International Gas Union Research Conference 2011

R&D OF THE GAS ENGINE HEAT PUMP WATER HEATER

Naoto Imada

Kunio Kitano
Kiyoshi Soh
Kouji Tanaka

TECHNICAL RESEARCH INSTITUTE
HIROSHIMA GAS CO.,LTD.
HIROSHIMA, JAPAN

ABSTRACT

In 2006, Hiroshima Gas started a study of “The Gas Engine Heat Pump Water Heater”, which is a combination of “The Small-type Gas Engine” and “The Heat Pump”.

In this ” Gas Engine Heat Pump Water Heater”, the compressor is driven by gas engine, and heat is pumped up from the atmosphere by heat pump cycle to produce low temperature warm water, it is further made into high temperature warm water through heat exchange with exhaust heat of gas engine. By making use of the engine exhaust heat for high temperature warm water, the total thermal efficiency of the heat pump can be improved.

By this characteristics, it has become possible to improve the decrease in total thermal efficiency in the wintry low temperature season, which was a weak point of air-source heat pump heater.

This experimental equipment is a product in which generally available all-purpose parts are utilized, and that device is an assembly of such main components as a gas engine, a compressor and a heat exchanger. Even if in these specifications and under winter-time environmental condition (air temperature: 5^{o}C; water temperature: 9^{o}C), we obtained the result reaching around 141% thermal efficiency (higher heating value, including electricity) in hot water condition (60^{o}C). That efficiency of the experimental equipment is about two times the conventional model gas water heater which is a widespread type in Japan, also this will enable us to substantially reduce the gas consumption and carbon dioxide emissions when operation this heat pump water heater .

This time we will report on the element study.

TABLE OF CONTENTS

1. INTRODUCTION

Currently, “Gas Instantaneous Water Heater” is mainly used as the gas water heater for household in Japan. With the rising demand for energy saving due to soaring energy prices and global environmental problems in recent years, “Condensing Type High Efficiency Water Heater (Eco Jouzu)” which recovers even latent heat of fuel gas, “Gas Engine Cogeneration (Eco-Will)” and “Fuel Cell Cogeneration (Ene-Farm)” both of which can generate electricity and provide hot water, have been developed for sale. However, because the machinery of the latter is still costly, they have not come to widespread use yet [1].

In “Ultra long-term energy technology vision” announced by the Japanese government in 2005, only “High Efficiency Heat Pump Water Heater” was shown as the vision for the future water heater [2]. Actually, the electrically-driven type heat pump water heater using CO2 as refrigerant (Eco-Cute) has been developed and explosively spreading on the back of the economical late-night electricity rate system and all electrification strategy of the electricity industry [3].

In the meantime, with respect to the heat pump technology in the gas industry, although there are many track records of the technology used for air-conditioning, there are rare cases of such technology used for water heating. Under such situation, in 2006, Hiroshima Gas, a local city gas company in Japan, started a study of “Gas Engine Heat Pump Water Heater” which is a combination of “Small-Type Gas Engine” and “Heat Pump.” This time we will report on the contents of the element study.

2. EQUIPMENT OUTLINE

Gas engine heat pump water heater is equipment in which heat pump used for air-conditioning is driven by gas engine, and heat is collected from the atmosphere to produce low temperature warm water in the heat exchanger(condenser), the equipment further produces high-temperature water through heat exchange with exhaust heat of the gas engine.(See Figure 1)

The characteristics of the system are as follows:

(1) Because the condensation temperature of heat pump cycle can be lowered by making use of the engine exhaust heat for heating warm water, the thermal efficiency of the heat pump can be improved.

(2) The equipment such as engine and compressor can be stored in the heat insulation box and the exhaust heat from such equipment can be effectively used as heat source for the heat pump.

By dint of these two characteristics, it has become possible to improve the decrease in thermal efficiency in the winter-time low temperature season, which was a weak point of the heat pump water heater.

