DOI: 10.13009/EUCASS2023-390
Aerospace Europe Conference 2023 – 10TH EUCASS – 9TH CEAS

KARI's Additive Rocket Initiative for Low-Cost and Sustainable Access to Space

Lim Byoungjik[†], *Lee Keejoo, Lee Keum-Oh, Lee Junseong and Park Jaesung*
Small Launch Vehicle Research Division, Korea Aerospace Research Institute
169-84 Gwahak-Ro, Yuseong-Gu, Daejeon City, South Korea
tachyon@kari.re.kr[†] – klee@kari.re.kr – kol@kari.re.kr – jsl@kari.re.rk – cronus@kari.re.kr

Abstract

In this paper, we will describe the additively manufactured liquid rocket engine components for the KARI's affordable and eco-friendly space transportation initiative. And we also introduce the current development status of thrust chamber and other components. Several thrust chamber parts have been manufactured by the additive manufacturing technologies, which are laser powder bed fusion(L-PBF) and powder directed energy deposition(p-DED), with the materials of pure copper, Inconel718, and CuCrZr for L-PBF and Al.bronze and Inconel 625 for p-DED. And manufactured thrust chambers had been conducted firing tests. Turbopump for 30 kN thrust liquid rocket engine is also under design and planning to be manufactured through additive manufacturing. Additionally, feasibility and applicability of additive manufacturing to engine nozzle extension, high-pressure vessels, heat exchanger and thrust frame has been evaluated and verified.

1. Introduction

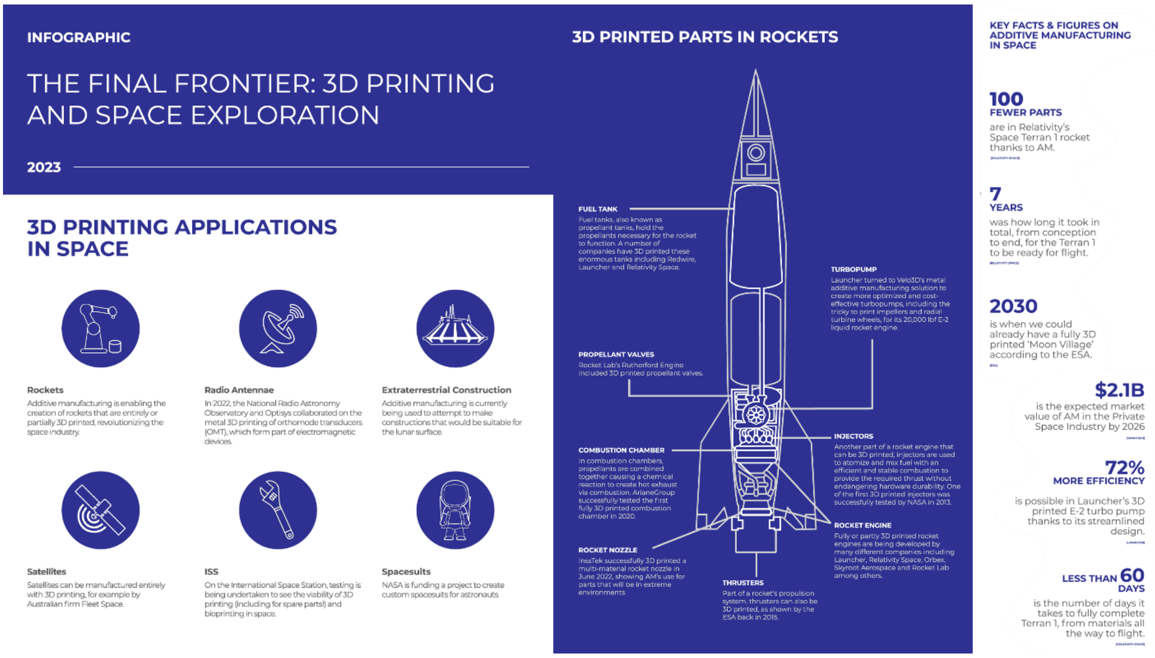
Now is the new space era, all over the world's launcher developers are desperately trying to lower the price for transportation services because it is a very crucial point for survival and directly affects sustainability. There may be several ways to reduce the price such as simplifying system design, standardizing launcher components and using standardized and commercial grade parts, lowering manufacturing and testing cost, re-using partially or fully launch vehicles, shortening logistic steps and periods, etc. In the case of liquid rocket engines, additive manufacturing (AM, or 3D printing) technology is becoming the dominant, essential, and inevitable manufacturing method by substituting for conventional subtractive and casting manufacturing technologies. AM technology has also been one of the major accelerators of the new space era by lowering the entry barrier into the space industries, especially for liquid rocket engine development.

Until now, there are three impressive moments for both AM technology and the space industry. First, on February 2013, a former president of the united states of America, Barack Obama's speech about 3D printing and policy for America Makes during the address to Congress [1] is very famous and influential despite a brief mention of less than 2 minutes speech out of the total 1 hour, in the line with the circumstance in 2014 when many key patents related to additive manufacturing technology were released [2]. At the same time, the number of small or micro-launch vehicle development private companies suddenly increased [3]. This phenomenon did not solely affect by AM technology, however, it cannot be deniable that AM technology has had a significant impact on it.

The second impressive and astonishing moments were the firing tests of SpaceX's Super Draco engine for the Crew Dragon Module [4] and Rocket Lab's Rutherford engine for the Electron rocket [5] manufactured by the powder bed fusion process which is the most representative technology for metal additive manufacturing using laser or electron beam. Until now, coincidentally, only these two companies which have succeeded in manufacturing liquid rocket engines through additive manufacturing are providing commercial space transportation services. The most recent heart beating scene was the inaugural flight test of the Relativity Space's Terran-1 rocket. In the case of this launch vehicle was made from metal AM technology about 85% by mass [6]. Nevertheless, it failed to ignite the second stage engine and consequently reach the target orbit, it proved that additively manufactured, or 3D printed, liquid rocket can withstand the max-Q load during flight and is structurally viable.

DOI: 10.13009/EUCASS2023-390

Actually, there are more companies and institutes that succeeded in firing tests and flight tests with the additively manufactured liquid rocket engines [7-19], but they haven't reached yet a stable state at the technology readiness level for launch flight test or regular commercial transportation services. However, it is true that most companies and institutes seeking affordable and sustainable space transportation systems have tried to adapt AM technology in engine fabrication to reduce cost, shorten the development period, enhance performance, and secure design variation and freedom. These trends show that additive manufacturing is one of the most important technologies to be secured for developing sustainable launch vehicles in the new space era with the rapid revolution and evolution of additive manufacturing technologies (Figure 1, [20-22]). To cope with this global technology transition to digital manufacturing in liquid rocket engines, Small Launch Vehicle Research Division (SLRD) in Korea Aerospace Research Institute (KARI) has been conducting fundamental and proceeding research on liquid rocket engine development and manufacturing through the AM technology.



