Corresponding to Southeast Asia Market by High-Efficient Gas Engine 28AGS

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In order to further improve the efficiency of gas engines, IHI Power Systems Co., Ltd. is continuing development based on the spark-ignition lean-burn gas engine 28AGS for power plants, which was developed in 2012, with a special focus on combustion stability in the main combustion chamber. Studies confirmed that the engine has strengthened ignition energy and reduced unburned area. Furthermore, a series of studies has realized higher efficiency gas engines to be provided to the worldwide market, especially Southeast Asia. This paper introduces these technologies to cope with differences in climate and fuel properties between in Southeast Asia and in Japan.

1. Introduction

Gas engines are environmentally friendly because of their relatively clean exhaust gases, and there is a growing market for them as onshore power generation facilities and marine propulsion engines. IHI Power Systems Co., Ltd. (IPS) manufactures and sells medium- and large-sized gas engines that pursue environmental friendliness and safety as well as economic efficiency in line with market demands.

Making the most of the technical knowledge that IPS has accumulated so far, the authors have been working to make the spark-ignition lean-burn gas engine 28AGS more efficient and to market it in Southeast Asia and other regions that are implementing economic reforms.

This paper describes the technical development of high-efficiency gas engines with the aim of encouraging greater market penetration.

2. Characteristics of gas engines

2.1 Combustion system

Gas engines literally use gas (e.g., city gas) as fuel. The fuel gas is mixed in advance with air and then supplied into the combustion chamber as an air-fuel mixture. This air-fuel mixture is ignited and burned. There are several ignition systems, each of which has different characteristics. **Figure 1** shows ignition systems for gas engines.

These can be broadly classified by ignition source into the spark ignition system, which uses sparks produced by

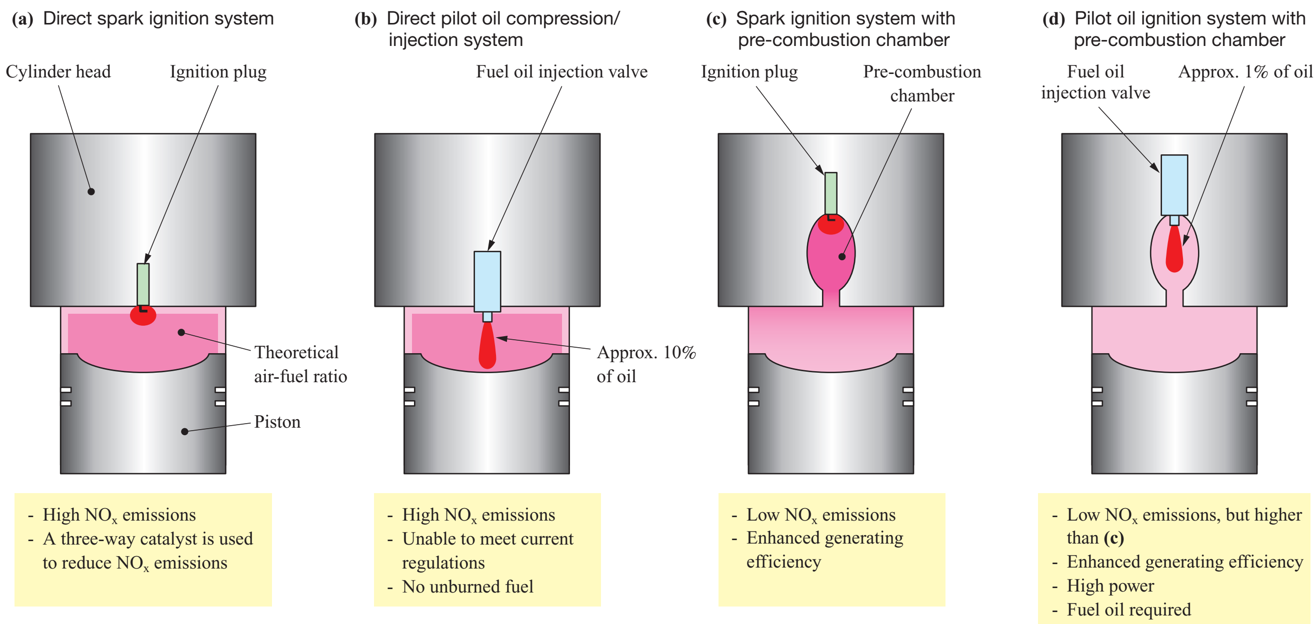


Fig. 1 Gas engine ignition methods

ignition plugs; and the pilot oil ignition system, which injects liquid fuel, allows it to self-ignite, and uses the flame jet produced by such self-ignition. Both of the systems may be used with a pre-combustion chamber to increase ignition energy in the spark ignition system, or to obtain ignition energy with as little liquid fuel as possible in the pilot oil ignition system. The pilot oil ignition system, if used with a pre-combustion chamber, can reduce the proportion of the heating value of liquid fuel to fuel consumption from 10% to 1%.

