DEVELOPMENT OF HIGH-EFFICIENCY GAS ENGINE HEAT PUMPS

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JAPAN
ABSTRACT

The demand for air-conditioning is growing at an especially fast pace in China and other parts of Asia, and is expected to continue growing over the coming years. This growth is being accompanied by a substantial rise in the demand for power for air conditioning, and there are apprehensions about a shortage of power generation capacity. Under these circumstances, gas engine driven heat pumps (GHPs) are coming to the fore as a technology able to reduce the power consumption requirement to less than one-tenth of the ordinary level. This is because they use a gas engine to run a compressor that conditions the air.

In the Japanese market for commercial-use air conditioners, they currently have a share of about 5% with sales numbering about 40,000 systems per year. They are installed mainly in schools, commercial facilities, homes for the aged, and hospitals.

The major features of GHPs are as follows.
* The level of power consumption can be reduced to about one-tenth as much as with electric heat pumps (EHPs).
* Due to their use of waste engine heat, GHPs have a high heating capacity and coefficient of performance (COP), and therefore deliver a particularly high benefit in cold regions.
* GHPs offer lower levels of CO₂ emissions than even the combination of conventional coal-fired power stations and EHPs.
* They are eligible for tax incentives in Japan because of their effect for shaving the peak summertime power demand.
* They open up a new field of demand for gas. In the service areas of Tokyo Gas, Osaka Gas, and Toho Gas, the combined stock of about 240,000 systems represents gas sales of about 650 million cubic meters per year. This accounts for about 10% of the total gas sales in the commercial market.

Gas companies have played a vital role in the spread of GHPs. They have cooperated in product development and undertaken the sales and maintenance under an integrated setup. Through this work, they have earned the confidence of customers. In accordance with this line, this new GHP was jointly developed with manufacturers through cooperation among Japan's three major city gas companies over a period of three years.

Thus far, GHPs have been mounted with reciprocating or vane compressors. For the new models, the companies developed a new high-efficiency scroll compressor for improved efficiency. They also improved efficiency by enlarging the outdoor heat exchanger and switching to the R410A refrigerant. Efficiency was further improved by adopting an engine with a displacement in the two-liter class.

The two manufacturers doing the actual development succeeded in creating high-performance (COP of over 1.5) GHPs with cooling-mode outputs ranging from 45 to 84 kW. These products were introduced into the market in April 2005.
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1. AIR CONDITIONING AND THE ENERGY SITUATION IN JAPAN

In Japan, the three major metropolitan areas of Tokyo, Osaka, and Nagoya experience conditions of high temperatures (above 35°C) and high humidity in the summer, when the air conditioning demand peaks on a high level. In the commercial-use sector, the air-conditioning season has a long duration of over six months (from May to November). The increase in the indoor heat load due to the spread of office automation equipment drives up the air conditioning load, and the peak air conditioning demand is raised even higher by the heat island phenomenon distinctive to large cities. Even in interim periods, when the temperature outdoors is lower than that indoors, households can adjust temperatures by opening windows, but commercial buildings continue to run air conditioners at low loads. Large mass merchandise stores in the field of electrical products run their air conditioners throughout the year, even in the middle of winter, because of the heat produced by their displays of large TV sets and other products that are constantly turned on.

In response to the increase in the peak power demand in summer, electric power companies have continued to construct power plants. At the same time, as facility-intensive enterprises, they are promoting the construction of pumped storage hydropower plants utilizing late-night power as well as the development and diffusion of heat storage air conditioners in order to level the load. Recently, however, they have been putting more resources into power sales along with the deregulation of the power sector. In this connection, they are actively participating in development and sales of high-efficiency turbo chillers and electric heat pumps (EHPs), and are working to increase the electrical share of the energy market. In Japan, this share is 42 percent, which is higher than in Germany, the United States of America, Canada, and the United Kingdom. It should be added that Japan has 53 nuclear power station units, the third-most in the world (the United States and France ranking first and second, respectively), and much more than Russia and Germany.

In Japan, the city gas demand has been led by water and space heating in the residential sector. The industry has long been making efforts to develop customers in the industrial and commercial sectors for further growth. In the commercial sector, many customers use oil-fired boilers to heat water and space, and gas companies have expanded their gas sales by selling them gas-fired boilers, which have low emission levels for nitrogen oxides. Because gas use declines in summer as water temperatures rise, gas air conditioners also have the attraction of offering an increase in the capacity utilization rate of gas supply facilities. While turbo chillers and EHPs have generally been used to meet the air conditioning demand led by space coolers, gas-fired absorption chillers have gained widespread recognition for use mainly for medium- and large-scale buildings (partly to cope with the power shortage during the summertime peak), and have come to account for about 10 percent of the
combined capacity of air conditioner sales.