Rockets Additive manufacturing is enabling the creation of rockets that are entirely or partially 3D printed, revolutionizing the space industry.

Radio Antennae In 2022, the National Radio Astronomy Observatory and Optisys collaborated on the metal 3D printing of orthomode transducers (OMT), which form part of electromagnetic devices.

Extraterrestrial Construction Additive manufacturing is currently being used to attempt to make constructions that would be suitable for the lunar surface.

Satellites Satellites can be manufactured entirely with 3D printing, for example by Australian firm Fleet Space.

ISS On the International Space Station, testing is being undertaken to see the viability of 3D printing (including for spare parts!) and bioprinting in space.

Spacesuits NASA is funding a project to create custom spacesuits for astronauts.

FUEL TANK Fuel tanks, also known as propellant tanks, hold the propellants necessary for the rocket to function. A number of companies have 3D printed these enormous tanks including Redwire, Launcher and Relativity Space.

TURBOPUMP Launcher turned to Velo3D's metal additive manufacturing solution to create more optimized and cost-effective turbopumps, including the tricky to print impellers and radial turbine wheels, for its 20,000 lbf E-2 liquid rocket engine.

PROPELLANT VALVES Rocket Lab's Rutherford Engine included 3D printed propellant valves.

COMBUSTION CHAMBER In combustion chambers, propellants are combined together causing a chemical reaction to create hot exhaust via combustion. ArianeGroup successfully tested the first fully 3D printed combustion chamber in 2020.

INJECTORS Another part of a rocket engine that can be 3D printed, injectors are used to atomize and mix fuel with an efficient and stable combustion to provide the required thrust without endangering hardware durability. One of the first 3D printed injectors was successfully tested by NASA in 2013.

ROCKET ENGINE Fully or partly 3D printed rocket engines are being developed by many different companies including Launcher, Relativity Space, Orbex, Skyroot Aerospace and Rocket Lab among others.

ROCKET NOZZLE InssTek successfully 3D printed a multi-material rocket nozzle in June 2022, showing AM's use for parts that will be in extreme environments.

THRUSTERS Part of a rocket's propulsion system, thrusters can also be 3D printed, as shown by the ESA back in 2015.

100 FEWER PARTS are in Relativity's Space Terran 1 rocket thanks to AM.

7 YEARS was how long it took in total, from conception to end, for the Terran 1 to be ready for flight.

2030 is when we could already have a fully 3D printed 'Moon Village' according to the ESA.

$2.1B is the expected market value of AM in the Private Space Industry by 2026

72% MORE EFFICIENCY is possible in Launcher's 3D printed E-2 turbo pump thanks to its streamlined design.

LESS THAN 60 DAYS is the number of days it takes to fully complete Terran 1, from materials all the way to flight.

Figure 1: 3D printing application on a liquid rocket and a space exploration, infographic by 3D Natives [23].

2. KARI's additive manufacturing initiative

Research on AM technology was started in 2019 with the preceding research on the two-stage small satellite launch vehicle for the affordable and competitive transportation system to respond to the rapidly growing small satellite launch service market, after the successful launch of the Test Launch Vehicle (TLV) of the Korea Space Launch Vehicle (KSLV) II. TLV was planned to verify the performance and technology maturity of the 75tonf class gas generator cycle liquid rocket engine which is used in the 1st and 2nd stage of KSLV-II, which uses kerosene as fuel.

The small satellite launch vehicle (KSLV-s) proposed by SLRD is a two-staged vehicle recognized as a global standard for liquid propellant launch vehicles (Figure 2, [22]). As shown in Figure 2, KSLV-s are under design to use the developed and flight-proven 75tf class engine for the 1st stage, and in the 2nd stage 3tf class liquid oxygen and liquid methane engine is proposed for the mission of deploying 500 kg payload into 500 km sun-synchronous orbit. Detailed considerations and conditions in selecting the design are described in the reference [24, 25].

Korea small satellite launch vehicle development project is specified in the 3rd master plan for promotion of aerospace development which was announced in 2018 by the National Space Committee. Last year, it was updated to the 4th master plan in Dec. 12. Personally, I think the restriction on the development of small satellite launch vehicles through the expansion of KSLV-II technology should be omitted and a solid focused small-lift launch vehicle plan should be revised. Anyway, at present, our division is carrying out system design for a small-lift launch vehicle platform optimized for the given requirements and constraints. And we also have been conducting preceding research on the core technologies such as the upper-stage engine, combined avionics system, and propellant tank for a commercially viable and sustainable launch vehicle.

DOI: 10.13009/EUCASS2023-390

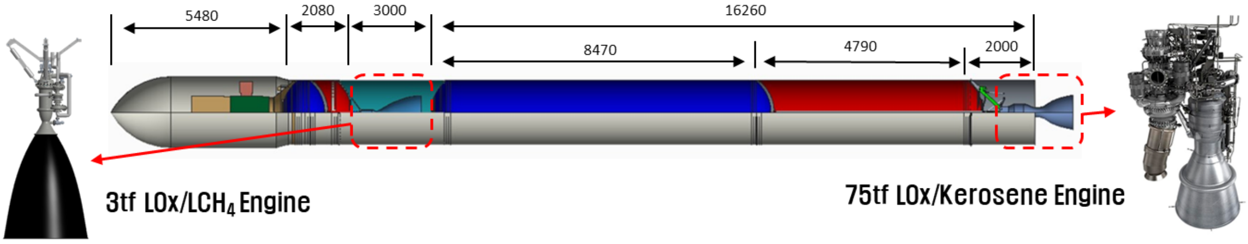


Figure 2: A two-stage small-lift launch vehicle designed by SLRD [22].

