CIMAC CONGRESS 25
ZURICH, MAY 19 – 23, 2025

2025 | 165

Development of the twin-circuit-injector for liquid and gaseous alternative fuels

Fuel Injection & Gas Admission and Engine Components

Tomohiro ASAI, NICO Precision Co., Inc.

Hisashi KARINO, NICO Precision Co., Inc.
Toshiyuki SAITO, NICO Precision Co., Inc.

ABSTRACT

In recent years, many engine manufacturers have been focusing on the development of new IC engines with various alternative fuels that can comply with the IMO's GHG reduction target. In particular, hydrogen or ammonia as carbon-free fuels, or methanol as a liquid fuel which can be used easier than other new fuels, seems to play an important role in the near future.

Since most of these alternative fuels have a lower calorific value than conventional fossil fuels, the injection volume needs to be increased to maintain the same power output as conventional fossil fuels, when using these alternative fuels. In addition, the different fuel specifications such as fluid phase, injection pressure, fuel temperature, etc. are required for each specific project respectively.

NICO Precision (NIP), the supplier of fuel injection systems, has supplied a significant number of common rail systems (CRS) to engine manufacturers for use in main injection and micro-pilot applications. Our injectors for conventional fuels utilize a hydraulic pressure to control the valve, and this proven technology is now being applied to our new injector concept for alternative fuels. The new injector is called "Twin-Circuit-Injector", which has been featured by separating the fluid circuits for control and injection. The advantage of this twin-circuit concept is that it is applicable to various fluids for control oil, such as MGO, MDO, lube oil, and any type of liquid or gaseous fluid which can be used as injection fuel. The use of the control oil for valve movement is advantageous when various types of fluids are used as fuel, because some of them have poor lubricity or are difficult to use due to their gaseous state, which may cause unwanted leakage. The control oil can be used so as to lubricate the valves and prevent gaseous fuel leakage, potentially reducing wear on the sliding and contact surfaces of the valves. Our development work was going through two different concepts of injector structure. The first design (Type A) has multiple holes, allowing the spray direction to be controlled directly by arrangement of the nozzle hole. The second design (Type B) has a poppet valve, which is suitable for the injector that requires a high flow rate, such as for gaseous fuel. This is achieved by applying a sufficiently larger flow area than Type A's.

These prototype injectors were run on the test facilities and the functionality was confirmed to be as intended. The performance measurements were evaluated in the use of liquid and gaseous fluids. Then their correlation, injection volume, injection rate and shot-to-shot variation have been verified, and finally confirmed to achieve the expected performance. As a conclusion of these development work, our design concept of a twin-circuit alternative fuel injector has been established.

This paper describes an overview and the test results of the prototype of the twin-circuit alternative fuel injector developed by NIP.

1 INTRODUCTION

In recent years, many engine manufacturers have been focusing on the development of new combustion technology with various alternative fuels that can comply with the 2023 IMO GHG strategy [1]. Today, the interest in hydrogen and ammonia is increased because of their potential to achieve carbon neutrality. The same is true for methanol, which is easier to handle than other possible alternative fuels.

However, the use of alternative fuels may raise various problems because each type of fuel has different characteristics. For example, there are concerns that the toxicity of the fuel may become an issue depending on the engine application or type of vessel. It is also expected that the availability of fuel will be limited due to differences in infrastructure depending on the country or region in which it is used. Furthermore, at present, it is necessary to use fuels that do not compete with other category such as aviation or automobiles. Therefore, it is difficult at this point to determine which fuels are likely to be widely used in the future, and there is an urgent requirement to develop the new injectors for various types of alternative fuel compatibility to meet this complicated situation.

NICO Precision Co., Inc. (NIP), the supplier of fuel injection systems, has supplied a significant number of Common Rail Systems (CRS) to engine manufacturers for use in main injection and micro-pilot applications. NIP has been supplied our CRS since 2014, and after 10 years of experience, total supply of injectors reached 10,000 in 2024 (Figure 1).

