Featured Articles

Innovative Technology for Using Bioethanol to Achieve a Low-carbon Society

Atsushi Shimada, Dr. Eng.
Yuzo Shirakawa
Takao Ishikawa

OVERVIEW: With the aim of creating an energy system of low-cost local production for local consumption that can reduce CO_2 emissions, Hitachi is developing technology for the highly efficient use of low-concentration bioethanol produced from unutilized locally available resources. Low-concentration ethanol contains a large quantity of water, and while it is cheap and safe, it is also a fuel that is difficult to burn and therefore difficult to use. To develop an engine system that can run on this difficult-to-burn fuel, Hitachi has conducted technical trials for improving the efficiency and feasibility of a system that uses hydrogen produced from water and ethanol. In examining efficiency improvements, Hitachi has achieved a thermal efficiency of 45% by using lean combustion in an engine running on a hydrogen mixture, and in feasibility trials, it has conducted operating trials using fuel produced on Miyakojima Island.

INTRODUCTION

MOVES to adopt renewable energy to reduce carbon dioxide (CO_2) emissions are picking up pace around the world, with bioethanol being a powerful energy source of this type. In places such as Brazil and Southeast Asia, ethanol is being produced from sugar cane through fermentation and blended with gasoline after going through distillation and dewatering processes to achieve a concentration of 90% or higher. Unfortunately, because of the financial and energy costs associated with concentration by distillation and dewatering[1], the challenges facing expanded use of bioethanol include providing systems that can manufacture and use ethanol efficiently. This has led Hitachi to look into low-concentration hydrous ethanol, which has the potential to become a low-cost fuel supply by eliminating the distillation and dewatering processes, and to set out to build an energy system of local production for local consumption. Because low-concentration ethanol contains a large quantity of water, one of its features is that it is not a dangerous fuel, and this safety can reduce investments in infrastructure. On the other hand, it is difficult to burn and therefore difficult to use. In response, Hitachi is developing an innovative engine system that combines engine combustion control technology with reforming technology that produces hydrogen from water and ethanol using waste heat from the engine.

WASTE HEAT RECOVERY SYSTEM USING HYDROUS ETHANOL

Assuming 100% of the energy in fuel, engines typically use only 30 to 40% for motive power, with 50 to 60% escaping as heat. This means that being able to recover this escaped heat could lead to the significant improvement of engine efficiency. Meanwhile, low-concentration ethanol fuel contains 60% or more water and 40% or less ethanol, with the high water content making it difficult to use as a fuel in this form. However, whereas the presence of water is detrimental to combustion, it can be advantageous in chemical reactions. This is because ethanol can react with water to produce hydrogen, which is extremely combustible. Moreover, because the reaction that produces hydrogen also absorbs energy (i.e. an endothermic reaction), it can be used to recover waste heat from the engine as chemical energy. This conversion to hydrogen requires heat of about 300 to 600°C and a catalyst, however, this temperature range exactly matches the range of heat found in engine exhaust. In other words, combining a hydrogen production system with an engine can create an ideal engine system in which waste heat recovered from engine exhaust is used to produce highly combustible hydrogen.

Waste Heat Recovery System Features

Fig. 1 shows the configuration of a waste heat recovery system that is fueled by low-concentration