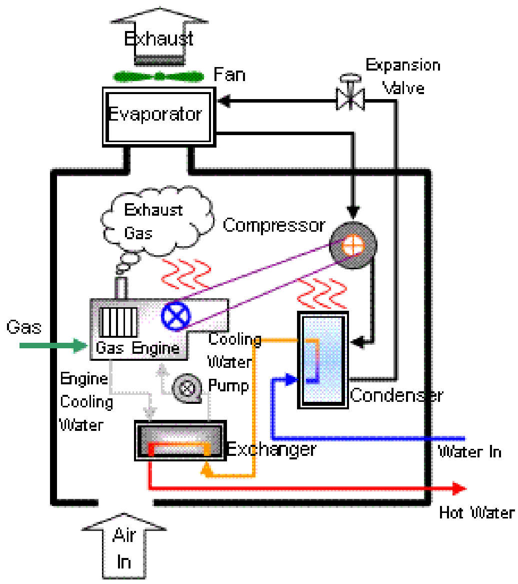

Figure 1: System Outline

We consider that the theoretical performance of gas engine heat pump water heater is as follows.
Coefficients of Performance (COP) of the latest electrically-driven type heat pump air conditioner is around 6.5 [4] in Japan, and the thermal efficiency is around 250% when converted into primary energy.
Assuming that the heating value of consumed gas in the gas engine heat pump water heater is 100%, and supposing that the shaft power of gas engine is 25% and COP of the heat pump is 6.5, the heating capability of heat pump (heat pump efficiency) will be gas consumption of 163%.
Supposing heat loss of the engine to be around 10%, exhaust heat recovery of the engine (exhaust heat recovery capability) will be around 65%.
The gas engine heat pump water heater has two heat sources which are heat pump and engine exhaust heat recovery, even if we considered the power of ventilation fan and water pumps, the expected heating capability of our system will exceed 200% in primary energy equivalent. (See Figure 2)

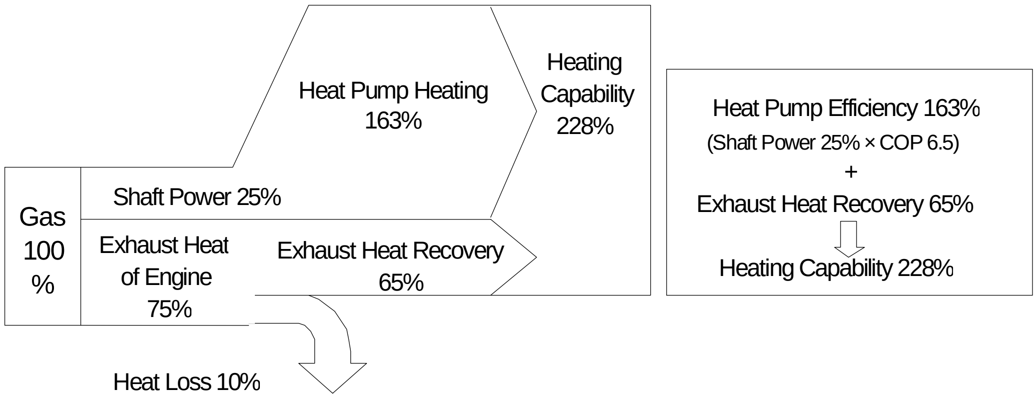

Figure 2: Expected the Best Thermal Efficiency of System

3. PRODUCTION OF EXPERIMENTAL EQUIPMENT

In producing the experimental equipment, we considered cost reduction and utilized the existing all-purpose products which are mass-produced, inexpensive and easily available.

Then, we used a gas engine which is used for the existing household gas engine co-generation, and a compressor which is used for car air-conditioning. Therefore, we used “HFC-134 a” refrigerant popularly used for automotive air-conditioning as refrigerant for the heat pump. The compressor is also driven by the engine with V belt. In addition, the revolution ratio between engine and compressor can be changed by changing pulley diameters of the engine output shaft.

We also used all-purpose products for the heat exchanger. In addition, considering that the equipment is experimental one, we used large capacity pumps to make feed water volume and air passing volume variable by controlled inverter. We completed the experimental equipment as shown in Figure 3.

