke and increases energy output.
- Dinitrotoluene (DNT): It is added as surface coating agent and coolant.
- Carbamite: This act as a stabilizer and surface moderant in DB propellant. It aids to enhance the propellant shelf life.
- Dibutyl phthalate: It improves the processability of a propellant remarkably and contributes to the thermal energy on oxidation. It is used to improve mechanical and extrusion properties. The action of DB propellant is gelation of NC that reduces the burning rate of the grain surface and flame temperature.

The photo of DB propellant used in the CV firing is shown in Fig. 2.

Solid propellant gas generator invariably contains polymeric macro-molecules. Pure substance, in which fuel and oxidiser are present in the same molecule, is called BASE for the propellants. DB propellant is a homogenous propellant type that contains NC and NG. A homogenous propellant is also called colloidal propellant as it forms a colloidal mixture of components or smokeless propellants because their combustion products contain water vapour, oxides of nitrogen and carbon and are free solids, soot, coloured gas, liquids or condensable gases. Although both bases of DB propellant are explosive in nature with a velocity of detonation of the order of 6-7 km/s, but with combination and proper compounding, they undergo a slow deflagration. This gives a burning rate of the order of a few mm/s at standard operating conditions. This propellant is thermoplastic in nature and can be softened on the application of high temperatures. However, the propellant with NG mass fraction more than 47% is difficult to process. Hence DB propellant is invariably fuel rich in nature. If oxygen balance of homogenous propellant is considered, ratio of NG to NC for balance composition is (31.18/3.24 =) 8.85:1 (or 89.85% NG). So, NG (oxygen rich part) is less than stoichiometric balanced composition. Any standard DB propellant is around 50% NC and 40-45% NG. Generally, NG/NC ratio is from 0.7 to 1.1 in propellant formulations. The energy content of DB gun propellants (Q value) varies from 3300 - 5200 Jg^{-1}. This propellant has a density around 1600 kg/m^3 and has heat of combustion of 900-1200 cal/g. It is translucent in appearance and has a smooth surface finish with an excellent mechanical property (high tensile strength, high compressive strength and high modulus). It has lower energy in terms of specific impulse (maximum around 200 s). The temperature sensitivity coefficient of burning rate for DB propellant is 0-0.3 $\%/^0C$. These propellants are found to be insensitive to spark up to 5 Joules. The friction and impact sensitivity are around 20-28 kg and 30-60 cm. The temperature of spontaneous ignition of propellant on progressive heating is 170-180 ^0C. The life of this propellant is ten years from the date of manufacturing under magazine condition. The cartridge has assigned total life of 10 years which includes 2 years installed life. The life of gas generator was assigned after satisfactory ballistic performance in VV after subjecting through high accelerated trials followed by vibration tests.

The propellants are fired in the CV at ambient conditions with a loading density of 0.2 g/cc as a part of characterisation to determine various parameters such as maximum pressure, force constant and vivacity etc. Loading density is the ratio of mass of the propellant to the inner volume available for expansion of the gases. Estimation of burning rates of the propellants whose form function is unknown is reported by Vittal [9], [10]. The author further studied that the CV technique is applicable to determine the burning rates of the propellants at low pressure. The interior ballistics of the propellant comprises a study of propellant energy transformation into working substance and recording performance parameters using data recording system [11]. Mehta et al. [12] carried out in the CV firing of gun propellant at the different loading densities for evaluation of its ballistic parameters. The author had reported that pressure in the CV is dependent on the loading density of the propellant. The CV volume is 100 cc. The mass of the propellant is taken as 20 g. The output of the CV firing is given in Table II. Many tubular grains are bundled inside in a cartridge case. Such a configuration increases the propellant burning profile and gives a very high burning area for available volume within the cartridge case.

III. Experimental

A. Pyro-Cartridge Testing in CV

The experimental setup for pyro-cartridge consists of the CV (internal volume: 10 cc), a pyrotechnic composition, an ignition system and a data acquisition to record static pressure [13], [14]. The experimental set up of pyro-cartridge and *P~t* graph obtained after firing are shown in Figs. 3 (a) and (b). Time to P_{max}, the maximum pressure (P_{max}) and ignition delay are recorded. The maximum pressure:11 MPa, time to P_{max} :5.8 ms, ignition delay 3 ms (10 % of P_{max}). This is one of the *P~t* graphs shown in Fig. 3 (b).