- **Top Requirements**

Items	Value
Thrust, kN	30
Isp, s	> 360
Propellants	LOX / LCH4(LNG)

- **Engine Initial Specifications**

Items	Value
Engine Cycle	Full Expander
Mixture Ratio	3.4
Chamber Pressure, MPa	4.5
Expansion Ratio	abt. 180
Nozzle Extension	Radiative cooling

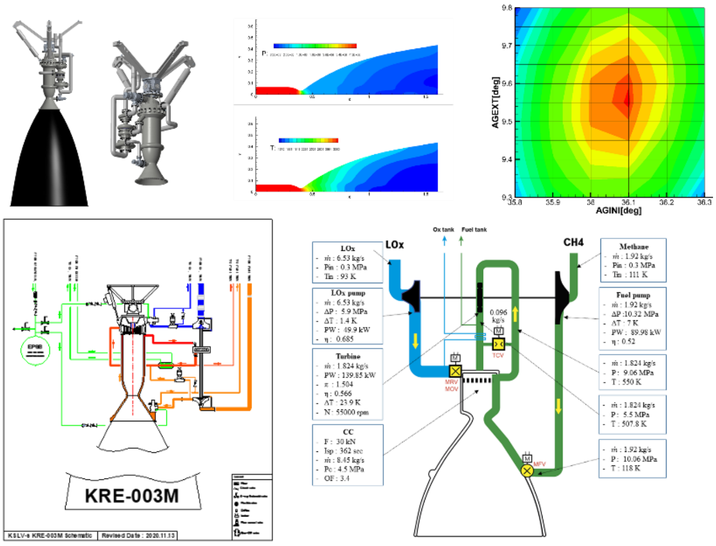


Figure 3: Requirements, initial specifications, and conceptual designs for the cryogenic upper stage of a two-stage small-lift launch vehicle.

Launch vehicle composition and staging had been set through the MCDM (multi-criteria decision-making) method [24] and other commercial software. For an expansion of the KSLV-II technology, a kerosene-based propulsion system is used in the 1st stage, but in the 2nd stage, the new methane engine was proposed to comply with the mission requirement of payload and orbit. A detailed upper-stage design and consideration can be found in the reference [22].

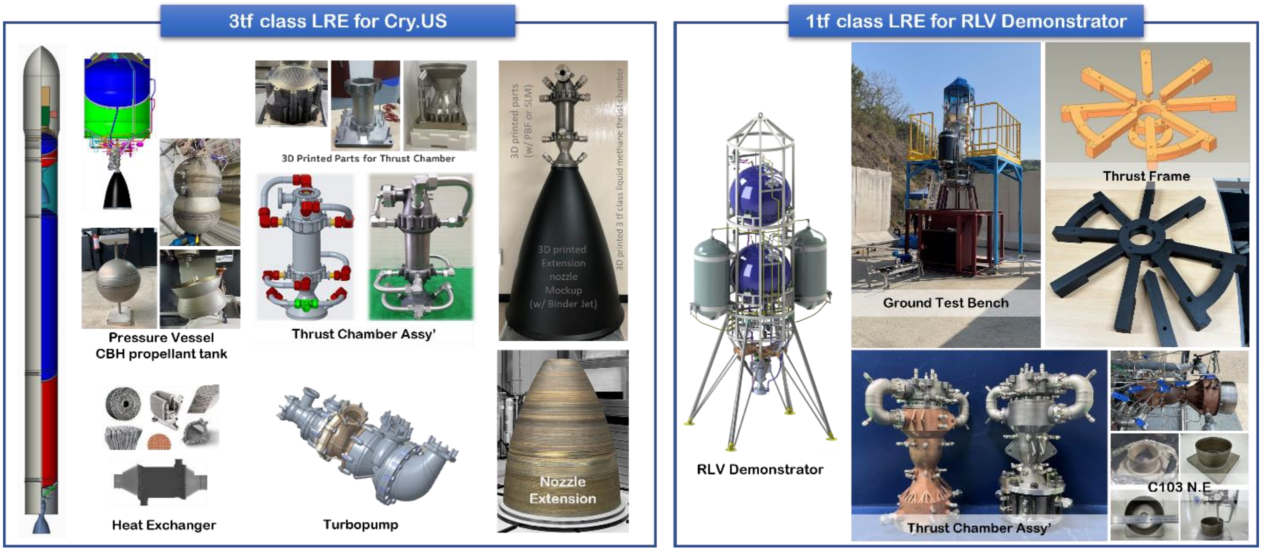


Figure 4: KARI's activities on additive manufacturing for liquid rockets.

DOI: 10.13009/EUCASS2023-390

Until now, KARI's activities in developing AM technology for a liquid rocket engine have been mainly focused on thrust chambers of 1tf and 3tf class engines and high-pressure vessels. But, recently use cases of AM technology are expanding in liquid rockets and engines, such as turbopump, heat exchanger, nozzle extension by metal AM, and a thrust frame for the VTVL demonstrator by the continuous carbon fiber extrusion technology to substitute the Aluminium alloy (Figure 4).

3. AM for thrust chamber

We have achieved the manufacturing and firing tests of the 3tf and 1tf class thrust chambers and conducted over 100 times tests including 80 times of hot firing tests (Figure 5, Table 1) with a mobile rocket engine test facility [25] that is using liquid oxygen (LOX) and liquid natural gas (LNG) as propellants. As shown in Figure 4 and Table 1, we made six thrust chamber assemblies, two are for the 3tf class engine and four are for the 1tf class engine. And a typical process for developing and evaluating the additively manufactured thrust chamber from design to verification was depicted in Figure 6.

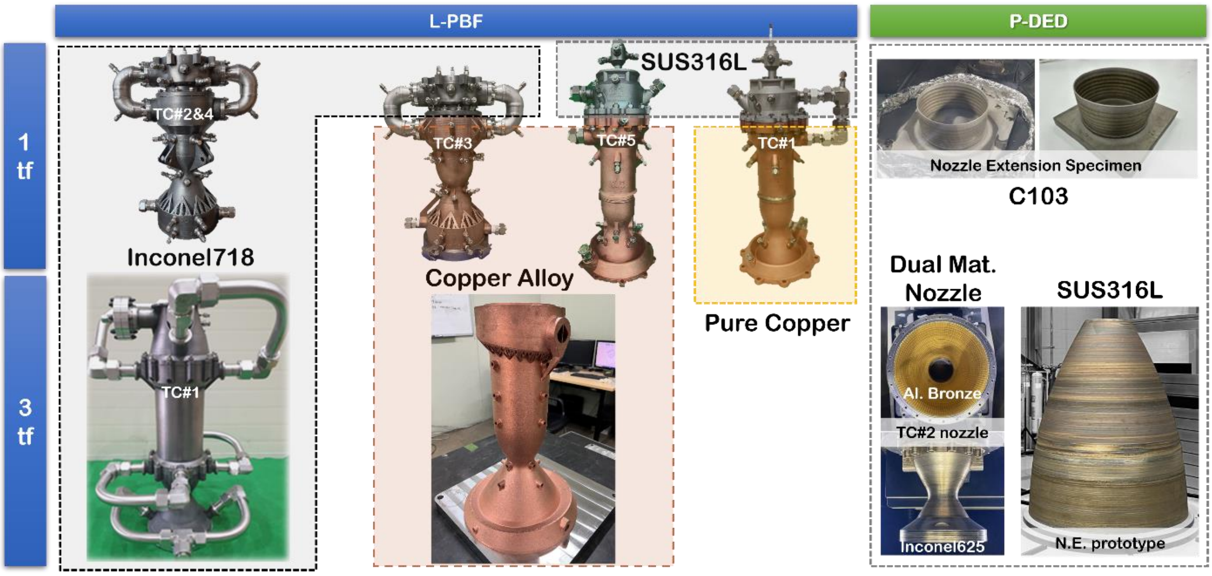


Figure 5: Additively manufactured thrust chamber components.