Medium- and large-sized gas engines generally employ an ignition system that uses a pre-combustion chamber. IPS's gas engine 28AGS uses a spark ignition system with a pre-combustion chamber, which has less nitrogen oxide (NO_x) emissions and does not require the use of fuel oil (**Fig. 1-(c)**).

2.2 Knocking

Knocking is a characteristic of gas engines. Knocking refers to the phenomenon in which fuel gas in the main combustion chamber self-ignites before being ignited by the flame jet from the ignition source. **Figure 2** shows the occurrence of knocking. Knocking occurs around the cylinder liner wall in the combustion chamber, and it causes a disturbance in the air layer when subjected to high temperature and high pressure. As a result, the lubricating oil film on the wall breaks, resulting in scuffing (abnormal wear) on the cylinder liner's sliding surface. In addition, excessive heat generation due to poor lubrication causes the surface of the material to melt locally. Therefore, knocking must be avoided to protect the engine; this is a significant challenge in gas engine development.

2.3 Types of fuel gas

Table 1 lists the types of gases used as gas engine fuels and their compositions. Gas engine performance depends greatly on the type of fuel gas, so adequate consideration is required.

In particular, the heating value is important, and the following three points must be noted:

(1) Whether or not the heating value is too high;
(2) Whether or not the heating value is too low; and
(3) Whether or not the heating value fluctuates.

2.3.1 Gases with a high heating value

Gases with a high heating value are more likely to cause knocking. Propane gases for household use and for automobiles have a high heating value and are more likely to cause knocking. Therefore, they are not suitable for medium- and large-sized gas engines.

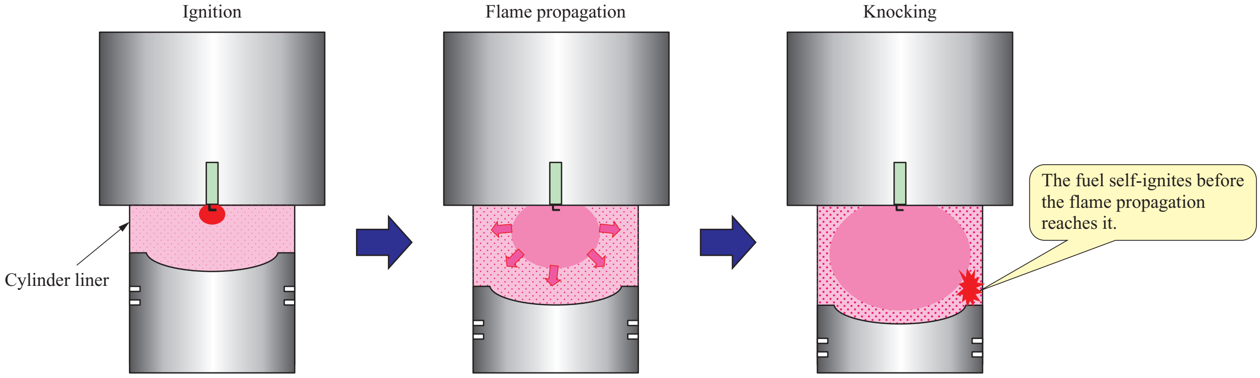


Fig. 2 Knocking process

Table 1 Composition of fuel gases

Ingredient	Unit	Natural gas (from Brunei)	Natural gas (from Alaska)	City gas 13A	Digestion gas	Wooden biomass gas	Natural gas (Southeast Asia)	Propane gas
Methane (CH_4)	vol%	89.0	99.5	89.6	60.0	5.0	69.0	—
Ethane (C_2H_6)	vol%	7.0	0.3	5.6	—	—	1.0	—
Propane (C_3H_8)	vol%	3.0	0.1	3.4	—	—	0.5	100.0
Butane (C_4H_{10})	vol%	1.0	—	1.4	—	—	—	—
Carbon dioxide (CO_2)	vol%	—	—	—	40.0	10.0	4.0	—
Carbon monoxide (CO)	vol%	—	—	—	—	30.0	—	—
Hydrogen (H_2)	vol%	—	—	—	—	20.0	—	—
Nitrogen (N_2)	vol%	—	0.1	—	—	35.0	25.5	—
Heating value	MJ/m^{3}N	40.5	36.0	40.7	21.6	7.8	29.5	93.0

(Note) Content and heating values vary, so this table lists reference values.

2.3.2 Gases with a low heating value

Gases with a low heating value (low calorific value gases) contain many ingredients which is hard to burn; therefore, combustion control is difficult. Special gases such as digestion gases and wooden biomass gases have a low heating value. The gas engine 28AGS, which is in practical use, has a strong ignition source and can thus provide stable combustion even when using a special fuel gas with a low heating value.

