DOI: 10.13009/EUCASS2019-521

Development of a Reliable Performance Gas Generator of 75 tonf-class Liquid Rocket Engine for the Korea Space Launch Vehicle II

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Abstract

In this paper, development history and result of a reliable performance gas generator of 75 tonf-class liquid rocket engine is described. Based on the experience acquired from the 30 tonf-class gas generator development, the almost identical concept was adopted to 75 tonf-class gas generator such as a coaxial swirl injector and a regeneratively cooled combustion chamber. During the entire development process using the full-scale and subscale technological demonstration model and development model up to now, combustion tests of over 430 times and cumulative time of over 17 700 seconds have been carried out for a 75 tonf-class gas generate. Now the 75 tonf-class fuel-rich gas generator shows very reliable and reproducible characteristics throughout the entire lifetime including the flight test which was done with the test launch vehicle in November 2018. Thus, it can be said that the development of a 75 tonf-class fuel rich gas generator which will be used in Korea first independent space launch vehicle, KSLV-II was finished successfully.

1. Introduction

As a leading institute for technology which is related with space launch vehicle and a national space development agency in the Republic of KOREA, the Korea Aerospace Research Institute (KARI) has been continuously researching and developing technology related to space launch vehicles since establishment in 1989. Figure 1 shows the specificatons of sounding rockets, small satellite vehicle(Korea Space Launch Vehicle I, KSLV-I), and Korea Space Launch Vehicle (KSLV-II) developed or under development by KARI. Korea Sounding Rocket(KSR)-I is a single stage scientific rocket launched in 1993 and KSR-II is a two stage scientific rocket launched in 1998. Both rockets used propulsion systems using solid rocket motor. KSR-III is the Korea first rocket using liquid propellant and launched in 2003[2]. Through this project, various basic technologies for space launch vehicle were acquired such as avonics, ground support system, launch operation technology, electronic system, etc [3]. KSLV-I (called as Naroho) launched successfully in 2013 is Korea's first space launch vehicle which launched a satellite in orbit, thus laying foundations for launch vehicle self-sufficiency in Korea. It was developed under international cooperation with Russia, the 1st stage development including a liquid rocket engine was undertaken by Russia Khrunichev and the 2nd stage development was carried out by KARI. And two parties operated the system and launching.

Since 2010, the Korea Space Launch Vehicle II (KSLV-II, called as NURI) under development is being carried out to put a 1.5 ton of practical satellite into the low earth orbit (600 km ~ 800 km). The KSLV-II development program consists of three phases and the 2nd phase was closed with the successful launch of the test launch vehicle (TLV) which consisted of the 2nd stage of KSLV-II and a ground type 75 tonf-class engine (KRE-075) in November 2018. The TLV was planned for verification of the KRE-075 because the development of KRE-075 is one of the core technologies for the KSLV-II. Throughout the third phase currently underway, it will conduct the qualification test of the first stage which consists of four KRE-075s, the qualification test of the third stage which consists of a 7 tonf-class engine (KRE-007), and flight test of the KSLV-II in 2021 based on the results of two qualification tests. Figure 2 shows the appearance and components of a KRE-075 and the internal aspect of the KSLV-II first stage which consists of four KRE-075s [1].

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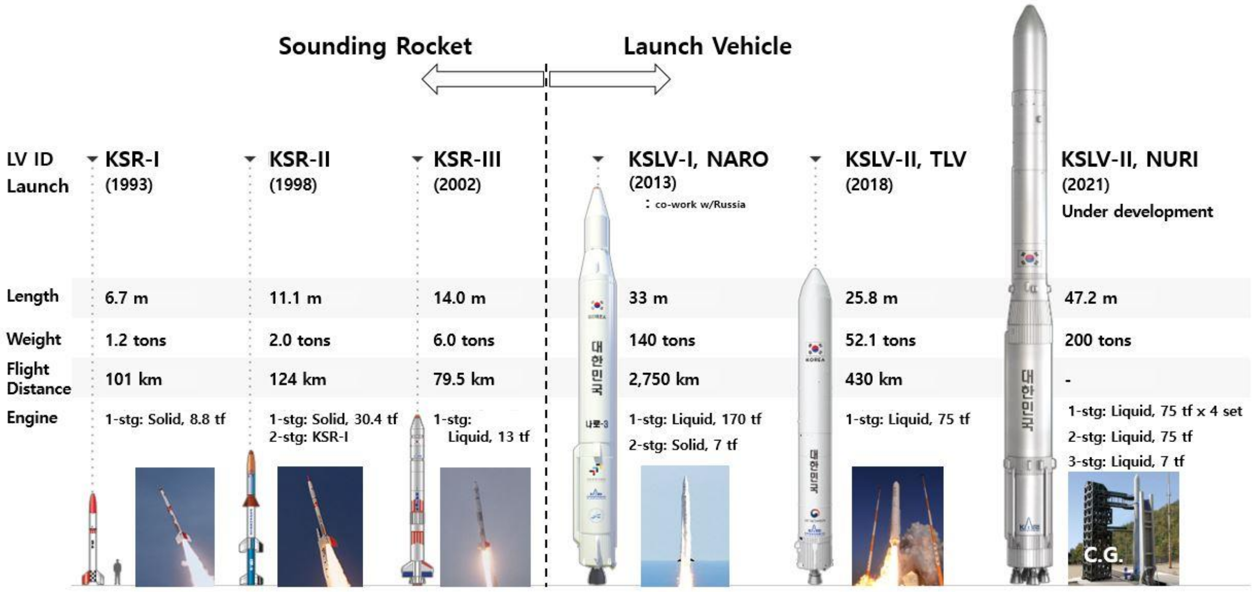
KRE-075 is an engine adopting an open-type gas generator cycle (figure 3) and uses about 4% of the engine-supplied propellants in the gas generator to drive the turbo-pump. The combustion gas that is produced in the gas generator and drives the turbine is discharged through the heat exchanger and the exhaust duct and it generates a thrust of about 1%. KRE-075 is designed to use the identical gas generator and turbo-pump at a ground engine for the first stage and a high altitude engine for the second stage of the KSLV-II. And during flight, it does not have any function to control the engine thrust and mixing ratio, however in the ground test it controls and maintains the engine operating condition by moving three control valves described in figure 3.
This paper describes the gas generator development phase, its design and the combustion test process of the 75 tonf-class gas generator (herein called as 75tGG) which is the main component of the KRE-075. Also, it describes the operation stability, performance reproducibility, and durability of the 75tGG that is confirmed through the numerous combustion test.



LV ID Launch	KSR-I (1993)	KSR-II (1998)	KSR-III (2002)	KSLV-I, NARO (2013) : co-work w/Russia	KSLV-II, TLV (2018)	KSLV-II, NURI (2021) Under development
Length	6.7 m	11.1 m	14.0 m	33 m	25.8 m	47.2 m
Weight	1.2 tons	2.0 tons	6.0 tons	140 tons	52.1 tons	200 tons
Flight Distance	101 km	124 km	79.5 km	2,750 km	430 km	-
Engine	1-stg: Solid, 8.8 tf	1-stg: Solid, 30.4 tf 2-stg: KSR-I	1-stg: Liquid, 13 tf	1-stg: Liquid, 170 tf 2-stg: Solid, 7 tf	1-stg: Liquid, 75 tf	1-stg: Liquid, 75 tf x 4 set 2-stg: Liquid, 75 tf 3-stg: Liquid, 7 tf

Figure 1: History and Specifications of the sounding rockets and space launch vehicles developed in Korea Aerospace Research Institute [1]