Although EHPs designed for medium- and small-scale buildings constitute a huge market occupying about 70 percent of the total installed air conditioning capacity, there had not been any gas products able to compete with them, and concerned parties had been hoping for the development and commercialization of some. Gas engine heat pumps (GHPs) were first developed in Japan as promising products for cultivation of a larger demand for gas in the summer. At present, some 240,000 systems have been installed in the service areas of the three major gas companies (Tokyo, Osaka, and Nagoya), and gas sales for them reach an estimated 650 million cubic meters per year.

2. HISTORY OF GHPS

GHPs were conceived and researched by gas companies beginning around 20 years ago, and were commercialized with the assistance of equipment manufacturers. The initial cost is higher than that of EHPs, but the gas tariffs for their use is held to a low level through utilization of the summertime surplus of gas facilities. This cost advantage powered their diffusion among customers. When first marketed, they were directed to the demand for air conditioning in schools. Many schools were averse to installation of EHPs because they did not have the spare capacity of electrical facilities sufficient for supply of power for them and would have to pay higher basic tariffs in spite of the lower operating rate due to summer vacation, etc.

In the initial phase of marketing, GHPs continued to be saddled with difficulties arising from vibration of the gas engines. Although it takes automobiles about ten years to be driven for 3,000 hours, it is not unusual for GHPs to reach the same number of operating hours in the space of a year depending on the customer. GHPs required a higher standard of their own for mechanical strength. Today, any such trouble is prevented by design applying computerized vibration analysis.

GHPs were accepted by customers and spread because of their eligibility for subsidies due to their contribution to power load-leveling and the reassurance deriving from performance of all work from sales to maintenance by the city gas company. As the installation volume expanded, even periodic maintenance began to impose a heavy burden on maintenance departments. GHP engines also require regular replacement of spark plugs, engine oil, oil filters, and air filters. Although the deadline for replacement was originally 3,000 hours, this was lengthened first to 6,000 hours and then to the current 10,000 hours as a result of ongoing efforts to extend the service life of these parts in light of the enormous expenditure of time and money for replacement every year.

Initially, the mainstay models were outdoor units with a cooling capacity in the range of 14 - 21 kW. Upon the development of multi types enabling operation of indoor units separately, models in the
56-kW class, which offered a lower initial cost, became the main ones. Some large buildings that had been centrally air conditioned by absorption chiller systems have switched to about 100 GHPs.

In Japan, commercial-use gas sales for GHPs continue to rise and are now on a par with those for absorption chillers. With their high heating capability, GHPs are spreading in Korea, where winters are harsh, and are also beginning to be exported to Europe and China.

3. FEATURES OF GHPs

GHPs apply the same principle as automobile air conditioners. They use the gas engine as a motor for belt-driven operation of a compressor that compresses the refrigerant. As a result, electrical power is needed only for components such as the fan, and power consumption can be reduced to only about one tenth as much as for EHPs. This feature presumably has a strong appeal in markets such as Europe, where there is currently a serious shortage of electrical power in summertime due to the growth of the power demand.

GHPs also demonstrate an overwhelming advantage in cold regions. For example, they do not require defrosting operation because the waste heat by hot water from the engine can be used for heating space. This is another big benefit in parts of Europe that have long winters. Suppliers have taken various steps to prevent the outside transmission of engine noise and vibration, which have been curtailed to levels that can bear comparison with those of EHPs (e.g., noise: 60 decibels).

There are also systems that can be connected to existing water pipes and therefore permit retrofitting on buildings already standing.

GHP systems can use the same indoor units as EHP systems, and the resultant magnification of the mass-production effect can lower the price. The outdoor units require maintenance distinctive to gas engines (i.e., replacement of engine oil, oil filters, spark plugs, and air filters), and it is consequently important for gas companies or other concerned parties to organize a maintenance setup for them. In Japan, companies have begun to centrally monitor GHPs by means of a remote surveillance system for prompt response to any trouble.

4. EFFECTS OF DEVELOPMENT OF TECHNOLOGY TO INCREASE GHP EFFICIENCY

If they are to sell, GHPs have to offer a lower running cost than EHPs. As such, an increase in performance that would bring a decrease in gas consumption was an essential item on the technology development agenda. There was a limit, however, to the investment that single manufacturers could make for development as compared to EHPs, which had a higher installation volume. In response, city
Gas companies collaborated in the setting of targets for performance improvement beyond EHP levels, and constructed a scheme for joint development of high-performance GHPs with a few manufacturers while sharing the burden of development expenses. As a result of this activity, the GHP coefficient of performance (COP; cooling capacity/(gas consumption + power consumption)) rose from 1.1 to 1.3, and further to 1.5 in this last development project (see Figure 1).