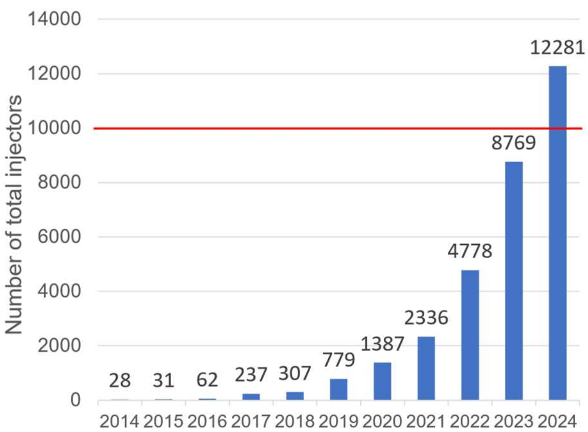

Figure 1. Total number of injectors delivered to customers

In response to the urgent need to develop injectors for different types of fuel, we decided to use the proven technology of our current injectors, which uses hydraulic pressure to control the injector valves. To achieve stable injection even the low-boiling alternative fuel using, independent control fluid has been implemented from the alternative fuel. Our new injector has two types of fluid circuit: one is control oil and the other is alternative fuel. This new injector is called a twin-circuit injector.

This paper describes the concept and development of NIP's newly developed twin-circuit injector for alternative fuels.

2 REQUIREMENTS FOR NEW INJECTOR DESIGN

Regarding the injector location and injection method, there are several options for alternative fuel supplying to the combustion chamber. Figure 2 illustrates the types of alternative fuels and typical injector locations. Regarding the injector location, port injection layout and direct injection layout would be assumed, and both liquid phase and gaseous phase will be adopted for this injector as fuel.

Comparing port fuel injection (PFI) with direct injection (DI), PFI has the advantage of flexibility in the location of the fuel supply system on the engine, as only the pilot injector needs to be installed on the cylinder head. Especially for small bore 4-stroke cylinder heads, this aspect is essential for the installation of the fuel supply system. On the other hand, an advantage of DI configuration is that it can potentially achieve zero fuel slip during valve overlap. Moreover, by injecting the fuel at a higher pressure than the compression pressure, which is called high-pressure DI (HPDI), it can achieve diesel combustion and can more easily increase mean effective pressure (Pme), although it has installation difficulties.

In addition, by considering use for both liquid and gaseous fuels, NIP has decided to develop the new injector for both HPDI injector and low-pressure DI (LPDI) injector. We also assume that the LPDI injector can be used as a PFI injector.

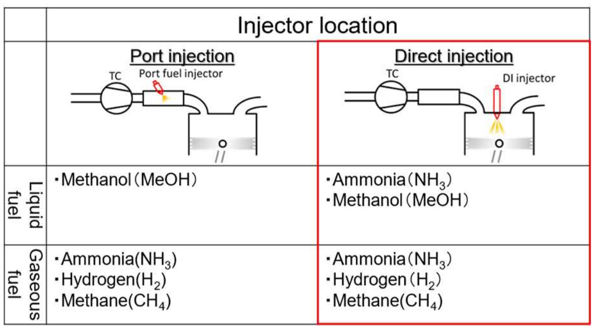

Figure 2. Estimated fuel and injector location

In order to establish a new injector design for various types of alternative fuel, including liquid and gaseous, several issues need to be considered from the functional aspect.

The first point is how to design the valve opening function for various types of alternative fuel. Several ways of valve opening function are considered, such as direct actuation, single-circuit hydraulic and twin-circuit hydraulic. A comparison of these ways is listed in the table below.

Table 1. Comparison of valve opening function for alternative fuel injector

	DA	SC	TC
Simplicity No need for complex systems	+	0	-
Pressure range Applicable for wide range of fuel pressure	-	0	0
Design flexibility Applicable for wide size range	-	0	0
Availability for gaseous fuel	+	-	+
Safety Prevention of toxic fluid's leak	-	-	+

DA: Direct Actuation by solenoid valve
SC: Single-Circuit hydraulic
TC: Twin-Circuit hydraulic

From our study, the twin-circuit construction is the most suitable option for our new injector because it can be used with the same solenoids over the wide pressure range of alternative fuels, and it has design flexibility through the appropriate design of internal hydraulic components. In addition, this twin-circuit design can eliminate concerns about harmful alternative fuel leakage via the control oil circuit by ensuring that the control oil pressure is always higher than the fuel pressure.

On the other hand, since twin-circuit injector uses control oil, it is necessary to separate the alternative fuel and the control oil in the injector. In order to achieve reliable separation, an appropriate design of the functional components is essential.

The second point is the requirement for a high injection flow rate compared to a conventional injector for fossil fuels. In general, alternative fuels have a lower calorific value than fossil fuels, therefore the injection quantity must be increased to maintain equivalent power output. Injection duration is typically limited to manage better combustion performance, so the higher injection flow rate is desired for the injector.

In order to satisfy this design requirement, the total nozzle hole area, seat diameters and fuel passage areas in the injector must be increased in size compared to the fossil fuel injector.

