High-Performance, High-Efficiency GHP Development

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Abstract: The gas engine-driven heat pump air conditioner (GHP) is a gas air-conditioning system that heats and cools by means of heat-pump operation. GHP has an outdoor compressor driven by the gas engine. Since the GHP were introduced for sale in 1987, they have been widely spread mainly in Japan because of its advantages such as savings in electrical power consumption as well as low operational cost. The development of high-efficiency GHP has steadily progressed since the product entered the market, but with the current energy conservation trend, and from the viewpoint of counteracting global warming through the reduction of CO2 emissions, there is a pressing need to improve GHP efficiency even more.

The performance of GHP has been evaluated up to now in COP (Coefficient Of Performance) at the rated point. However, GHP is hardly driven in rated point actually, and most is driven by the partial load. APF (Annual Performance Factor) was provided for as a performance evaluation index considered the partial load driving in JIS (Industrial Standards of Japan) in 2006. It is important to maintain a highly effective operation to improve APF in the area where the air conditioning load is small.

In our development efforts, GHP system efficiency improvements were devised as the means to increase the efficiency of the gas engine driving source as well as to enhance efficiency from the aspect of the refrigeration cycle, where the improvement of performance at the outdoor air/heat exchanger was investigated. A comparison of the newly developed GHP to existing models indicates that reductions of primary energy up to 19% and of CO2 up to 20% are possible.

In this paper we will introduce a high-performance, high-efficiency GHP jointly developed by Tokyo Gas, Osaka Gas, Toho Gas and the GHP manufacturers.

Key Words: GHP, gas engine, high efficiency, energy saving

1 INTRODUCTION

1.1 Outline of GHP

The gas engine-driven heat pump air conditioner (GHP) has outdoor compressors powered by a gas engine. This is a gas air-conditioning system that heats and cools by means of heat-pump operation. The GHP, in contrast to an electric type of heat pump air conditioner (EHP) that drives the compressor by means of an electric motor, drives the compressor by means of a gas engine. Thus it follows that the GHP has the advantage of using very little electrical power as compared to EHP. The refrigeration cycles for both the GHP and EHP are based on the same fundamentals. However there are advantages such as a significantly reduced defrost operation because, it's possible for the GHP to utilize the engine exhaust heat during heating. Figure 1 shows the outward appearance of the typical GHPs.

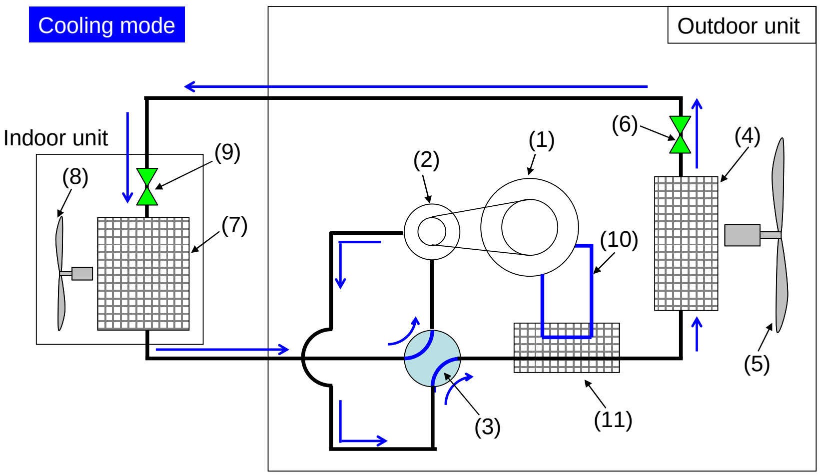
Figure 1 Outward appearance of the typical GHPs

1.2 Operating principle of GHP

The refrigerant circuit of GHP has compressor(s), outdoor air heat exchanger, expansion valve gear, and indoor air heat exchanger. The refrigerant flow this circuit changing its phase from gas to liquid and from liquid to gas.