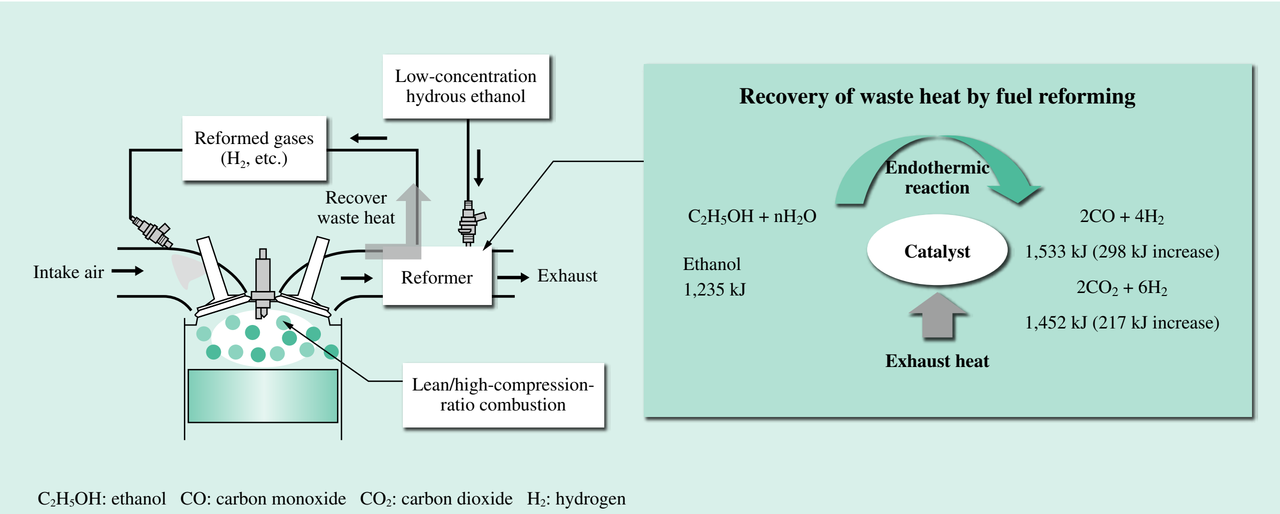

Fig. 1—Waste Heat Recovery System Using Low-concentration Hydrous Ethanol.
The figure shows the system configuration when using low-concentration hydrous ethanol to fuel an engine. The reforming reactor uses waste heat from the engine to produce a reaction gas containing hydrogen from low-concentration ethanol via a catalytic reaction. Because this reaction is endothermic, exhaust heat that would otherwise be lost is chemically recovered in the form of fuel energy.

hydrous ethanol. While low-concentration hydrous ethanol has a high water content, it can be used to generate hydrogen using a chemical reaction called “reforming.” Because this reaction is endothermic, the fuel energy after reforming is higher compared to the fuel energy before reforming. In other words, the use of waste heat from the engine in this reaction means that this waste heat is recovered as fuel energy.

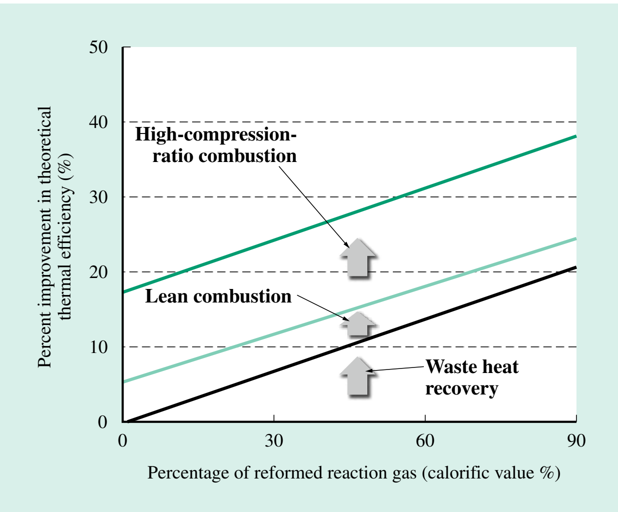

Fig. 2—Improvement in Theoretical Thermal Efficiency.
The figure shows the results of trial calculations made for improvements in theoretical thermal efficiency when waste heat recovery, lean combustion, and high-compression-ratio combustion are performed. The results indicate an estimated 38% improvement in thermal efficiency compared to conventional combustion.

In the case of a reforming reaction that produces hydrogen and CO_2 from hydrous ethanol, for example, the heat energy from combustion of the reformed gas is 1,452 kJ, which is 217 kJ higher than the 1,235 kJ of energy in the hydrous ethanol before reforming, representing an increase of approximately 1.2 times the fuel energy. Furthermore, because the hydrogen in the reformed gas is an extremely combustible component, supplying it to the engine enables combustion with an excess of air (lean combustion). Also, the octane rating of ethanol is 111, higher than the 90 to 100 octane rating of gasoline, meaning that it has an excellent anti-knocking effect, permitting the use of high compression ratio combustion. That is, the use of low-concentration hydrous ethanol as a fuel can dramatically boost the thermal efficiency of generation systems through the synergistic combination of waste heat recovery with the use of hydrogen for lean combustion, and high-compression-ratio combustion[(2), (3)].