The third point is that certain types of fuel can cause material damage to injector components such as ammonia corrosion or hydrogen embrittlement. Considering this aspect, it is important to select appropriate materials for parts and seals in contact with alternative fuels that are resistant to these phenomena.

According to the above considerations, the essential design points are summarized as follows;

(1) Application of the twin-circuit construction.

(2) The requirement for a higher injection flow rate than the conventional one.

(3) Selecting the suitable material for the intended alternative fuels.

3 DETAILED DESIGN

The alternative fuel injector developed by NIP is shown in the figure below. As mentioned previously, our alternative fuel injectors are designed to use various types of alternative fuel which have a wide range of pressure levels and phases (liquid and gas), hence two different design concepts have been prepared.

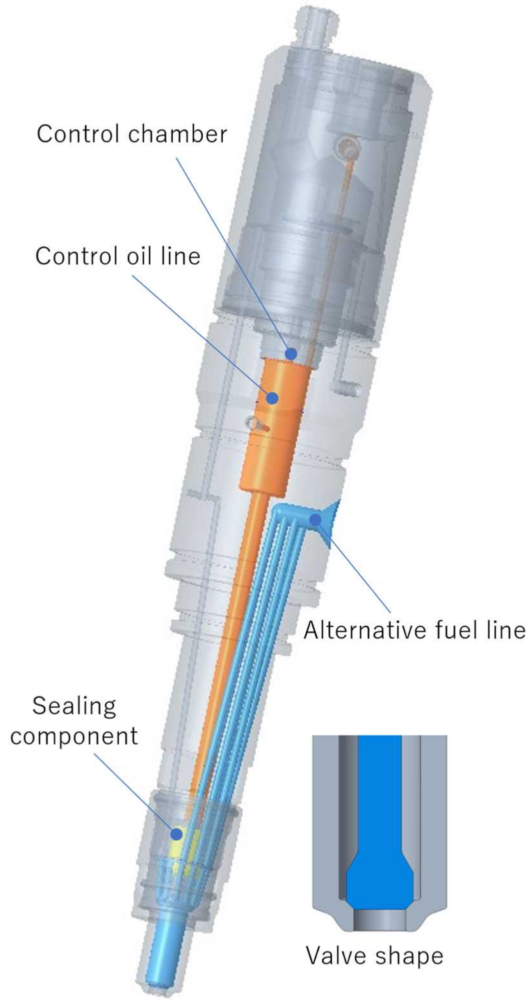

Figure 3. Needle type injector

The needle valve design concept (Figure.3) has a needle valve similar to a conventional injector, this concept is suitable to optimize spray diameter and direction. Since liquid fuel must be atomized to increase the total surface area of the droplets and promote mixing with the air, the needle valve design concept is suitable. In this concept, multiple injection holes can also be applied, which allows fine atomization to be achieved through hole size, number, angle, etc. Some gaseous fuels, which require a more homogeneous distribution in the cylinder, are also suitable to use this concept to control the fuel diffusion.

