A World-first Configuration – a Dual Fuel Engine Direct Coupled with an FPP Z-Peller on a Harbour Tug

Hideyuki Takahashi (author/speaker), **Daiki Ikeda** (speaker), Niigata Power Systems, Japan

SYNOPSIS

As emission regulations for marine engines become more restrictive year on year, the use of alternative fuels is growing. Gas fuels, typified by natural gas, are in high demand as they outperform liquid fossil fuels in limiting greenhouse gases, acid rain and soot dust. In response to these trends, Niigata Power Systems has developed the 28AHX-DF dual fuel engine, featuring revolutionary characteristics. The engine's target is harbour tugboats with directly driven propellers, especially fixed pitch. The engine can tolerate rapid load change operation by leveraging advanced combustion technology and air-fuel ratio control technology. It was delivered to a tugboat as a main engine in January 2015, then operated over a one-year period from September 2015 in Tokyo Bay. Taking advantage of good transient properties, it is possible to use this engine not only as a main engine for tugboats but also for research vessels, cargo carriers and ferries, as well as auxiliary engines for large container vessels. This paper describes the performance and technology of the 28AHX-DF engine and the results of its one-year tugboat operation.

INTRODUCTION

Controlling marine engine emissions has been mainly discussed in the context of countermeasures to suppress acid rain. Levels of nitrogen oxides (NO_X) and sulphur oxides (SO_X) are regulated by the IMO, with emission control regulations having increasingly intensified in recent years. For NO_X, the Tier III regulations enforced in 2016 stipulate a reduction of approximately 80 per cent versus Tier I emission control areas (ECAs). For SO_X, the value was strengthened to the current regulatory limit in 2015 by the sulphur contain rate in fuel gas within ECAs. Further regulations to limit the sulphur rate in fuel gas outside of ECAs will start in 2020.

Niigata Power Systems has been engaged in developing multiple low-emission technologies, including a method to combine a conventional diesel engine with exhaust after-treatment, utilising alternative fuels such as natural gas, and hybrid propulsion units combined with

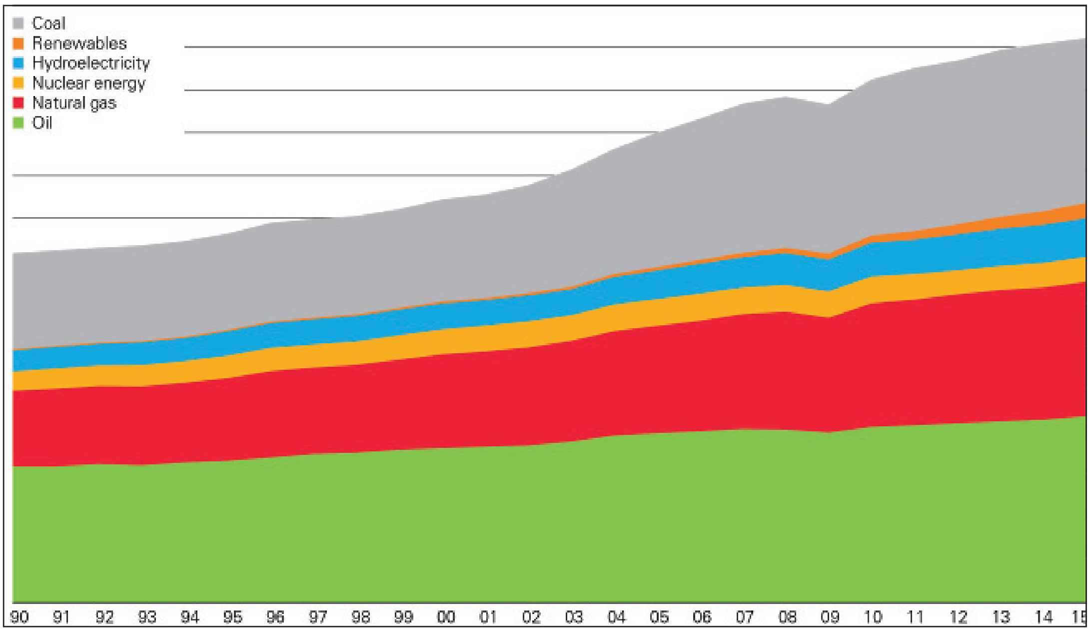


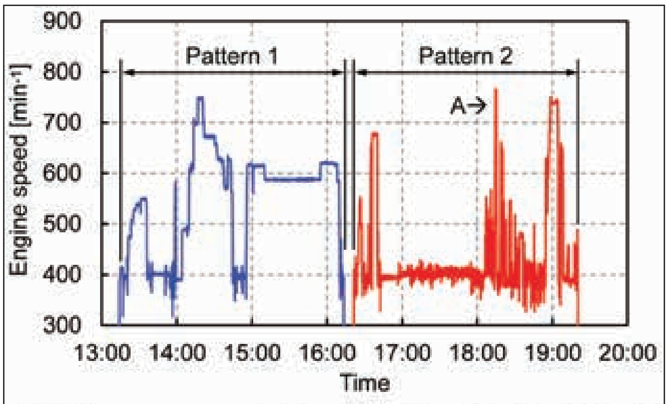
Figure 1: Trend of primary energy consumption[1]

electric motors and electric propulsion systems[2,3]. Using gas fuels is an ideal way to meet emission controls on marine engines, as it is possible to adopt homogeneous premixed combustion that generates minimum NO_X emission, and is completely SO_X emission-free (naturally, since gas fuel contains no sulphur components).