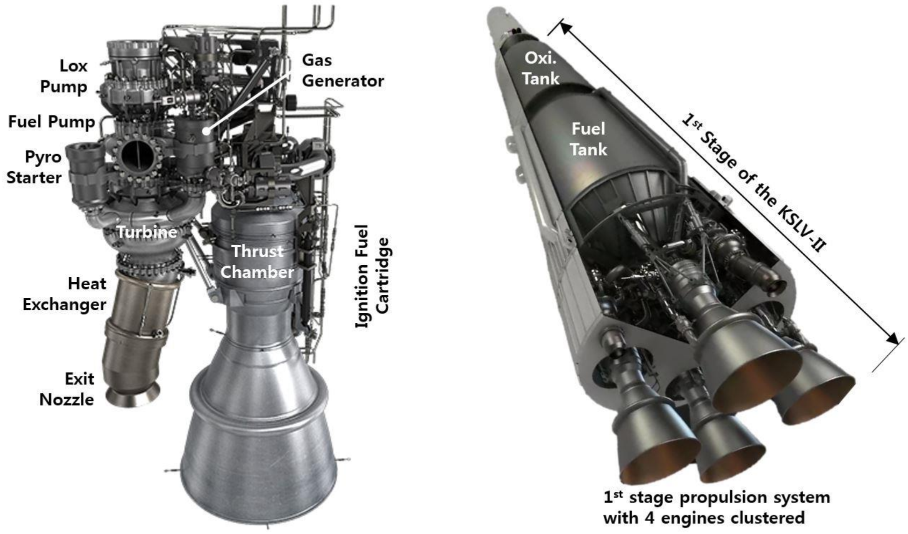


Figure 2: (Left) 75 tonf-class liquid rocket engine and (Right) 1st stage propulsion system clustered with four 75 tonf-class engines of the KSLV-II [1]

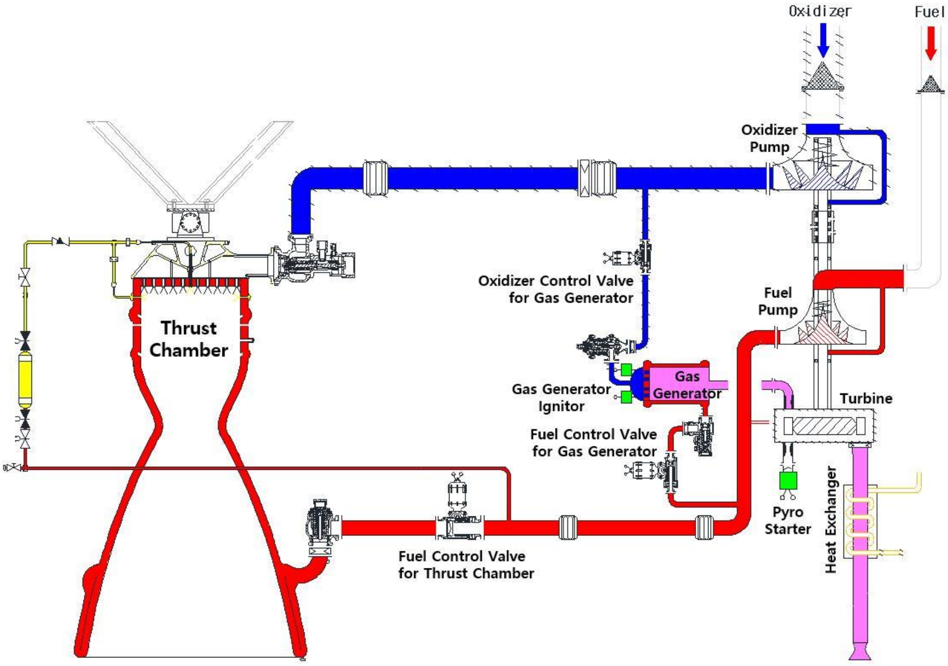


Figure 3: Schematic of the 75 tonf-class open type gas generator cycle liquid rocket engine which was used in the test launch vehicle flown in nov. 2018 and also will be used in the KSLV-II

2. Development process of a 75 tonf class gas generator

Development of the 75tGG for the open-type gas generator cycle liquid rocket engine was based on the development experience and technology acquired in the course of the 30 tonf-class liquid rocket engine gas generator (herein called as 30tGG) development [4, 5] conducted during the previous KSLV-I project. Development of 30tGG (figure 4, [4]) which is operated under fuel-rich condition was started in 2002, and 8 sub-scale and 11 full-scale hardware models were produced and tested by 2008. Using 11 full-scale gas generators, 21 combustion tests with an accumulation time of 470 seconds were performed. In addition, 30tGG had been tested successfully the engine power pack in combination with the turbo pump using the overseas test facility and obtained a satisfactory result on combustion characteristics, combustion stability, and durability.

75tGG is almost identical to the 30tGG, except that the propellant flow increases about three times as the engine thrust increases. Therefore, based on the technology obtained in 30tGG, cylinder-type combustion chambers, coaxial swirl injectors, and regeneratively cooled combustion chamber were applied to 75-ton gas generators identically.

Figure 4: Gas generator developed for the 30 tonf-class open cycle liquid rocket engine

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Technology Demonstration Model Phase (Full scale) | Technology Demonstration Model Phase (Sub scale, 1/5) | (Engine &) Development Model Phase I | (Engine &) Development Model Phase II

Figure 5: Appearances of the assembled or welded 75 tonf-class gas generators at each phase

75tGG development program can be divided into four phases: full scale technology demonstration model (TDM), subscale TDM (STDM), phase I and II of the development mode (DM) and engine development model (EDM) (Table 1). Details of each development phase and test methods will be described in the following sections.

Table 1: Categorization of the 75 tonf-class gas generator

	Number of hardwares	**Number of injectors**	**Din[a] / Lcyl[b]**	**Number of tests / accumulated time[c]**
TDM (full scale)	2	37	165 mm / 146 mm	6 / 17 s
TDM (subscale)	5	7	74 mm / 146 mm	60 / 266 s
DM, EDM - phase I	4	33 / 35	157 mm / 167 mm	131 / 3,928 s
DM, EDM - phase II[d]	19	30	157 mm / 167 mm	238 / 13,062 s

[a] Inner diameter of the gas generator's combustion chamber

[b] Length of the cylinder part of the gas generator's combustion chamber

[c] number of tests and the accumulative time are the sum of autonomous tests, engine system tests, stage qualification tests, and test launch vehicle flight test.

[d] presented numbers of test gas generator, tests, and accumulated time are still increasing.

2.1 Full scale technology demonstration model

TDM corresponds to the prototype model of the DM, and it as a prototype identifies the necessary skills and problems that could be possible to encounter during the design, fabrication, and combustion test at the beginning of new hardware development.

Because KARI has developed 30tGG in advance, the development of the 75tGG TDM has been carried out from a full-scale model despite the increase of the flow rate by three times compared with the previous one. But injector head and combustion chamber are separated for easy access to and replacement of the injector head.

Two heads and two (dump cooled and regeneratively cooled) combustion chambers were made for the 75tGG TDM test (figure 6) and combustion tests were carried out in a model rocket engine test facility (mRETF, where the tests of the 30tGG were performed) located in Daejeon for two months (Sep. 2009. ~ Nov. 2009) [6].

In the development of 30tGG, burnt gas produced from the gas generator was injected into a noise suppression system (NSS) which is opened to ambient, and water was injected at the inlet and the rear of the NSS to prevent further ignition of unburned gas and to cool down the gas temperature. However, since the amount of unburned gas from the 75tGG increases about three times compared with 30tGG, the risk in case of an explosion inside the NSS which experienced once during the 30tGG development has increased highly. So, the gas outlet of the gas generator is connected to NSS with an enclosed connector without a gap so that the external air can't flow into the NSS. Additionally, to eliminate

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the unexpected ignition burnt gas was cooled down and the gas mixture was made below the ignition limit by injecting liquid nitrogen into the NSS. Cooling water was also sprayed into the NSS to lower the gas temperature and to protect NSS (figure 7).