Table 1: Materials and firing tests histories of the additively manufactured 1tf and 3tf class thrust chambers

3tf class Thrust Chamber		
Model	TC#1	TC#2
Head	Inconel718	
Cylinder	Inconel718	
Nozzle	Inconel718	Al.Bronze + Inconel625
Firing Tests	17	5
Acc. Time	240 s	42 s

1tf class Thrust Chamber				
Model	TC#1	TC#2	TC#3	TC#4
Head	SUS316L	Inconel718	Inconel718	
Chamber	Pure Copper	Inconel718	CuCrZr	Inconel718
Nozzle Extension	-	-	C103 or C/SiC	-
Firing Tests	16	19	21	2
Acc. Time	138	295	453	7

Our first part which was manufactured by additive manufacturing technology was the cylinder part of a 3tf class thrust chamber in 2019 with M400-4 installed in EOS Singapore because at that time there was no available 3D printing machine corresponding to the part size in Korea. After the first part was made successfully, we additionally printed the head and nozzle parts of the 3tf class thrust chamber in 2021 with EOS M290 installed in the 3D printing Gyeongnam Center in Gyeongsang National University in Korea and 1tf class thrust chamber in 2020 with Velo3D Sapphire in AVACO and EOS M290 in VitzroNextech. The 1tf class thrust chamber was started from the necessity of a propulsion system for the ground test of the lunar lander and it is now expanded to the main engine of the VTVL demonstrator for researching core technologies on reusable launch vehicles.

DOI: 10.13009/EUCASS2023-390

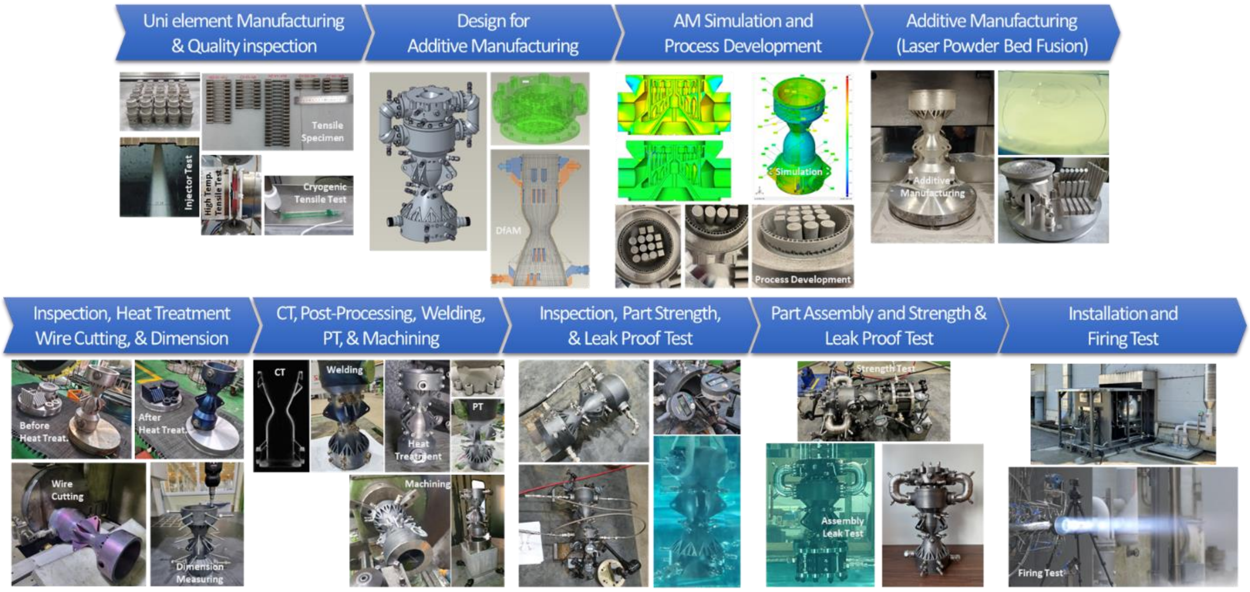


Figure 6: Typical manufacturing and evaluation process including additive manufacturing for a thrust chamber.

In the case of the 3tf class thrust chamber, only one head and cylinder part made from Inconel718 was used in hot firing tests, however, two of the 3tf nozzle parts were made from different materials and processes. The first one was made from Inconel718 by laser powder bed fusion technology (3D printing Gyeongnam center, EOS M290) and the other was made from al. bronze for the inner wall and inconel625 for the outer jacket by powder directed energy deposition technology (Insstek, MX-Fab& PCM-Multi.). The latter one is the world's first rocket engine thrust chamber part which was made by a multi-material simultaneous deposition technology and was conducted hot fire tests.

We had planned to evaluate a 3tf class combustion chamber (chamber part + nozzle part) made from copper alloy (CuCrZr), unfortunately, additive manufacturing had not been successful. In non-destructive inspection (computed scan, CT), it was found that almost regenerative cooling channels were clogged and in the leak-proof test some cracks toward the outer shell were found. So, the consolidated combustion chamber was cut by wire-cutting method for a detailed inspection. From the inspection results, it could be concluded that clogging had occurred during the transportation and storage period after the AM and automated de-powdering processes. From this and other clogged cases, we have learned the importance and necessity of de-powdering and consecutive work process from AM to wire-cut right after AM process.

For the 1tf class thrust chamber, four thrust chamber assemblies were made and tested. The first one (TC#1) was a conventional thrust chamber that is regeneratively cooled by a fuel, LNG. TC#1's head was made from stainless steel 316L and the combustion chamber was made from pure copper (Vitzro Nextech, EOS M290) in 2020. Despite, at that time, AM using inconel718 and copper alloy was not available in Korea and M290 with 400W laser was not proper for AM from copper, TC#1 manufacturing was launched to validate the possibility and effectiveness of AM in rocket engine component manufacturing. As the first hot firing test model (TC#1) and the first attempt for the LNG fuelled rocket engine in KARI, TC#1's firing tests were conducted very carefully [25-27] and in a step-by-step manner in parallel with the test condition adjustment and the safety control of the movable test facility [25].