In addition, the use of gas fuel leads to significant reductions in carbon dioxide (CO_2) emissions compared to petroleum, due to differences in fuel composition. From an energy utilisation perspective, since gas fuel is more advantageous than petroleum in terms of ready availability across a large production area, natural gas will see greater utilisation *(Figure 1, previous page)*. Taken together, these considerations create favourable conditions for using gas as a marine engine fuel.

The target for the development of Niigata's dual fuel engine was a harbour tugboat. Harbour tugboats are mainly operated in ECAs, and it was possible to combine the engine with one of Niigata Power Systems' main products, the Z-Peller azimuth thruster.

Prior to commencing development, Niigata took the existing diesel harbour tugboat operating pattern data and verified it *(Figure 2)*. The operation load patterns were classified into Pattern 1, comprising a heavy workload, and Pattern 2, comprising a long standby time. Statistically analysing each load revealed that low loads dominated, with a low ratio of high loads (exceeding 75 per cent load) in both operational patterns. According to that, a harbour tugboat has the longest periods of low load operation during sailing to work sites or in a standby situation. As shown in *Figure 2*, the rise in load from idling (corresponding to a 15 per cent load) to rated load was achieved in less than 20 seconds. This indicates an exceptionally abrupt load change during operation.



Load [%]		0 ~ 25	25 ~ 50	50 ~ 75	75 ~ 100
Incidence [%]	Pattern 1	27	41	27	5
	Pattern 2	82	8	5	5
	Total	55	24	16	5

Figure 2: Measured engine operation pattern of a harbour tugboat

Azimuth thrusters on tugboats are supplied as either fixed pitch propellers (FPPs) or controllable pitch propellers (CPPs). Niigata Power Systems has FPP and CPP options on the same model of azimuth thruster, enabling comparison of the performance of each. A CPP has the freedom to operate the propeller pitch control, which means that when performing the same thrust on CPP and FPP, a CPP-coupled main engine needs more power. This is due to increased drag around the larger propeller hub, required to accommodate the pitch-changing structure of the CPP *(Figure 3)*.

In addition, comparing the CPP characteristics at a controlled load at rated speed with FPP characteristics at a controlled load with variable speed, FPP fuel consumption becomes better than that of CPP as the load becomes smaller *(Figure 4)*. From the characteristics shown in *Figures 3 and 4*, FPPs also have an advantage in fuel consumption, which becomes larger as the loads become smaller. When CPPs must be used, it is possible to reduce fuel consumption by controlling the engine speed and propeller pitch at the same time.

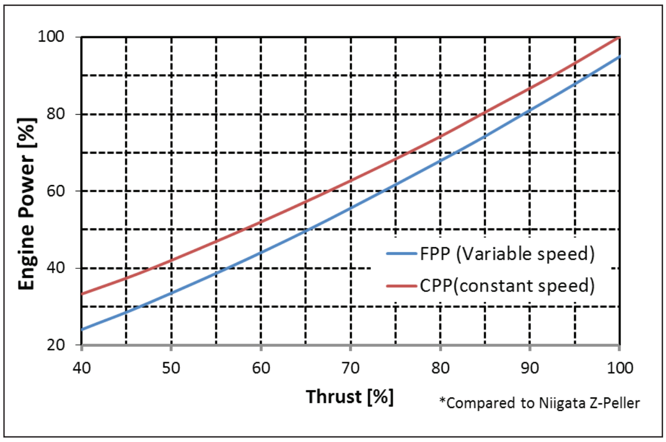


Figure 3: Performance curve comparison between FPP and CPP units

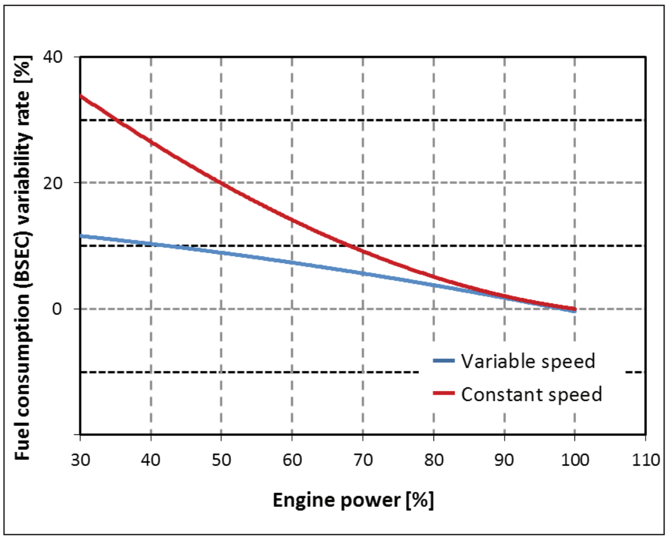


Figure 4: Fuel consumption comparison between FPP load and CPP load

Based on these considerations, the development target for 28AHX-DF we adopted was parity of performance with conventional diesel engines. We aimed to meet the transient performance characteristic requirements of harbour tugboat main engines, and to adapt the FPP to loads controlled by engine speed.