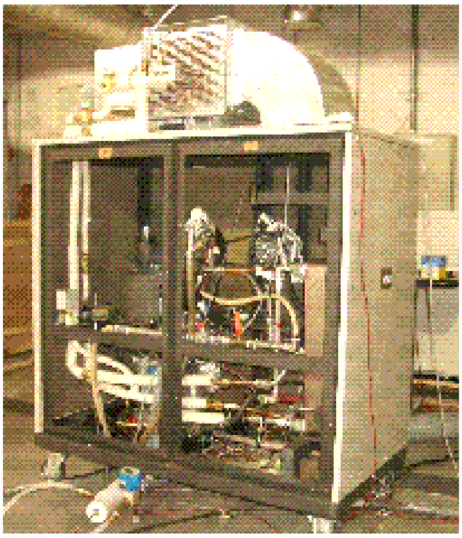

Figure 3: The Experimental Equipment

We carried out preliminary tests before conducting full-scale performance confirmation tests. The contents are as follows:

Confirmation of

(1) The relation between engine starting torque and compressor starting torque
(2) Heat pump start-up time
(3) Hot water outflow volume (heating capability)

As a result, considering the practical operation of household water heater in light of the longer start-up time and lower hot water outflow rate, we decided to add a “Hot Water Tank” in our concept of gas engine heat pump water heater. (In the case of 45^{o}C hot water outflow, start-up time: 5 minutes, and hot water outflow rate: 7 liter/min; in the case of 60^{o}C hot water outflow, start-up time: 10 minutes, and hot water outflow rate: 2 liter/min)

In addition, as a result of our confirmation of compatibility of the components, we changed some parts of the equipment (enhancement of the evaporator capability, adoption of the electronic expansion valve, etc.) to complete the experimental equipment.(See Figure 4)

Figure 4: The Experimental Equipment After Remodeling

Table 1: Experimental Equipment Specifications

Name of Components	**Specifications**	**Note**
Gas Engine	163cc Single Cylinder, 4 Cycle	
Compressor	Belt Drive Compressor , Oblique Plate Capacity-type	For Automobile
Condenser	1.4m^2, Plate-type Heat Exchanger	
Evaporator	23m^2, Coil-type Heat Exchanger	For Refrigerator
Expansion Valve	Temperature Control System-type Electronic Expansion Valve	Super Heat Control
Refrigerant	HFC -134a	
Ventilation Equipment	400～2100m^3/h , Ventilation Fan	Flow Control by Inverter
Storage Box	1.2m×0.6m×1.1m, Steel Box	Heating Insulation Inside
Engine Exhaust Recovery Equipment	0.7 m^2, Plate-type Heat Exchanger	
Hot Water Tank	150 liters Capacities , Pressure-type Tank	
Circulation Pump Hot Water	0.5～25 liter/min, Magnetic-type	Flow Control
Circulation Pump Cooling Water	25 liter/min, Magnetic-type	For Engine Coolant

4. TARGETS PERFORMANCE OF EXPERIMENTAL EQUIPMENT

Since we utilized the existing all-purpose products for the gas engine, compressor and heat exchanger which is main components of the experimental equipment, this time we predicted that its target heat efficiency would be slightly lower in comparison with the exclusive use design.

For this reason, in order to grasp theoretical performance of the experimental equipment and decide on target thermal efficiency, we reproduced its constitution in a process simulator (VMG Sim) to predict the performance.

Calculation of thermal efficiency is made by calculating the ratio of the sum of the heating value of hot water heated by the heat pump (condenser) and heating value of hot water heated by the engine exhaust heat recovering device to the consumed primary energy equivalent heating value (higher heating value of city gas , electric power) at that time.

As a result of the analysis by the process simulator, because thermal efficiency in primary energy equivalent was assumed to be 151% at hot water outflow temperature of 60^{o}C under winter environmental condition, we carried out the performance confirmation tests with this as a target. (See Table 2, Figure 5)

Table 2: Result by Process Simulator (Winter-time, Hot Water Outflow Temperature 60^{o}C)

Seasons	Ambient Temperature (^{o}C)	Thermal Efficiency (%)	Heat Pump Efficiency (%)	Engine Exhaust Heat Recovery Efficiency (%)	Engine Revolution (RPM)	Compressor Revolution (RPM)	Hot Water Outflow Volume (ℓ/min)	Hot water Capability (kW)
Winter	5	151	90	61	1000	1000	1.14	4.04

Here, the heat pump efficiency and engine exhaust heat recovery efficiency are the ratio of the heating value of hot water heated by each of the heat exchangers (condenser and engine exhaust heat recovering device) to the consumed primary energy equivalent heating value (higher heating value of city gas, electric power).