TABLE II
OUTPUT FROM CV FIRING

Maximum Pressure (Pmax)	218.75 MPa
dP/dt (Max)	24.79 MPa/ ms
Vivacity	6.22×10^{-4} MPa.ms
Force constant	887 J/g
Time to Pmax	29 ms
Pressure index	0.9325
Burning rate	1.12 cm/s

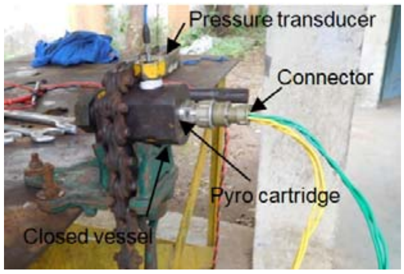

Fig. 3 (a) An experimental set up for pyro-cartridge

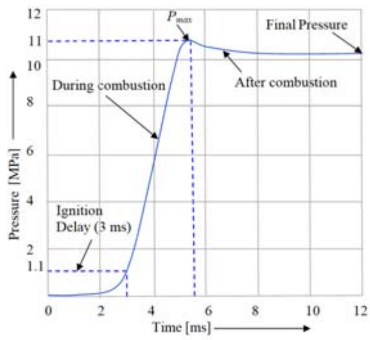

Fig. 3 (b) P~t graph

B. Ignition System

The ignition system of pyro-cartridge has six pins which are molded to form the squib. There are three squibs in parallel that makes the system more reliable. The pins are made up of brass material and soldered with a fine Ni-Cr wire. The pyro-cartridge is ignited by applying 1.5 A current at ambient conditions.

C. Ignition Delay

The ignition delay measured as time taken from firing pulse to 10 % of time to P_{max} from *P~t* graph as indicated in Fig. 3 (b). It is less than 10 ms. It is the start from zero to a point where pressure start rising. It is expressed in ms and indicates the how the pyrotechnic is sensitive to time factor.

D. Gas Generator in a VV

The difference between the CV and the VV is that gases are sealed from all the sides for CV. However, in the VV firing, the propellant gases during combustion are allowed to pass through a hole called as a vent or orifice. An experimental set up for gas generator is similar to CV firing except with a vent. The size of vent is 3 mm. The VV experiment simulates the approximate motion of the piston- cylinder of the system. The

VV is shown at Fig. 4 (a). The pressure in the VV is a significant indicator of a gas production of EM [15], [16]. Cartridge filled with propellant weight of 17.6 g (16 such propellant grains) is fired in the VV at hot and cold conditions. Hot and cold temperature profiles are differentiated with red and blue colors. Time to reach TP_{max}, time to half maximum pressure (½ TP_{max}) and maximum pressure (P_{max}) are shown in Fig. 4 (b). A typical $P\sim t$ profile with P_{max}: 28 MPa, TP_{max}: 80 ms, and T ½P_{max}:130 ms in VV at hot (60^{0}C) condition and P_{max}: 26 MPa, TP_{max}:110 ms, and T ½P_{max} :160 ms at cold (-40 ^{0}C) conditions is depicted at Fig. 4 (b). The rate of rise of pressure from the beginning of propellant combustion to the corresponding time is expressed as $\Delta P_{max}/\Delta T_{max}$. This signifies the chemical reaction rate. The final pressure of the gases at the exit of a vent is above the atmospheric pressure.

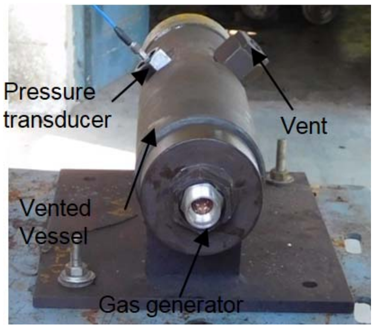

Fig. 4 (a) An experimental set up of VV

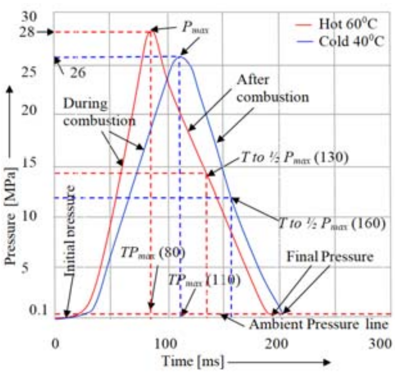

Fig. 4 (b) P~t profile

IV. Result and Discussion

A. Characterisation and Assessment of Pyro-Cartridge

Characterisation and assessment of various parameters such as all fire current test (AFC) and no fire current (NFC) are very crucial considering the performance, safety and reliability. These parameters are determined by Bruceton staircase method [17].

- Minimum AFC Test

A minimum applied current which 'squib firing probability' is 99.9% that will ensure all the time firing of pyro-cartridge. A steady DC of 4 *A* should be passed through any one of the three squibs of pyro-cartridges. All pyro-cartridges should function satisfactorily.

- Maximum NFC Test

It is the maximum current that can be applied for sufficiently long duration with the probability of pyro-cartridge not firing' as 99.9%. A steady DC of 1 *A* should be passed through each of the three bridges for duration of 5 seconds. No pyro-cartridge should fire. All pyro-cartridges used in this test should be destroyed after this test.