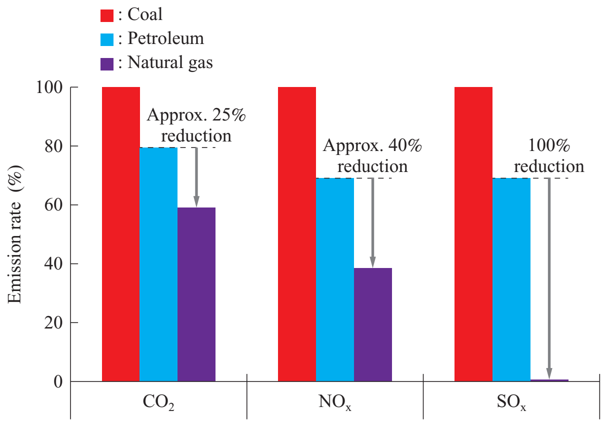
Figure 3 shows typical applications of special fuel gases. When using a gas with a low heating value, the amount of gas supplied must be increased to obtain the same level of output as city gas 13A, and modifications to the fuel gas supply system are required.

2.3.3 Gases with a fluctuating heating value

If the heating value fluctuates, knocking or poor combustion is likely to occur. City gas 13A, which is commonly used in Japan, has a stable heating value and is unlikely to experience fluctuations.

2.4 Clean exhaust gas properties

A major characteristic of gas engines is that they have the property of clean exhaust gas. Diesel engines emit smoke (black smoke); on the other hand, gas engines emit little smoke and instead emit colorless, transparent exhaust gas. Compared to diesel engines, gas engines emit smaller amounts of NO_x, which causes photochemical smog and acid rain, and carbon dioxide (CO_2), which is a greenhouse gas. Also, gas engines emit a smaller amount of sulfur oxide (SO_x), which correlates with breathing problems and particulate matter (PM) emissions. **Figure 4** shows a comparison of exhaust gases by fuel type. This compares the amount of exhaust gas between petroleum (diesel engines) and natural gas (gas engines) when the amount of coal's exhaust gas is set to be 100.



(Note) Source : Natural Gas Prospects to 2010 (1986), International Energy Agency

Fig. 4 Comparison of fuel and exhaust gas

3. Measures for the Southeast Asian market

3.1 Challenges

Ambient conditions present an issue to putting our gas engine on the Southeast Asian market. The differences in ambient conditions in Southeast Asia compared to Japan are as follows:

(1) Low calorific value gas (different gas properties);
(2) Climate in South Asia;
(3) Fluctuation in atmospheric conditions (temperature and humidity); and
(4) Adoption of the radiator system (engine cooling water is not sufficiently available).

These effects were verified in order to take the necessary measures.

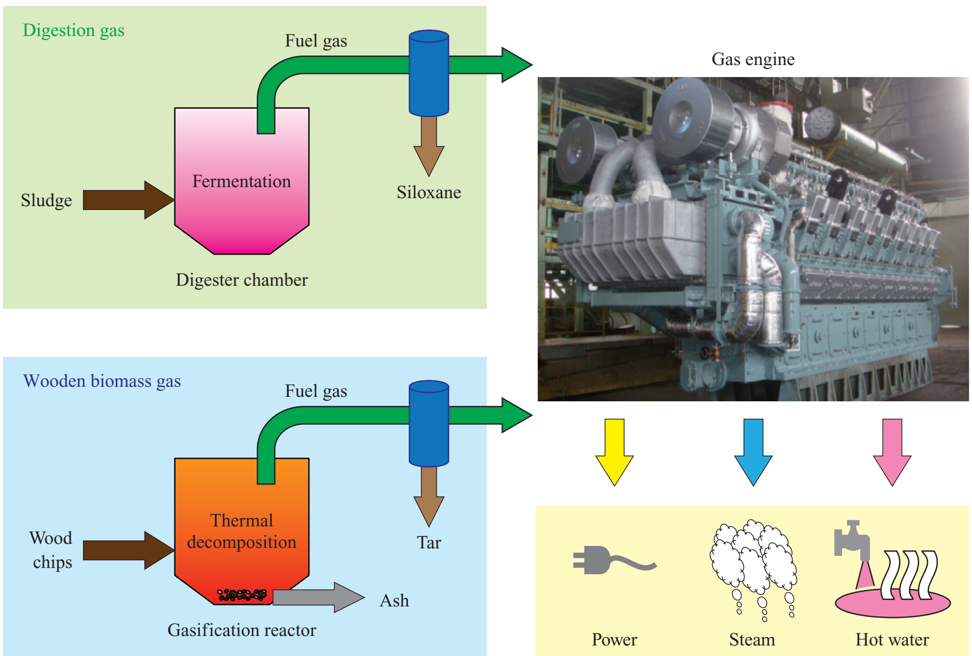


Fig. 3 Application of special fuel gas

3.2 Low calorific value gas

3.2.1 Effects on engines

As described in **Section 2.3**, the city gases used in Japan are stable in terms of composition and heating value throughout the year, but some of the natural gases used in Southeast Asia are not.

An example natural gas is a mixture gas of methane (CH_4) and nitrogen (N_2) or CO_2. City gas 13A has a heating value of approximately 41 MJ/m^3N, but the given natural gas has a low heating value of 27 to 36 MJ/m^3N. The natural gases used in Southeast Asia have such low heating values.

If a fuel gas has a low heating value per unit volume, a larger amount of fuel gas must be supplied to the combustion chamber in order to maintain engine power. Therefore, the amount of fuel gas supplied is important.