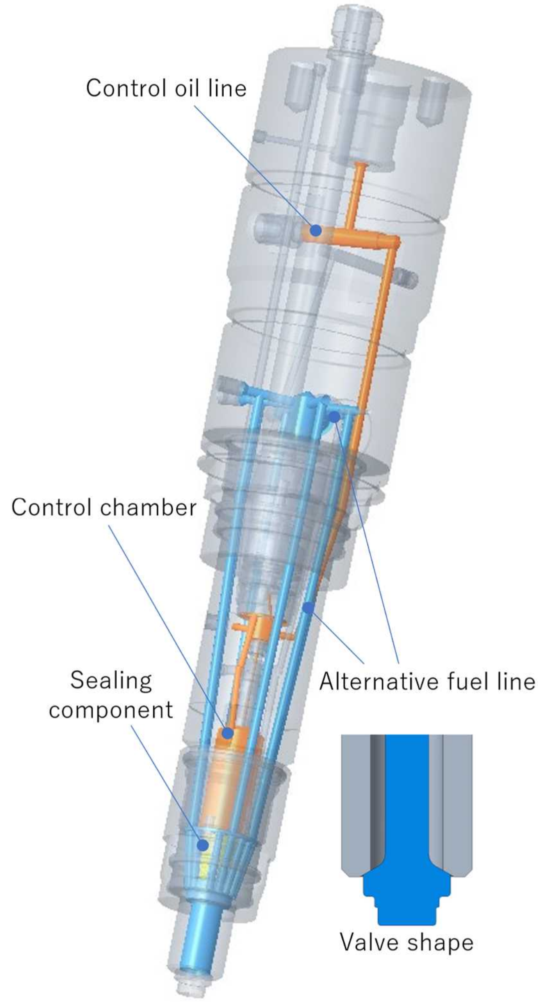

Figure 4. Poppet type injector

The poppet valve design concept (Figure.4) has an outward opening valve. The feature of the poppet valve structure is that it is easier to achieve a larger total nozzle area than with a needle valve structure, and it seems to be suitable for injectors with a higher volume flow rate, especially for gaseous fuels. The flow area of the nozzle of the poppet valve design concept can be made 1.5-1.8 times larger than that of the needle valve design concept with the same outer diameter of the nozzle body.

The injector for alternative fuels developed by NIP has been designed to meet the concerns described in the previous section, presented as follows.

The first point is the employment of a twin-circuit hydraulic control structure that uses control oil to operate the opening valve regardless of the type of alternative fuel. The fuel valve is actuated by the hydraulic pressure of the control oil, and the mechanism of valve movement is enabled by dropping the oil pressure precisely at the control chamber which located at the end of the piston.

Thanks to using the twin-circuit structure, avoiding direct contact with metal and alternative fuels, concerns about material corrosion and seizure due to low lubricity can be eliminated. In addition, it is possible to achieve stable injection even with low-boiling alternative fuel by using control oil. If the low-boiling alternative fuel is used directly as a control fluid, vaporization may occur at the outlet of the control chamber due to pressure drop by discharge, resulting in unstable injection.

In order to separate control oil and alternative fuel, the NIP twin-circuit injector is designed to separate these two fluids at the sliding parts of the injector components. In order to achieve the smallest mixture of these fluids on the sliding surface, NIP designed two options for the sealing concept of the twin-circuit injector.

If a small amount of control oil can be accepted in the fuel, the amount of mixing of control oil can be managed by the clearance of the sliding parts without sealing elements.

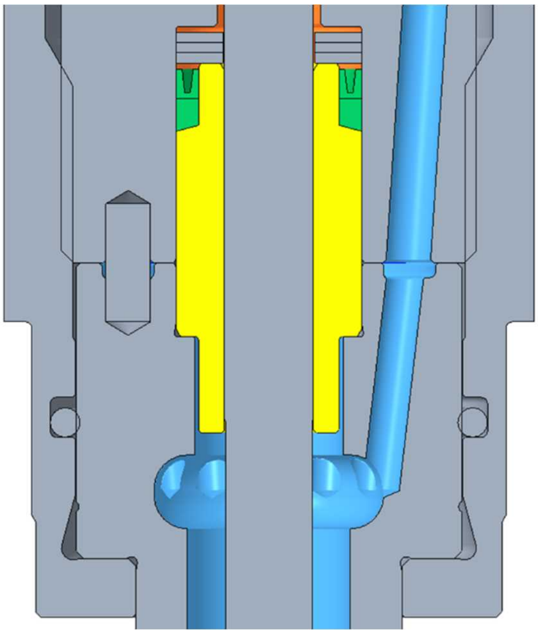

Figure 5. The design of the sliding parts without sealing element

To minimize the amount of control oil mixed into the fuel, the clearance of the sliding parts should be as small as possible, and the length of the sliding parts should be as long as possible. However, a small clearance of the sliding parts increases the risk of seizure, so the clearance must be determined to the best compromise point.

On the other hand, if it is necessary to minimize the amount of control oil mixed into the fuel, sealing elements compatible with each fuel can be installed in the sliding parts.

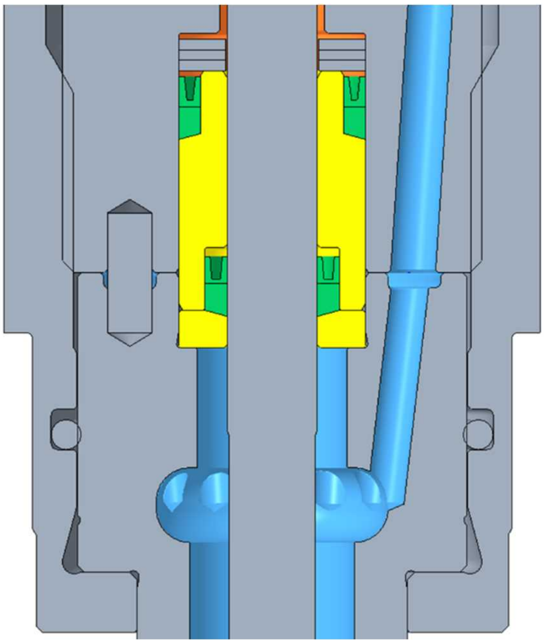

Figure 6. The design of using sealing element into the sliding parts

The sealing element can significantly reduce the amount of control oil that enters the fuel. These seals are made from materials that are not affected by alternative fuels.