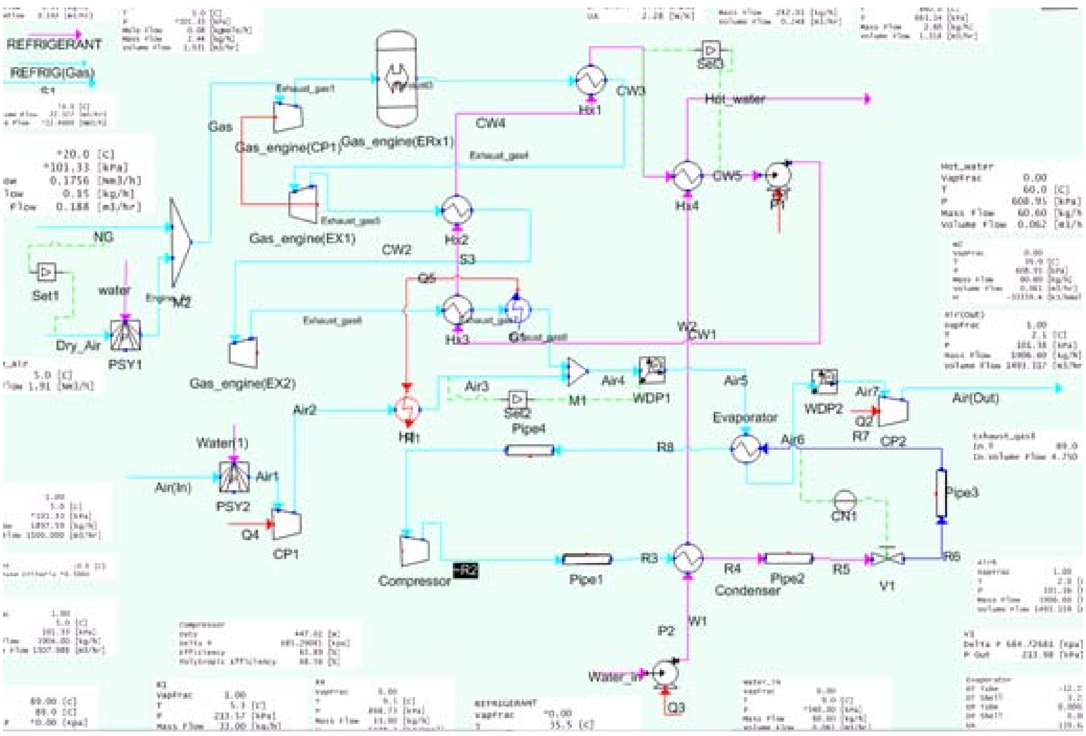

Figure 5: Examination Performance of Experimental Equipment in a Process Simulator

5. PERFORMANCE CONFIRMATION TESTS METHOD

We confirmed the best thermal efficiency of the experimental equipment under seasonal environmental conditions (summer -time, intermediate-time and winter -time).

As for the specific test method, the room temperature and feed water temperature in the environmental test room were kept constant, then we controlled “Gas Engine Heat Pump Water Heater” at predetermined engine revolutions, we conducted performance confirmation tests after making the operation of the experimental equipment stable by adjusting feed water so that it can reach the targeted hot water outflow temperature.

The main test conditions are as follows:

(1) As for the environmental conditions, we conducted the tests in the environmental test room so that the air temperature, humidity and water temperature became constant with reference to the regulation of “Household Heat Pump Water Heater, Japan Refrigeration & Air-Conditioning Industry Association” [JRA4050-2007]

(2) The hot water outflow temperature conditions were 60^{o}C as the standard one, 75^{o}C, 45^{o}C and 30^{o}C.

(3) Considering the compressor operating torque from the result of the preliminary test results, we selected and used the most suitable one from eight kinds of pulley diameters of 63mm to 118mm for the engine output shaft.