The following describes a theoretical analysis of the efficiency improvements provided by this waste heat recovery system.

Theoretical Thermal Efficiency Benefits

As noted above, an engine system that uses low-concentration hydrous ethanol as fuel has the potential to provide a significant improvement in thermal efficiency. To assess the extent of these improvements, a theoretical analysis was used to conduct a stepwise estimate of the respective increases in thermal efficiency due to the use of fuel reforming as a means of waste heat recovery, the use of hydrogen for lean combustion, and for high-compression-ratio combustion (see Fig. 2).

The greater the proportion of reformed gas (indicating the extent to which the hydrous ethanol has reacted), the greater the quantity of recovered waste heat. A maximum improvement of 20% is possible compared to conventional thermal efficiency when reforming is not used. Synergistically combining the benefits from using the hydrogen in the reformed gas for lean combustion and from using a higher compression ratio, has the potential to improve the theoretical thermal efficiency up to a maximum of 38%, compared to conventional thermal efficiency.

As these results indicate that use of low-concentration hydrous ethanol as a fuel offers a significant improvement in thermal efficiency, Hitachi has conducted efficiency improvement trials on a test engine as well as feasibility trials with the aim of early implementation of high-efficiency engine systems capable of using low-concentration hydrous ethanol in society as soon as possible. This article describes some details of this work.

TEST ENGINE TRIALS FOR IMPROVING EFFICIENCY

Hitachi conducted trials on a test engine aimed at improving efficiency by using low-concentration hydrous ethanol. The trials used a 2.5-L displacement, 40-kW output test engine. Testing was conducted under the three conditions listed below to determine the base engine efficiency when fueled by ethanol alone, the benefits of mixing in hydrogen, and the benefits of waste heat recovery.

(1) Using high-purity ethanol as a fuel

(2) Using a mixed gas of hydrogen and CO_2 supplied from a commercial gas cylinder

(3) Using hydrous ethanol supplied to a system with a built-in reforming reactor

The efficiency improvement was studied based on low-concentration hydrous ethanol under two different conditions, with ethanol concentrations of 26% and 38% respectively, by coordinating control in consideration of the heat balance of the engine and the reforming reactor, and by controlling the combustion timing based on the combustion pressure in the engine.

Whereas the thermal efficiency when running the test engine on high-purity ethanol with a stoichiometric air-fuel mixture was only 36%, this

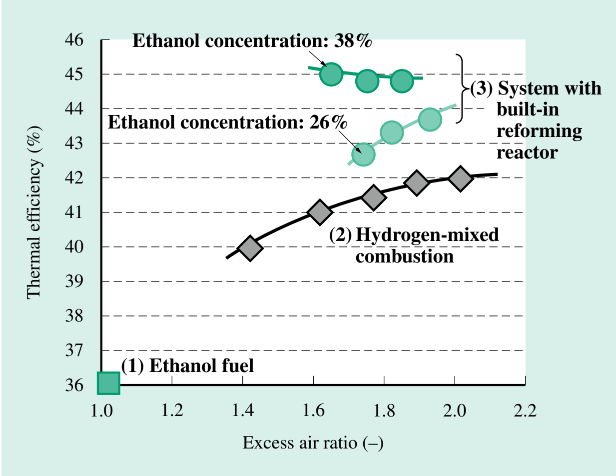

Fig. 3—Test Results of Efficiency Improvement Study.
The graph shows the thermal efficiency results obtained using a 40-kW test engine. A thermal efficiency of 45% was achieved using hydrous ethanol with an ethanol concentration of 40% or less.

improved significantly when using hydrogen-mixed combustion to enable combustion with excess air (lean combustion). When the effects of chemical waste heat recovery provided by incorporating the reforming reactor were added, a maximum thermal efficiency of 45% was achieved with an ethanol concentration of 38% (see Fig. 3).

The efficiency remained in the 43 to 44% range even when running with an ethanol concentration of 26%, indicating significant efficiency improvement at both concentrations. In terms of nitrogen oxide (NO*x*) engine emissions, which are subject to regulatory controls, the system with the built-in reforming reactor had emissions in the 800- to 200-ppm range, much less than the 1,600 ppm for ethanol combustion. In particular, using an excess air ratio of 1.8 or more satisfies the regulations with emissions in the 400- to 200-ppm range, indicating that the system is able to achieve both high efficiency and low NO*x* emissions.