The second point is the design of alternative fuel injectors to enable high flow injection. It is necessary to increase the maximum injection rate from the low calorific of alternative fuel characteristic, which requires a larger nozzle area, seat diameter and fuel flow passage area than in conventional injectors. To increase the flow area, it is likely to design a large outer diameter of the injector, but on the other hand, considering the installation to the cylinder head, it is desirable to keep the outer diameter as small as possible. Therefore, the shape of the alternative fuel injector is designed with a compromise by considering the maximum flow area within the constraints of the external shape.

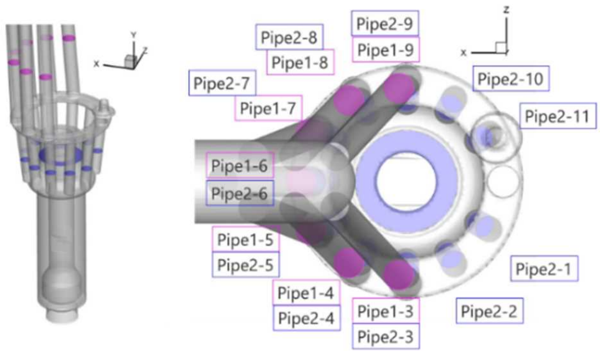

Figure 7. Fuel passage in the injector

It is also important to determine the correct valve lift, as too little lift will result in an insufficient flow rate, while too much lift will result in a longer valve travel, which will shorten the life of the sliding surface.

Therefore, a computational fluid dynamics (CFD) analysis of the fuel passage was carried out to optimize the valve lift. The mass flow transition is compared for different valve lift at the same pressure drop. Figure 8 shows an example of the relationship between valve lift and mass flow from the CFD calculation results.

From the results, the mass flow increases with higher valve lift, but beyond 2.1 mm valve lift, the increase is saturated. To account for this relationship the maximum valve lift is designed to be approximately 2.1 mm.

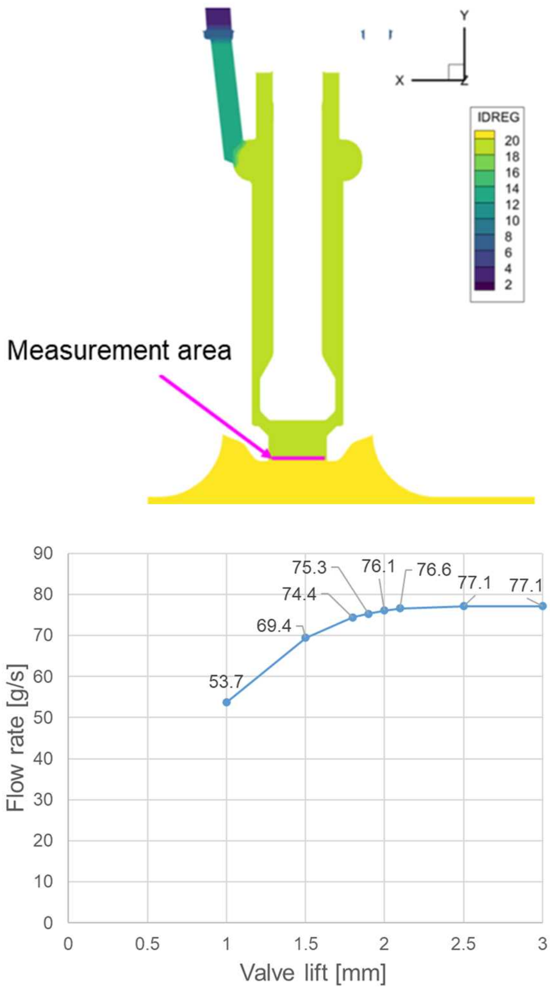

Figure 8. The relationship between valve lift and mass flow from the calculation results of CFD

The third point is that material selection which is considered for resistance to alternative fuels. NIP alternative fuel injector will select suitable material depending on specific alternative fuel for each design, such as ammonia corrosion and hydrogen embrittlement. In terms of prototype development, NIP selected stainless steel, which generally has a high resistance to corrosion or hydrogen embrittlement. On the other hand, stainless steels generally have low strength. In order to find a critical surface pressure, which is the limit at which permanent deformation of the surface occurs, an investigation was carried out and the results are shown in Table 2 and Figure 9. As can be seen from the results, the critical surface pressure of some stainless steels is lower than that of a low-alloy steel, which is widely used in conventional CRS injectors. In order to apply the stainless steel to the alternative fuel injector, the contact pressure at a metal-to-metal seal was evaluated in detail using Finite Element Analysis (FEA).

