High-Performance, High-Reliability Gas Heat Pump*

Hideaki Kasahara, Atsushi Yoshimura
Air-conditioning & Refrigeration Systems Headquarters

Ryuuji Morishima, Hisao Iwata
Nagoya Research & Development Center,
Technical Headquarters Mitsubishi Heavy Industries, Ltd.

Introduction

Gas heat pumps (GHP), which drive the compressor by an engine fueled by city gas or LP gas, can provide a high level of heating performance during the winter season, because as a heat source such GHP can utilize engine exhaust heat that is unavailable in conventional electric heat pumps (EHP). Moreover, GHP consume so little electric power compared with EHP that they lower peak electricity levels during the summer season in particular when the usage of the air conditioning energy becomes greatest. Therefore, GHP are considered as a trump card for leveling both electric and gas energies.

Table 1 GHC-5 specifications (P560, 60 Hz)

External dimensions		H 2135 × W 1750 × D 960 mm
Unit weight		880 kg
Engine		In-line 4 cylinders water-cooled OHV 1 998 cc
Compressor		Reciprocating V type 4 cylinders
Cooling mode	Capacity	56 kW
	Gas consumption	46.7 kW
	Electric power consumption	1.50 kW
Heating mode	Capacity	67 kW
	Gas consumption	46.4 kW
	Electric power consumption	1.12 kW
Low temperature heating capacity		67 kW
Mean COP of cooling/heating		1.30
Operating noise level		60 dB(A)
Maintenance intervals		5 years or 10 000 hours

Features of GHC-5

The GHC-5 outdoor unit series of gas heat pumps (P355, P450, and P560) for the multi-indoor unit system for use in buildings has been developed recently. In particular, the engine performance and the refrigeration cycle were improved, and incorporate reviewing of the vibration isolation and the sound proofing was implemented based upon the previous model of Mitsubishi Heavy Industries, Ltd. (MHI) GHC-4 favorably put on the market in April 2000. At the same time, the environmental characteristics of these units were further improved by extending their maintenance intervals. **Table 1** shows the major specifications of GHC-5, while **Fig.1** shows

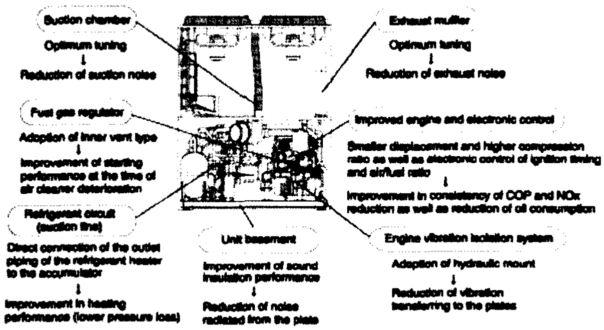

Fig. 1 Major items of improvement
The major technical changes from the GHC-4 system are shown.

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the major items of the improvement.

Performance Improvement Technology

Refrigerant circuit

In order to recover engine exhaust heat efficiently, the MHI GHP employs a small size, high performance plate type refrigerant heater and a high performance refrigerating circuit unique to MHI in which the heater is arranged in parallel with the air heat exchanger. Its purpose is to obtain a stable heating capability, using both the air heat exchanger and the refrigerant heater during heating operation, while switching to the operation of the refrigerant heater only when the evaporation performance of the air heat exchanger becomes low at very low outdoor temperatures.

Fig. 2 shows the refrigerant circuit of the GHC-5. In existing GHC-4 units, the circuit flowing toward the compressor from the refrigerant heater was merged with the tubing from the air heat exchanger at the place before the four-way valve. In the GHC-5, however, it was changed after review, so as to be merged at the accumulator section. This change reduces refrigerant circulation flow through the four-way valve at the heating operation so drastically that the pressure loss in the refrigerant low-pressure side was also reduced, thereby contributing greatly to improved performance. In addition, a fast defrosting operation of the outdoor unit air heat exchanger that utilizes engine exhaust heat was made possible by switching the four-way valve to the cooling operation side, with the solenoid valve in the refrigerant heater side is kept open. Since the heat exchanger of the indoor unit and indoor/outdoor connect piping can maintain a high temperature at this time, heating is so comfortable after defrosting operation that the same level of comfort as that achieved in cases without the defrosting operation could be realized from a practical standpoint. As a result, the air heat exchanger can now be used at temperatures of up to -2oC (that is, utilization of the air heat source), although it previously was turned off at outdoor temperatures of around 2oC in order to avoid defrosting. Moreover, improvements in COP (Coefficient of Performance) have also become possible.