(4) We carried out the tests changing the engine revolutions every 100rpm within the range of 900 to 2000rpm.

(5) Calculation of thermal efficiency is made by calculating the ratio of the sum of the heating value of hot water heated by the heat pump (condenser) and heating value of hot water heated by the engine exhaust heat recovering device to the consumed primary energy equivalent heating value (higher heating value of city gas, electric power) at that time.

(6) We set 1,600m^3/h as the basic for ventilation air volume, and we increased or reduced the air volume depending on thermal efficiency situation at the time of the tests.

6. PERFORMANCE CONFIRMATION TESTS RESULT

First, in order to have the characteristics of the experimental equipment understood, the temperature change of the air and water under winter-time environmental conditions in the case of 75^{o}C hot water is as shown in Figure 6 and Figure 7.

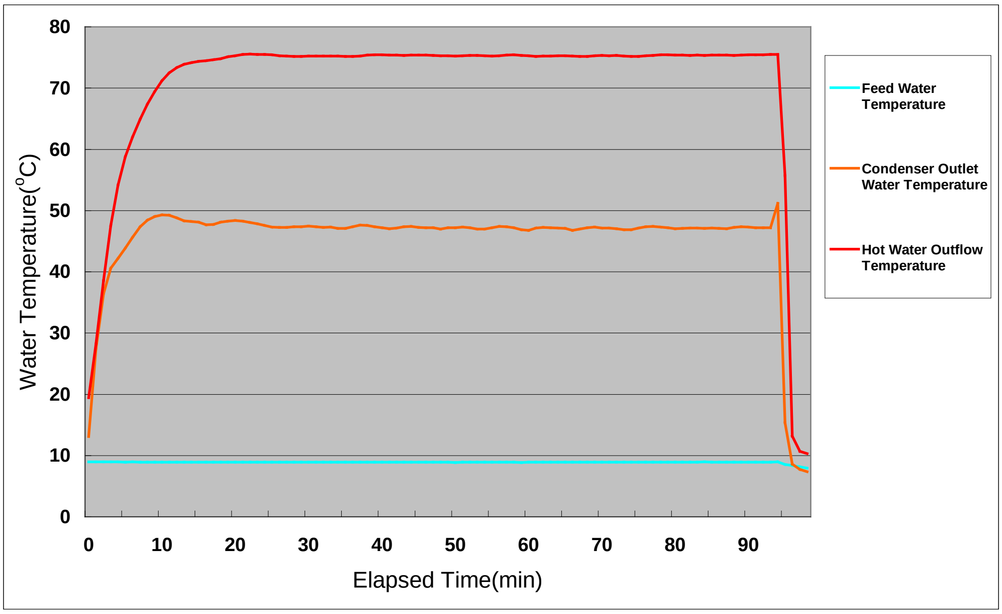

Figure 6: Temperature Change of Water in the Case of 75°C Hot Water (Winter-time)