Table 2. Characteristics of the materials

Material	Hardness	Critical surface pressure
SUS316L	HRB22	282 MPa
SUS304N2	HRB34	339 MPa
SUS630	HRC42	1412 MPa
SUS420J2	HRC53	1808 MPa
SNCM439	HBW322	1043 MPa

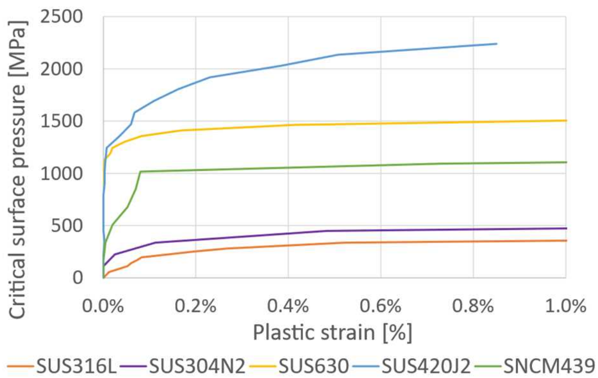

Figure 9. Relationship between plastic strain and critical surface pressure

When using stainless steel for injectors, there is also a concern that the sliding parts may stick easily due to the low hardness and low thermal conductivity of the surface. To overcome this concern, additional surface treatment may be required to prevent seizure of the sliding parts.

4 TEST RESULTS

Based on the concept as we explained, two types of prototype injectors were made: one for liquid fuel and one for gaseous fuel. The liquid fuel injector assumes the use of high-pressure liquid fuel and uses a nozzle with multiple spray holes. The gaseous fuel injector assumes the use of low-pressure gaseous fuel and uses a large single-hole nozzle. The specifications of each injector are given in Table 3.

Table 3. Prototype injector spec.

Intended for	HPDI	LPDI
Expected fuel	Liquid	Gas
Injection pressure	~ 650 bar	~ 100 bar
Control oil pressure	700 bar	400 bar
Nozzle orientation	Multiple ϕ0.8×10	Single ϕ7×1
Nozzle outer diameter	ϕ18	ϕ18

4.1 Test results of HPDI injector

The test results were obtained by assuming the use of liquid fuel. Table 4 shows the test conditions, Figure 10 shows the injection quantity curve from the current duration supplied to the solenoid and the injection rate from 5ms of the current duration.

Table 4. Test condition of HPDI injector

Injected fluid	Calibration oil
Injection pressure	~ 650 bar
Control oil pressure	700 bar
Back pressure	50 bar

From the injection quantity curve, it was confirmed that the injection quantity increases as the current duration increases.

In addition, as the injection quantity increased linearly after the needle reached full lift at approximately 2.5 ms of the current duration. Furthermore, the shot-to-shot variation in injection quantity (COV) was generally 1.0% or less after reaching the full lift, which was considered a good result.

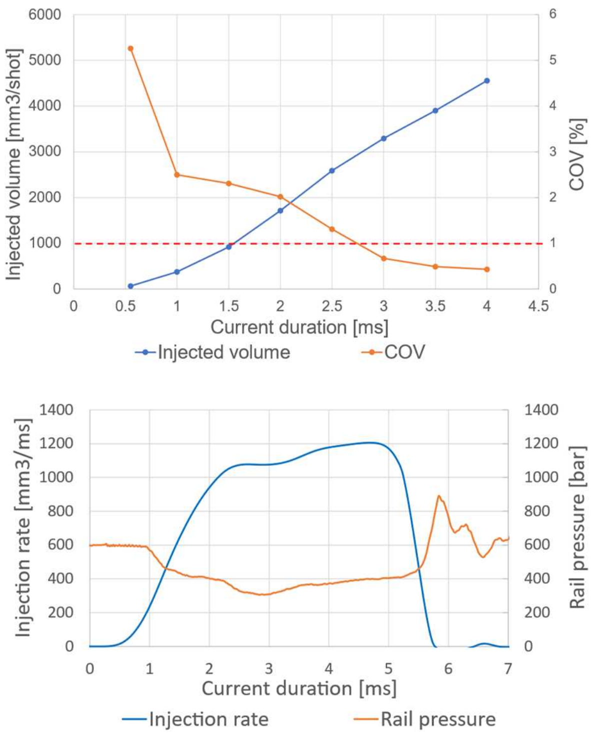

Figure 10. Inj. quantity curve and inj. rate

From these test results, the twin-circuit-injector can stably inject liquid fuel, and the injection amount can be adjusted by changing the current duration.