The gas engine 28AGS uses a solenoid valve system to supply fuel gas. With this system, an appropriate amount of gas is supplied in each cycle via the solenoid valve installed onto each cylinder, and at this time, the amount of gas is adjusted according to the solenoid valve's opening time. This means that the amount of gas supplied can be increased by extending the opening time of each solenoid valve. **Figure 5** shows how fuel gas is supplied[1]. Fuel gas is supplied in the upstream of the intake valve; therefore, even if the solenoid valve's opening time is extended, no fuel gas enters the combustion chamber if the intake valve closes before the solenoid valve. In addition, if the opening of the solenoid valve is done further in advance, before the exhaust valve closes, or when both the intake valve and exhaust valve are open (overlap), part of the supplied gas does not stay in the combustion chamber and instead is emitted, resulting in wasteful fuel gas consumption.

This means that when a low calorific value gas is used, the efficiency may change significantly; therefore, the timing of fuel gas supply is important.

3.2.2 Improvements for stable combustion

For low calorific value gases, an ignition source is important to ensure stable burning.

The gas engine 28AGS uses ignition plugs as an ignition source, but these are not enough to efficiently burn the air-fuel mixture in the large combustion chamber. Therefore, the gas engine 28AGS has a small chamber called a pre-combustion chamber. **Figure 6** shows the construction of this combustion chamber[1]. Sparks produced by the ignition plug are used to burn the air-fuel mixture in the pre-combustion chamber, and the flame jetted from the pre-combustion chamber is used to ignite the air-fuel mixture in the main combustion chamber. This means that the flame jet from the pre-combustion chamber serves as an ignition source for burning the low calorific value gas. Therefore, the efficiency of jetting the flame from the pre-combustion chamber into the main combustion chamber becomes considerable, and the shape of the pre-combustion chamber is important to achieve such efficiency. Thus, the shape was parameterized, and the parameters were adjusted through computational fluid dynamics (CFD) to evaluate the flame jet and determine an appropriate shape. **Figure 7** shows the analytical results of the flame jet in the pre-combustion chamber by CFD[1]. A shape appropriate for the pre-combustion chamber was determined so that the flame jet reaches the entire surface of the main combustion chamber, leading to the low calorific value gas to burn stably with such a strong ignition source.

3.2.3 Peripheral components

To ensure stable combustion of a low calorific value gas, the supply pressure of the fuel gas must be made higher than what is specified for city gas 13A; therefore, the fuel gas pipe size was increased to reduce pressure loss.

Also, increasing the pressure of the gas supplied to the engine requires giving consideration to the gas supply equipment. When using a low calorific value gas, the amount

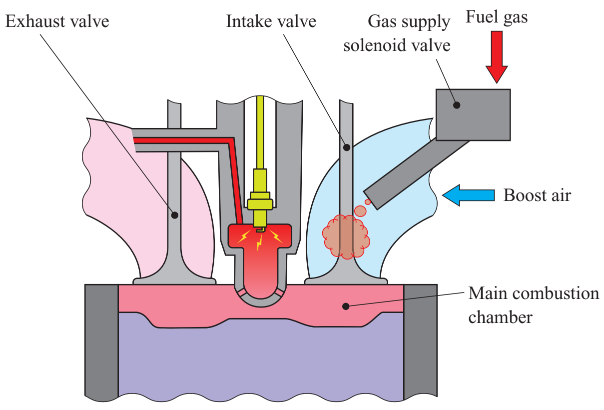


Fig. 5 Outline of fuel gas supply[1]

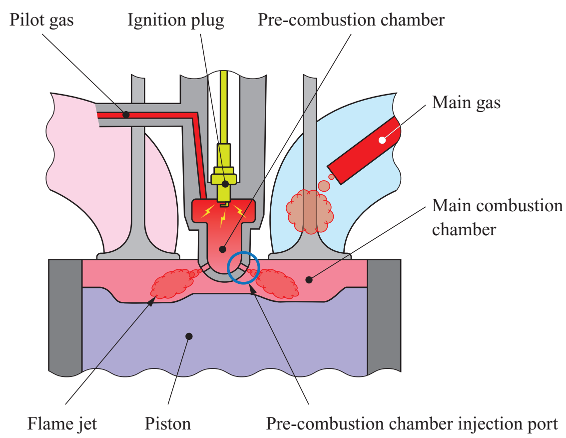


Fig. 6 Schematic of combustion chamber[1]

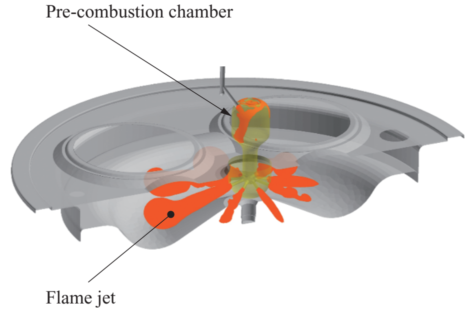


Fig. 7 CFD result of flame jet from pre-combustion chamber[1]

of fuel gas supplied increases as described in **Section 2.3**; therefore, a fuel gas pressure regulating valve having appropriate flow characteristics for the increased fuel gas supply is required. At the same time, as the engine load decreases, the required gas supply pressure decreases and the flow rate is low; this makes it difficult to finely control the pressure at a low load solely by increasing the valve size in order to increase the flow rate.

