HCCI Engines - Opening Up a New Age in Energy

(Unofficial Translation)

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1. Introduction

Natural gas entails less emissions of carbon dioxide (CO_2) per unit of calorific value than oil, coal, and other fossil fuels, and is produced in a wide range of countries around the world [(1)]. Development of shale gas is moving ahead, and measures to encourage the use of natural gas are under study. The gas industry is promoting the installation of combined heat and power (CHP) and gas engine-driven heat pump (GHP) systems fueled with natural gas for the purpose of saving energy, reducing CO_2 emissions, and shaving power demand peaks. Nevertheless, the rise in levels of efficiency at large-scale thermal power plants and the performance of electric heat pumps (EHPs) is creating needs for a further increase in the efficiency of CHP and GHP systems. In 2011, targets for the generation efficiency of CHP systems were posted by the Japan Gas Association (JGA) (Figure 1) [(2)]. The JGA set target values in each size class. Manufacturers of small engines (in the class of a few tens of kilowatts), which are being installed mainly in hospitals as well as supermarkets and other small-scale business facilities, are being asked to increase the generation efficiency by at least 8 points relative to the present, by 2020. It is, however, difficult to achieve a big increase in the generation efficiency of small gas engines used in small-scale CHP and GHP systems, owing to limitations associated with flameout and knocking. To raise efficiency in this class, we focused on homogeneous charge compression ignition (HCCI) combustion, a new type of combustion method offering high efficiency and low emissions of nitrogen oxides (NOx), and launched efforts for a dramatic increase in efficiency with lower NOx emissions.

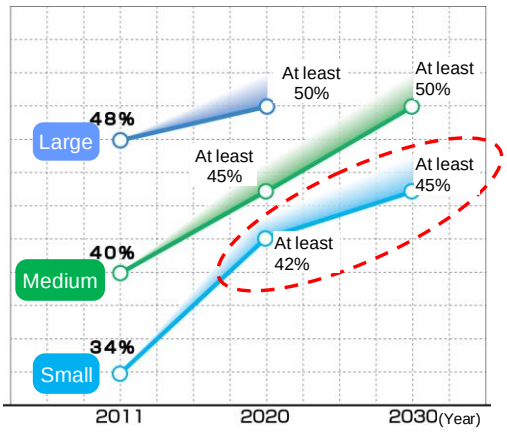

Figure 1 Targets for the generation efficiency of gas engine cogeneration systems

Besides summarizing the results of past study on HCCI engines, this paper describes the production and performance proving test of a naturally aspirated (NA) package prototype built to probe the possibilities of its use as an engine system.

2. Features of HCCI engines

Engine efficiency rises with increases in the leanness of the premixed gas (the gas composed of premixed fuel and air), in the combustion rate, and in the compression ratio. In the HCCI engine, ultra-lean premixed gas is highly compressed by the piston and ignited at the self-ignition temperature. Then, combustion occurs in the entire combustion chamber, and the combustion rate is very high. As a result of ultra-lean combustion with a high compression ratio, high thermal efficiency and extremely low NOx emission are achieved as compared to the conventional spark ignition engines. Figure 2 shows photos of the spark ignition and HCCI combustion processes using engines affording visualization. In this figure, the portions shining white indicate combustion. It can be seen that, unlike the spark ignition combustion, the HCCI combustion occurs rapidly and throughout the combustion chamber. In other words, the use of HCCI engines fueled with natural gas for CHP and GHP systems could be expected to deliver an even better energy-saving benefit and lower environmental burden.

In self-ignition combustion, the ignition timing varies with the temperature of the intake air, cooling water, and lubricating oil. Because the efficiency changes along with this variation, the ignition timing must be precisely controlled. Studies on HCCI engines have revealed that the load range over which HCCI engines can operate is limited by the risk of misfire, combustion instability, and engine knock. [(3)]. Furthermore, the higher pressure of gas within cylinders due to the higher compression ratio and more rapid combustion creates a need for engines with a higher withstand pressure.

In short, for practical use, ignition timing control, operation control, including how to start or load input, and ensuring durability, remain to be investigated.

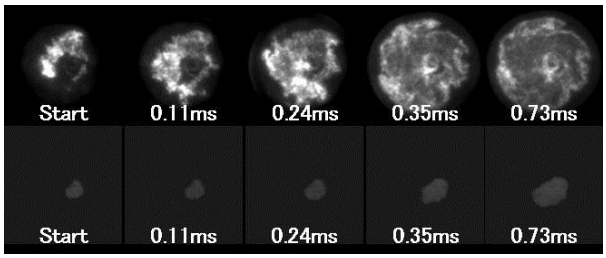

Figure 2 Comparison of HCCI (upper row) and spark ignition (lower row) combustion processes

3. Potential of HCCI engines

Studies on HCCI engines [4] revealed that they have higher efficiency and lower NOx emissions. One study [5] indicated that turbocharged HCCI engines could attain a generation efficiency of more than 40 percent. Figure 3 shows the performance of a turbocharged HCCI engine compared with a conventional spark ignition engine and a NA HCCI engine. The conversion efficiency of the generator and the power inverter was assumed to be 95%. The base engine used for this test was a NA water-cooled, 4-cycle natural gas engine. The brake mean effective pressure (BMEP) of the NA HCCI engine was on a par with or higher than that of the conventional spark ignition engine upon optimization of the engine specifications. In addition, the power generation efficiency was about 4% higher than that of the conventional spark ignition engine. The BMEP and the power generation efficiency of the turbocharged HCCI engine were much higher than those of the conventional spark ignition engine. In particular, the BMEP was about twice as high as that of the conventional spark ignition engine, and the power generation efficiency was about 40%. This indicates that the turbocharged natural gas-fueled HCCI engine has considerable potential.