DEVELOPMENT OF THE 28AHX-DF

Specifications

To secure the level of redundancy required for a marine engine, we adopted a dual fuel design. *Table 1* shows the main specifications.

Engine type	28AHX-DF
Bore x Stroke	280 x 390 mm
Maximum continuous rating	1920 kW (6L) 2560 kW (8L) 2880 kW (9L)
Rated speed	800min^{-1}
Brake Mean Effective Pressure	2.0MPa
Fuel gas for Gas mode	Natural Gas
Pilot fuel oil for Gas mode	Marine Diesel Oil or Marine Gas Oil
Fuel oil for Diesel mode	Marine Diesel Oil or Marine Gas Oil
Combustion system (at gas mode)	Micro- pilot direct injection lean burn system

Table 1: Main specifications

Based on the 28AHX diesel engine's model platform, which has excellent operational results as a marine main engine, a fuel gas admission valve and pilot fuel injection equipment were added in order to achieve gas fuel combustion. In addition, with safety in mind, the gas supply piping was designed in the form of a double-pipe structure, so that if fuel leaks from the supply system it is able to be detected promptly. The rated output was made identical for both gas and diesel modes to enable full load operation regardless of the selected fuel. The engine was built to use natural gases that have a methane number of 65 and above.

Static performance

To achieve both low fuel consumption and low NO_X emissions, the engine employs a micro-pilot ignition system. *Figure 5* shows a concept diagram of the combustion chamber and its immediate mechanisms. The cylinder head is equipped with a main injection nozzle, which is used in diesel mode with a micro-pilot injection nozzle to inject diesel fuel to ignite the gas mixture selected by the current operation mode. To create an optimised distribution pattern of diesel fuel spray (the source of ignition for the gas mixture in the cylinder), a common rail injection system is applied to the micro-pilot injection system. This system delivers stable ignition even at low load, as it can inject at high pressure regardless of load.

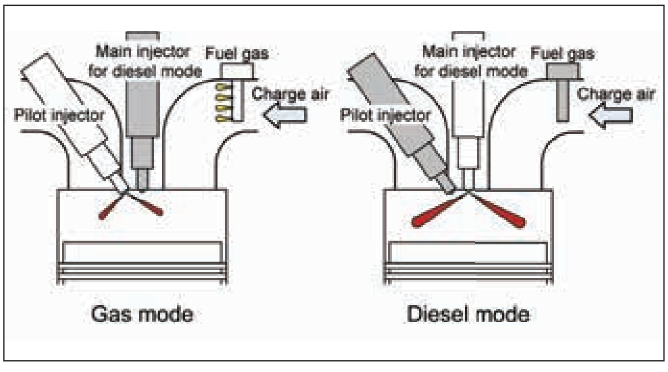


Figure 5: Schematic of the combustion concept

As described above, fuel consumption during part-load operations has a high impact on economic efficiency. In order to improve this, we investigated the thermal efficiency at part-load conditions in gas mode operation. *Figure 6* shows the improvement of thermal efficiency due to advanced pilot injection timing and an adjustment of charge air flow at 75 per cent load. When the injection timing of pilot oil is more efficient, thermal efficiency increases. In addition, NO_X emissions decrease in inverse proportion to the increase in the excess air ratio (lambda), thus the fuel consumption at part-load in gas mode can improve until the onset of knocking. By contrast, an increase in the excess air ratio has no effect on NO_X emissions reduction in conventional diesel combustion, which mainly consists of diffusion combustion. The dual fuel engine should therefore be operated mostly in gas mode from the viewpoint of economic efficiency and environmental protection.

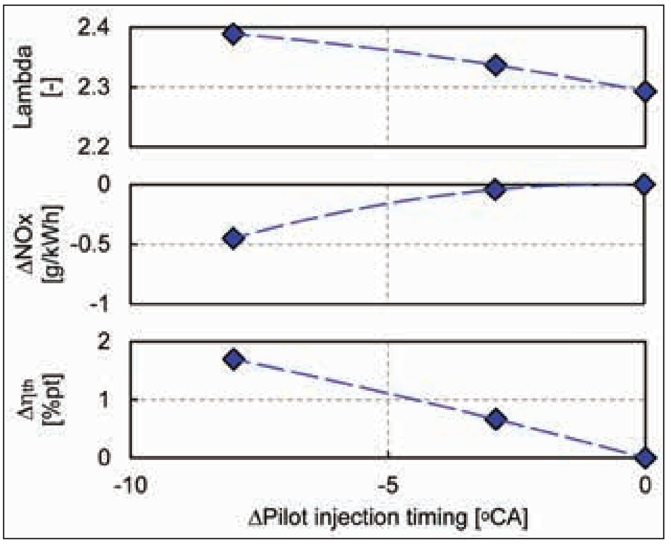


Figure 6: Improvement of thermal efficiency at part load by pilot injection timing advance

Regarding compliance with IMO NO_X regulations, the engines meet Tier II regulation in diesel mode and Tier III in gas mode for the both the E3 and E2 test cycles *(Figure 7)*. The engine is not only suitable for variable speed operation, but also for constant speed operations, such as exhibited with CPPs and in electric power generation. The NO_X emission level in gas mode changes according to the performance adjustments for each application and operation condition; however, there is still the potential to meet the Tier III standard.