![Figure 1: Movement of GHP high-efficiency](image)

In this project, the companies succeeded in developing a high-efficiency scroll compressor to be mounted in the GHP manufactured by Yanmar Energy System. They undertook this development jointly with Daikin Industries, an EHP manufacturer, through negotiation among city gas companies. In addition, a high-performance compressor was newly developed by Mitsubishi Heavy Industries and installed in its own GHP.

The development aimed at raising the COP to 1.5 faced high technical barriers, and the companies consequently developed constituent technologies for the engine, compressor, and waste heat utilization (see Figure 2). They succeeded in developing a heating system that made more extensive use of waste heat, but decided to attempt its commercialization in the next project owing to the high cost. They also created a prototype of a new high-efficiency engine, but decided against its commercialization at present because of the huge capital investment required for mass production.

![Figure 2: Development factor of technology to increase GHP efficiency](image)
Nevertheless, an unforeseen factor for efficiency improvement arose when a switch was made to R410A for refrigerant. Coupled with the results of technology development for the compressor and other factors, this made it possible to bring out GHPs that attained the COP target in April 2005. Figures 3 and 4 show the GHPs in question, which are manufactured by Mitsubishi Heavy Industries and Yanmar Energy System, respectively. Table 1 presents the product specifications. The following is an outline of the technical achievements related to the increase in efficiency.

![Figure 3: GHP manufactured by Mitsubishi Heavy Industries](image1)

![Figure 4: GHP manufactured by Yanmar Energy System](image2)

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Mitsubishi Heavy Industries</th>
<th>Yanmar Energy System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>450MT7 560MT7</td>
<td>450G1 840G1</td>
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<tr>
<td>Capacity (Cooling/Heating) kW</td>
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<td>Gas Consumption (Cooling/Heating) kW</td>
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<td>1.77/1.67</td>
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<td>COP (average for the cooling and heating modes)</td>
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<tr>
<td>External Measurement Height Width Depth mm</td>
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<td>2176 1990 800</td>
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<tr>
<td>Mass kg</td>
<td>920</td>
<td>940 1270</td>
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</table>

COP : Capacity / ( gas consumption + power consumption )

Table 1: Product specifications

* **High-efficiency scroll compressor**: The mainstream type of compressor for GHPs changed from reciprocating to vane, and is now scroll. The companies increased the compressor efficiency by
applying a tertiary compression technology, the most advanced type in the category of scroll compressors. In addition, the compressor was equipped with a mechanism enabling variation of the engine rpm, cooling capacity, and compression volume per revolution.

* **Optimization of the refrigerant circuit by adoption of R410A:** The switch from R407C to R410A (which has an ozone depletion potential of zero) for refrigerant increased the refrigerant density, and this helped to improve efficiency.

* **Engine tuneup:** The GHP engine applies a lean burn method. Lean burn in the vicinity of the stable combustion limit is an agenda for higher thermal efficiency. To optimize the swirl within the combustion chamber, the companies refined the shape of cylinder heads and pistons to widen the scope of lean combustion with stability. The engine also adopted technology for control of the air-fuel ratio. This technology enables continuous control of dilution at the limit of stable combustion while sensing change in rpm, and makes it possible to keep combustion efficiency on the optimal level.

* **Improvement of the outdoor air heat exchanger performance:** To improve the efficiency of heat intake from the air, the program increased the heat exchange area for improved performance.

Relative to the former ones with a COP of 1.3, the new models feature a more than 10-percent reduction of running cost and CO2 emissions. In EHP terms, the COP of 1.5 is equivalent to one of 4, which is the highest level of efficiency in the same class.

5. CONCLUSION

In Japan, installation of GHPs is spreading due to the subsidies provided for their reduction of power consumption for air conditioning (cooling mode) and the integrated setup for performance of everything from sales to maintenance by gas companies. To assure their competitiveness and reduce their energy consumption, the companies developed high-efficiency GHPs with a COP of 1.5 and injected them into the market in April 2005. Their consumption of gas was curtailed to only about two-thirds as high as that of heaters utilizing gas-fired boilers that recover latent heat. We are convinced that these high-efficiency GHPs will grow into air conditioners that are accepted in cold regions and other regions around the world.
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