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Development of a 30kN Class LOX/methane Upper Stage Engine

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Abstract
Liquid Methane as a rocket propellant is gaining attention due to its superior energy density, low soot formation, low volatility and reduced leakage risks, especially when compared to liquid hydrogen. For these reasons, methane is particularly attractive for low-cost rockets and reusable space transportation systems. IHI recognized these advantages early on and has conducted independent research and joint development with JAXA since the 1990s, advancing various LOX/LCH4 engine technologies. In 2024, leveraging past research, IHI initiated the development of a 30 kN-class methane engine for upper-stage applications. This paper outlines IHI's development history and current progress on this engine.

1. Introduction

In recent years, the space industry has shifted its focus from government-led initiatives to private-sector efforts, spurred by the rapid growth of startup companies. In the United States, private enterprises have successfully developed reusable rockets, significantly reducing launch costs and expanding commercial applications. For example, global satellite internet networks are driving transformative changes in commercial space utilization. Additionally, significant advancements have been achieved in areas such as small, high-frequency launch services, space probes, landers, and private satellite communications, further broadening the scope of the industry.
In Japan, private startups are innovating space exploration and communications through advanced landers, satellites, and satellite constellations, while also developing small, high-frequency launch vehicles to meet growing demand, with future concepts including point-to-point transportation and in-space logistics services. To support these initiatives, the Japanese government has strengthened policies to promote private-sector contributions, raising expectations for the growth of Japan's space utilization market.
One notable development in the industry is the growing interest in methane rocket engines. Compared to traditionally selected liquid hydrogen, liquid methane offers several advantages. Albeit having a slightly lower specific impulse, methane has a higher fuel energy density than hydrogen, allowing for more compact launch vehicle designs. Additionally, liquid methane's higher storage temperature, lower volatility, and larger molecular structure reduce leakage risks and minimizes the need for specialized equipment, resulting in lower launch cost. Methane also produces less soot compared to hydrocarbon fuels like RP-1, enhancing reusability and simplifying maintenance. Furthermore, the potential for in-situ methane production on Mars and other celestial bodies enhances its appeal as a fuel for deep-space exploration.
Methane engines are expected to play a vital role in commercial transportation and exploration, contributing to more affordable and sustainable access to space.

2. The History of Methane Engine R&D at IHI

IHI recognized the potential benefits of methane engines early on and has been at the forefront of research and development in this area, surpassing global trends. This section highlights the history of methane engine development at IHI, focusing on key milestones such as the gas generator cycle 100-kN class LE-8 and SRx engines, as well as the full expander cycle 30-kN class engine, illustrated in Fig. 1.

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Item	Unit	1990s to 2000s	2000s to 2010s	2010s to 2020s
				
		LE-8 engine	SRx engine	FE 30kN engine
Thrust (Vacuum)	[kN]	98	98	30
Cycle	[-]	GG Cycle	GG Cycle	Full Expander Cycle
C/C Configuration	[-]	Ablative Cooling	Regenerative Cooling	Regenerative Cooling
Isp (Vacuum)	[sec]	313	356	368

Figure 1: A timeline of methane engine development at IHI

(1) Development of the LE-8

The LE-8 engine [1] was a 100-kN class LOX/LCH4 gas generator cycle engine developed by IHI in collaboration with JAXA for the upper stage of the GX rocket(*1). Development began in the late 1990s, with IHI responsible for the design and manufacturing of the LE-8 engine. The engine utilized an ablatively cooled combustion chamber, incorporating silica fiber composite material as the ablator. Ablative cooling works by leveraging the endothermic thermal decomposition of the ablator to transfer heat away from the combustion chamber walls. Additionally, the decomposition gases act as a protective barrier, preventing direct contact between the combustion gases and the chamber surface, thereby further reducing convective heat transfer.

IHI successfully designed and manufactured a fully operational LE-8 engine and conducted combustion tests at IHI's Aioi Rocket Engine Test Facility. Over the course of development, 11 tests were completed, including continuous combustion for durations exceeding 500 seconds, with a cumulative operational time of 2207 seconds. These tests demonstrated the engine's stability and durability during extended operation. Furthermore, the engine showed promising results of achieving a specific impulse of 313 seconds.

(*1) The GX rocket was a medium-class launch vehicle aimed at flexibly meeting the diverse launch demands of the small and medium-sized satellite launch market, complemented by the integration of methane engine technology. The GX project was cancelled in 2009.

(2) Research on the SRx Engine

In 2007, IHI initiated research and development on a new engine configuration designed to achieve higher performance by utilizing a regeneratively cooled combustion chamber. The SRx engine [2-4], developed as a demonstration model, is a 100-kN class LOX/LCH4 gas generator cycle engine. This project was independently led by IHI with the goal of applying the engine to next-generation transportation systems, including reusable spacecraft and vehicles for deep space exploration.

Between 2010 and 2013, IHI conducted a total of 27 ground combustion tests, resulting in a cumulative operating time of 1650 seconds. These tests evaluated engine performance across a broad operational range and during extended combustion cycles. Additionally, the regenerative cooling properties of the combustion chamber and the durability of critical components were thoroughly validated. The SRx engine demonstrated remarkable results, achieving a vacuum specific impulse exceeding 350 seconds—significantly higher than the performance of the earlier LE-8 engine.