In the design phase for the other (TC#2~TC#4) thrust chamber, we tried to implement and utilize the extended design freedom, the most important value of additive manufacturing in terms of the research engineer's point of view, that is unlocked by the additive manufacturing technology in the hardware design. Based on the enlarged design freedom, additive manufacturing stimulates disruptive innovations from conventional and traditional features. The exclusive features of the 1tf class thrust chamber can be said with the following two things which are the essential and key functionality of the engine system for a reusable launch vehicle and an in-space transport system. One is the dual regenerative cooling scheme to secure a thermally robust inner wall at throttled operating conditions, and the other is the head-integrated ignitor using propellants branched from main pipelines to secure a simple and infinite re-ignitable engine system by eliminating independent ignitor propellant reservoirs and related fill-drain valves and pipes from a rocket propulsion system [25, 28-31].

Liquid oxygen (LOx) and liquid natural gas (LNG) enter into the thrust chamber at the nozzle exit and flow toward the nozzle throat and chamber cylinder part in parallel side by side in contact with the ribs of the regenerative cooling

DOI: 10.13009/EUCASS2023-390

channel in between (Figure 7). In the cross-sectional drawing at the right in Figure 7, the areas in red and blue represent the flow fields of fuel and oxygen, respectively, precisely separated by the channel ribs formed through the AM process. If conventional techniques, machining/brazing or electro-plating, were used in manufacturing cooling channels, this scheme would not be realized and it would be very difficult to establish reliable manufacturing and verification processes in terms of machining of propellant merging and dividing walls and bonding each channel with the capability of 100% blocking propellants mixing between alternatively arranged cooling channels. In fact, this is more easily possible because it uses LOx and LNG as propellants, which are not much different in terms of temperature. Other fuels, such as kerosene and hydrogen, can be used in this scheme but in that case, icing phenomena in cooling channels and consequent reduced cross-sectional area effect should be evaluated carefully.

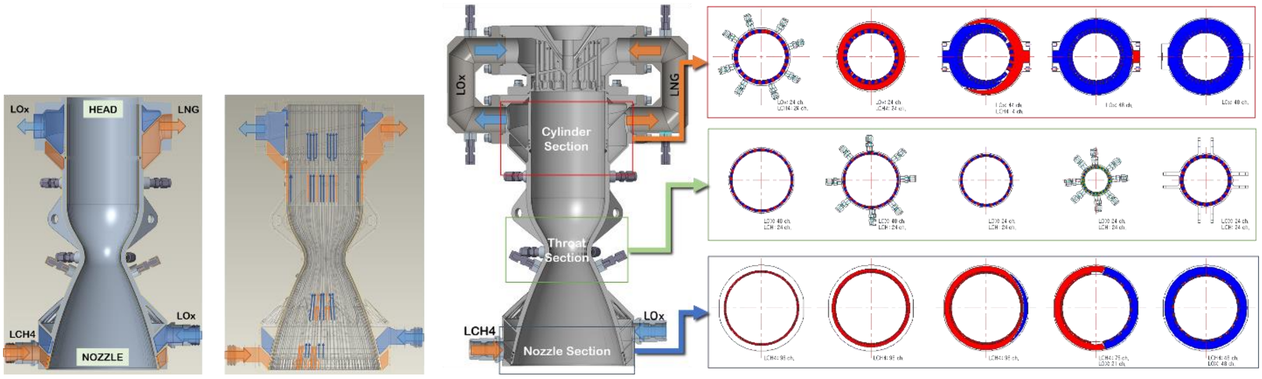


Figure 7: Dual regenerative cooling channel scheme and cross-sectional drawings represent each propellant flowing area along the thrust chamber axis.

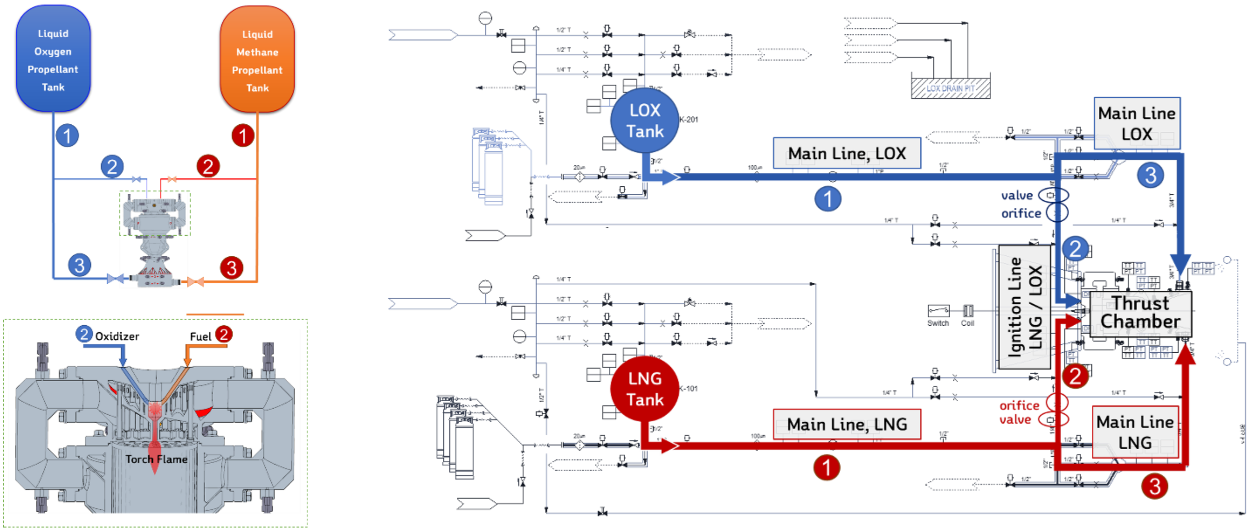


Figure 8: Main propellants line branched ignitor system scheme and its test configuration

In general gas torch ignition system for liquid rocket engines, such as Vinci, M10, SSME, etc, has separate pressure vessels for ignition propellants. In this research, without using these separate pressure vessels, ignition propellants are supplied by branching the main propellant supply lines (Figure 8). While supplying the liquid propellants through the branched lines, they are to be vaporized by heat exchange with the pipes, orifices, and valves. Supplied gases will be turned into gases eventually at the moment they enter the igniter chamber. By applying the concept, it is possible to realize the ignition system which has infinite times of re-ignition capability as long as only the main propellant remains. Additionally, applying additive manufacturing enabled the igniter chamber to be integrated into a mixing head, i.e. the separate part is a spark plug only. For the verification of this concept, a torch igniter chamber was manufactured separately with the same shape integrated into a mixing head. The ignition system had been tested 5 times for ignition capability and showed stable consecutive re-ignition capability.