In the future, Hitachi intends to continue pursuing even higher efficiencies and lower NO*x* emissions through measures such as higher compression ratios and improvements in waste heat recovery.

OPERATIONAL TRIALS AT MIYAKOJIMA ISLAND FOR FEASIBILITY STUDY

Because low-concentration hydrous ethanol is a new type of fuel that contains a large quantity of water, its feasibility requires the standardization of things like fuel and engine components. Accordingly, Hitachi

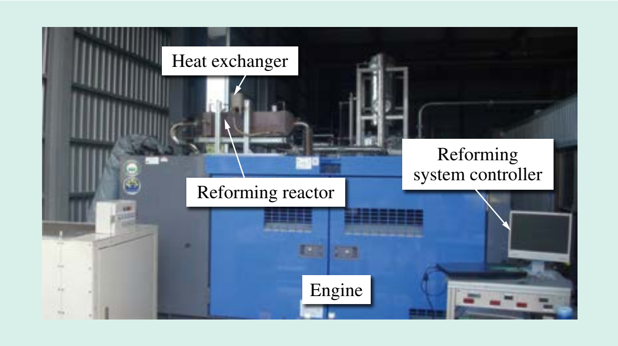

Fig. 4—Feasibility Test Engine System Installed at Miyakojima Island.
The photo shows the prototype system, which has a partially-modified 60-kW diesel engine. Feasibility testing was conducted using a low-concentration hydrous ethanol, with an ethanol concentration of 40% or less, produced from Miyakojima molasses.

conducted technical trials on Miyakojima Island in Okinawa prefecture aimed at the standardization of things like engine components and oil. The technical trials involved the performance testing of a prototype engine-generator fueled by a 40%-hydrous ethanol produced from raw molasses and obtained from an ethanol production process technology demonstration project run by the trial partner, the Miyakojima Bio-Industrial Innovation Agency. The trials also included monitoring of pistons, piston rings, and other engine components, as well as changes in the properties of the engine oil (see Fig. 4).

With a view toward feasibility, the system was modified in only three places (see Fig. 5). The first modification was of the air intake to provide an inlet for the gas produced by the reforming reactor. The second modification was the fitting of injectors on each cylinder next to the intake valves to supply the low-concentration hydrous ethanol. The third modification was attaching the reforming reactor's connection port to the exhaust pipe to connect the reforming reactor.

The engine control system was left as-is, because switches on the side panel of the engine-generator unit can be used to operate it. A personal computer was used to build a control system capable of freely modifying the quantity of hydrous ethanol to inject and the quantity of reformed gas to use as required, since these are operated by the controller of the reforming system (see Fig. 4).

Because the system used a diesel engine, ethanol fuel could not be used directly as a fuel. Accordingly, the existing diesel supply line was left as-is, with the engine operating as a dual-fuel system in which the diesel served as the ignition agent. To improve the thermal efficiency of the reforming reactor system, heat exchange between the high-temperature gas discharged from the reforming reaction and the low-temperature hydrous ethanol fuel was used to simultaneously cool the reformed gas and preheat the fuel. This significantly improved the thermal efficiency of the system by recovering the heat of vaporization and sensible heat of the hydrous ethanol fuel from the