In case of cooling cycle, the refrigerant circuit utilizes the behavior of the refrigerant that absorbs the heat of vaporization when it evaporates from liquid to gas as shown in Figure2.

a. The refrigerant gas compressed by the compressor has high temperature and high pressure. This refrigerant gas passes through the four-way valve and condenses in the outdoor air heat exchanger. The condensing heat is radiated to the atmosphere. At this step, the phase of refrigerant changes from gas to liquid, but its pressure still remains high.
b. This refrigerant liquid passes through the expansion valve gear. The refrigerant lowers its temperature and pressure, then portion of refrigerant liquid vapors to gas.
c. The refrigerant changes its phase from liquid to gas in the indoor air heat exchanger. At this time the refrigerant absorb the heat of vaporization from room air, then the temperature of room air is lowered.
d. The refrigerant gas goes back to the outdoor unit and is compressed by the compressor again and repeats same cycle.



(1)gas engine
(2)compressor
(3)four-way valve
(4)outdoor air heat exchanger
(5)outdoor cooling fan
(6)outdoor unit expansion valve gear
(7)indoor air heat exchanger
(8)indoor fan
(9)indoor unit expansion valve gear
(10)coolant water circuit
(11)exhaust heat recovery exchanger

Figure2.Refrigerant circuit of GHP when cooling mode

In case of heating cycle, the refrigerant flows in the reverse direction. The four-way valve changes the path of the circuit as shown in Figure3.

e. The refrigerant gas is compressed by the compressor then its temperature and pressure rises. This refrigerant gas passes through the four-way valve and goes into the indoor air heat exchanger. The refrigerant condenses from gas to liquid in the indoor air heat exchanger. At this time, the condensing heat is radiated to the room (- the indoor unit blows the hot wind and warms the room temperature).

f. After that, the refrigerant liquid returns to the outdoor unit and passes through the expansion valve gear. And then the refrigerant lowers its temperature and pressure, portion of refrigerant liquid vapors to gas.

g. The refrigerant goes into the outdoor air heat exchanger, and there changes its phase from liquid to gas with absorbing the heat of vaporization from atmosphere. After this step, almost all refrigerant is gas phase with lower temperature and lower pressure.

h. In addition the refrigerant passes trough the exhaust heat recovery exchanger. There the refrigerant absorbs heat from coolant water (hot water) of gas engine.

i. The refrigerant is compressed by the compressor again and repeats same cycle.

Referring to the refrigerant cycle, GHP is different from EHP at “h.” step above substantially. GHP have high heating capacity because utilize the exhaust heat of engine. So GHP can operate defrosting cycle without interrupting the heating operation.

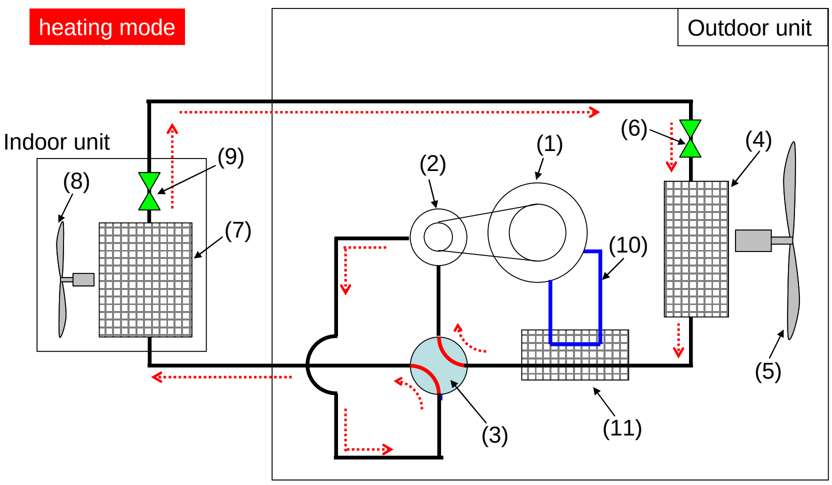


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Figure3. Refrigerant circuit of GHP when heating mode

2 Feature of GHP

2.1 Electrical power saving

GHP uses electrical power for only cooling fan and some components. So GHP don’t use much electrical power. For example, GHP with 14kW cooling capacity consume electrical power of 0.7kW. The electricity consumption level is equivalent to that of hair dryer. If GHP is installed as air-conditioning equipment, access to electricity can be cut down. And we can utilize the saved electricity that is supposed to be consumed by EHP for illumination or office automation equipment.