The engine's development leveraged a design methodology called Total Design Management (TDM) [5], which integrates multipurpose trade-off design and a risk management system. IHI successfully achieved a high-performance and robust design within a shortened development timeline through this design methodology.

Through the development of the SRx engine, IHI acquired foundational design tools and critical technologies, as well as valuable experience in designing and developing regeneratively cooled methane engines. These advancements positioned IHI as a leader in the field and laid the groundwork for future innovations in methane engine technology.

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(3) Research and Development of a Full Expander Cycle 30kN-Class Methane Engine
Beginning in 2013, JAXA and IHI embarked on joint research and development of a compact full expander cycle methane engine [6]. This initiative aimed to capitalize on liquid methane's advantages, including its high energy density, relatively high specific impulse, and excellent storability, for use in future reusable launch vehicles, orbital transfer vehicles, and propulsion systems for space exploration.
The gas generator cycle used in the SRx engine is an open cycle, where part of the propellant is discharged externally. In contrast, this engine adopts a full expander cycle, which utilizes the full propellant flow for combustion, minimizing losses and achieving high specific impulse.
Initial research focused on the innovative design of key components required for this new engine cycle. Between 2017 and 2019, component-level tests were conducted on critical elements such as the combustion chamber, injector, and turbopump. These tests successfully confirmed essential performance characteristics of the system, including combustion efficiency, cooling performance, and turbopump stability.
From 2021 to 2023, engine system-level firing tests were carried out, evaluating ignition, startup, and shutdown transients to validate operating sequences and demonstrating stable operation and performance at the system level. A total of 9 combustion tests were conducted under ground conditions at various engine operating levels. The results indicated a vacuum specific impulse of 368 seconds, further exceeding the performance of the SRx engine and highlighting the potential of this engine for advanced space applications.

3. Flight Engine Development

As of 2024, IHI has moved to the development of a flight-ready 30-kN class full expander cycle methane engine, optimized for upper-stage applications, as depicted in Fig. 2. Upper-stage engines require compact designs while delivering high performance, particularly high specific impulse. Leveraging the validated design of the compact 30-kN class full expander cycle engine from prior collaborative research with JAXA, IHI is now pursuing rapid development of a flight-capable version. Detailed flight engine design and testing are currently underway, building on the foundational research engine.
A key challenge for upper-stage engines is minimizing inert mass, including the engine's dry weight, as this directly impacts the maximum payload capacity and achievable orbital altitude. To address this, IHI is employing innovative weight reduction strategies. For example, the nozzle extension of the upper-stage engine is designed to use radiative cooling in combination with lightweight, high-temperature composite materials, enabling significant reductions in component weight without compromising performance.
In addition to technical advancements, IHI is making strides toward mass production of the methane engine, with cost reduction as a primary goal. The engine incorporates three types of valves: pneumatic valves and solenoid valves for on/off control, and motorized valves for flow regulation. Traditional valve designs often prioritize reliability over simplicity, leading to the use of custom components that increase manufacturing costs. To overcome this, IHI is developing simplified valve mechanisms with fewer components, striking a balance between reliability and cost efficiency to support scalable production. These innovations position the engine as a competitive solution for next-generation space applications.

Item	Unit	
Vacuum Thrust	[kN]	30
Cycle	-	Full Expander Cycle
Propellant	-	LOX/Methane

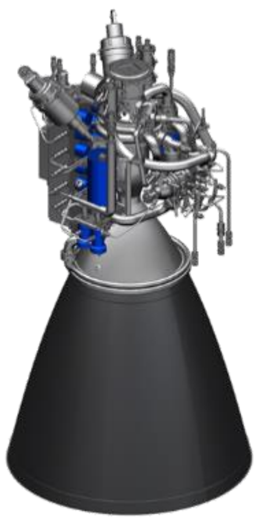

Figure 2: LOX/LCH4 upper stage engine concept

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4. Future Developments

Having identified the advantages of liquid methane rocket engines early on, IHI has established itself as a leader in this field by pursuing continuous development of compact, high-performance methane engine solutions. Drawing on the extensive expertise gained from previous research and developments, IHI is now advancing the development of a flight-ready upper-stage engine designed for a small launch vehicle. This activity represents a key milestone, as it aims to demonstrate the success of IHI's methane engine designs in actual flight conditions.

Looking beyond successful flight demonstrations, IHI is actively advancing the research and development of broader applications for methane engine technology aimed at in-space exploration and point-to-point transportation system concepts. The company plans to develop methane engines capable of enduring long-duration missions and supporting emerging space exploration initiatives that require reliability and sustainability. Additionally, IHI is exploring the development of reusable methane engines tailored for reusable spacecraft and launch vehicles, further enhancing cost efficiency and environmental sustainability in space operations.

By harnessing methane engine technology, IHI seeks to drive innovation in space transportation while contributing to the sustainable growth of the space industry. The company remains committed to creating societal value through the advancement of this cutting-edge technology, positioning itself as a key player in the future of space exploration and transportation.

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