4.2 Test results of LPDI injector

The test results were obtained by assuming the use of gaseous fuel. Table 5 shows the test conditions and Figure 11 shows the injection quantity curve and the injection rate.

Table5. Test condition of LPDI injector

Injected fluid	Nitrogen gas
Injection pressure	40 bar
Control oil pressure	400 bar
Back pressure	8 bar

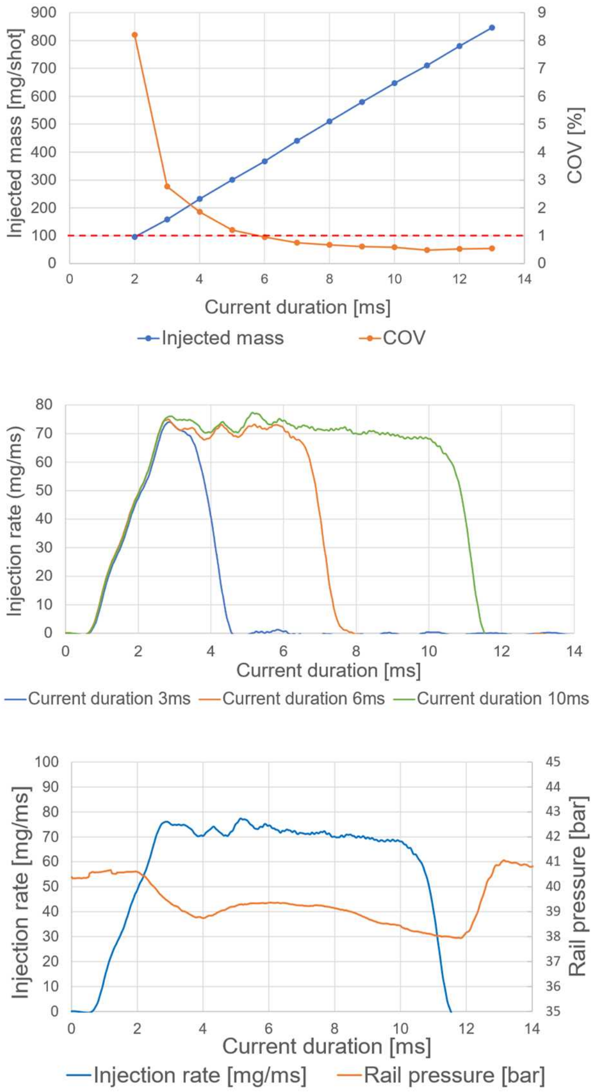

Figure 11. Inj. quantity curve and inj. rate

From the injection quantity curve, it was confirmed that the injection quantity increased as current duration increased. It was also confirmed that the valve seat was properly seated as designed without any gas leakage. Furthermore, it was confirmed that the shot-to-shot variation in injection quantity (COV) was less than 1.0% among large injection quantities, similar to the test results with liquid.

From the above, the twin-circuit injector is capable of stable injection of gaseous fuel, and the injection quantity can be adjusted by changing the current duration.

As regards the LPDI injector for gaseous fuels, the injection test had conducted with calibration oil for reference purposes. Table 6 shows the test conditions and Figure 12 shows the injection rate comparison(ref.).

Table 6. Test condition of LPDI inj. (ref.)

Injected fluid	Nitrogen gas	Calibration oil
Injection pressure	40 bar	40 bar
Control oil pressure	400 bar	400 bar
Back pressure	8 bar	8 bar
Current duration	10 ms	10 ms
Measured inj. quantity	647 mg/shot	4417 mg/shot

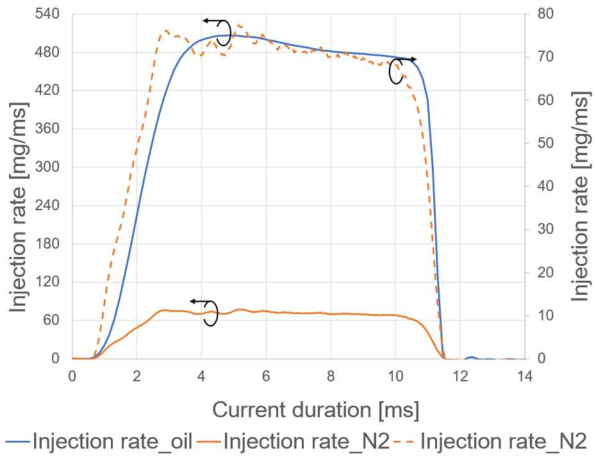

Figure 12. Injection rate comparison (ref.)