2.2 The effect of the temperature of outdoor air on heating capability

The heating capability of EHP decreases when the temperature of outdoor air becomes lower because the heat source is outdoor air. In contrast, as previously explained, because GHP utilizes the engine exhaust heat, there is little decrease of the heating capability.

3 Advantages and the spread of GHP

The accumulated sales capacity of GHP in Japan from FY1995 to FY2010 becomes 21.2 million kW (104% compared with the previous fiscal year) as shown in Figure4. The sales volume in Japan is about 227,700 units from FY2003 to FY2010 whereas the volume of it in other regions in the world is about 34,400 units as shown in Figure5. The volume of sales in Japan is about 6.5 times of it in other regions in the world. This depends on the following reason.

- The summer season in Japan is hot and high humidity. Therefore, the peak of power demand in Japan appears in daytime of summer to use the electricity-type air conditioner. GHP which can reduce the peak of power demand is socially necessary.

Furthermore, to enlarge a GHP market, it will be necessary in future that the improvement of the efficiency and the correspondence to the huge variety of customer needs.

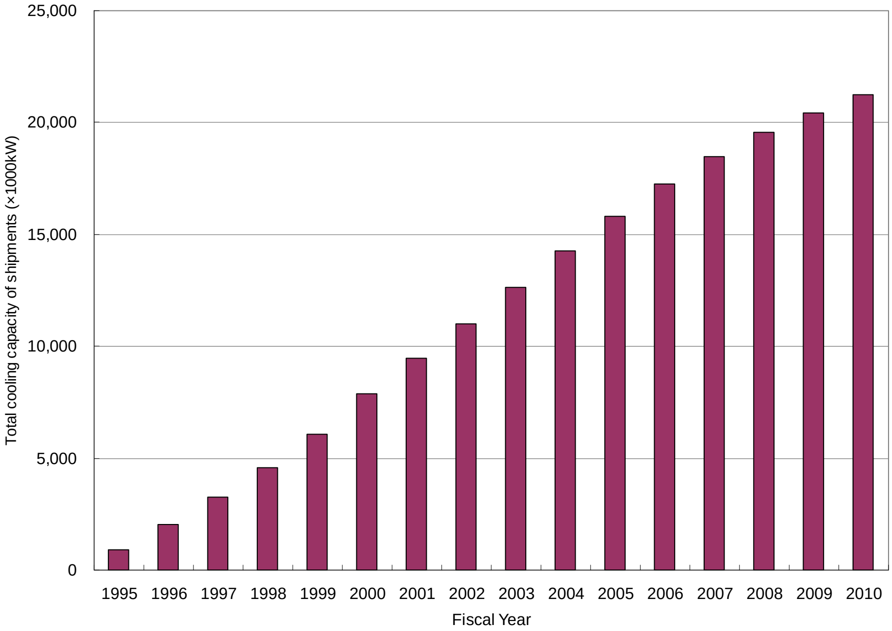

Figure4. Spread of GHP in Japan (FY1995-FY2010)

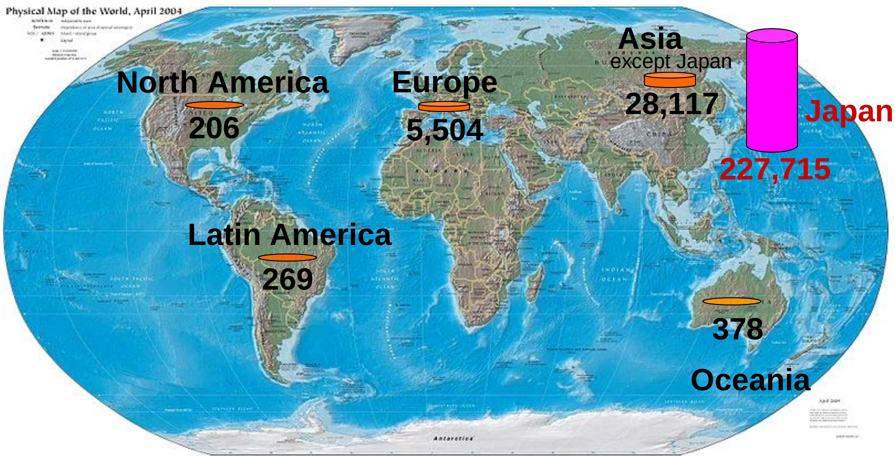

Figure5. Spread of GHP in the world (FY2003-FY2010)

4 Improvement of efficiency

It stands to reason that the development of high-efficiency GHP has steadily progressed since the product entered the market as shown in figure6. However, with the current energy conservation trend, and from the viewpoint of counteracting global warming through the reduction of CO_2 emissions, there is a pressing need to further improve GHP efficiency.