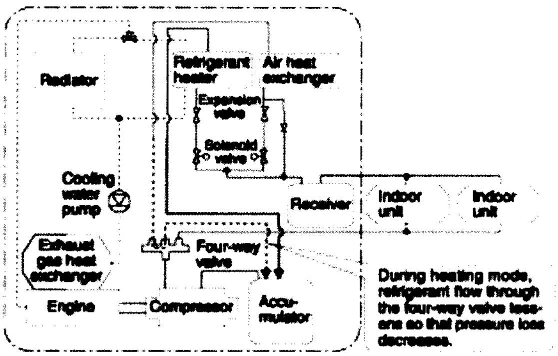

Fig. 2 Refrigerant circuit (heating mode)
Stable heating performance was realized by arranging the refrigerant heater used for engine exhaust heat recovery in parallel with the air heat exchanger.

Enhancement of engine efficiency and reduction of NOx

· Influence of air excess ratio and ignition timing

The thermal efficiency of the engine and NOx emission levels are highly dependent on the air excess ratio (a ratio of the intake air to the supply fuel gas) and the ignition timing (timing at discharge of the ignition plug). Fig. 3 shows the impact of the air excess ratio and ignition timing on engine thermal efficiency, while Fig.4 shows the impact of the air excess ratio and ignition timing on NOx emission levels. These figures

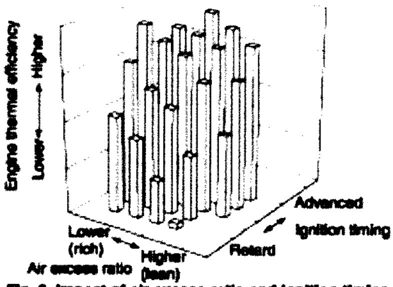

Fig. 3 Impact of air excess ratio and ignition timing on energy efficiency.
Thermal efficiency is improved when the air excess ratio becomes lower and the ignition timing is advanced.

reveal that while thermal efficiency is improved by making the fuel gas richer (i.e., the air excess ratio smaller) and by advancing the ignition timing, such actions result in an increase in NOx emissions.

· *NOx reducing by EGR system*

Whereas NOx emission levels have been reduced by making the fuel content lean in past GHP units, consideration needs to be given to alternate methods in order to realize further reduction. A wide variety of methods are available that can be used to reduce NOx emission levels, including the use of catalysts and EGR (Exhaust Gas Re-circulation), amongst others. MHI utilized the EGR system since the GHC-4 because of its benefits in terms of reliability. In the new system, a review of the specifications of the engine has led to an EGR also being simultaneously optimized, as well. Fig. 5 shows an overview of the system.

The EGR is a system designed to recycle part of the exhaust gas into the intake manifold, that inert gas causes to increase the specific heat of intake air and fuel gas mixture in order to restrict any excessive rise in the combustion temperature so as to reduce NOx generation. Fig. 6 shows the effects of an EGR on reducing NOx emissions. By optimizing the EGR, it became possible to reduce NOx emission levels to one-half or one-third without any deterioration in thermal efficiency.

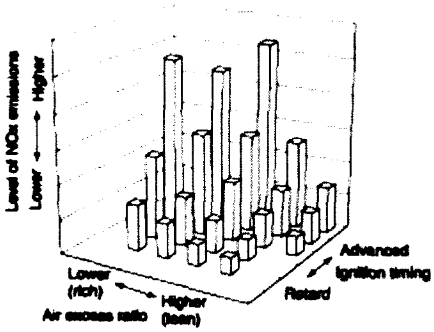

Fig. 4 Impact of air excess ratio and ignition timing on NOx emission levels
NOx emission levels are reduced when the air excess ratio becomes higher and the ignition timing is retarded.