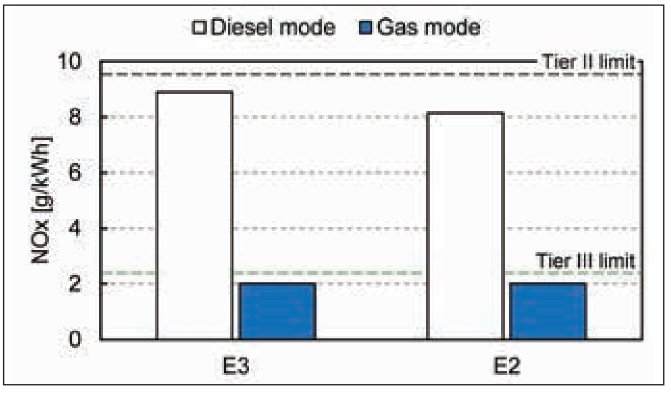


Figure 7: NO_X emission from 28AHX-DF

Transient performance

Operation in gas mode is shown in *Figure 8*, which indicates a limit line and an allowable operation area against knocking and misfiring, determined by the excess air ratio and the mean effective pressure. Excellent transient characteristics were achieved and stable operation maintained in the expanded allowable operation area by using the improved control system of air-fuel ratio and micro-pilot injection.

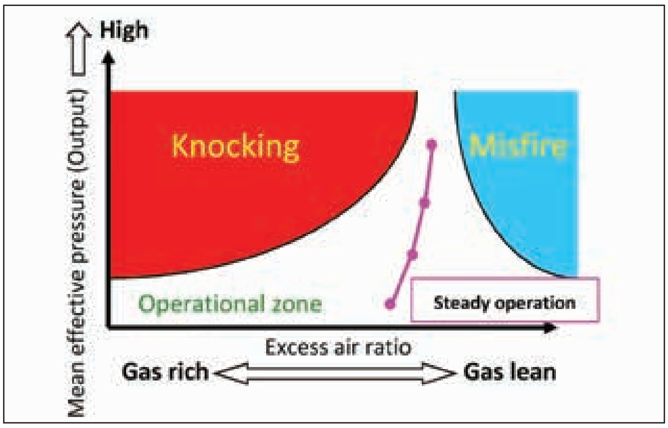


Figure 8: Knocking and misfire limit line

Figure 9 shows a schematic diagram of the intake and exhaust systems of the developed engine, including the configuration of the turbocharger, bypass system, air cooler and fuel gas admission valve. The fuel gas needed is charged into the cylinders via a gas valve installed in the intake port. Part of the intake air compressed by the turbocharger is returned to the area upstream of the compressor to adjust the excess air ratio within a suitable range. By securing the required amount of air for engine output and enhancing the response and accuracy of intake air cooling, an air-fuel mixture supply system capable of responding to any rapid load fluctuation was established. As described in the foregoing section, a common rail fuel injection system was adopted alongside micro-pilot fuel injection, which can control ignition according to the reaction of the combustion state. Knocking may occur when there is an insufficient excess air ratio, and therefore the pilot injection timing is delayed when it is confirmed that the main engine is in an accelerating condition. The air-fuel ratio and micro pilot injection system are controlled optimally in the various operational states by an engine control unit (ECU).

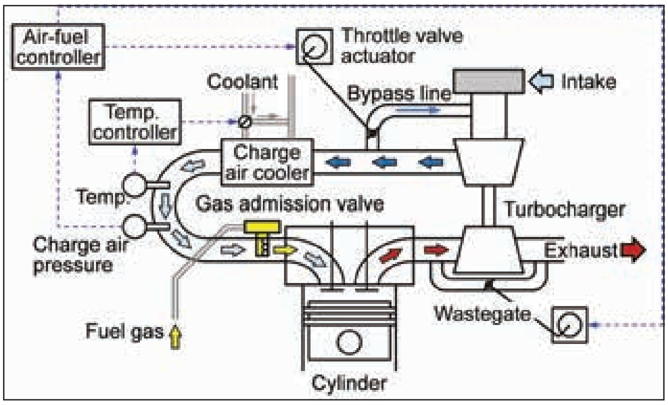


Figure 9: Schematic of the charge air control system

Figure 10 shows the one case of load operation test results in gas mode that was verified in the factory. The analysed data from the harbour tugboat equipped with the diesel engine indicated that increasing the load from idle speed to rated speed occurred within 20 seconds. Based on this, the possibility of an equivalent load operation was evaluated for the gas mode in a dual fuel engine. In a factory test, the load change started from an idle speed of 450 rev/min with approximately 18 per cent load and increased to a rated speed of 800 rev/min with 100 per cent load. When a load increase from an idling state in gas mode was requested, the engine load and speed increased smoothly, and the rated load could mostly be achieved within the target time set by the factory test.