Accordingly, since 2008 we have worked on the development of a high-efficiency GHP. As a result, we commercialized the GHP having maximum efficiency in the market segment for variable refrigerant flow in April of 2011. In this chapter, we report the high-efficiency GHP in detail.

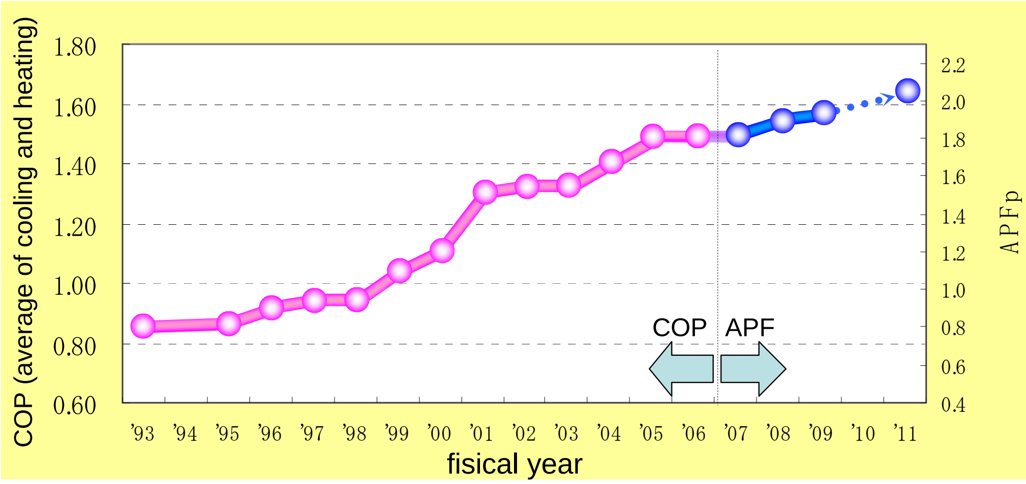

Figure6. GHP efficiency trend

4.1 Performance evaluation index

The performance of GHP has been evaluated up to now in COPp (Coefficient Of Performance [Primary Energy Base]) at the rated point. However, GHP is hardly driven in rated point actually, and is mostly driven by the partial load. Recently, the evaluation of performance under the condition near an actual usage has come to be attached to importance with the rise of the concern to the energy conservation. APF (Annual Performance Factor) was provided for as a performance evaluation index considered the partial load driving in JIS (Industrial Standards of Japan) in 2006 (see Figure7). To evaluate the performance of GHP and EHP by the same standard, it is necessary to convert the amount of all energy consumption including power consumption into primary energy. APF converted into primary energy is shown APFp. In Rationalization in Energy Use Law in Japan, it is provided to the conversion of the electric power of 1kW into primary energy 9760kJ.