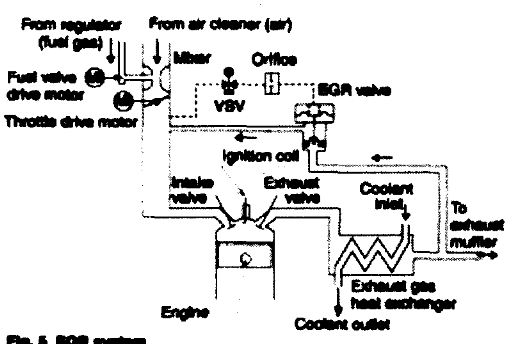

Fig. 5 EGR system
In the EGR (Exhaust Gas Re-circulation) system, part of the exhaust gas is returned to the intake manifold in order to decrease combustion temperature due to increased inert gas, which in turn leads to a reduction in NOx emission levels.

· Reduction of gas consumption and NOx levels by *electronic control*

In order to achieve high levels of efficiency and low levels of NOx emissions throughout all operating ranges of engine, it is necessary to choose optimum values for the air excess ratio and ignition timing. In the past, although it was possible to set values so that efficiency was maximized at the rated point using mechanical controls, it was difficult to set values to optimal levels through a wide range of partial load operation zones.

In the GHC-5, the air excess ratio, ignition timing, and EGR are all electronically controlled. This has made possible to set each item to the optimum value throughout all operational zones. As a result, power levels equivalent to the GHC-4 could be ensured even though the displacement of the engine was made smaller. In addition, seasonal gas consumption was reduced by as much as 80%

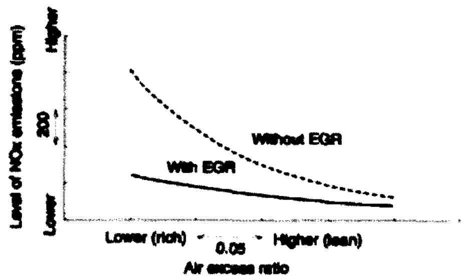

Fig. 6 NOx reduction effect due to EGR
When the ignition timing is constant, reduced NOx emission is possible due to the effect of the EGR, even if the air excess ratio becomes lower.

and the NOx emission by as much as 60% over the previous system. Fig. 7 shows a comparison of these performance levels for both systems.

· Reduction of operating noise

As more and more business use air-conditioning units are installed in residential areas, there is growing demand for GHP outdoor units to exhibit lower levels of noise. As a result, one aim of this development was to produce a unit that has an operating noise level of only 60dB(A). For this purpose, an analysis was made of the contribution of each noise radiation surface of the GHC-4, and radiation surfaces were defined that required countermeasures to accomplish the target operating noise as well as the required noise reduction levels. Measurements were carried out on various parts of the unit using the acoustic intensity method as part of the operating noise contribution analysis. This included measuring radiation noise from every surface part of the outdoor unit, engine suction and exhaust noise, and radiation noise from the heat exchanger, as well as certain specified radiation surfaces that have high noise contributions at each frequency. Acoustic intensity is calculated from sound pressure and surface normal velocity on vibrating structure. A feature of the acoustic intensity method is that the noise contribution from arbitrary radiation surface can be analyzed by multiplying the area of the vibrating body to them. The surface acoustic intensity probe used to measure the radiation noise from each part of the surface is a new one, which differs from a conventional two-microphone acoustic intensity probe. It measures accelerations on a vibrating surface directly and the sound pressure in its vicinity to calculate the acoustic intensity precisely.

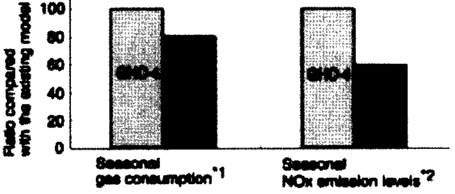

Fig. 7 Reduction of seasonal gas consumption and NOx emissions
The use of electronic engine control greatly reduces seasonal gas consumption and NOx emission levels.