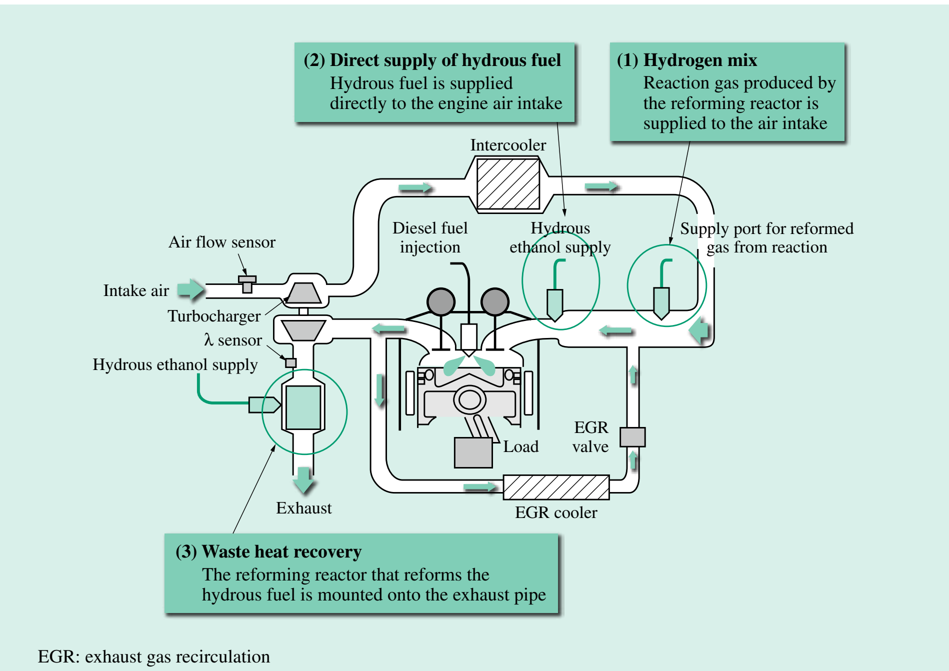

Fig. 5—Configuration of Engine System Installed for Feasibility Trials.
The diagram shows the modifications made to supply hydrous ethanol to a commercially-available engine system.

high-temperature reformed gas. The high water content of low-concentration hydrous ethanol meant that the heat of vaporization of the water was extremely high. Although this posed a major issue because, in addition to using high-temperature waste heat in the reforming reaction, heat is lost to fuel vaporization, the problem was solved by installing a heat exchanger, enabling the system to be made both smaller and more efficient.

The system became fully operational in December 2015 and had recorded around 200 hours of operation as of this writing. Under these initial conditions, no adverse impact has been observed on the engine components and engine oil. The system will continue operating into the future, and data will continue to be collected on its feasibility.

CONCLUSIONS

Ethanol production dates back thousands of years. In Japan, up until now there have been efforts to produce ethanol for use as a fuel from not only sugar cane but also rice, wheat, and wood, as well as from waste products such as food scraps and paper. Whereas conventional bioethanol concentrations have been 90% or more, being able to use bioethanol at concentrations of 40% or less is making it possible to achieve both safety and low cost, with potential for use as a form of local distributed power generation with significant reductions in CO_2 emissions compared to oil-fired generation.

In the future, Hitachi intends to use island locations as a starting point for pursuing industrial revitalization and vitalization of local economies by building locally autonomous energy systems, including integration with wind and photovoltaic power generation systems, and expanding new applications using safe and low-cost ethanol fuel from many unutilized resources by using low-concentration hydrous bioethanol as a fuel.

ACKNOWLEDGMENTS

Much of the work described in this article was conducted under the three-year project of "Low Carbon Technology Research and Development Program (innovative high-efficiency engine fueled by low concentration bio-ethanol contractor)" which is funded by Ministry of the Environment of Japan. The authors would like to express their thanks for the assistance and advice of everyone involved.

REFERENCES

(1) JOMA News Letter, Vol. **4**, No. 11 (2011), in Japanese.
(2) A. Shimada et al., "Improved Thermal Efficiency Using Hydrous Ethanol Reforming in SI Engines," SAE Technical paper (2013).
(3) A. Shimada et al., "Improving Waste Heat Recovery Systems through Fuel Reforming and Engine Cycle Efficiency through Reforming Fuel," Automobile Waste Heat Regeneration Technology, Science & Technology Co., Ltd., Tokyo (Dec. 2014) pp. 171–180 in Japanese.

ABOUT THE AUTHORS

Atsushi Shimada, Dr. Eng.
Center for Exploratory Research, Research & Development Group, Hitachi, Ltd. He is currently engaged in the research and development of hydrous ethanol-fueled engine systems. Dr. Shimada is a member of the Society of Automotive Engineers of Japan (JSAE).

Takao Ishikawa
Center for Exploratory Research, Research & Development Group, Hitachi, Ltd. He is currently engaged in the research and development of hydrous-ethanol-fueled engine systems.

Yuzo Shirakawa
Center for Exploratory Research, Research & Development Group, Hitachi, Ltd. He is currently engaged in the research and development of hydrous-ethanol-fueled engine systems.