Therefore, a pressure regulating value with equal percentage characteristics which enable high controllability even at low flow rates has been adopted. **Figure 8** is a graph that illustrates the characteristics of the pressure regulating valve.

For auxiliary equipment, such as gas filters, a capacity appropriate for the increased flow rate was selected so that the pressure loss would not increase.

3.2.4 Verification with actual equipment

To support low calorific value gases, IPS conducts tests of actual equipment by using a simulated gas made by mixing liquefied natural gas (LNG) and CO_2. **Table 2** shows the test results with the CO_2 mixture gas.

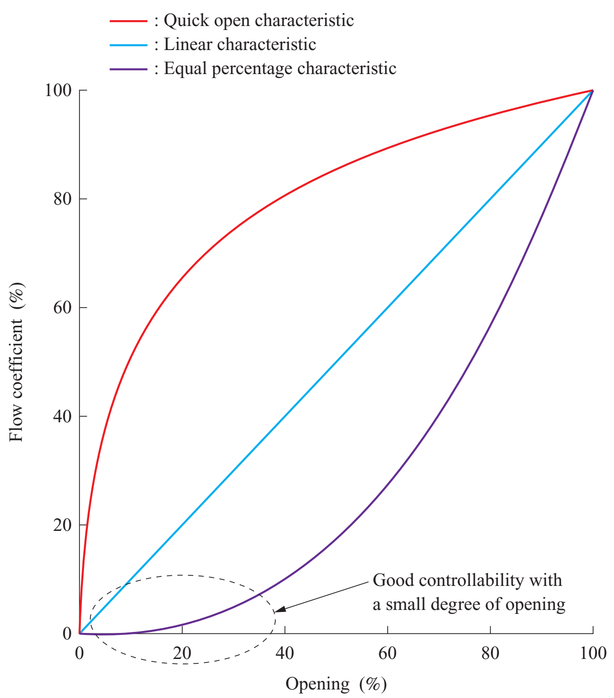


Fig. 8 Characteristics of the pressure regulating valve

Even with low calorific value gases with heating values of 25.7 and 24.4 MJ/m^{3}N, stable combustion could be achieved by providing a strong ignition source as described in **Section 3.2.2**. It was confirmed that it is possible for natural gases used in Southeast Asia having heating values of 27 to 36 MJ/m^{3}N to operate the engine at the same power as with the reference gas (city gas 13A or equivalent) without a significant decrease in efficiency.

In such cases, however, there is a need to increase gas supply while maintaining the solenoid valve opening time equivalent to that for the reference gas, which requires the fuel gas supply pressure to be increased. It was also revealed that in order to obtain a stronger flame jet in the pre-combustion chamber as an ignition source for the combustion chamber, there is a need to increase the amount of gas supplied to the pre-combustion chamber.

3.3 Climate in Southeast Asia

Engine performance greatly depends on the intake air (atmosphere) conditions. Southeast Asia has many hot regions where, in general, there are concerns about engine performance deterioration.

As intake air temperature increases, air density decreases. Because a turbo supercharger is used to supply air to the combustion chamber, the intake air's mass flow rate decreases as air density decreases. As a result, knocking occurs. To prevent this, in general, the supercharger's workload is increased in order to increase the intake air's mass flow rate; however, this decreases engine efficiency. This means that engine efficiency will decrease as the intake air temperature increases.

Maintaining efficiency at high temperatures requires studying the system for supplying intake air to the engine. In a general intake air supply system, air in the room where the engine is placed is sucked by the engine, but as a measure for high temperatures, outside air is supplied directly to the engine in order to introduce cooler air.

The climate in Southeast Asia tends to be not only hot but also humid. The increase in humidity causes the decrease in efficiency. The high humidity also affects intake air temperature due to the decrease in cooling efficiency, resulting in concern about occurrence of knocking and other undesirable phenomena. We are now working on the

Table 2 Results of CO_2 mixture test

Item		Unit	Reference gas	CO_2 mixture gas	
Load factor		—	100	100	100
CO_2 mixture proportion		%	0	36	39
Low-heating value		MJ/m^{3}N	40.4	25.7	24.4
Main gas	Pressure	times	1 (reference)	1.3	1.3
	Supply start	degrees (crank angle)	0 (reference)	10 (advance)	10 (advance)
	Supply duration	times	1 (reference)	1.3	1.4
	Flow rate	times	1 (reference)	1.57	1.67
Pilot gas	Pressure	times	1 (reference)	1.2	1.2
	Flow rate	times	1 (reference)	1.8	1.8
Shaft-end efficiency (Reference gas = 100%)		%	100 (reference)	99.5	97.7

development to ensure efficiency and to improve cooling system for intake air under the high-humidity environment.