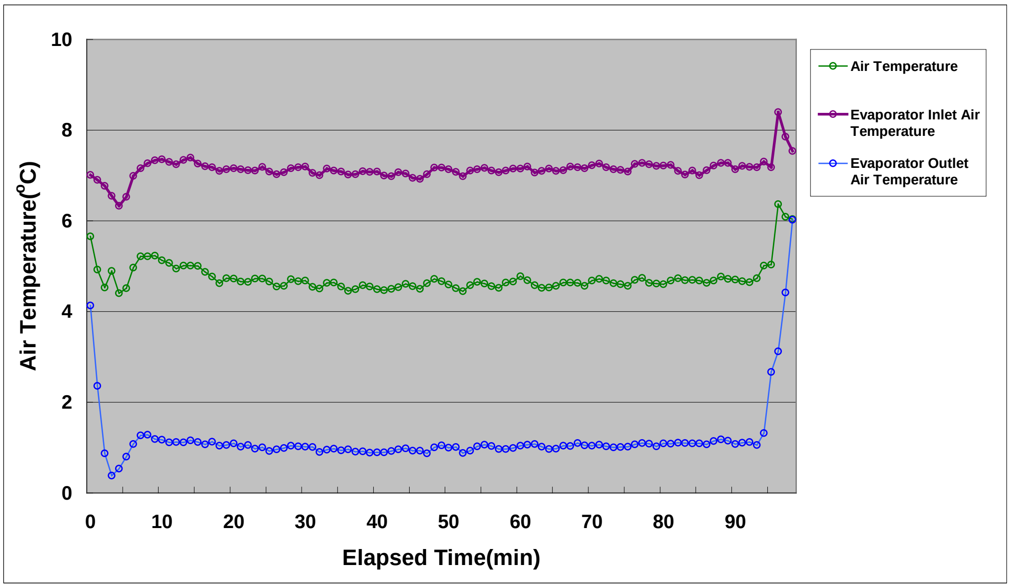

Figure 7: Temperature Change of Air in the Case of 75°C Hot Water (Winter-time)

This graph shows the changes of the air temperature and water temperature of each part from start-up of the engine to outflow approximately 100 liters of 75°C hot water.

At first about "thermal changes from water feeding to hot water outflow," water is taken in at 9°C is heated up to 48°C by "heating with the condenser of the heat pump" in the first stage; and it is further heated up to provide 75°C hot water through "exhaust heat recovery of gas engine" in the second stage.

You will understand the process of water heating up to 75°C in stages with these two heat sources.

Next, about “air-related process,” air is taken in at the ambient temperature of 4^{o}C, air temperature in the box rises to 8^{o}C by exhaust gas, engine exhaust heat and equipment exhaust heat; as a result of heat energy in the air being taken in by the evaporator of the heat pump, “the air temperature coming out of the evaporator“ falls to 1^{o}C, which is lower than the ambient temperature. From these temperature changes, you will understand that the engine exhaust heat is effectively recovered by the heat pump.

In the meantime, each temperature changes greatly for about 10 minutes after the engine start-up. You will understand that it takes so long before the water temperature reaches a predetermined outflow temperature and it is difficult to provide hot water instantaneously.

Figure 8 shows thermal efficiency and the breakdown (heat pump and engine exhaust heat recovery efficiency) with various values of engine (compressor) revolutions under the seasonal conditions at the hot water outflow temperature 60^{o}C as an example.

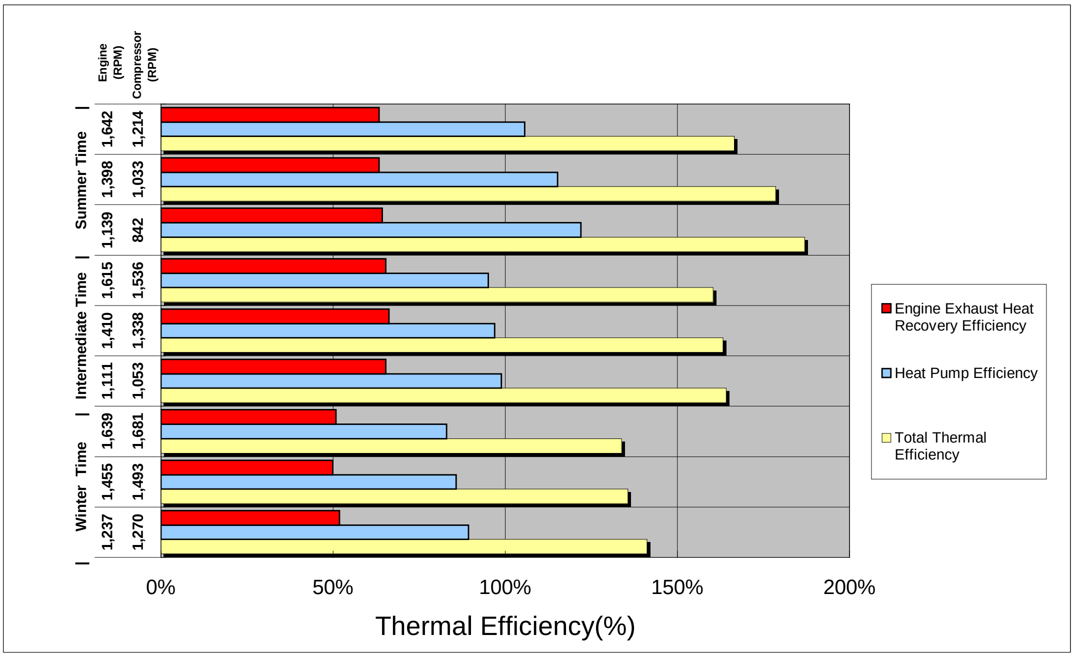

Figure 8: Thermal Efficiency with Various Values of Engine Revolutions under the Seasonal Conditions (Hot Water Outflow Temperature 60^{o}C)