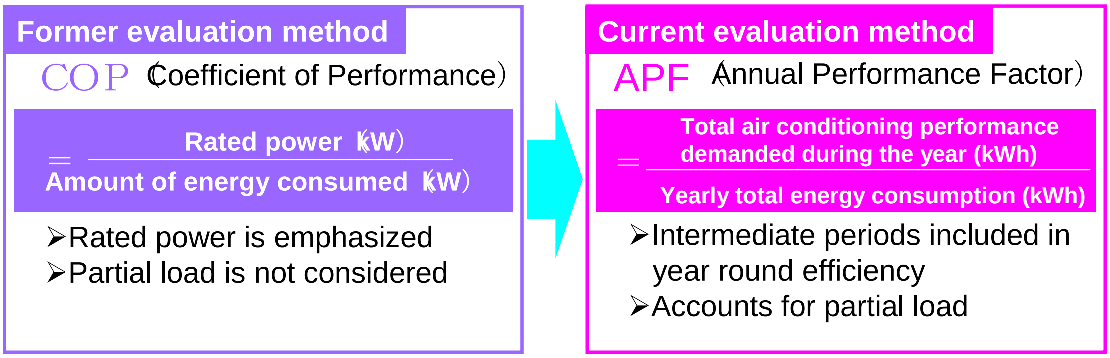

Figure7. Performance evaluation index

4.2 Initiatives for efficiency improvement

The efficiency of GHP is determined by the product of the gas-engine drive source's efficiency and the refrigeration cycle efficiency. Accordingly, for our development we decided to work on both aspects of the issue: efficiency improvements for the gas engine as well as the refrigeration cycle.
As previously discussed, we focused on the APFp as the efficiency during the partial-load operation. It was particularly important to improve the efficiency during 50% load in order to

improve the APFp. Consequently, it was important for us to incorporate a number of technologies that improved the partial-load operation efficiency. There are differences in the adopted technologies, depending on the GHP manufacturer, but the key technical details are explained below.

4.3 Gas engine efficiency improvements

4.3.1 Downsizing the gas engine

In order for an engine to intake combustion air into the combustion chamber, as well as to expel the exhaust gases, a pumping motion is used. A portion of the engine output power is used for this pumping motion, and that portion is seen as a loss from the net power of the engine. This is referred to as the “pumping loss.” A throttle valve is used to regulate the amount of intake air, which controls the output power of the gas engine, but under conditions in which the throttle is constricted, the throttle valve resists the incoming air and the efficiency is reduced.

Regarding the case where identical output power is obtained from engines having different displacements, because there is no power margin in the smaller-displacement engine, the throttle tends to stay open, resulting in a lower degree of pumping loss. On the other hand, because there is an output power margin for the larger displacement engine there is a tendency for the throttle to be constricted and the pumping loss to increase. Because this difference in pumping loss becomes apparent in the engine efficiencies, generally speaking, for cases in which the identical output power is obtained from engines having various displacements, the engines with smaller displacements will have lower fuel consumption. Moreover, the engines with smaller displacements have the effect that friction loss reduces. For the gas engines used for the GHP, the engine displacement corresponding to the air-conditioning capacity is selected. However, because general-purpose engines are diverted to this application there are cases in which a small amount of excess power will be provided. Focusing on that fact in our product development, in order to optimize the engine output we sought improved efficiency by reducing the engine displacement (downsizing).

4.3.2 Drive at high torque

As shown in Figure 8, in the RPM range of gas engines for the GHP, there is a basic tendency for the efficiency of an engine to improve as it operates at higher torque. A typical GHP is shown in Figure 9, showing that the rotational motion of the gas engine is output to a pulley, whereupon a belt transmits the power to the compressor pulley, rotating the compressor. Because of this arrangement it is possible to increase the rotational torque by increasing the diameter of the engine pulley.

Another basic characteristic of GHP is that the air-conditioning power output is controlled by adjusting the engine RPM up or down. Because the air-conditioning power output is proportional to the quantity [engine RPM x torque] when only the torque is increased, it isn’t possible to run at conventional low-load conditions. Therefore, for identical air-conditioning output it is necessary to reduce the engine RPM in the case of high-torque operation. For conventional GHP, the engine RPM is also reduced to be near the limit, and even lower engine-rotation speeds will give rise to issues such as vibration and durability. These are challenges we are undertaking.

In our development, when the engine pulley diameter was increased it was possible to operate at high torque by simultaneously expanding the engine range on the low-RPM side. In this way the engine efficiency was improved and an improvement in GHP efficiency was achieved.