Fig. 8 shows the results of frequency analysis of the sound power from each radiation surface of the GHC-4. The x-axis indicates the A-weighted 1/3 octave center frequency bands, and the y-axis indicates the sound power spectrum A. It was obtained that the contribution of the engine suction and exhaust noise is high to the overall noise level of the system, and the radiation noise from the bottom plate contributes in the low frequency range. This result was used to estimate the operating noise reduction level required for the GHC-5. Then the suction air resonator and exhaust muffler were redesigned, and measures were implemented to insulate sound emanating from the bottom plate. In this way, the targeted operating noise levels could finally be attained. Furthermore, the quality of the operating noise was also improved since the much fluctuating suction and exhaust noise was reduced.

· Extension of maintenance intervals

MHI GHP uses a unique design in which the compressor is driven by direct connection to the engine. Whereas periodic replacement and adjustment of the belt are unavoidable in belt driven type systems which drive through a pulley,

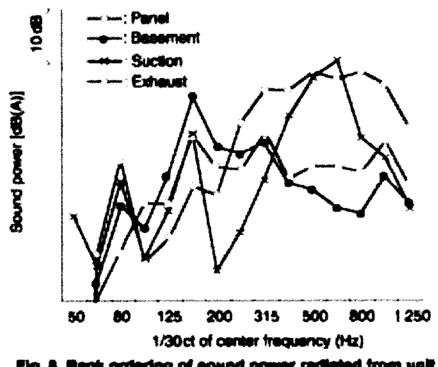

Fig. 8 Rank ordering of sound power radiated from unit surfaces using acoustic intensity probe
It can be seen that suction and exhaust noises are predominant.

the direct connect drive system ensures considerably high reliability, since no maintenance is needed for the drive section. Moreover, special skill is not required when carrying out maintenance work as valve clearance adjustment is unnecessary, because the hydraulic lash adjuster is adopted in the intake and exhaust cam lifters of the engine. This consequently makes it possible to service a lot of outdoor units on site within a short period of time, thereby resulting in reduced maintenance costs.

In order to match the smaller engine displacement, the cooling performance of around the water-cooled cylinders and its vicinity has been improved, and the parameters of each kinetic part have been optimized, resulting in a reduction in engine oil consumption. Even though the intervals between periodic maintenance work have been extended from 8000 hours to 10000 hours compared with the GHC-4, the amount of oil replaced during maintenance has actually been reduced, because the amount of oil used to fill the system has been decreased to about 70% that of past levels.

Reliability Improvement Technology

Engine vibration isolation technology

Engine vibration isolation is an important technical issue that has a significant impact on reliability, since it influences the vibration resistant design of the components within the unit. Thus, efforts were concentrated this time on improving engine vibration isolation in order to reduce vibration further.

Since the release of the GHC-3 in 1988, a unique double engine vibration isolation system has been developed in the MHI GHP, which cannot be found in other company's models. The aim of this system is to prevent structure-borne of the outer panels and the heat exchanger caused by vibration transferred from the engine as well as the vibration transfer to the facility to be prepared. In the double vibration isolation system, the directly connected engine and compressor are supported on the frame structure with vibration isolation (primary vibration isolation), while the entire frame is supported on a unit basement with yet another level of vibration isolation (secondary vibration isolation), with various pressure vessels fixed on this frame. **Fig.9** shows the double vibration isolation system of the GHC-5. In aiming to improve the vibration isolation performance of the GHC-5, improvements were made to a liquid containing mount mainly used in automobiles (hereinafter called hydraulic mount), which was then applied as the primary vibration isolation. **Fig.10** shows the internal structure of the hydraulic mount.

The hydraulic mount consists of an upper section that incorporates a cavity inside a solid rubber, a lower section with a diaphragm put up, and an

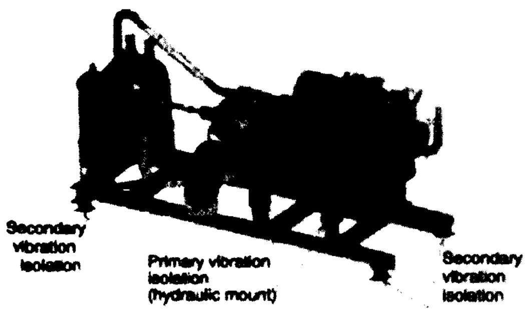

Fig. 9 Design of double vibration isolation system
Engine and compressor are supported on a frame in which vibration has been isolated, while the frame itself is further supported with isolated vibration.