3.4 Fluctuation in atmospheric conditions

In addition to high temperatures and high humidity, daily and seasonal fluctuation in atmospheric conditions greatly influence the combustion stability and efficiency of gas engines.

Therefore, to reduce the impact of atmospheric conditions, the amount and temperature of air supplied to the combustion chamber (boost air) are controlled. **Figure 9** shows the configuration of the air adjustment system.

3.4.1 Boost air flow control

Medium- and large-sized engines use a supercharger to compress the air supplied to the combustion chamber and to secure the boost air flow required for combustion. However, too much boost air causes a misfire, while too little boost air causes knocking. Therefore, the boost air flow must be adjusted.

There are two ways to adjust the boost air flow: an air bypass system and a wastegate system. **Figure 10** shows these boost air flow adjustment systems.

In the air bypass system, part of the boost air compressed by the supercharger is returned to the supercharger's inlet to decrease the boost air flow. This system is advantageous in the following respects: The boost air flow can be controlled

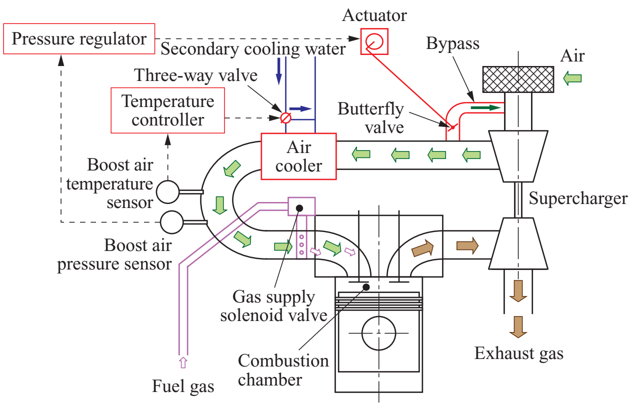


Fig. 9 Adjustment system configuration for boost air

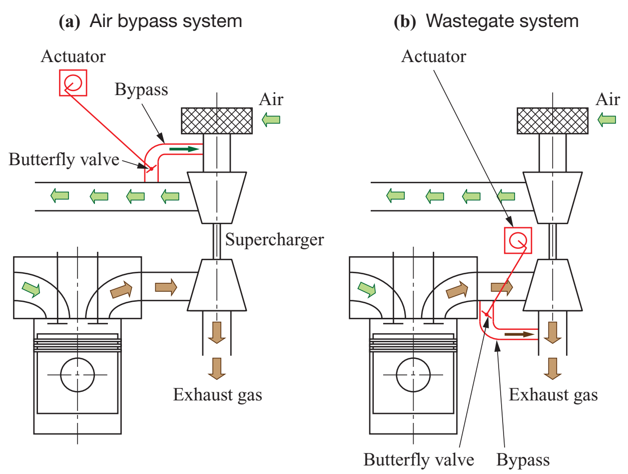


Fig. 10 Adjustment systems for boost air flow

with a relatively good response; the bypassed boost air temperature is relatively cool (around 200°C); and it does not much affect control valve durability. However, some of the boost air compressed by the supercharger is released, causing energy loss, which is disadvantageous in terms of efficiency.

In the wastegate system, part of the exhaust gas used to operate the supercharger is bypassed to the supercharger's turbine outlet in order to decrease the supercharger's rotational speed and decrease the boost air flow. In this system, hot exhaust gas in the supercharger's upstream is bypassed, which causes the supercharger outlet temperature to increase, resulting in an increased amount of heat recovered in the exhaust gas boiler and other components. In addition, the force operating the supercharger decreases, and the pressure at the combustion chamber's outlet decreases accordingly. As a result, the compression workload for discharging the burned gas decreases, which may lead to reduced fuel consumption. This means that this system is advantageous as it can improve total efficiency. However, because the boost air flow is adjusted according to changes in the supercharger's rotational speed, the responsiveness is low due to the effect of the supercharger's inertia; in addition, because the exhaust gas is hot (around 500°C), the control valve must have high heat resistance, which is a disadvantage.

In both systems, feedback control is performed for the boost air pressure so that the pressure of the boost air supplied to the combustion chamber is appropriate at each load, thereby adjusting the boost air flow to an appropriate level.

3.4.2 Boost air temperature control

If the boost air temperature is too high, abnormal combustion is likely to occur, resulting in knocking. If the boost air temperature is too low, a misfire will occur due to poor combustion. Although the boost air pressure is controlled to adjust the boost air flow, the mass flow rate changes as the temperature changes. Therefore, the boost air temperature must be kept at an appropriate level.

The temperature of the intake air compressed by the supercharger is approximately 200°C, and this hot air is cooled in the first stage and then the second stage of the two-stage air cooler. **Figure 11** shows the configuration of the boost air temperature adjustment system.