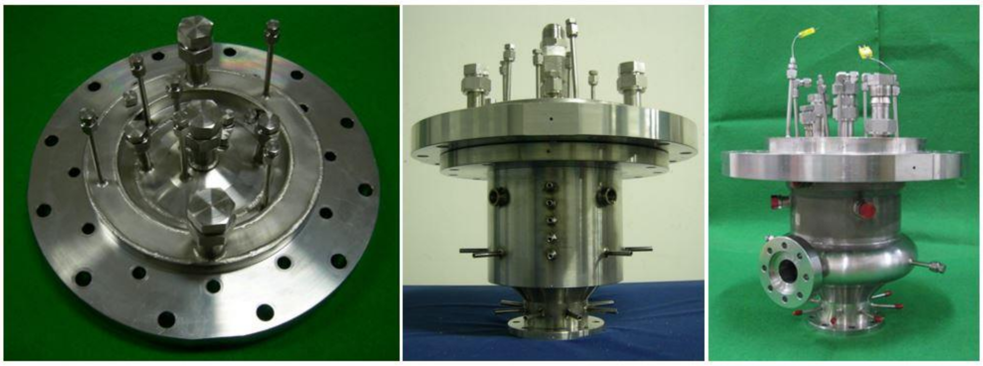

Figure 6: Full-scale technology demonstration model, (left) head assembly implemented with propellant injector, manifold and ignitor connecting port, (center) gas generator assembly with a dump cooling chamber, (right) gas generator assembly with a regenerative cooling chamber

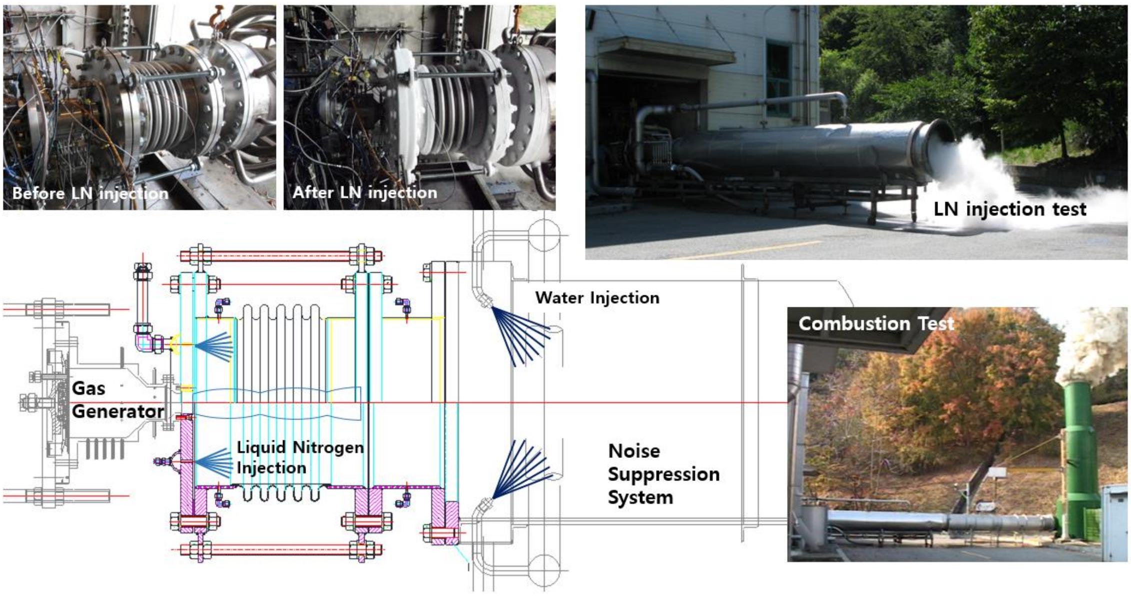

Figure 7: Test facility configuration and method for quenching the unburnt gas exhausted from the 75 tonf class gas generator corresponding to full scale technology demonstration model.

After hardware fabrication and test facility changing combustion test with TDM was carried out 6 times and the cumulative combustion time was 17 s. The less number of tests and cumulative time performed using the two TDMs was due to the test facility problems (the shrinkage stress of test facility and leakage of fastening part caused by the injection of liquid nitrogen, impact on the connector during the ignition period, sprayed water pollution), hardware breakage (fuel leak due to crack of head face plate welding part caused by fuel lead propellant supply sequence and explosion during ignition due to fuel leakage), increase of oxidizer injection pressure compared to injector cold flow test with water.

For this reason, the full-scale TDM test was closed in six times firing tests, and no combined test with the regenerative cooling chamber corresponding to the second combustion chamber test was performed. And to find solutions mentioned above quickly and to speed up the processing time, a test using subscale TDM had decided.

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2.2 Subscale Technology demonstration model

In order to identify and resolve the cause of increase in the differential pressure of the oxidizer injector quickly mentioned at the end of previous section, and to select the candidate injector for a DM, it was decided to use a subscale technology demonstration model (STDM) corresponding to 1/5 scale of TDM. In STDM, to focus on the combustion characteristics according to the injector design, one identical uncooled combustion chamber was used for all tests. Injectors were designed with varying the dimension of tangent hole diameter, swirl chamber diameter, nozzle diameter, and the like to change the spray angle, momentum and velocity rato between oxidizer and fuel, and pressure drop. With five different injector designs five STDM injector heads were made sequentially(figure 8) and using them a total of 60 firing tests were performed with a cumulative time of 266 seconds for about 2 years (2010.02 ~ 2012.01) and most tests were conducted with a duration of 4 seconds with combustion pressure and supply flow reaching steady state. Through these firing tests injector's differential pressure characteristics, combustion characteristics and combustion stability according to the injector design were evaluated [7, 8, 9].

Although the flow rate of STDM is reduced to 1/5 scale compared to TDM, the burnt gas treatment is a difficult matter to be resolved. But it is apparent that the method of quenching and cooling by liquid nitrogen injection in the closed NSS is not suitable for the current test facility and furthermore it is not obvious that it could prevent an explosion. So, in the early stage of the STDM test, burnt gas was sent into the NSS and water was sprayed in the same manner as the 30tGG development test without after-burning.

However, in order to ensure the safety of the following tests, it was needed to adopting a method of burnt gas afterburning in the atmosphere. The burnt gas from the gas generator flows through the closed pipe, then it is discharged from the four exhaust pipes into the atmosphere and ignited by two gas torches (Figure 9, [10]).

Figure 8: STDM, (left) head assembly, (center) dump cooling combustion chamber, (right) gas generator assembly

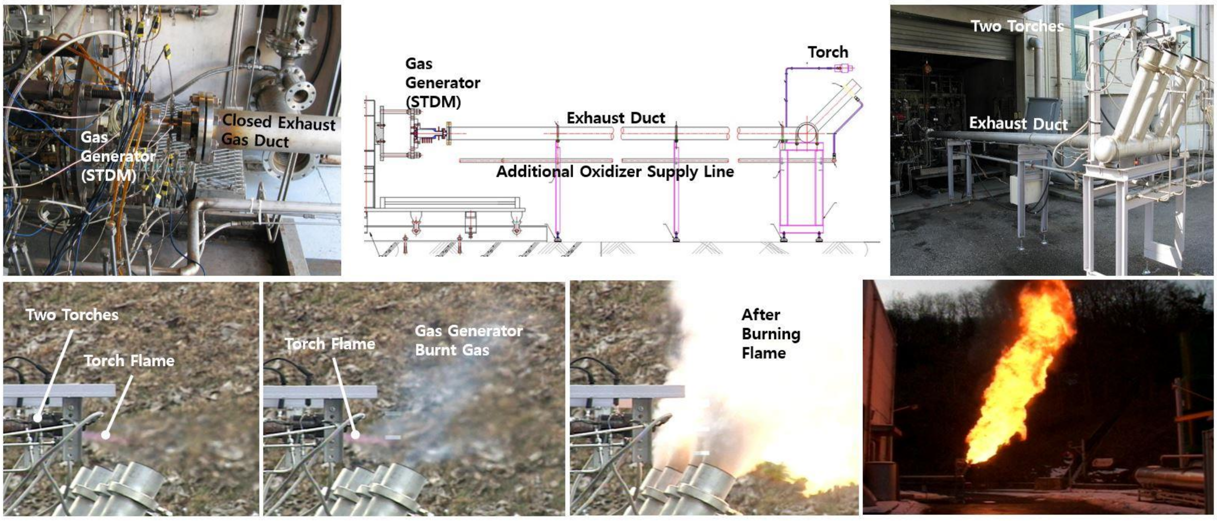

Figure 9: Test facility configuration and captured images during the combustion test

Additional oxidizer supply line in figure 9 is a redundant device for further supply the oxidizer to the gas outlet in case of the flame length of the afterburning is too long. The flame intensity and length change with additional oxidant supply were also verified through the firing tests. Since the length of the flame in the absence of additional oxidant supply is sufficiently acceptable in the test facility, there is no need to supply the additional oxidizer to reduce it.