Even though this result depended on such conditions as environmental temperature, supplied fuel gas condition and engine temperature (eg, lube oil, cooling water, etc), it indicated that gas mode operation attained equal load-increasing performance to diesel. *Figure 11* shows the results of the tugboat's simulated operations during the factory test. The solid line (gas mode) and dotted line (diesel mode) show the equivalent load response.

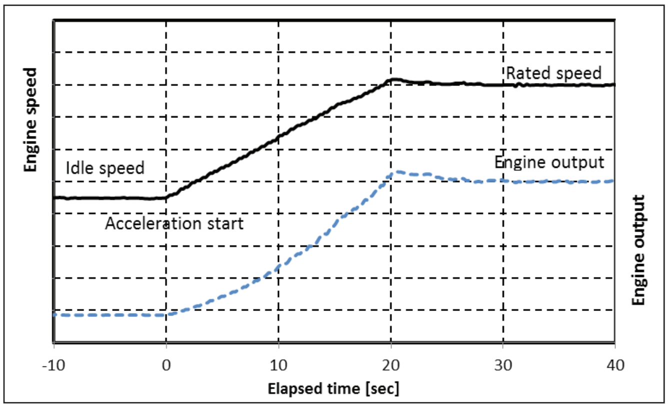


Figure 10: One case of acceleration test results

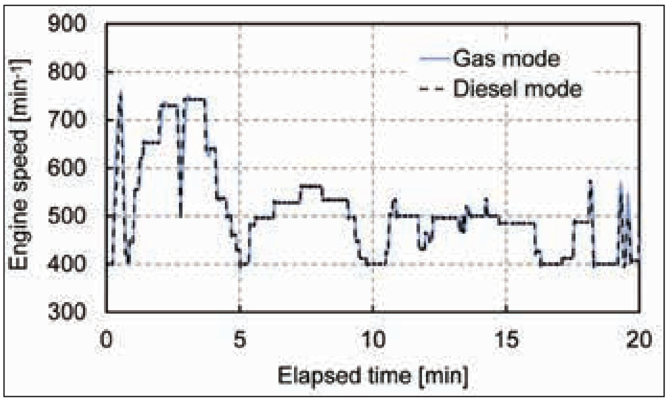


Figure 11: Demonstration test with practical operation pattern

During actual vessel navigation, sudden load variation often occurs in rough weather. A sudden increase in engine load causes knocking, caused by the decrease of the excess air ratio due to the difference between the fuel charge variation and turbocharger acceleration. Likewise, fuel of low methane numbers also tends to cause knocking due to component fluctuation in the vaporised LNG. Details of this phenomenon are described below. Under these circumstances, gas mode operation can only be barely maintained due to serious knocking. This has to be prevented in order to have stabilised vessel navigation, and the engine must be able to continue in operation during the shift from gas to diesel mode.

First, the engine combustion condition can be managed by monitoring in-cylinder pressure. The measured in-cylinder pressure (Pcyl) curve is processed by filtering. When the value after filtration exceeds the threshold value, a knocking condition is recognised and the gas mode is changed to diesel mode at once. *Figure 12* shows the result of changeover on the rated load. By constantly monitoring the combustion condition and promptly switching modes, continued vessel operation and service is assured.

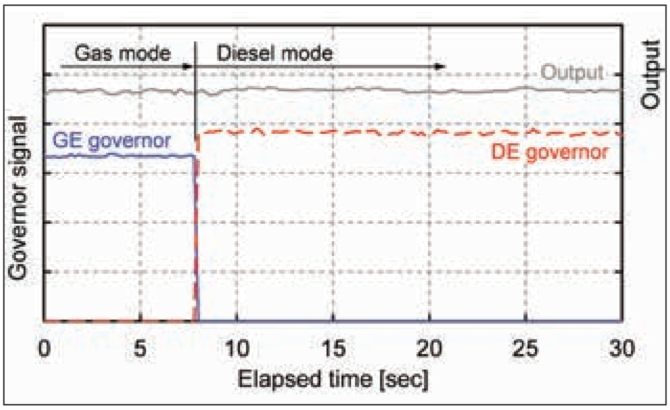


Figure 12: Change-over test result

Application

When installing the engine on a vessel, ensuring robustness against fuel supply is key to stable operation. *Figure 13* represents the basic configuration of a 28AHX-DF engine on a vessel. Stored fuel gas in the LNG tank is heated and vaporised and sent to the engine via the gas valve unit. When the fuel gas passes through the vaporiser, its velocity is changed according to the fuel consumption rate. The velocity of the gas is consequently changed according to the load variation and switching mode.