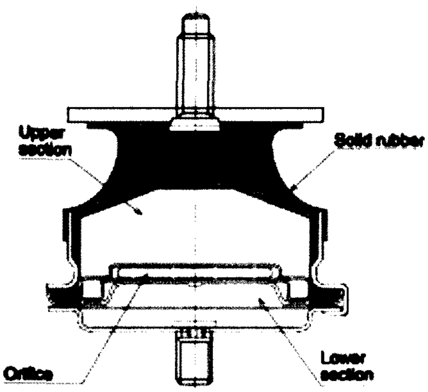

Fig. 10 Structure of hydraulic engine mount
Internal structure of the hydraulic mount is shown.

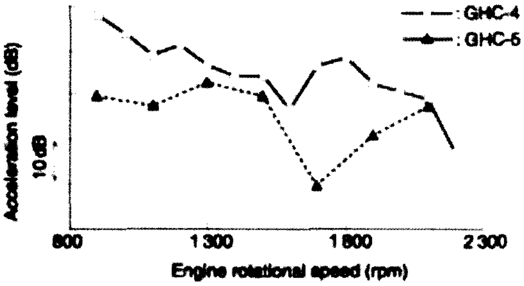

Fig. 11 Comparison of vibration on isolation unit between GHC-4 and GHC-5 systems
Compared to the GHC-4 system, vibration in the GHC-5 system was drastically reduced over all operating zones.

orifice that connects these two sections. As liquids are contained inside both sections, when external forces are applied, elastic deformation of the solid rubber causes the liquids to transfer between both sections through the orifice due to volumetric changes in the upper section. A major feature of the hydraulic mount, which was developed aiming to optimize the vibration characteristics of this unit, is to effectively utilize the reacting force of the liquids. A dynamic spring constant was thus realized within the operating speed range of the engine that is lower than existing ones. At the same time, higher damping performance was adjusted to the natural frequency of engine vibration isolation system in order to restrain displacement during start up. In this way, it was possible to both suppress the excessive stress that occur during start up and reduce the transmission of vibration under unit operation. This resulted in a drastic reduction of the vibration level in the whole range of engine rotational speeds in the GHC−5 compared with existing systems. Fig.11 compares the vibrations of the GHC−4 and 5 that are mounted on vibration isolation mounts (installed between the outdoor unit and the facility).

Reliability improvement of compressor

A reciprocating type compressor was adapted as the compressor for the unit for which there is much experience with respect to durability. Various measures were used to adopt the compressor to the GHP in order to improve the quality of the design. The main aim here was to improve the reliability drawing upon the abundant know−how obtained from the EHP, bus air−conditioning, refrigeration unit for truck and trailer, and similar types of systems.

One example of this is the approach taken to ensure the oil viscosity of the compressor. Evaluations were made of the reliability of multi−indoor unit commercial use air−conditioning systems that must be able to accommodate various ways of operation and different installation configurations, assuming a range of operating conditions. In particular, if any liquid refrigerant were to flow into the compressor, a seizure could be developed due to inappropriate compressor lubrication since diluting of the refrigerator oil may decrease the viscosity of the oil. It was possible to suppress these risks for the MHI GHP by adopting the design structure described in the preceding paragraph, that is, the directly connected engine and compressor type design. This is because the heat transfer from the engine main unit maintains the compressor temperature at its appropriate level and prevents the refrigerant from migrating into the refrigerator oil. This design is widely used in the air−conditioning systems on large MHI tour buses and large−sized refrigeration vehicles that transport fresh foods in frozen and chilled storage. These systems have come to enjoy a high reputation among users.

Conclusion

The GHC−5 was developed using the new technology and evaluation method described above in response to customer needs for systems that are capable of further reducing environmental loads and reducing maintenance management costs. It is expected that this unit will come to have a high market reputation in the future, not only in view of the high performance of the system but also in view of its reliability.