2.3 Development model and engine development model

Development (design, manufacturing, and firing test) of a full-scale DM of 75tGG is started from the selected injectors through the five STDM tests, and EDM of 75tGG to be delivered to the engine system is manufactured with the design of the best DM at that moment. In the early phase of 30tGG development and TDM, STDM phase, head and combustion chamber were separated and assembled with bolts. However, in the 75tGG, considering the experience, technology level and reliability of production verified through TDM and STDM phases, DM was started as an integral piece that cannot be separated.

In a typical fuel-rich gas generator cycle engine, combustion gas temperature of a gas generator is limited to relatively low values due to the material and structural reasons of turbo-pump turbine blades which rotates at very high speed [11, 12, 13]. At the specified temperature for the 75tGG, it is verified by structural analysis that the combustion chamber of the 75tGG can be made without cooling if nickel alloy which maintains relatively high strength at the high temperature condition is used in the combustion chamber. It also verified experimentally from the TDM and STDM tests, because the combustion chamber made with stainless steel has no defect and structural problems throughout the entire development tests at the identical temperature condition.

However, consideration is given to blocking the possibility of thermal deformation due to during repeat use and cumulative time, ensuring structural stability and durability, minimizing the influence of the engine components around the gas generator due to radiation heat, preventing additional weight due to the use of thermal insulation, workability and handling difficulty of the material, then 75tGG chamber was determined to be a regenerative cooling type that was cooled with fuel. Except for the duplex material used in the outer jacket, almost parts of the 75tGG are manufactured with stainless steel, which is widely used in the general industry. Therefore, no particular problems come from material such as material characteristics variation, supply, etc. had been encountered.

Structural analysis on the 75tGG with regenerative cooling combustion chambers was performed to verify structural stability for the cooling channel, outer jacket, fuel ring, injector manifold, and head dome. Through the analysis process, the thickness of the injector faceplate and the middle plate were increased to enhance the structural stability, and thickness of the outer jacket was able to be decreased due to it had enough structural margin. Through the analysis and design modification, the 75tGG design with a moderate structural margin was obtained in the operating range, and some weight savings had been possible (figure 10).

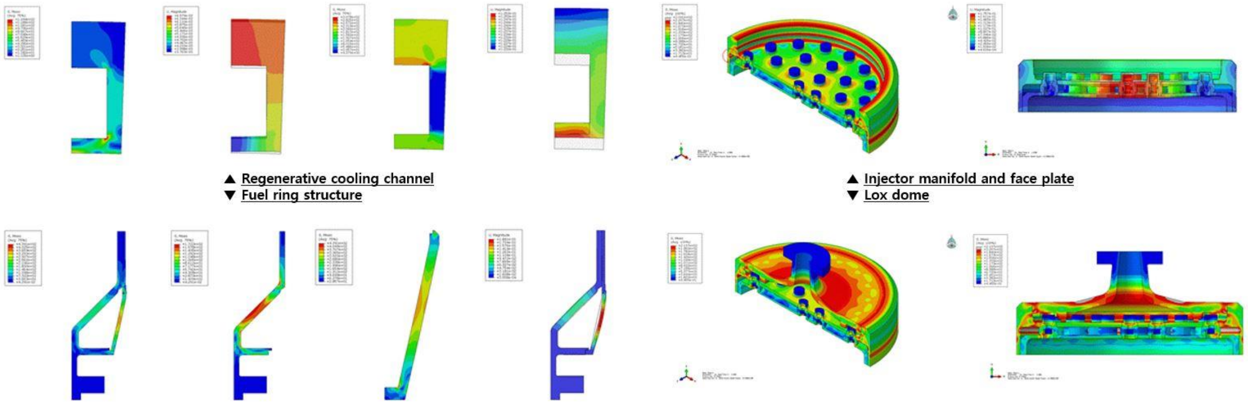

Figure 10: Structural analyses on the 75tGG, (left) regenerative cooling channel and fuel ring, and (right) injector manifold and faceplate, and oxidizer dome

The acoustic analysis was performed on the field containing the turbine nozzle collector (TNC, figure 11, [14]), considering the position of gas generator choking. Due to the role of the gas generator as an engine component and its operating characteristics, it is difficult to understand the quantitative and qualitative characteristics of the gas generator without the turbine nozzle collector. Moreover, because the acoustic characteristics are solely dependent on the spatial shape, the acoustic analysis should be done on the filed containing the TNC.

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However, since the use of the actual turbo-pump component in the initial development stage of the gas generator is a burden on both time and cost. So, in the 30tGG firing test straight pipe type simulator was used to simulate the length of the turbine nozzle collector [15], but it was insufficient to properly reflect the flow path divided into two at the inlet of the TNC and the characteristics of each of the combustion gases exhausted from the multiple turbine nozzles
In order to compensate for this, in the development of 75tGG DM, a product having the same internal shape as that of the real TNC is manufactured separately which is similar to the Fastrac engine gas generator development test [16], and a simulator that equally matched the internal flow length and the relative position of the nozzle was used as needed. The actual TNC disassembled from 75 tonf-class engine was used from the tests of the 6th DM and the 4th EDM [17 (Figure 12).

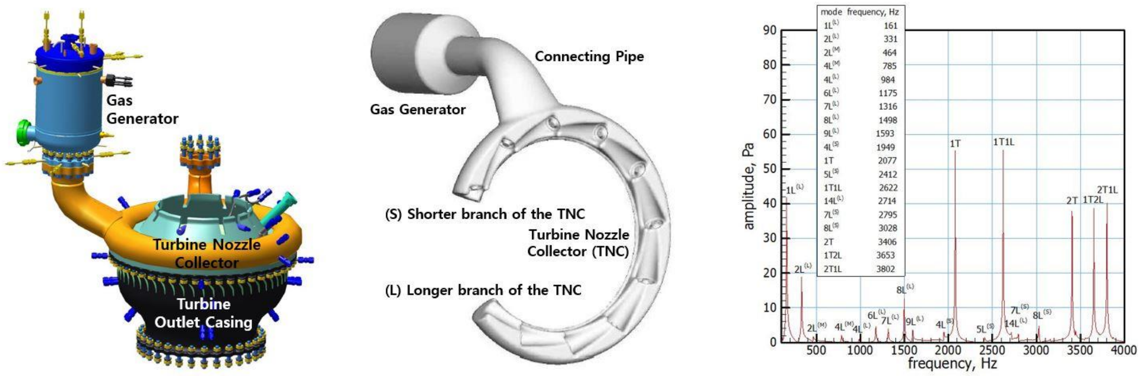

Figure 11: Acoustic mode analysis of the 75tGG, (left) gas generator and turbine assembly, (center) contour of an acoustic mode analysis domain, (right) mode analysis result

Figure 12: Turbine nozzle collectors, its simulators, and single choking nozzle used in the course of gas generator development test for simulating the actual combustion field

The flow analysis for the propellant was also performed to verify the propellant distribution and pressure loss supplied by each injector in the designed shape. Figure 13 shows the results of the analysis of the pressure and streamline distribution. In the flow analysis, the oxidizer and the fuel are supplied at a higher flow rate to the centrally located injector, and the maximum flow rate deviation for an individual oxidizer and fuel injector is 2.2% and 0.93% respectively. It is not a good condition that the propellant is concentrated spatially in a small area, however in a gas generator, the mixture ratio defined as the ratio of an oxidizer mass flow rate to a fuel mass flow rate (O/F ratio) is more important to supply burnt gas with a uniform temperature. Using the oxidizer and the fuel supply flow rate for the individual injector, the deviation of the mixture ratio in the coaxial injector is calculated. As a result, the maximum and minimum mixture ratio deviations are 1.91 % and -1.5 %, it is sufficiently acceptable values.