Figure 14 shows how LNG is produced using multiple hydrocarbons such as methane, ethane, propane and butane. All these differ in their boiling point. The vaporisation quantity changes according to the rapid variation of flow rate in the transition period. Therefore the component ratio after vaporisation is changed. In some cases, the component ratio of propane and butane is increased. This may easily cause knocking. The component ratio also differs according to the production area from which the gas was sourced. The fuel may have a chemical composition excluding methane, which will have a huge influence on the variation of flow. Furthermore, the mixing ratio of fuel gases from different supply facilities varies. The type and characteristic of the vaporiser and the engine's operational condition therefore depend on the gas's components.

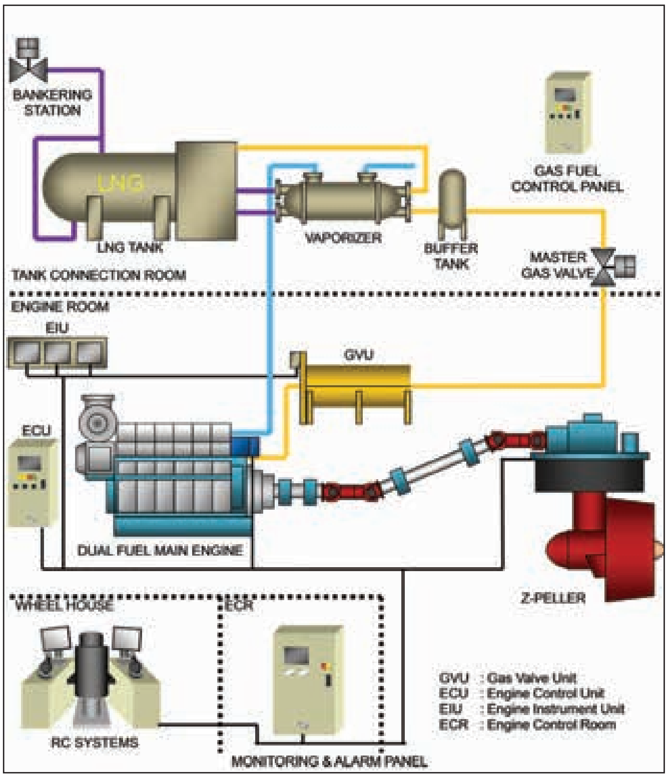


Figure 13: Basic configuration of 28AHX-DF engine installation

	Methane	Ethane	Propane	n-Butane
Boiling point [ºC]	-162	-89	-42	-1
LHV [MJ/Nm³]	35.8	59.9	93.6	122.6

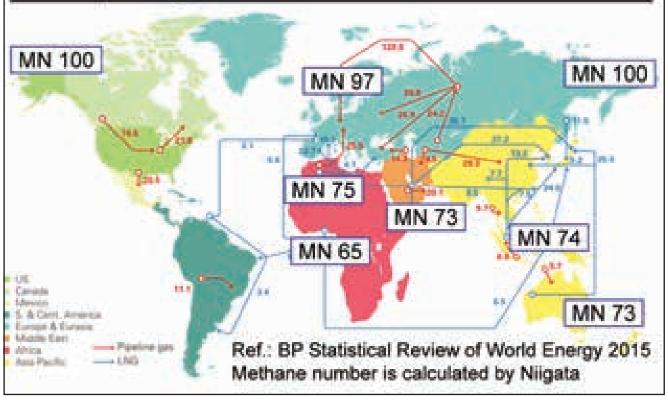


Figure 14: Difference in fuel characteristics depending on production area and composition[4]

Consequently, the fuel's calorific value and anti-knock characteristics are changed. *Figure 15, next page* shows the result of monitoring the calorific value of methane and concentration of methane at the point where the velocity of gas is changed. It shows that gas consumption is increased dramatically from the engine start when the calorific value varies a lot at the same time, and the gas component also varies in the short term. When the engine load decreases temporarily, gas consumption decreases temporarily, and the calorific value also decreases. In other words, when the fuel gas supply is stable, the engine load steadies.

Stabilised operation of the fuel supply facility is necessary for the stable operation of a duel fuel engine. A buffer tank should be installed between the vaporiser and engine inlet to ensure stable operation.

The Japanese test vessel used LNG with a methane number of 65, which had many hydrocarbons in addition to methane. Use of the buffer-tank meant that the destabilising effects of the gas supply were able to be excluded.