The first stage is located on the high temperature side and

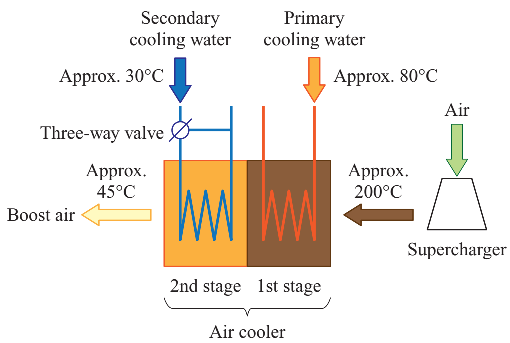


Fig. 11 Structure of control system for boost air temperature

uses the primary cooling water (approximately 80°C) to cool the engine. After that, the second stage, located on the low temperature side, uses lubricating oil and the secondary cooling water (approximately 30°C), which is used mainly to cool the primary cooling water, to cool the engine. At this time, the amount of secondary cooling water supplied to the air cooler is adjusted by a three-way valve to control the boost air temperature.

The feedback control is performed for the boost air temperature. During load change operation, the boost air temperature may change significantly due to overshooting or undershooting caused by a delay in feedback control, resulting in a misfire or knocking. Therefore, during load sharing control, the degree of opening of the three-way valve is corrected by open loop control instead of feedback control. This control is performed so that the boost air temperature is kept within the appropriate range not only during constant load operation but also during load sharing control.

With a two-stage air cooler, if the boost air temperature in the supercharger's downstream is low at a low load, such as during a cold start, the boost air on the high temperature side of the air cooler's first stage can be heated to an appropriate temperature by the heated (approximately 60°C) primary cooling air. During normal operation, the energy of the hot water can be recovered from the primary cooling water heated on the high temperature side of the air cooler's first stage via the heat exchanger and used effectively as a heat source for heaters and absorption refrigerators.

3.5 Adoption of the radiator system

3.5.1 Cooling system for secondary cooling water

While the boost air at the supercharger's outlet, which has been compressed by the supercharger and become hot, is cooled by the air cooler, the secondary cooling water supplied to the air cooler must be cooled to an appropriate temperature because it affects boost air temperature control.

There are two ways to cool the secondary cooling water: the cooling tower system, which makes use of the vaporization heat of the circulating water, and the radiator system, which makes use of heat exchange with outside air. **Figure 12** shows the cooling systems for secondary cooling water.