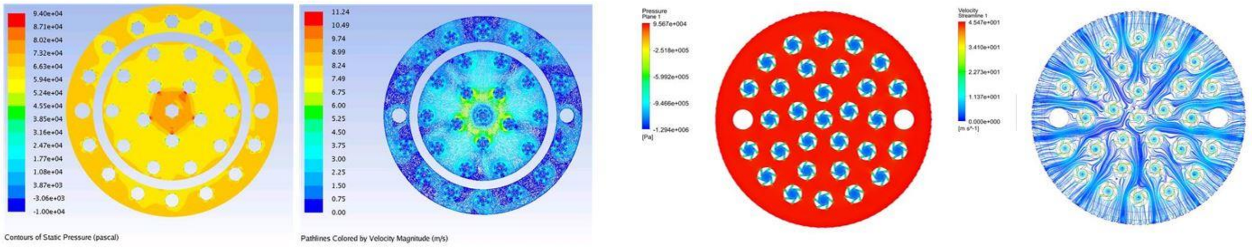

Figure 13: Propellants flow analysis results at the plane of injector for (left) oxidizer, (right) fuel

The design specifications of the 75tGG were changed from the 1st DM according to the TDM and STDM test results and the turbo pump development progress. And in the 5th DM, the specification was changed again, then the current and final specification of the 75tGG was derived. The main reason for the change of specification is that the gas temperature according to the mixture ratio and turbo-pump performance are different from the initial predicted value as the development tests progressed. Compared with the specification of the TDM phase, the final gas generator specification of the flow rate decreased by more than 20%, the combustion chamber pressure increased by 4%, and the mixing ratio decreased by 5.2%.

In the case of the DM, development procedure was completed with 8 articles and 117 times development tests with the cumulative time of 2 934 seconds were conducted during approximately 4 years (Sep. 2013 ~ Sep. 2017). Most of the combustion tests were performed for 20 seconds to assure the time to reach a thermal equilibrium state.

The 7th DM gas generator, qualification model of the 75tGG, was tested 29 times with 1 155 cumulative seconds. In the rated condition and the maximum and minimum operating conditions of the 75 tonf-class engine, which are defined by the combustion pressure and O/F ratio were carried out. Through these tests, 75tGG has been verified its durability, performance repeatability, and combustion stability over an operating time of more than 20 times and more than 10 times of flight time.

The gas generator EDM undergoes an acceptance test to confirm that there is no unacceptable performance difference after manufacturing and before delivering to engine system, and then the engine system test will be performed after the engine assembly. For the EDM of 75tGG, up to now, 136 acceptance tests, and 113 engine tests with a total cumulative burning time of 14 247 seconds have been conducted and will it will increase continuously.

The 4th EDM gas generator was carried out acceptance test, engine system test, and combined test only for the heat exchanger sequentially. It underwent firing tests 56 times with a cumulative time of 2 960 seconds over these processes. Throughout the test program, its stable operation and durability in the aspect of the injector differential pressure, combustion characteristics, regenerative cooling, and combustion stability were confirmed

The 11th EDM gas generator, which is used in the engine qualification model, was performed 18 times of firing test with a cumulative time of 2 021 seconds including acceptance tests. The duration test, twice the mission time in a single ignition, was performed twice in the engine test.

So far, 24 EDM gas generators had been manufactured and delivered to the engine system and the 15 assembled engines had been tested. The 7th engine was mounted on the TLV and it successfully launched the TLV in November 2018. A total number of 34 EDM gas generators are planned to manufacture and supply. Although 19 engines are left to be tested, most of the remaining engines will be used for the 1st stage qualification test and flight test of KSLV-II, so it may be said that the 75 tonf-class engine qualification test is almost completed.

At the beginning of the development of the 75tGG, a dedicated test facility (named as Combustion Chamber Test Facility, herein as CCTF) in Goheung was being constructed and the alternative test facility in Daejeon was revealed that it was inadequate for a full-scale 75tGG test through the TDM test. Therefore, before CCTF completion, development tests for the 75tGG were performed by borrowing the test facility of the external organization. After CCTF completion in 2014, the first firing test was carried out with the 4th DM gas generator.

The safe handling a fuel-rich burnt gas was still a challenge to be resolved. Generally, it can be said that afterburning in the atmosphere is the safest way to neutralized or stabilize the fuel-rich burnt gases, besides the facility complexity of the need for large space and the need for a separate facility for ignition torch operation. So, afterburning of the burnt gas in the atmosphere, which was used in the latter model of the STDM firing test, was adopted instead of the quenching method by the injection of liquid nitrogen used during the TDM test. In the external facility, due to the space constraint problem, many exhaust pipelines were integrated in a narrow space and burnt gas was injected into the NSS which is directly open to outside through the short length of the gas duct, and afterburning was carried out with two ignition torches which were was mounted on the right after the exhaust pipelines. The afterburning system in the CCTF has 18 discharge pipelines and burnt gas ignition was done with 6 gas torches. Taking into consideration multiple and long-time tests performed during development, a water injection system was also installed to protect surrounding facilities and nature from high temperature flames (Figure 14).

DOI: 10.13009/EUCASS2019-521

Figure 14: Test facilities for the 75tGG firing test, (top) leased test facility at the early stage of development, (bottom) dedicated test facility in Goheung

3. Test results

Figure 15 shows the test time and the number of the test carried out with DM and EDM (except for the TDM and STDM tests) gas generator per half-year.

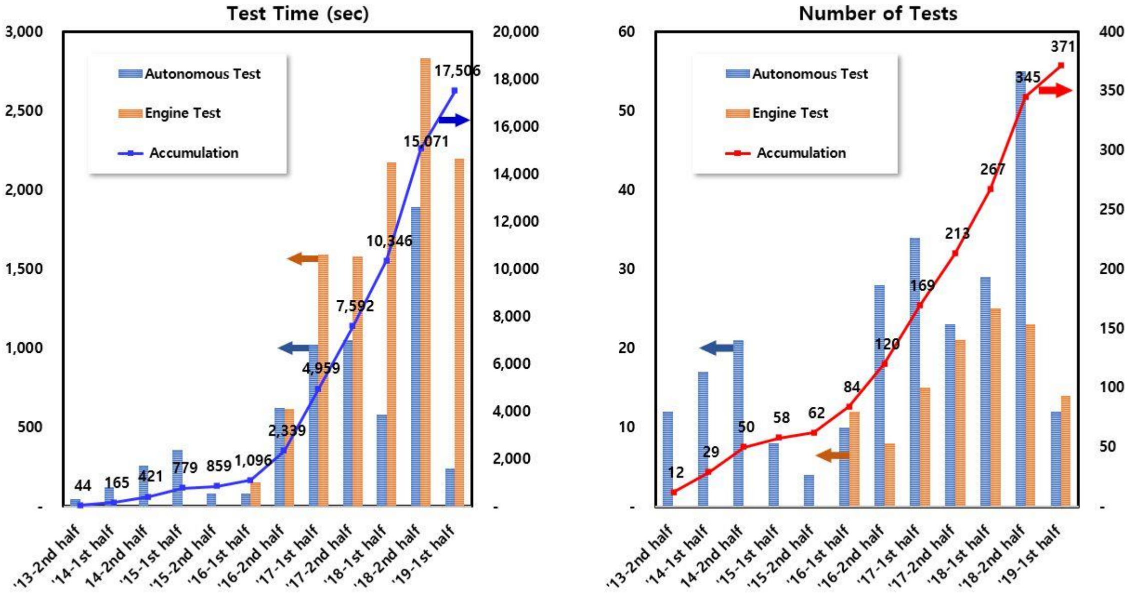

Figure 15: Semi-annual histories of test time and a number of tests conducted in the course of autonomous tests, acceptance tests, and the engine tests with the 75tGG DM and EDM. Presented data include the test histories of the 1st stage qualification tests and the flight test of TLV but exclude those of TDM and STDM.