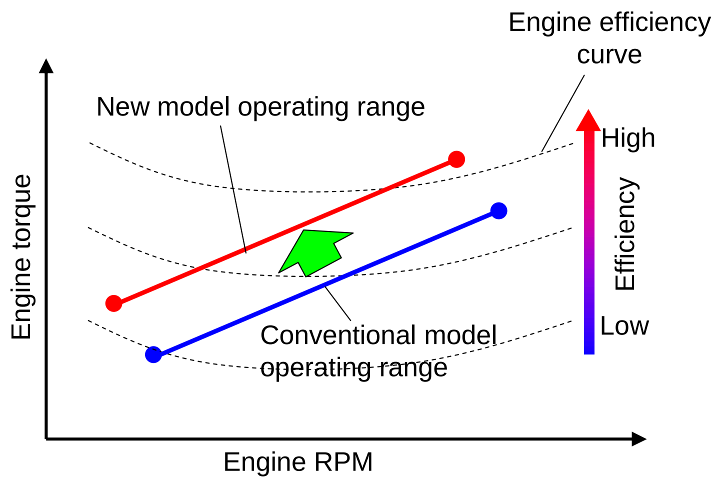

Figure8. Engine efficiency characteristics

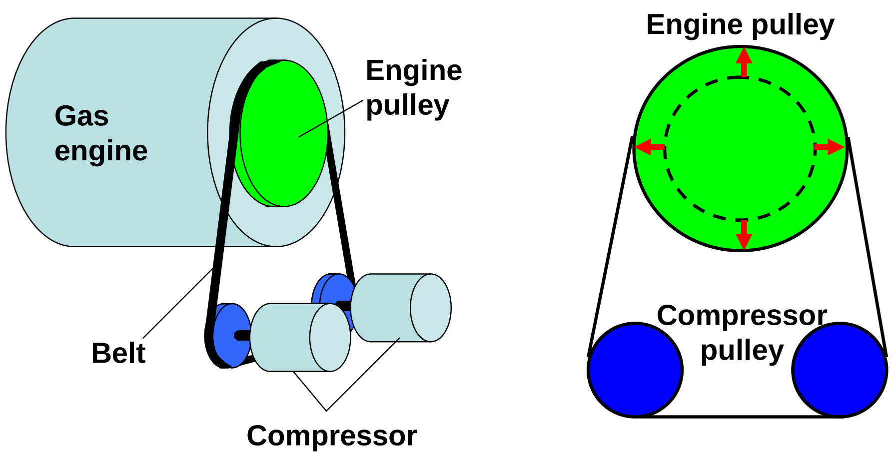

Figure9. Rotational power transmission schematic diagram

4.4 Efficiency improvements of the refrigeration cycle

The outdoor air heat exchanger is an important component that influences the efficiency of the refrigeration cycle. During cooling operation we can see that the outdoor air heat exchanger functions as a condenser, with the high-pressure gas refrigerant from the compressor being cooled by the outside air and thereby condensing into a liquid refrigerant. We worked on the performance improvement of the outdoor air heat exchanger with the objective of improving the efficiency of the refrigeration cycle.

4.4.1 Optimization of the refrigerant line of outdoor unit heat exchanger

The heat exchanger performance is dependent on the heat-transfer coefficient on the refrigerant side. Here the heat-transfer coefficient is expressed as a function of the Reynolds number, as shown in the equations below. Because the Reynolds number is proportional to the flow rate, it is possible to improve the performance of the heat exchanger by increasing the flow rate of the refrigerant. On the other hand, when the flow rate is increased there is also an increase in pressure loss. Because there is an increased pressure loss when the flow rate of the gaseous portion is increased, the average condensation temperature is decreased and the performance of the heat exchanger is degraded. Moreover, the pressure loss decreases as the refrigerant density increases. Therefore, for the gas portion of the flow, the pressure loss increases; for the liquid portion, the pressure loss decreases.

$$h = Nu \cdot k/L$$
$$Nu = 0.664 \cdot Re^{1/2} \cdot Pr^{1/3} \quad (Re<105)$$
$$Re = U \cdot L/v$$

h: heat-transfer coefficient [W/($m^2 \cdot$K)]
k: fluid thermal conductivity [W/(m·K)]
U: flow rate [m/s]
L: length in flow direction [m]
Nu: Nusselt number
Re: Reynolds number
Pr: Prandtl number
v: kinematic viscosity [m^2/s]

For conventional outdoor unit heat exchangers, as shown in the upper part of Figure10, the gas refrigerant that is compressed in the compressor diverges at the entrance to the heat exchanger, where there are multiple rows of pipes and flows are in parallel. At the exit of the heat exchanger, the piping arrangement allows the streams of the refrigerant, now liquid, to recombine. As shown in the lower portion of Figure10, the structure of our developed system separates the liquid and gas portions of the flow. For the gas portion the flow line is increased over conventional arrangements, resulting in reduced pressure loss. On the liquid side, where the pressure loss is small, the number of flow lines is reduced; as a result, the flow rate increased. Thus there is both a reduction in pressure loss and an increase in the heat-transfer coefficient, resulting in an improvement in the heat exchanger performance.