The injection quantity of calibration oil is approximately 6.83(4417/647) times greater than that of the nitrogen gas. If the injection rate of nitrogen gas is multiplied by 6.83, as illustrated by the dotted line in Figure 12, we can see a similarity in the shape of the injection rate. When using nitrogen gas, the gradient, which is considered to be approximately proportional to the speed of valve movement, is faster at the beginning of the injection and slower at the end of the injection.

We assume that this is caused by the frictional force on the wall around the needle valve seat, as the direction of fluid flow is opposite to the valve movement at the start of injection and the same direction at the end of injection. As the viscosity of liquid fluid is greater than that of gaseous fluid, the use of calibration oil would slow the valve speed at the start of injection and accelerate it at the end of injection. This effect of viscosity would be less if gaseous fluid was used than liquid fluid.

4.3 Problems revealed after operation

There are two examples of problems that arose during the operation of a prototype injector. The problems and the countermeasures are shown.

The first example is the occurrence of seizure on the sliding part that separates the alternative fuel and the control oil. The cause of this problem was that the material used to prevent corrosion and embrittlement was of low hardness and prone to seizure. As a countermeasure, a diamond-like carbon (DLC) coating was applied to the shaft parts to increase the surface hardness of the parts and prevent seizure. However, there are concerns about the durability of the coating and its resistance to alternative fuels, so further evaluation is ongoing.

In addition to the coating, we plan to select materials that combine corrosion resistance and hardness and verify their applicability.

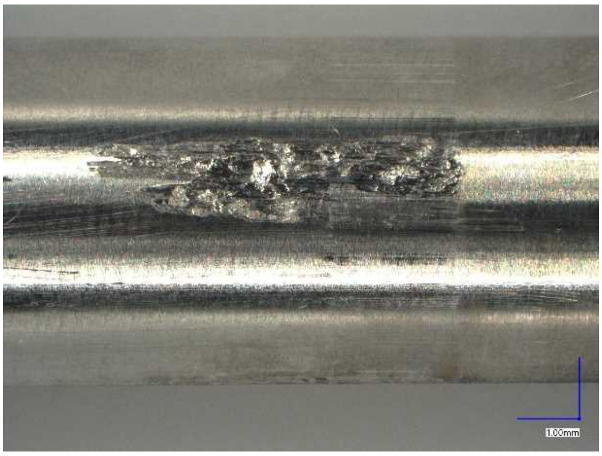

Figure 14. Seizure on sliding parts

Figure 15. Improved sliding surface with diamond-like carbon (DLC) coating

The second example is the wear of the sealing parts. It was confirmed that the use of the sealing parts can almost completely eliminate the amount of control oil that mixed into the fuel. However, the sealing parts would wear out through running time. As wear progresses, the amount of control oil getting mixed in increases. Therefore, improving the durability of the sealing parts should be a future challenge.

Figure 16. Worn seal element after running

5 CONCLUSIONS

In order to help reducing GHG emissions, NIP has developed the twin-circuit injector compatible with alternative fuels. The adoption of a twin-circuit structure that uses control oil to operate the valve makes it possible to inject a wide variety of alternative fuels including low calorific fuel which requires high flow rate injection. In addition to liquid fuels, this twin-circuit injector can stably inject gaseous fuels as well. To maximise the flow rate of gaseous fuels, the development of the poppet valve injector will be proceeding as well as needle valve injector. Also, the evaluation of durability for various alternative fuels will be evaluated in the next steps.

Using this technology, we also plan to develop a twin-needle injector that can inject both alternative fuels and fossil fuels with a single injector in next challenges.

6 ACKNOWLEDGMENTS

The authors of this paper would like to extend their gratitude to all NIP colleagues who participated in its development.

7 REFERENCE

[1] 2023 IMO Strategy on Reduction of GHG Emissions from Ships

https://www.imo.org/en/OurWork/Environment/Pages/2023-IMO-Strategy-on-Reduction-of-GHG-Emissions-from-Ships.aspx