As an engine for the upper stage and in-space transport system, nozzle extension is an inevitable part to enhance engine performance. Generally, there are two types of nozzle extension (NE), i.e. a regeneratively cooled NE (Vulcain series, SSME, LE-9, and Nuri's 3rd stage engine) and a radiatively cooled NE (Vinci, Merlin Vacuum, RL-10, and Rutherford Vacuum). To reduce engine weight and system power requirement, it is better to apply a radiative cooling nozzle with a refractory metal. The most well-known refractory metal for liquid rocket engines is the niobium-based alloy, C103. It is the patented product name code of ATI metals and almost materials in the form of sheets or bars used in liquid rockets and other applications have come from ATI metals. However, recently, thanks to the development, advance, and maturity of powder-based additive manufacturing new suppliers in the form of the powder are appearing, including ATI metals. SLRD has tried to find an appropriate process to make a nozzle extension from C103 powder by the P-DED with the research partner, Insstek. Before making NE specimens from C103, Insstek had conducted build-up tests of cubes to investigate the effect of the manufacturing processes (laser power, travel speed, and hatching path) and circumstance (closed argon gaseous condition and open atmospheric shield gas condition). Based on this preceding test, two C103 NE specimens, which had a dimension of about Ø150 mm x h75 mm, were made by Insstek's 3D printing equipment. One specimen was made in an atmospheric environment and the other in an argon circumstance with O_2 content under 50 ppm. Three hot firing tests using TC#3 were conducted with two C103 NE specimens and two additional tests with C/SiC nozzle, which was not made by the AM technology, were also conducted (Figure 9).

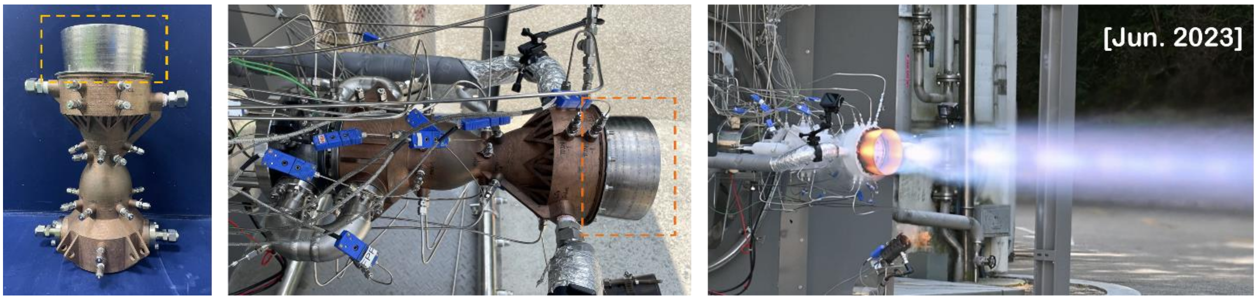


Figure 9: 1tf class thrust chamber and its hot firing test with C103 nozzle extension made by P-DED.

Additionally, SLRD is considering research to manufacture the entire 3tf class rocket engine nozzle extension using P-DED technology in cooperation with research partner Inssek who are developing the large size format P-DED platform, named NARAE, which had a capability up to Ø3.5 m x h7.5 m. The photo in the left box of Figure 4, is a build test product for process adjusting from stainless steel 316L.

4. AM for others

Application of additive manufacturing to other parts of a liquid rocket engine is always and continuously trying. Actually, we have been proceeding with these manufacturing activities for a common bulkhead propellant tank, high-pressure gas vessel, turbopump, heat exchanger, and thrust frame.

4.1 Common bulkhead propellant tank and high-pressure vessels

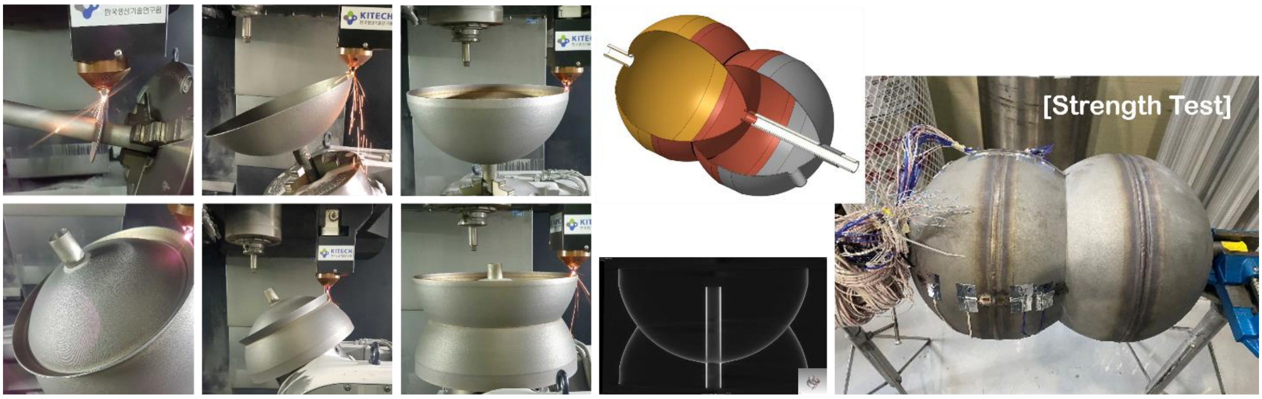


Figure 10: Common bulkhead propellants tank.

As shown in the two-stage small-lift launch vehicle design in Figure 2, a common bulkhead type of propellant tank is considered to reduce the length and structural weight of the launch vehicle. The prototype product in Figure 10 was manufactured from stainless steel 316L by the P-DED process in the Korea Additive Manufacturing Innovation Center

DOI: 10.13009/EUCASS2023-390

(KAMIC) of the Korea Institue of Industrial Technology (KITECH) and had passed the non-destructive inspection and the pressurized strength test up to 2 MPa. And now we have been manufacturing typical spherical high-pressure vessels and special space-optimized high-pressure vessels by various AM technologies such as P-DED, laser wire DED (LW-DED), L-PBF, and electron beam melting (EBM) from various materials such as stainless steel 316L, Inconel718, Titanium alloy.