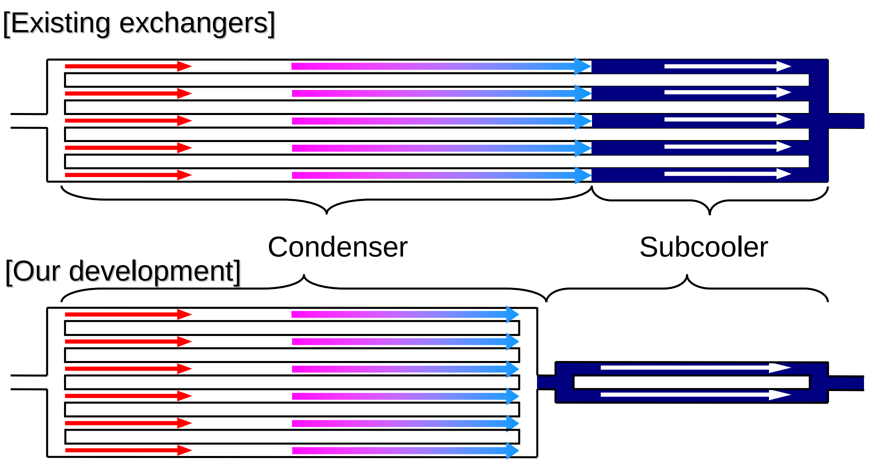

Figure10. The refrigerant line of outdoor unit heat exchanger

4.4.2 Modification of the fin pitch of outdoor unit heat exchanger

GHP outdoor air heat exchangers are of the direct-flow type, with aluminum plate fins attached to copper refrigerant pipes as shown in Figure11. The spacing alignment of these aluminum fins has been made narrower than in the prior versions, and consequently it has become possible to increase the number of fins without increasing the size of the heat exchanger. Accordingly, the heat transmission area was increased and the heat exchanger performance was improved.

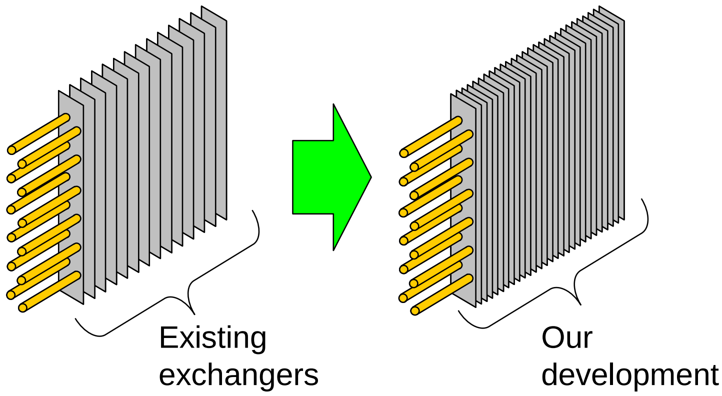

Figure11. Heat exchanger fin pitch

4.5 New model performance
4.5.1 Efficiency

There is a lineup of newly developed GHPs with cooling capacities ranging from 45 kW to 85 kW, available for sale since 2011. By combining the technologies introduced in this paper, the efficiency targets have been reached, with the frontrunners attaining an APFp of 2.05. Each model has an APFp of 2.00 or greater as shown in Figure12. An APFp of 2.05 is the highest efficiency in the market segment for variable refrigerant flows (regardless of gas or electric type).