B. Design Qualification Tests (DQT)

To qualify the design aspects of the gas generator, various tests such as drop test, vibration, sealing tests are performed as per JSG 0102 [18]-[20]. All these tests are simulating how real-world behaves in actual environment conditions using induced force. They are explained in the following section.

- Drop Test

During installation, transport or repair, cartridges have a risk of being dropped. To ensure safety in handling and transportation, cartridges are dropped, in vertical with different orientations. Drop testing ensures that the product stays in its original condition from manufacturing to implementation.

- Sealing Test

It is conducted to confirm the hermetical sealing of all joints at a half atmosphere.

- Vibration Test

A vibration test is performed to examine the response of a specimen under test (SUT) to a defined vibration environment level. The gas generator qualifies all above mentioned tests and performance was found satisfactory after conduct of each test as explained above.

C. Propellant Characterisation in the CV

The maximum pressure and time parameters for the propellants are evaluated in a CV at ambient conditions using a DAS. In order to determine the burning rate coefficients and burning rate law, instantaneous burning rate values *vs.* pressure on log scale are plotted. The log *R* values are plotted *vs.* log *P*. The propellants burn rate profiles are depend on many factors such as ignition characteristics, propellant chemical composition, shape and size of propellant, loading conditions etc. The propellant firings are carried out at a standard loading density of 0.2 g/cc as per the standard practice followed internationally. Pressures *vs.* time profile of CV firing results and vivacity *vs. P/Pmax* ratio in the graphical forms of DB propellant are depicted in Figs. 5 (a) and (b).

As the propellant burns inside the CV, the pressure is continuously increasing to reach the maximum value. After reaching the maximum pressure, it decreases due to heat loss by conduction, convection and gas expansion. The output results are tabulated and details of the same are given in Table II. The pressure-time profile from static evaluation of DB propellant in the CV can be analysed to give significant information about the propellant behaviour. Although, the propellant is evaluated for its physical properties (density), but the complete test of the propellant is ensured in the static firing.

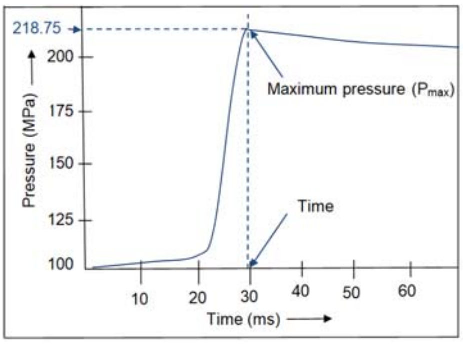

Fig. 5 (a) Pressures vs. time profile

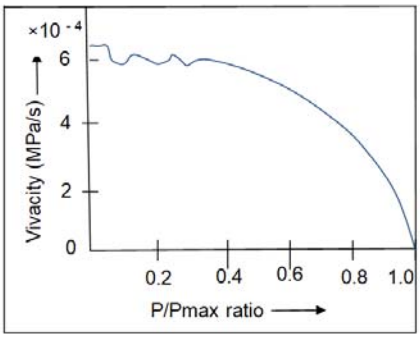

Fig. 5 (b) Vivacity vs. P/Pmax

D. Experimental Results of Gas Generator Evaluation in VV

The maximum pressure recorded by pyro-cartridge is between 8 to 14 MPa and ignition delay (10 % of P_{max}). A gas generator generates the pressure in the range of 20 to 36.5 MPa, time to P_{max} :65 to150 ms, and time to half P_{max} :100 to 210 ms in VV at hot (60 ^{0}C) and cold (-40 ^{0}C) condition having 240 cc volume. The proof limits for the gas generator in the VV are generated by firing 50 numbers each at hot and cold conditions. The proof limits will govern for production of the cartridge. The front view and top view of the gas generator after the firings are depicted in Figs. 6 (a) and (b). The cartridge shows no cracks and bulging after firing from the chamber.

Fig. 6 (a) Front view of gas generator after firing

Fig. 6 (b) Top view of gas generators after firing

V. Conclusions

In this paper, the design and development in terms of performance evaluation of pyro-cartridge and gas generator for dropping empty fuel tank in fighter aircraft application is explained using different test vessels for dropping empty fuel tank in fighter aircraft. AFC, NFC of pyro-cartridge using Bruceton stair case method and performance evaluation trials of gas generator in the CV were carried out. The gas generators were subjected to various design qualification tests and performance was found satisfactory within specified proof limits. It is a kind of gas generator that is described using testing methodology with pyro-cartridge and a gun propellant technology which deliver energy for an aircraft application in an emergency. There is no adverse feedback from the user for the failures till date after successful development. Thus, users' requirements were met by conducting various stipulated tests for this gas generator application.

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Declaration of Competing Interests

It is hereby declared that the author has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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He had the original idea for writing the manuscript and performed the experimental trials related to research activities. The author of this paper participated in the writing of manuscript, literature survey, planning, and execution, interpretation of results and analysis of this study. He also finalised the research article.

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