In figure 15, the bar graphs represent the test time and the number of the tests performed in each half year, and solid lines represent the cumulative test time and the cumulative number of the tests for whole tested gas generators. So far now, the total test time and the number of the firing tests are over 430 times and over 17 700 seconds respectively and these include all the 75tGG autonomous tests, 75 tonf-class engine tests, and qualification tests of the TLV's 1st stage engine and the flight test of the TLV. The final target of the KSLV-II program is still going on, but the development of the 75tGG as a component of a launch vehicle and a 75 tonf-class liquid rocket engine can be said that it was completed.

75tGG operating specifications and actual firing test conditions are presented in figure 16, and axes and data are normalized with a value of the rated condition. In the figure the abscissa represents the O/F ratio and the ordinate represents the combustion chamber pressure. 75tGG shows a stable combustion feature in all of the presented conditions, and the verified range enveloped with red dash line means that within this range, a 75tGG is guaranteed the stable combustion.

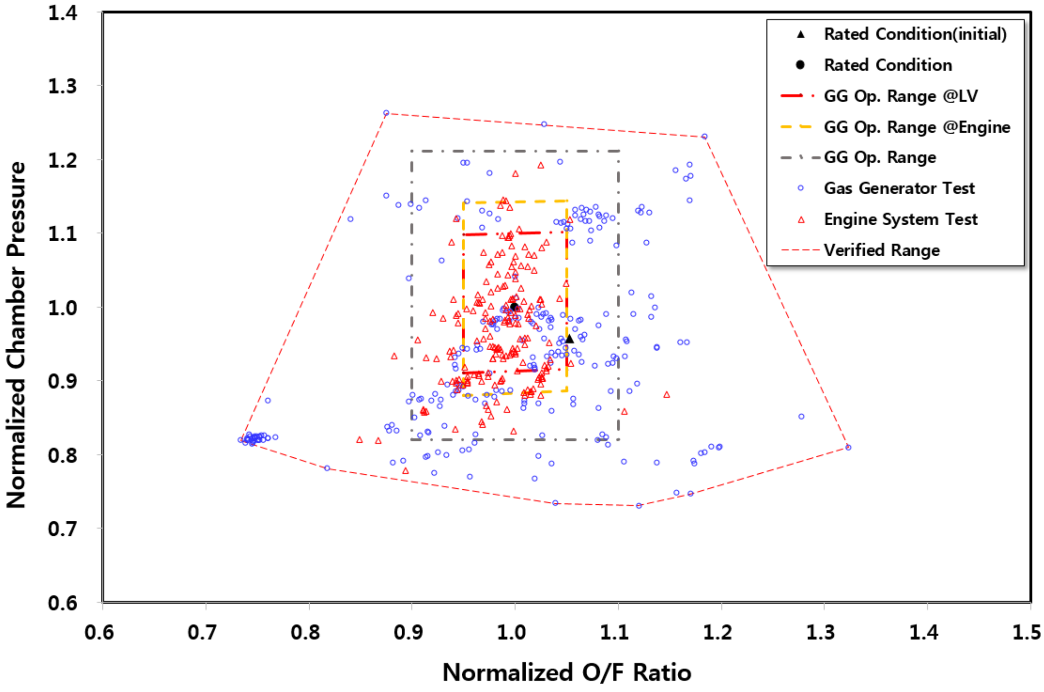

Figure 16: Normalized operating ranges by the rated condition of the 75 tonf class gas generator in terms of O/F ratio and chamber pressure

3.1 Chamber pressure and characteristic velocity

In the rated condition of the 75tGG, only about 10 % oxidizer is supplied to gas generator compared with propellant flow ratio at the stoichiometric condition. So, most of oxidizers participates in the combustion and reacts with the fuel. The heat released by the chemical reaction raises the remaining fuel temperature. Therefore, the combustion chamber pressure due to the volumetric expansion caused by the propellant chemical reaction is dominantly influenced by the oxidizer flow rate. And it also varies with the O/F ratio, which determines the temperature of a combustion gas. Considering this relationship, it is possible to derive a parameter that can be correlated with the combustion pressure using oxidizer flow rate and O/F ratio.

The values of two graphs shown in figure 17 are normalized with variable values corresponding to the rated condition of the 75tGG. Combustion chamber pressure and O/F ratio of the test results are divided with those rated condition values and correlation parameter and characteristic velocity which are calculated by equation 1 and 2. Equations are expressed by the total flow rate ($\dot{m}_{total}$), the oxidizer flow rate ($\dot{m}_{oxidizer}$), the O/F ratio, the combustion chamber pressure (P_{gg}), and the turbine nozzle cross-section area ($A_{turbine\ nozzle}$). As mentioned previously in chapter2, the results shown in figure 17 comes from the firing test in phase II of DM and EDM and the results come from the 239 tests for 22 gas generators using 3 turbine nozzle collectors. The test results show that there is a high correlation between the parameters regardless of the tested 75tGG.

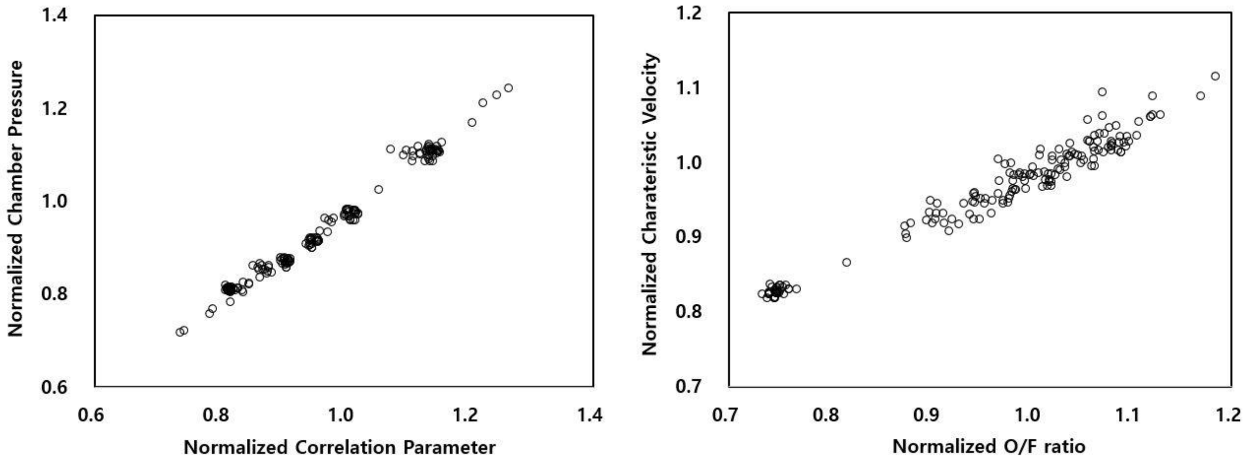

Figure 17: Data plots of (left) the chamber pressure as a function of correlation parameter and (right) the characteristic velocity as a function of oxidizer flow rate to fuel flow rate

$$\dot{m}_{oxidizer}\ x\ (O/F\ \ ratio)^{-0.13} \tag{1}$$

$$P_{gg}\ x\ \sum A_{turbine\ nozzle}\ \ /\ \dot{m}_{total} \tag{2}$$

3.2 Gas temperature

Since the gas temperature generated from the gas generator is one of the key parameters that determine the operating environment of the turbopump turbine blade, it is important that the quantizing of the temperature trends according to the O/F ratio. And it is also important that the 75tGG exhibits identical temperature trend regardless of the tested 75tGG with a small deviation. From the test results in figure 18, it can be said that gas temperature deviation at the same O/F ratio is within ± 2.0% and the spatial temperature deviation inside TNC is within 20 K. The measured temperature deviation satisfies ± 27.8 K [16] of the Fastrac engine and ± 50 K [18] of the Vulcain engine, and ± 70 K of the KSLV-II.