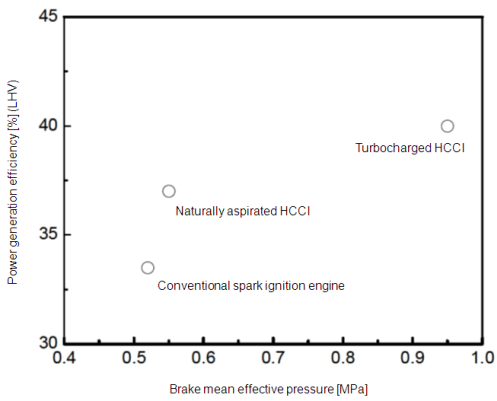

Figure 3 Potential of HCCI engines

4. Proving test of HCCI engine performance

The HCCI engine has a very high potential for a CHP power source. However, for practical use, ignition timing control, operation control, including how to start or load input, and ensuring durability, remain to be investigated. To clarify these items, we carried out an endurance test of a 25 kW HCCI package prototype without supercharging. Figure 4 shows this 25 kW HCCI package prototype. The prototype was prepared by mounting an HCCI engine on the enclosure of the existing CHP system. For the base engine, we used a 25 kW CHP engine. For control of the ignition timing in HCCI combustion, the prototype was mounted with an intake air temperature adjustment system (using engine coolant to control the temperature of the intake air in conformance with the state of operation) and an ignition timing control system including cylinder internal pressure sensors.

Figure 5 shows the performance of the HCCI package prototype at rated load. With optimization of the control map of intake air temperature and ignition timing control, the prototype attained a generated output of 25 kW, generation efficiency of 38% (lower heating value basis), and NOx emission level of 95 ppm (the value after conversion at an oxygen concentration of 0 percent). The efficiency was extremely high as compared to that of the conventional model, and the test results exceeded the generation efficiency attained in past proving tests.

Figure 4 25 kW HCCI package prototype

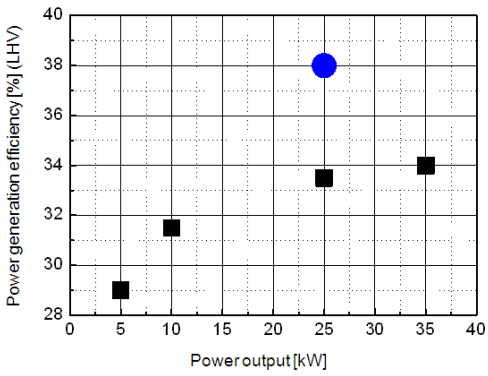

Figure 5 HCCI package prototype performance
(● : HCCI package prototype, ■ : Conventional model)

5. Conclusion and future plan

We compiled the results of past research on methods of HCCI combustion fueled with natural gas and pursued additional research by designing and preparing a package prototype for testing to prove control capabilities, durability, and high efficiency. The NA HCCI system we prepared attained a generation efficiency of 38 % and NOx emission concentration of under 150 ppm,

proving its high efficiency and low NOx emissions. We also constructed a system for control of ignition timing and proved the prototype's durability through operation for 4,000 hours. An overhaul inspection of the engine revealed that there were no problems with the engine pistons, liners, or crankshaft. Nevertheless, an emergency shutdown occurred due to variation in the combustion condition of cylinders, and further study is required on the control algorithm applied for the ignition timing control system.

As for future activities, we intend to study means for achieving even higher efficiency and output with a turbocharged HCCI engine in a CHP system, and higher efficiency at partial load with a NA HCCI engine in a GHP system.

References

(1) http://www.osakagas.co.jp/company/efforts/eco/clean/

(2) "Approaches by the City Gas Industry Based on the Direction of Future Energy Policy" The Japan Gas Association (2011)

(3) T.Ishiyama, M.Shioji, H.Tanaka, H.Nakagawa, and S.Nakai: "Performance and Exhaust Emissions of a Premixed Charge Compression Ignition Engine Fueled with Natural Gas Employing Direct Injection," JSAE Lecture Proceedings, 236, 2002, p.15-20, (in Japanese).

(4) http://www.nedo.go.jp/iinkai/kenkyuu/hyouka/18h/11/4-2-3.pdf

(5) T.Sako, S.Morimoto, and N.Iida, "Performance Improvement for Natural Gas Fueled HCCI Engine with Turbocharger (Second Report)," JSAE Lecture Proceedings, 5876 2006 p.7-12, (in Japanese).