The engine exhaust heat recovery efficiency is not relationship with the engine revolutions, and there is much the same value, but there decreased under winter-time. We presume that the engine exhaust heat recovery efficiency declined because we operated the increased ventilation quantity from outside to maximize the total thermal efficiency under winter-time condition, and because the temperature inside the box did not rise in comparison with the summer-time and intermediate-time by heat loss of the storing box.

Next, we have found that the less the engine revolutions are, the higher the heat pump efficiency becomes. We assume that this is attributable to the mechanical loss increase due to friction as the compressor revolutions increase.

You will understand that the combination of these two heat sources determines thermal efficiency of the gas engine heat pump water heater.

As for the test results at hot water outflow temperature 60^{o}C under the seasonal conditions, the best thermal efficiency are as shown in Table 3

The thermal efficiency under winter-time condition was 141% which was 93% in performance of the target value (151%). The heat pump efficiency is the same, but the engine exhaust heat recovery efficiency declined remarkable than the result of analysis simulator. As mentioned above, we predict that it was caused by ventilation quantity from outside and heat loss of the storing box due to lower temperature inside the box.

Table 3: Tests Result under the Seasonal Conditions (Hot Water Outflow Temperature 60^{o}C)

Seasons	Ambient Temperature (^{o}C)	Thermal Efficiency (%)	Heat Pump Efficiency (%)	Engine Exhaust Heat Recovery Efficiency (%)	Engine Revolution (RPM)	Compressor Revolution (RPM)	Hot Water Outflow Volume (ℓ/min)	Hot water Capability (kW)
Summer	24	187	122	64	1186	877	2.0	5.8
Inter-mediate	16	164	99	65	1111	1053	1.7	5.6
Winter	5	141	89	52	1237	1270	1.4	5.0

In addition, the relation between test air temperature at each hot water outflow temperature and thermal efficiency (Performance Curves) is as shown in Figure 9.

Because the relation between thermal efficiency and test air temperature at each hot water outflow temperature is linear, because the inclination and interval became constant, we can predict thermal efficiency of the experimental equipment at the ambient temperature. Focusing attention on the point that the lower the hot water outflow temperature is, the higher heat efficiency becomes, we thought of an efficient operation method using good thermal efficiency of low temperature water as follows.