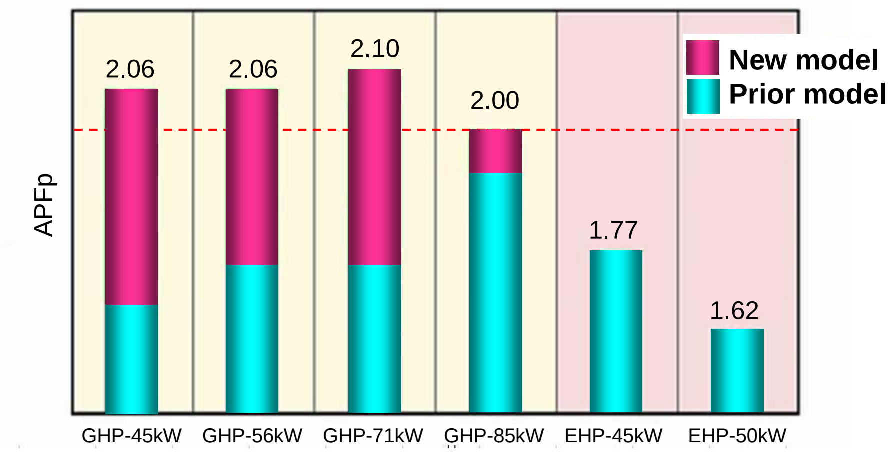

Figure12. New model GHP efficiencies

4.5.2 Environmental performance

Accompanying the improved efficiency, environmental performance is also improved. An objective comparison of the environmental performance as compared to a prior model is given in Figure13. For the 45 kW model having the greatest efficiency improvement, the year-long primary energy consumption amount is reduced by 19%, and the yearly CO_2 discharge amount is reduced by 20%.

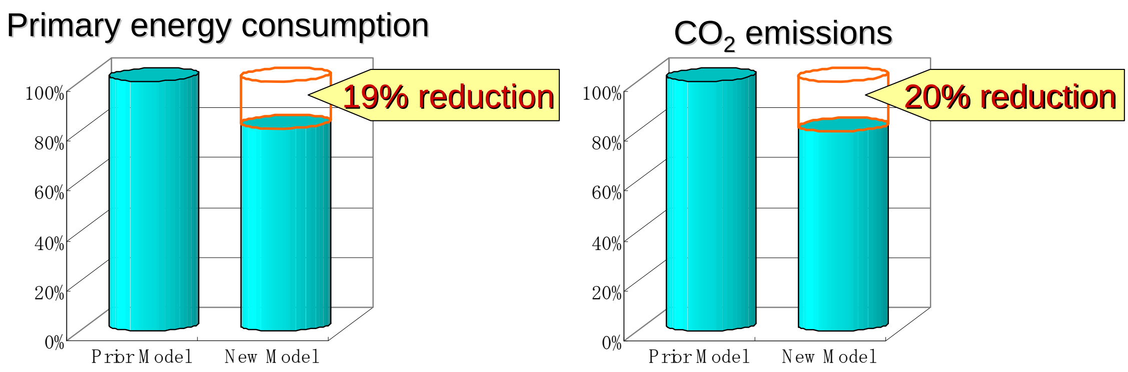

Figure13. Environmental performances of the new model GHP

4.5.3 Installation

More than 25 years have elapsed since the first GHP units were sold, and there is increased demand to replace the old models that have outlived the service life. As a result of this demand for replace, it is necessary for the installation area of the new models to be equal to or less than that of the old models. From that standpoint, the installation area of the newly developed GHP is equal to or less than those of the prior models.

5 CONCLUSION

Recently, customer needs of energy saving and environmental improvement have risen. Therefore development of high efficiency GHP required, we developed high-performance, high-efficiency GHP having maximum efficiency in the market segment for variable refrigerant flow using the following techniques.

- we improved the engine efficiency by reducing the engine displacement (downsizing).
- it was possible to operate at high torque by expanding the engine range on the low-RPM side and increasing the engine pulley diameter. In this way, we improved the engine efficiency.
- we improved the heat exchanger performance by optimization of the refrigerant line of outdoor unit heat exchanger.
- we improved the heat exchanger performance by modification of the fin pitch of outdoor unit heat exchanger.

We will work in the development of the GHP that may be able to use the waste heat effectively and the improvement of more highly efficient GHP in the near future.

6 REFERENCE

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