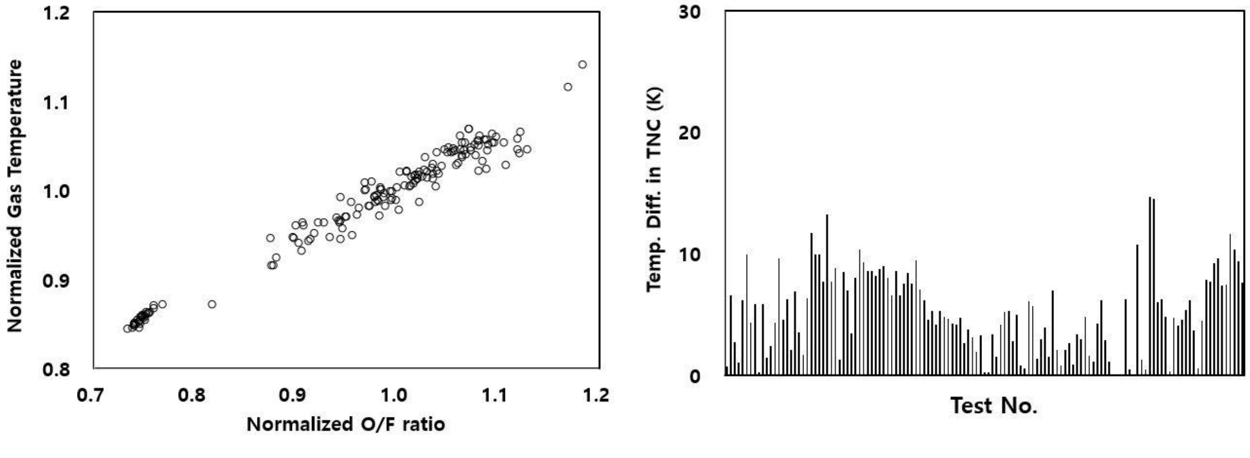

Figure 18: Data plots of (left) the combustion gas temperature as a function of oxidizer flow rate to fuel flow rate (right) the spatial temperature difference in the turbine nozzle collectors

DOI: 10.13009/EUCASS2019-521

3.3 Pressure loss

Assigned pressure drops to the 75tGG through the propellant supply passage including injectors should be satisfied. In the engine system, the nominal operating condition can be adjusted by changing the position of control valves, but generally, it is very desirable if the deviation of the each component can be zero or minimized. From the presented data in figure 19, it can be presumed that the deviation in the manufacturing process of the gas generator is well managed because it is confirmed that the deviation between the 75tGGs is within ± 2% in both the oxidizer and the fuel injector.

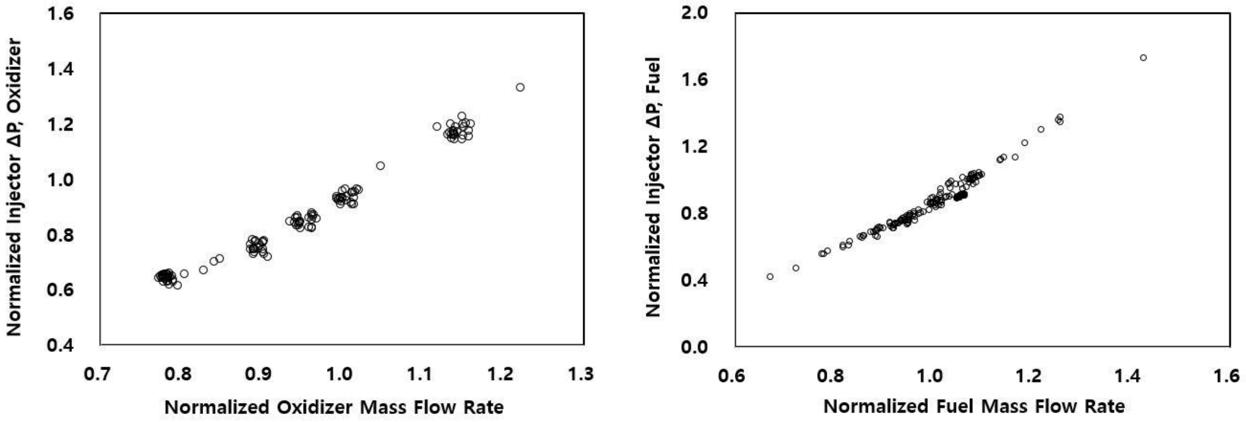

Figure 19: Data plots of the pressure loss of (left) the oxidizer injector (right) the fuel injector

3.4 Pressure fluctuation

In figure 20, the strengths of the pressure fluctuation in the combustion chamber are presented in the manner of normalization with a chamber pressure of each test (pressure fluctuation ratio). The diameter of circle is the normalized relative values and its position represents the firing test condition. The size of the circle is proportional to the root mean square value of the pressure fluctuation divided by the combustion pressure in the test and presented values corresponding to the pressure fluctuation ratio calculated in those conditions.

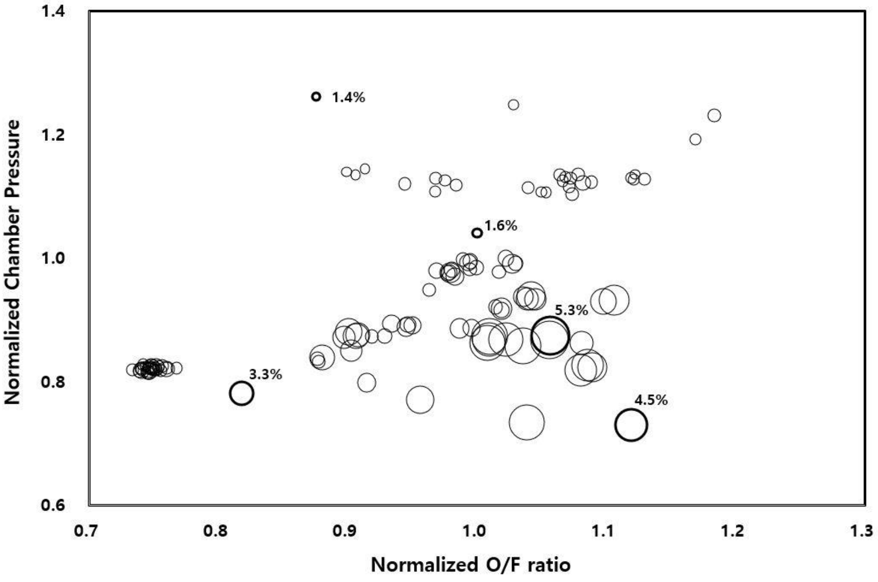

Figure 20: Data plot of the pressure perturbation: circle diameters represent the relative root mean square value of each test condition defined with the ratio of oxidizer to fuel flow rate and the chamber pressure.

DOI: 10.13009/EUCASS2019-521

The pressure fluctuation ratio identified in the test results represents a maximum of 5.3% and about 2% at the rated conditions. The reasons why the pressure fluctuation ratio is large in the low combustion pressure condition are the relatively higher pressure fluctuation and lower chamber pressure. A low combustion chamber pressure in the gas generator means that the oxidizer flow rate is relatively reduced, and which means that the test conditions shift to near the oxidizer critical pressure, 5.03 MPa. In the previous study, Ahn et al. [8] reported that the pressure fluctuation ratio increases at a pressure condition lower than the oxidizer critical pressure. Also in some types of injectors, low-frequency fluctuation occurred under certain a condition, and there was a phenomenon in which the fluctuation magnitude further increases when the fuel flow rate decreases at low chamber pressure conditions.

Tests of the 75tGG were carried out up to the chamber pressure of 87.8% the oxidizer critical pressure. And as in the previous study, the pressure fluctuation ratio increased with the increase of the mixture ratio and increased with the decrease of chamber pressure. However, there was no phenomenon in which specific frequency fluctuations were strongly appeared and persisted.

Figure 21 shows the results of the frequency analysis of the data measured with 50 kHz sampling for each interval of 6.0 ± 0.5 seconds and 130 ± 0.5 seconds after ignition at the same test, showing that the pressure fluctuation is low overall and no specific frequency concentration phenomenon. As shown in the figure, about 2 000 Hz and 2 300 Hz frequencies in the figure correspond to the 1T and 1T1L modes predicted from the acoustic analysis. Since energy concentration on the specific frequency and the increase of fluctuation does not appear, it can be presumed that it is a natural phenomenon determined by the shape of the gas generator and the combustion condition. As a result, stable operation of the 75tGG is conformed in the wide operating range shown in figure 16.