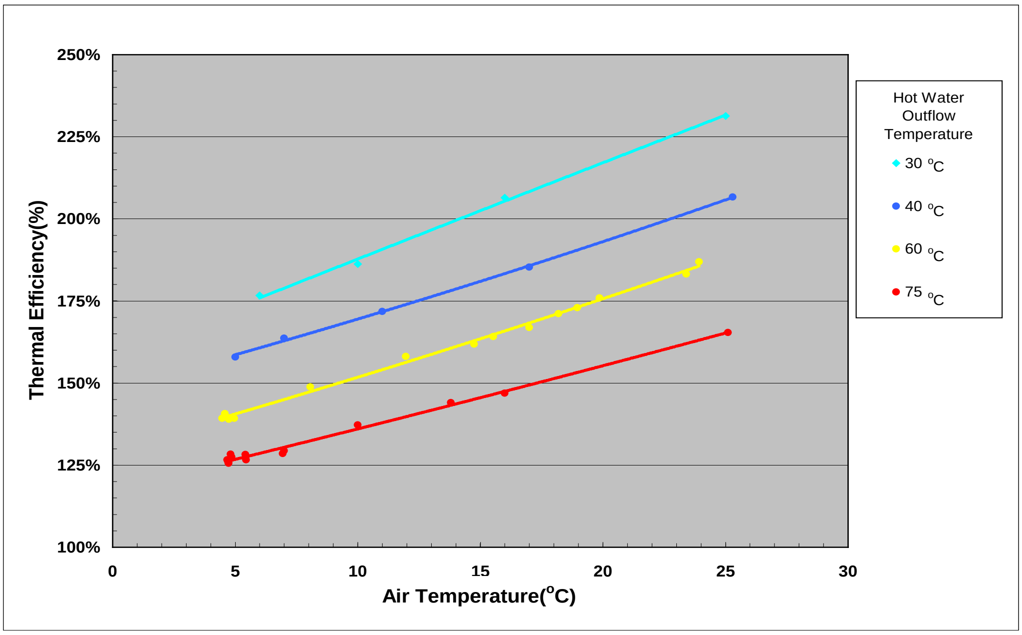

Figure 9: Relation between Thermal Efficiency and Air Temperature
(Performance Curves of Experimental Equipment)

7. EFFICIENT OPERATING OF SUPPLYING A LARGE VOLUME OF HOT WATER

We took note of the fact that the lower the stored warm water, the higher total efficiency becomes, and we thought of an effective method of supplying a large volume of hot water as is the custom of filling the bathtub in Japan. It is to mix the high-temperature water (60～75^{o}C) from the hot water tank with low-temperature water (around 30^{o}C) by operating the heat pump water heater as the total thermal efficiency is better than mixing with only general tap water.

We called this assist in warm water outflow by the gas engine heat pump water heater "Assist Operation".
To confirm the effect of the assist operation, we conducted such operation on the assumption of filling the bathtub with hot water under the environmental condition by the seasons. The study results of the assist operation under the condition of supplying 10 liter/min of 40^{o}C hot water are as shown in Table 4.

Table 4: Assist Operation Efficiency under the Seasonal Conditions

Seasons	Low-Temperature Water			High-Temperature Water		Warm Water Outflow Condition	Assist Operation Efficiency
	" Water Heater" Outflow (Temperature × Volume)	Heating Capability	Thermal Efficiency	"Hot Water Tank" Outflow (Temperature × Volume)	Thermal Efficiency		
Summer	35^{o}C × 8.0liter/min	6.1kW	215%	60^{o}C × 2.0liter/min	187%	40^{o}C × 10liter/min	209%
Inter-mediate	33^{o}C × 7.4liter/min	8.3kW	191%	60^{o}C × 2.6liter/min	164%		184%
Winter	27^{o}C × 6.0liter/min	7.5kW	165%	60^{o}C × 4.0liter/min	141%		155%

We have confirmed that the assist operation efficiency considerably exceeds the normal water heating operation efficiency , and it has been understood that the assist operation is effective in improving thermal efficiency of the supplying a large volume of hot water by the gas engine heat pump water heater.

8. CLOSING

We produced this experimental equipment using generally available all-purpose main components which we can get easily such as the gas engine. However, we succeeded in achieving thermal efficiency (primary energy equivalent) of 141% (93% in performance of the target value) under the severe winter-time environmental conditions (air temperature 5^{o}C).

This is about two times higher than the efficiency of the conventional type gas water heater which has been widespread in Japan. This will enable us to substantially reduce gas consumption and carbon dioxide emissions when operating the water heater.

In addition, we also were able to confirm that the assist operation when consecutively supplying hot water is effective in increasing efficiency of the whole water heater system.

We were able to deepen the knowledge about the gas engine heat pump water heater through this study.

We consider that we will be able to greatly contribute to conservation of the global environment in the course of our further study by changing the components and seeking the optimal operation method with the aim to achieve higher efficiency of the experimental equipment.

In closing, we hope that the results of this study will enable us to contribute even a little to promotion of lower carbon society in the future.

REFERENCES

1. Report “City Gas and the Environment “. The Japan Gas Association. (In Japanese)
2. “Ultra Long-term Energy Technology Vision 2005”. Ministry of Economy, Trade and Industry .(In Japanese)
3. “The State of The Heat Pump・Thermal Storage 2007”. Heat Pump & Thermal Storage Technology Center of Japan. (In Japanese)
4. “Energy Saving Performance Catalog 2009 Winter”. Ministry of Economy, Trade and Industry. Agency for Natural Resources and Energy. (In Japanese)