4.2 Turbopump and heat exchanger

Turbopump and heat exchanger for the liquid rocket engine are one of the most considered parts that are applicable and effective in the adoption of the AM technology because of their complex geometry, need for special machining and casting technology to form internal flow paths, and constraints such as dividing components for machining and assembly.

Figure 11: Single-shaft liquid methane and liquid oxygen turbopump for a 3tf class expander cycle rocket engine.

SLRD is developing a turbopump critical design, which is based on additive manufacturing, with the cooperation of an international partner, we planned to finish the design phase works this year and are simultaneously investigating manufacturability and making prototypes with the domestic partners.

The heat exchanger is also one of the components that is of great interest and effective in the field of additive manufacturing. The most important factors in applying additive manufacturing technology to heat exchangers are the possibility of performance improvement through the implementation of complex flow paths, shape optimization, part consolidation and minimization of size. With the recent advance in optimization software, tools, algorithm and additive manufacturing technology in terms of material and fine feature generation, a heat exchanger is the most emerging part of the general industry as well as in the aerospace and liquid rocket industry. SLRD’s activity on the heat exchanger is in starting phase, and we are now coordinating requirements, reviewing manufacturability, and adjusting the post-production checklist with the partner.

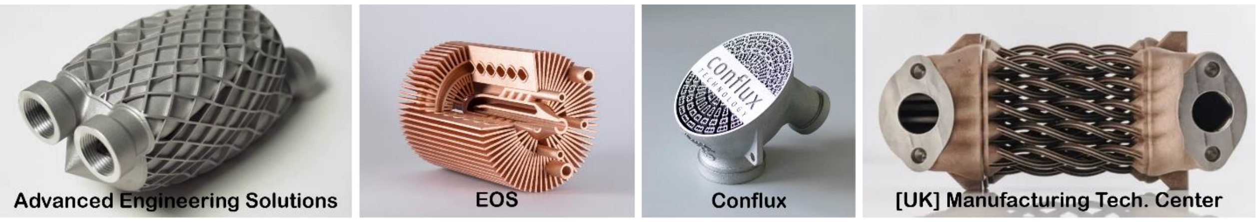


Figure 12: Heat exchangers optimized with AM technology.

4.3 Others

The application of additive manufacturing technology is not limited to engine components from metal but is also applied to manufacturing tools and thrust frames from continuous carbon fiber extrusion technology. Using our own

DOI: 10.13009/EUCASS2023-390

fused filament fabrication (FFF or FDM) equipment (Raise3D pro2 plus), we have been verifying additive manufacturing models, and manufacturing assembly jigs and protective covers for test parts (Figure 13).

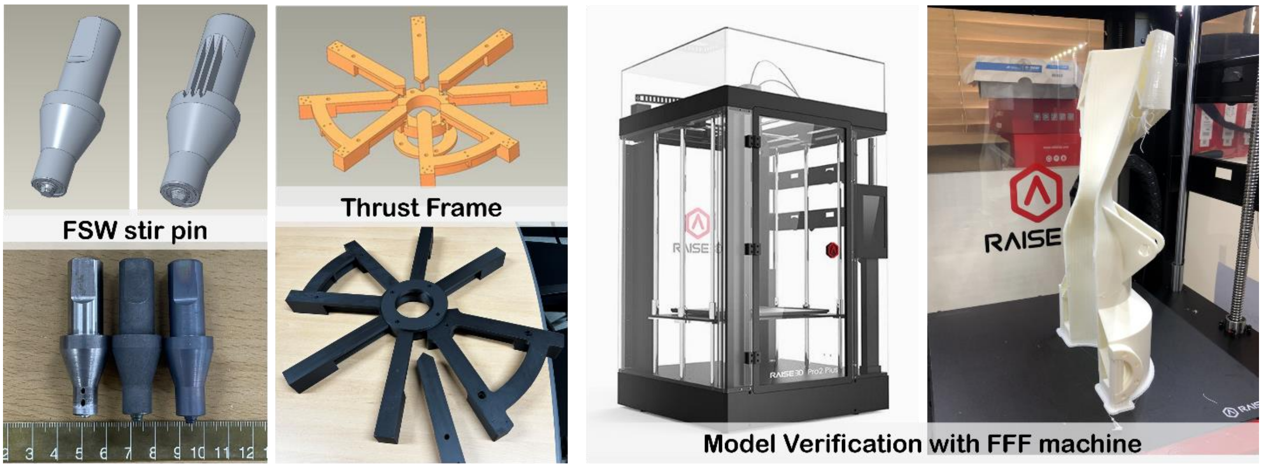


Figure 13: The other use cases of AM technologies in KARI.

5. Conclusions

Research on AM technology for low-cost and sustainable access to space has been started from 2019. As a current status, we have made some additively manufactured thrust chambers, 3tf class engine for the upper stage of a small-lift launch vehicle and 1tf class engine for the VTVL demonstrator, by changing design and material and also conducted 80 times of firing tests using the movable test facility. SLRD has also designed propellants tanks and pressure vessels for liquid rockets to optimize space and consequently reduce structural weight, manufactured by various additive manufacturing technologies and materials.

Through these activities, SLRD will find the best solution for the specific shape and application and also indirectly wish to stimulate and enlarge the domestic additive manufacturing industry. SLRD will continuously research the additive manufacturing technology for a liquid rocket engine and try to expand the liquid rocket application area to accelerate the new era of access to space for all.

References

[1] The Obama White House, The 2013 state of the union address (enhanced version), https://www.youtube.com/watch?v=S7doAXkmGJw, 13 Feb. 2013, retrieved on 25 Jun. 2023.
[2] Christopher Mims, Get ready: 3D printing will explode next year, when key patents expire, https://qz.com/106483/3d-printing-will-explode-in-2014-thanks-to-the-expiration-of-key-patents, 22 Jul. 2013, retrieved on 11 Mar. 2023.
[3] Erik K., Small launcher – 2021 industry survey and market analysis, *72nd International Astronautical Congress*, Dubai, United Arab Emirates, Oct. 2021.
[4] Jim Sharkey, SpaceX completes super draco qualification testing, https://www.spaceflightinsider.com/space-flight-news/spacex-completes-superdraco-qualification-testing/, retrieved on 25 Jun. 2023.
[5] Rae Rostsford End, Rocket Lab: the electron, the Rutherford, and why Peter Beck stared in the first place, https://www.spaceflightinsider.com/missions/commercial/rocket-lab-electron-rutherford-peter-beck-started-first-place/, retrieved on 25 Jun. 2023.
[6] Jackie Wattles, Startup's 3D-printed rocket delivers stunning night launch but fails to reach orbit, https://edition.cnn.com/2023/03/22/business/relativity-rocket-launch-florida-scn/index.html, retrieved on 25 Jun. 2023.
[7] Ursa Major Technology Inc., https://www.ursamajor.com/
[8] Launcher Inc., https://www.launcherspace.com/
[9] Orbex Express Launch Ltd., https://orbex.space/news
[10] Galactic Energy, https://www.galactic-energy.cn/index.php/List/cid/5

DOI: 10.13009/EUCASS2023-390

[11] P. Sabin, A. Michallet, N. Meyers, S. Durteste, J.-F. Delange, S. Saubadine, and J.M. Ruault, Vulcain 2.1, the European Reference for Ariane 6 Lower Stage cryogenic Propulsive System, *8th European Conference for Aeronautics and Space Sciences*, EUCASS2019-FP0639, Madrid, Spain, 2019.