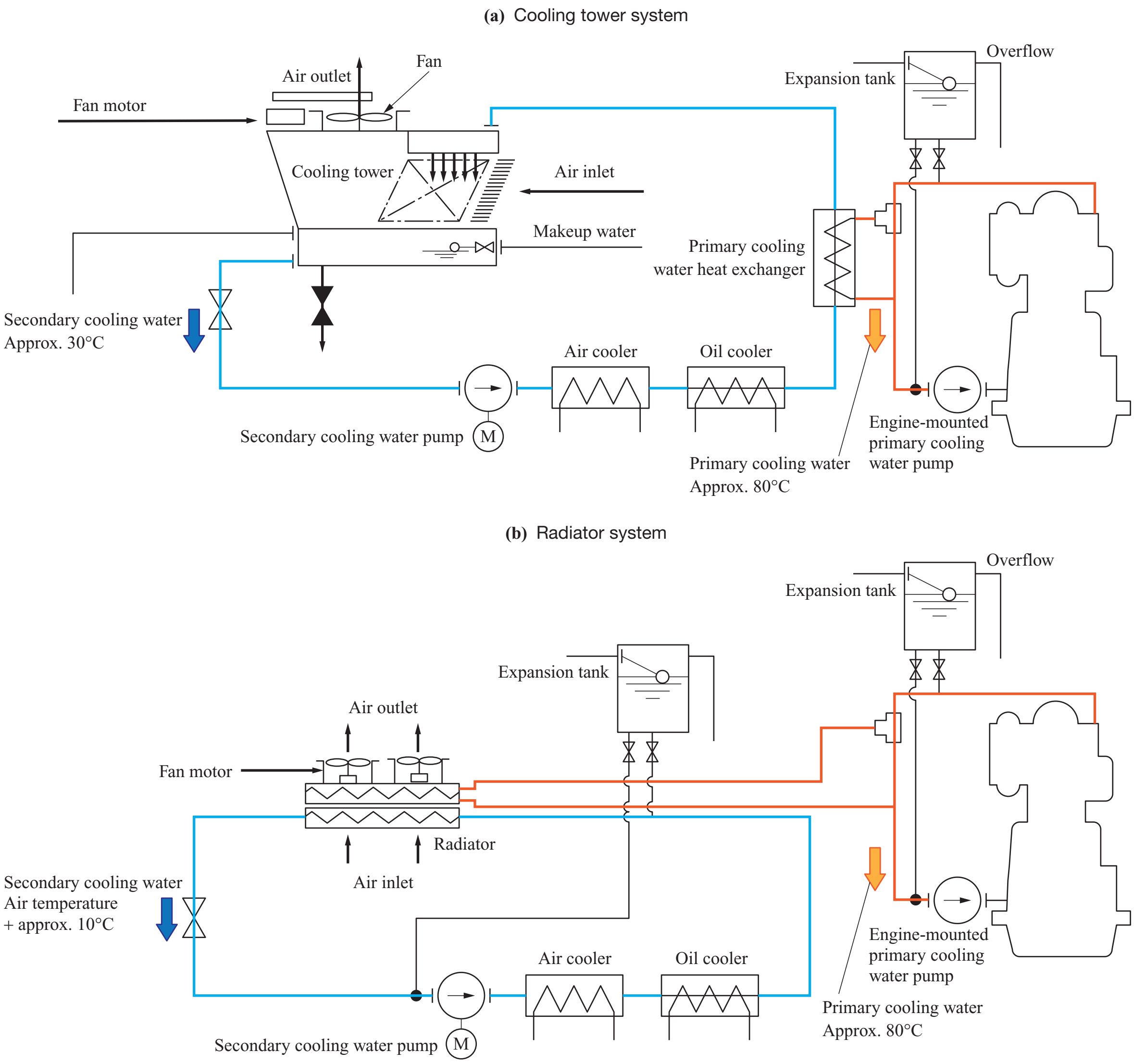


Fig. 12 Cooling methods for cooling water

The cooling tower system makes use of vaporization heat, enabling efficient cooling. The secondary cooling water can be cooled to 35°C or lower regardless of the outside air temperature. However, a relatively large amount of cooling water is consumed in order to maintain vaporization and cooling water properties by blowing (draining).

The radiator system makes use of heat exchange with outside air and consumes less cooling water but requires a large fan capacity. The secondary cooling air cannot be cooled to lower than the outside air temperature, and thus may be 40°C or higher.

Because of the aforementioned characteristics, in general, the cooling tower system is adopted in regions where sufficient makeup water can be secured, giving priority to decreasing the boost air temperature, and the radiator system is adopted in regions where makeup water cannot readily be secured. In Japan, abundant water is available, but in other countries, water may not be readily available. For this reason, a radiator may be used as a cooling system for the secondary cooling water.

With a radiator, if the outside air temperature is high, the secondary cooling water cannot be cooled sufficiently, causing the boost air temperature to remain high (around 50°C). This increases the probability of knocking.

When adopting the radiator system, the following measure is taken, where possible, to decrease the secondary cooling water temperature. The primary cooling water, which is normally cooled by the secondary cooling water, is cooled by the radiator, instead of the secondary cooling water, thereby decreasing the secondary cooling water temperature as much as possible (**Fig. 12-(b)**). This prevents the boost air temperature from increasing.

3.5.2 Prevention of knocking

When adopting the radiator system, measures are taken to prevent knocking even when the boost air temperature is high and to ensure stable engine operation.

The occurrence of knocking depends not only on the boost air temperature but also on the maximum combustion pressure (Pmax). In addition, Pmax varies across cycles and cylinders, and knocking is more likely to occur with higher Pmax values. This means that by reducing variation in the Pmax value, knocking can be prevented even at high boost air temperatures, thereby achieving stable combustion.

The gas engine 28AGS reduces variation in Pmax across cycles through the optimized shape of the pre-combustion chamber described in **Section 3.2.2**. Also, Pmax is measured with a pressure sensor installed on each cylinder in order to automatically adjust the ignition timing so that variation across cylinders is kept within an appropriate range.

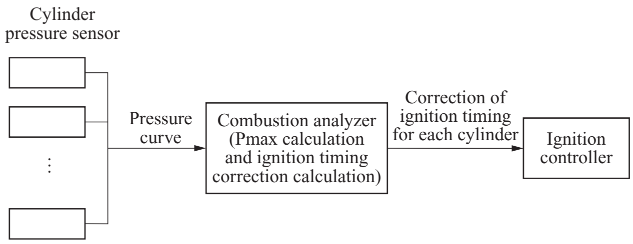


Fig. 13 Control process of Pmax control system

Figure 13 shows the control flowchart for the Pmax control system. This prevents knocking even if the boost air temperature increases to a certain extent.

However, there is still a possibility of knocking. Therefore, if knocking occurs sporadically, the amount of gas supplied to the relevant cylinder is decreased to avoid recurrence. If knocking occurs repeatedly, the engine power is reduced, and if knocking still persists, the engine is brought to an emergency stop.

For these controls, the gas engine 28AGS is equipped with a knocking detector. This makes it possible to operate the engine without concerns about engine damage or sudden engine stops (power generation shutdown) due to knocking.

4. Conclusion

Gas engines are environmentally friendly thanks to clean exhaust gases, and there is a growing market for them as onshore power generation facilities and marine propulsion engines. IPS has developed the gas engine 28AGS based on its gas engine combustion technology accumulated over many years.

Moreover, IPS has boosted research aimed at greater market penetration of its high-efficiency engine. As a result, even in Southeast Asia, which is expected to be a gas engine market but, unlike Japan, has hot and humid climate conditions and a tendency to use low calorific value fuels, it is now possible to operate the developed gas engine stably while maintaining the same level of power as in Japan. To minimize efficiency deterioration, matching between the engine and its peripheral components has been optimized.

The gas engine 28AGS will contribute to stable power supply in other countries as well as Japan with its high efficiency and usability in harsh environments.

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