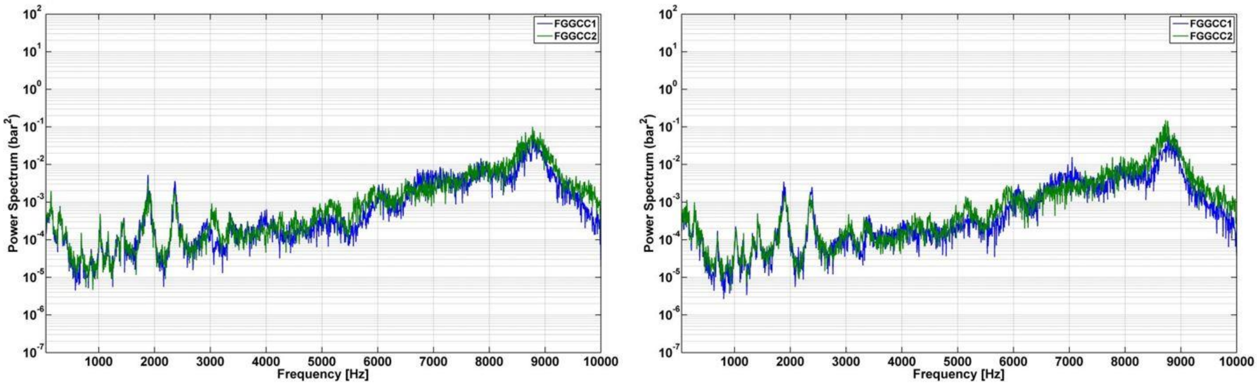

Figure 21: Data plots of the frequency analysis of a combustion test with DM#7, (left) for 5.5 s to 6.5 s interval after ignition, (right) for 129.5 s to 130.5 s interval after ignition

3. Summary

Korea Aerospace Research Institute has been developing a Korea Space Launch vehicle II to develop a practical satellite launch vehicle with its own technology from 2010, and the flight test of the 75 tonf-class liquid rocket engine verification was carried out in Nov. 2018. The flight test was successful, for the flight test of the three stage KLSV-II, the first stage and the third stage qualification test and assembly process are undergoing.

75tGG, as a component of the 75 tonf-class liquid rocket engine adopting the open type gas generator cycle scheduled to be used in the KSLV-II, has been developed through the 8 development model gas generators. And most of the 75 tonf-class engine development model using the 75tGG are tested also, then there are only a few engines are being prepared for engine qualification tests, so there is little possibility of troubles in gas generators in the remaining tests. The remaining 75tGGs are only the component for the flight test and those are scheduled to be completed in the first half of 2020.

In this paper, the overall development processes of the 75tGG such as design, fabrication, autonomous test, engine test, qualification test, and flight test using TLV and so on are described. And it was confirmed that the 75tGG has a suitable, stable, and enough characteristics for a flight test using the data obtained 437 times firing test with cumulative 17 789 seconds during the development processes.

DOI: 10.13009/EUCASS2019-521

References

[1] https://www.kari.re.kr/kslvii

[2] Hwan-Seok, Choi, Woo-Suk, Sul, and Soo-Yong, Lee, 2004, Development of liquid propellant rocket engine for KSR-III, 2004, Journal of the Korean Society of Propulsion Engineers, Vol.8, Issue 3, 75-86.

[3] Gwang-Rae, Cho, Jeong-Joo, Park, and, Eui-Seung, Chung, 2008, The Korean sounding rocket program, Acta Astronautica, Vol. 62, Issue 12, 706-714

[4] Hwan-Seok, Choi, Seonghyeon, Seo, Young-Mog, Kim, and Gwang-Rae, Cho, 2009, Development of 30-tonf lox/kerosene rocket engine combustion devices(II) – gas generator, Journal of the Korean Society for Aeronautical and Space Sciences, Vol. 37, Issue 10, 1038-1047.

[5] Seonghyeon, Seo, Yeoung-Min, Han, Hwan-Seok Choi, Young-Mog, Kim, and Gwang-Rae, Cho, 2009, Fuel-rich gas generator development for a lox/kerosene space rocket engine, 60th international astronautical congress,

[6] Kyubok, Ahn, Seonghyeon, Seo, Munki, Kim, Byoungjik, Lim, Jong-Gyu, Kim, Kwang-Jin, Lee, Yeoung-Min, Han, and Hwan-Seok, Choi, 2009, Hot-firing test of technology demonstration model gas generator for 75 tonf-class liquid rocket engine, Proceeding of the Korea Society of Propulsion Engineers 2009 Fall Conference, pp.225-230.

[7] Munki, Kim, Byoungjik, Lim, Donghyuk, Kang, Kyubok, Ahn, Jong-Gyu, Kim, and Hwan-Seok, Choi, 2012, Effect of injector shape on combustion performance of a subscale gas generator, Proceeding of the Korea Society of Propulsion Engineers 2012 Spring Conference

[8] Kyubok, Ahn, Byoungjik, Lim, and Hwan-Seok, Choi, 2014, Stability characteristics of bi-swirl coaxial injectors in fuel-rich combustion, Transaction of the Japan Society for Aeronautical and Space Sciences, Vol, 57, No. 6, pp.317-324.

[9] Byoungjik, Lim, Seonghyeon, Seo, Munki, Kim, Kyubok, Ahn, Jong-Gyu, Kim, and Hwan-Seok, 2013, Combustion characteristics of swirl coaxial injectors at kerosene-rich conditions, Fuel, Vol. 106, pp.639-645.

[10] Munki, Kim, Byoungjik, Lim, Donghyuk, Kang, Kyubok, Ahn, Jong-Gyu, Kim, and Hwan-Seok, Choi, 2011, Hot-firing tests of afterburning device for a gas generator, Proceeding of the Korea Society of Propulsion Engineers 2011 Spring Conference.

[11] Sutton, G. P. And Biblarz, O., Rocket Propulsion Elements, 7th Edition, Wiley-Interscience

[12] Randy C. Parsley and Baojiong Zang, Thermodynamics power cycle for pump-fed liquid rocket engines, Liquid Rocket Thrust Chamber: Aspect of modeling, analysis, and design, Progress in Astronautics and Aeronautics, Vol. 200, pp.621-648.

[13] NASA Space Vehicle Design Criteria(Chemical Propulsion), Liquid Propellant Gas Generator, 1972, NASA SP-8081

[14] Byoungjik, Lim, Munki, Kim, Jong-Gyu, Kim, and Hwan-Seok, Choi, 2015, Hot firing tests of gas generator for liquid rocket engine using a turbine manifold simulator, Journal of the Korean Society of Propulsion Engineers, Vol. 19, No. 5, pp.22-30

[15] Kyubok, Ahn and Hwan-Seok, Choi, 2012, Combustion dynamics of swirl coaxial injectors in fuel-rich combustion, Journal of Propulsion and Power, Vol. 28, No. 6, pp.1359-1367.

[16] Dennis, Jr.H.J. and Sanders, T., 2000, NASA Fastrac Engine Gas Generator Component Test Program and Results, 36th AIAA/SAE/ASME/ASEE Joint Propulsion Conference, Huntsville, A.L., USA, AIAA 2000-3401, pp. 17-19, Jul. 2000.

[17] Byoungjik, Lim, Munki, Kim, Jong-Gyu, Kim, and Hwan-Seok, Choi, 2016, Current status of 75-tonf liquid rocket engine gas generator for KSLV-II, Proceeding of the Korea Society of Propulsion Engineers 2016 Fall Conference.

[18] Thiard, B., 1990, Vulcain Gas Generator Development Status, 26th AIAA/SAE/ASME/ASEE Joint Propulsion Conference, Orlando, F.L, USA, AIAA-90-2252, pp. 16-18.