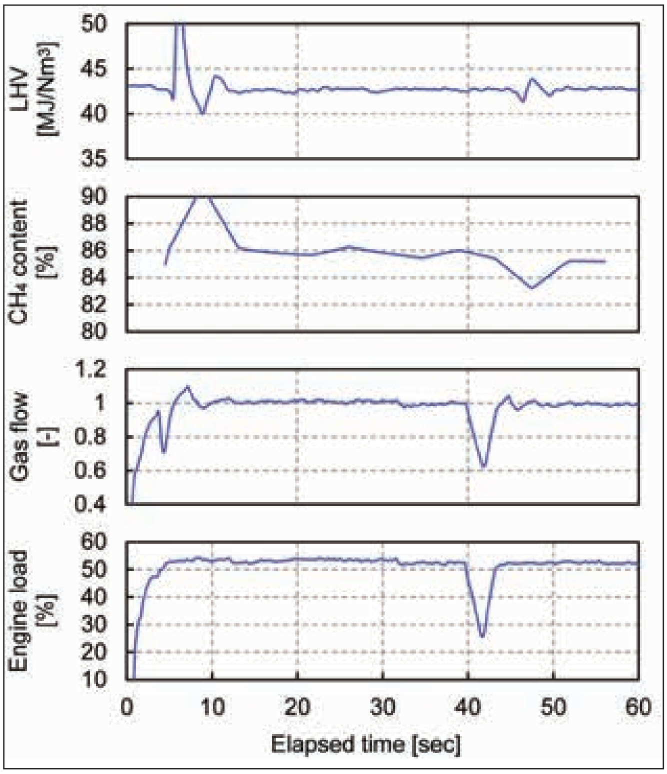


Figure 15: Change in calorific value and methane content due to engine load change

On the other hand, the engine should be designed to prevent such abnormal combustion as knocking and misfiring due to variation in the fuel supply condition. The design of the air-fuel mixture in the cylinder for ensuring ignition and combustion is significant. The combustion chamber's enclosure was designed with this in mind.

The micro-pilot ignition system injects a small amount of liquid fuel and produces a flame. The flame ignites and burns the gas mixture. This system has been designed for gas with low ignitability and low calorific value[5]. The ignition of micro-pilot fuel depends on the ignition condition of the fuel, the pressure ratio and specification of engine. The ignition of micro-pilot fuel ignites in any conditions and burns stably, enabling operation regardless of the gas components and environmental conditions.

Figure 16 indicates output stability when the diesel mode is switched to gas mode. In this test, the amount of diesel fuel injection decreased gradually and the amount of gas injection increased gradually in proportion. This changeover mode completed the switch in approximately 30 seconds. The variation in engine torque was a maximum of 6.3 per cent during the switching. Subsequently, the torque variation ratio was controlled at around 1 per cent, even if the calorific value varied from 43.9 to 40.8 MJ/Nm^3 due to the state of the fuel gas supply facility. The test indicated sufficient speed adjustment ability. The speed adjustment characteristic adapts for the fuel property change over time, which is one of the requirements for a main engine.

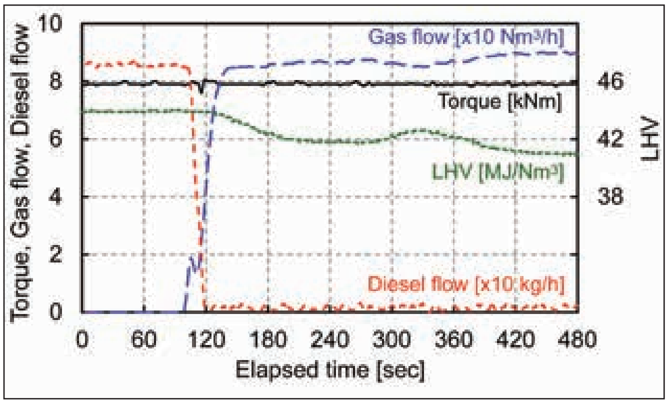


Figure 16: Engine output stability

The engine was developed according to the safety concept that switching from gas mode to diesel mode completes automatically once any conditions are reached that risk the engine knocking or misfiring. Furthermore, if any of the engine's peripheral devices have a failure that exceeds certain limit values, the switch is also made. When the engine is not running on gas fuel, the gas valve is automatically closed. The LCD touchscreen on the ECU enables the crew to check and operate the gas valve unit *(see Figure 17)*.

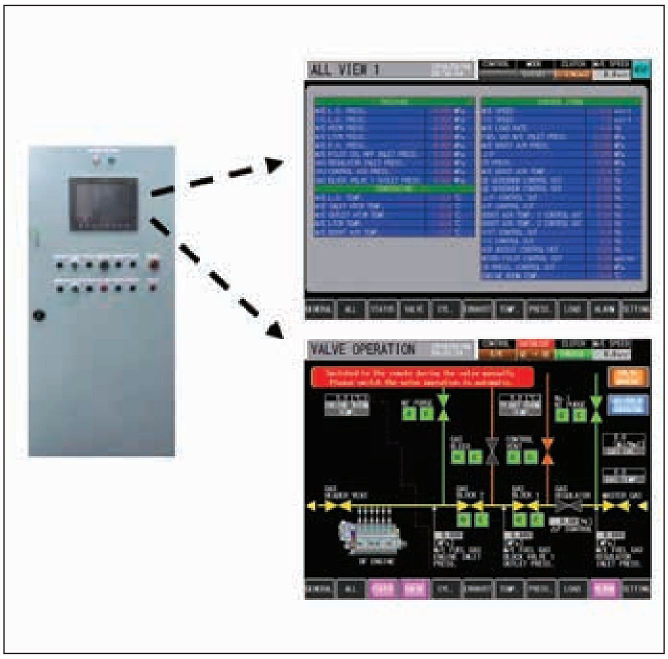


Figure 17: The engine control unit

The 28AHX-DF engine was developed to be installed as a main engine for other vessels besides tugboats. The series has 8- and 9-cylinder models using the same design concept, covering an output range of 2-3MW. Among these models, the first two sets of 6-cylinder engines were delivered for use as the main engine, coupled with FPPs, for a harbour tugboat in January 2015 (*Figure 18, next page*), and started commercial operation in Yokohama and Kawasaki harbours from September 2015[6]. The engines were installed with FP

Z-Peller azimuth propellers[7], giving a 55 tonne towing force. The engine output is 1,618kW at 750 rev/min in both diesel and gas modes.