[12] P. Simontacchi, R. Blasi, E. Edeline, S. Sagnier, N. Ravier, A. Espinosa-Ramos, J. Breteau, and Ph. Altenhoefer, PROMETHEUS: Precursor of New Low-Cost Rocket Engine Family, *8th European Conference for Aeronautics and Space Sciences*, EUCASS2019-FP0743, Madrid, Spain, 2019.

[13] Tchou-Kien, D., Iannetti, I., Girard, N., Bonhomme, C., Ravier, N. Edeline, E., PROMETHEUS, a low cost LOX/CH4 Engine Prototype, *53rd AIAA/SAE/ASEE Joint Propulsion Conference*, AIAA 2017- 4750, 2017.

[14] Forsberg, L. and Andersson, J., Development and Qualification of Turbines for the Vinci Upper Stage Engine for Ariane 6, *69th International Astronautical Congress (IAC)*, IAC-18- C4.3.8, 2018.

[15] F. Battista, D. Ricci, P. Natale, D. Cardillo, M. Fragiacomo, M. Ferraiuolo, R. Borrelli, and V. Salvatore, The HYPROB Demonstrator Line: Status of the LOX/LCH4 Propulsion Activities, *8th European Conference for Aeronautics and Space Sciences*, EUCASS2019-FP0621, Madrid, Spain, 2019.7.

[16] D. kajon, D.Liuzzi, D. Boffa, M. Rudnykh, D. Drigo, L. Arione, N. Ierardo, and A. Sirbi, Development of the Liquid Oxygen and Methane M10 Rocket Engine for the Vega-E Upper Stage, *8th European Conference for Aeronautics and Space Sciences*, EUCASS2019-FP0315, Madrid, Spain, 2019.7.

[17] Ogawara, A., Kimura, T., Adachi, M., Nagasaki, A., Hiramatsu, N., Minoya, M., Tamura, T., Okita, K., Kawashima, H., Sakai, H., Higuchi, N., Additive Manufacturing Development for LE-9 Engine, *69th International Astronautical Congress (IAC)*, IAC-18.C4.3.3, 2018.

[18] Satoshi, U., Kazuki, S., Yasuhiro, I., Hiroyuki, S, and Shinji, I., Component tests of a LOX/methane full-expander cycle rocket engine: Inejctor and regeneratively cooled combustion chamber, *8th European Conference for Aeronautics and Space Sciences*, EUCASS2019-FP0315, Madrid, Spain, 2019.7.

[19] Tsukano, T., Nagao, N., Tomaru, H., and Kuga, T., Component tests of a LOX/methane full-expander cycle rocket engine: Single-shaft LOX/methane turbopump, *8th European Conference for Aeronautics and Space Sciences, EUCASS2019-FP0315*, Madrid, Spain, 2019.7.

[20] Paul G., Omar M., Christopher P., and Chance G., Metal Additive Manufacturing for Propulsion Applications, Volume 263, *Progress in Astronautics and Aeronautics*, AIAA, Georgia, USA, 2022.

[21] Lim B., Lee K.-O., Lee J., Lee K., and Park J., Evolution and evolution of the metal additive manufacturing for space propulsion, *Proceeding of the Society for Aerospace System Engineering 2023 Spring Conference*, May 2023.

[22] Lee K., Lee J., Im S., Yi M., Lee K.-O., and Seo D., Cryogenic upper stage development for future Korean small-lift launch vehicles, *Aerospace Europe Conference 2023-10th EUCASS-9th CEAS*, Lausanne, Switzerland, 2023.

[23] Madeleine P. Infographic: 3D printing and its role in space exploration, https://www.3dnatives.com/en/infographic-3d-printing-and-its-role-in-space-exploration-190120225/#!, retrieved on 27 Jun. 2023.

[24] Choi S., Kim C., Seo D., Lee K., Lee J., Lim B., Im S., Park J., and Ahn J., Comparison of Small Launch Vehicle Design Based on Multi-Criteria Decision Making Method, *Proceedings of KSAS 2020 Fall Conference*, Jeju, Korea, 2020.

[25] Lee K., Lim B., Lee J., and Park J., A movable rocket engine test facility for the newspace methalox initiative of KARI, *Proceeding of the GBSF 2022*, Marseille, France, Dec. 2022.

[26] Lim H., Lee K., Ahn K., and Kim J., Manufacturing of 1 ton class oxygen/methane thrust chamber using metal 3D printing, *Proceeding of the 56th Korean Society of Propulsion Engineers Spring Conference*, Busan, Korea, 2021.

[27] Lim B., Lim H., Lee K., and Park J., Testing an additively manufactured thrust chamber for 1-tonf class methane engine, *Proceeding of the 56th Korean Society of Propulsion Engineers Spring Conference*, Busan, Korea, 2021.

[28] Lee K.-O., Lim B., Lee J., Lee K., and Park J., Combustor of liquid rocket engine, *Patent US11598290B2*, 07 Mar. 2023.

[29] Lim B., Thrust chamber integrated with igniter of rocket engine using cryogenic fuel and liquid oxygen and rocket including the same, *Patent pending US20220120242A1*, 24 Apr. 2022.

[30] Lim B., Lee J., Lee K., and Park J., A Mixing head integrated, multi-ignition device for liquid methane engine, *Journal of the Korean Society of Propulsion Engineers*, Vol.26, No.3, pp.54-65, 2022.

[31] Lim B., Lee J., Lee K., and Park J., A multi-ignition and deep throttleable methane engine for future in-space transport system, *Proceeding of the 11th Asian Joint Conference on Propulsion and Power 2023*, Kanazawa, Japan, Mar. 2023.