Figure 18: The delivered 6L28AHX-DF for an LNG fuelled tugboat with direct drive propulsion

RESULTS OF DF TUG OPERATION

During factory tests, it was confirmed that gas operation under the propeller's cubical characteristics was within acceptable limits. However, in real-world testing, the permissible limits for gas operation were frequently met, due to the precipitous load change involved in clutch engaging/disengaging, or azimuth thruster steering and general tug work.

Sea trials

During sea trials before delivery, the tugboat sometimes triggered the permissible limits of gas mode when operating in low load conditions and in transient condition. Low load conditions are clutch engaging, or increasing the load from the disengage condition. The transient condition is acceleration from idle speed to rated speed. In these conditions it is easy for combustion to become unstable. When each case occurred, Niigata analysed engine operation data and improved the engine control logic and parameters, then carried out factory tests to check the revised control parameters. After confirmation of the soundness of control parameters applied to the ship engines, and stable operation being achieved, the vessel was delivered and started operation.

Tug operation after delivery

After starting work, further improvements in the transient load condition were added with respect to assisted ship control. During escort work to assist ship entry into port, two - five tugboats control the assisted ship via a rope connection. When the assisted ship is a large vessel, such as a VLCC, engine load exceeds the safe area constituted by the propeller's cubical characteristics.

In this situation, it was difficult to maintain gas mode operation. When rapid load changes accompany loads exceeding the propellers' cubical curve, the excess air ratio in the combustion chamber is decreased. Diesel operation can sustain this operation, but produces black smoke, whereas in gas operation combustion will be unstable. To address these situations, Niigata repeated the modification processes resulting from analysis of the engine data during tug operations and improved the controls. The effect was confirmed by the test engine in the factory and reflected to the ship engines, and then confirmation of the condition during the tug work on board. As a result of these modification works, the operational possibility area was extended, and it became possible to operate stably.

DF (gas) tugboat and diesel tugboat

From these experiences during the first year of operation, the DF (gas) tugboat was able to perform almost equally with a diesel tugboat. However, it is a fact that it is hard to continue gas operation at low speed and high load conditions after extending the operational possibility area. On the other hand, it is also an obvious fact that it is possible to make considerable contributions to reducing environmental strain. Therefore the number of DF tugboats is expected to grow in the future.

Future dual fuel engine delivery plan

At the moment, there are plans to deliver four sets of 6L28AHX-DF engines in the autumn of 2017 for two tugboats operating in Singapore. Their commercial operation is planned to commence in the spring and summer of 2018. In addition, two sets of 8L28AHX-DF engines are planned to be delivered at the start of 2018 for a single tugboat in Ningbo port, China, which will start commercial operations in summer 2018. Through these further delivery plans, Niigata Power Systems will continue to make a contribution to reducing the strain on the environment.

Figure 19:The tugboat **Sakigake**

CONCLUSION

The dual fuel 28AHX-DF engine has been developed as the key component to meet marine engine emission control regulations. Niigata targeted the harbour tugboat, packaging with the Z-Peller azimuth thruster. The findings obtained during the course of this development are as follows:

1. From the operational profile of the harbour tugboat that used the existing diesel engine, low load operation is a big part of operations. During operations, engine load change is exceptionally sharp.

2. During both the E3 and E2 test cycles, the emission gas performance of the new engine satisfies Tier II regulations in diesel mode and Tier III regulations in gas mode. As well as being adaptable to direct propeller drive systems, the engine is also applicable to constant speed operations such as CPP use and electric power generation.

3. In various operational conditions, the engine exercises good load following capability by optimally controlling the air-fuel ratio, and using a micro-pilot injection system controlled by the ECU. During gas mode, if the limit values for knocking, misfiring or engine peripheral devices are breached, the operational mode will be switched to diesel at once, and the engine will continue to work without problems.

4. The first two sets of 6L28AHX-DF engines have been installed in an LNG-fuelled tugboat with direct drive. These have been operated in Yokohama and Kawasaki harbours since September 2015.

5. It became possible to operate the tug stably throughout the one-year period by making use of operational experiences and following up on board.

6. The DF (gas) tugboat became able to perform on an almost equal footing with the diesel tugboat. With a DF tug, it is possible to make a considerable contribution to reduction of the environmental load of operation. The number of DF tugboats is therefore expected to grow in the future.

7. Two DF tugboats are planned to start commercial operation in spring/summer 2018 in Singapore, and one DF tugboat is planned to start commercial operation in summer 2018 in China with the 28AHX-DF engine.

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