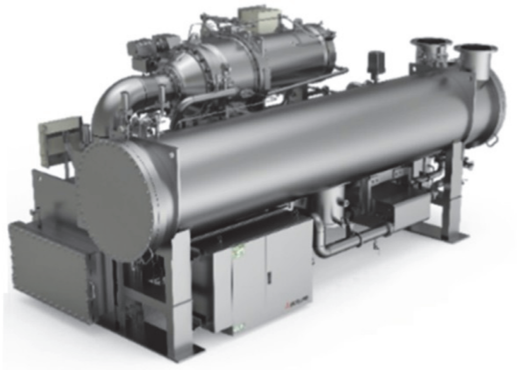
New "JHT-Y" Series of Centrifugal Chillers with Low-GWP Refrigerants Contributing to Carbon Neutrality



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The Montreal Protocol aims to protect the ozone layer. In the protocol, the "Kigali Amendment" was adopted in October 2016 to reduce HFC refrigerants in phases to curb global warming. In Japan, the Fluorocarbon Emissions Control Act came into effect and the regulation on centrifugal chiller products using HFC refrigerants with a high global warming potential (GWP) will be started in fiscal 2025 (starting April 1, 2025). Mitsubishi Heavy Industries Thermal Systems, Ltd. newly developed a centrifugal chiller "JHT-Y" using the HFO-1234yf refrigerant with a GWP of less than 1, which achieved the performance, compact size and cooling capacity range equal or superior to those of an existing centrifugal chiller using HFC-134a. This report describes the technologies adopted for the development of the JHT-Y and the comparison with the existing product.

1. Introduction

Centrifugal chillers are used in district heating and cooling and air conditioning for large buildings, the semiconductor industry, pharmaceutical and food factories, etc., and produce chilled water at cooling capacities ranging from about 150 to 5,400 USRt (U.S. Refrigeration ton). HFC-134a, which is a hydrofluorocarbon (HFC) conventionally used for centrifugal chillers, has a GWP of 1,430(1) and at the 28th Meeting of the Parties (MOP 28) to the Montreal Protocol held in October 2016, the phase-down of the production and consumption of HFCs was made mandatory.

In Japan, the Fluorocarbon Emissions Control Act was amended in January 2019 and a centrifugal chiller was designated as a regulated product, and the regulation on shipment of centrifugal chillers using HFC refrigerants will be started in fiscal 2025 (starting April 1, 2025) so that the average GWP weighted by the number of centrifugal chillers shipped will not exceed 100. In foreign countries, Singapore introduced the regulation on shipping of centrifugal chillers using HFC refrigerants in October 2022, and a switch to low-GWP refrigerants will be further promoted in the future.

Regarding centrifugal chillers using HFO (hydrofluoroolefin), MHITH launched the ETI-Z series using HFO-1233zd(E) with a GWP of 1 in September 2015 and the GART-ZE series using HFO-1234ze(E) with a GWP of less than 1 in April 2017. Thus, we could offer a lineup of centrifugal chillers using low-GWP refrigerant in all our series that covered all the cooling capacities for the first time as a domestic manufacturer. In addition, we developed the JHT-Y series using HFO-1234yf with a GWP of less than 1 by using the technologies cultivated so far and started sales in June 2022.

2. Selection of HFO-1234yf

In adopting low-GWP refrigerants, we set the selection criteria described below. The comparison of the conventional HFC refrigerant and the low-GWP HFO refrigerants is shown in **Table 1**.

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Table 1 Comparison of refrigerants

	Conventional refrigerant (HFC)	New refrigerants (HFO)		
	HFC-134a	HFO-1233zd(E)	HFO-1234ze(E)	HFO-1234yf
Global warming potential (GWP)*1	1,430	1	< 1	< 1
Ozone depletion potential (ODP)	0	0	0	0
Classification (Refrigeration Safety Regulation under High-Pressure Gas Safety Act)	Inert gas	-*2	Specific inert gas	Specific inert gas
Classification (ASHRAE Standard 34)	A1*3	A1*3	A2L*3	A2L*3
Fluorocarbon Emissions Control Act	Applicable	Not applicable	Not applicable	Not applicable
Long-duration exposure toxicity (allowable value) [ppm]	1,000	800	800	500
Boiling point (at atmospheric pressure) [°C]	-26.1	18.3	-19.0	-29.4
Saturation pressure (at 6°C) [kPa(G)]*4	260.7	-39.3	167.3	283.9
Saturation pressure (at 38°C) [kPa(G)]*4	861.8	100.7	624.3	866.4
Latent heat of evaporation (at 6°C) [kJ/kg]*4	194.0	200.7	180.3	159.3
Specific volume of saturated gas (at 6°C) [m^3/kg]*4	0.056	0.278	0.069	0.047
Specific volume of saturated gas (at 38°C) [m^3/kg]*4	0.021	0.091	0.026	0.018
Theoretical COP*5	6.58	6.93	6.56	6.31
Application (except the application to centrifugal chillers)	Refrigerant (automotive air conditioners)	Foaming agent	Propellant	Refrigerant (automotive air conditioners)

*1 Fourth Assessment Report (HFC) and Fifth Assessment Report (HFO) of the Intergovernmental Panel on Climate Change (IPCC)[(1), (2)]
*2 The High Pressure Gas Safety Act is not applicable to HFO-1233zd(E) when it is used for chillers under the specified conditions.
*3 A1: nonflammability/ lower toxicity, A2L: lower flammability/lower toxicity, B1: nonflammability/higher toxicity
*4 Calculated from the NIST Reference Fluid Thermodynamic and Transport Properties - Refprop Ver. 10.0.
*5 Two-stage compressor/two stage expansion sub-cooler cycle. Refrigeration cycle efficiency at evaporation temperature of 6°C, condensation temperature of 38°C and adiabatic efficiency of 90%

2.1 Environmental performance

The refrigerant to be selected shall have an ozone depletion potential (ODP) of 0.001 or lower, a GWP of 150 or lower and low toxicity (Class A of ANSI/ASHRAE Standard 34).

→ HFO-1234yf has an ODP of 0, a GWP of less than 1 and toxicity which is classified as Class A (low toxicity) and satisfies all the criteria for environmental performance. In addition, it is not subject to regulation under the Fluorocarbon Emissions Control Act.

2.2 Physical properties

(1) Refrigeration cycle efficiency (COP: Coefficient Of Performance)

The refrigerant to be selected shall have a refrigeration cycle efficiency equal to that of the conventional refrigerant. When the refrigeration cycle efficiency is low, the energy consumption increases and CO_2 emissions increase.

→ The refrigeration cycle efficiency (ideal refrigeration cycle COP) of HFO-1234yf is about 96% of that of HFC-134a. In order to make the developed chiller have a performance equal to that of the existing chiller, a high-efficiency compressor, etc., described later, were adopted for the developed chiller to improve its performance.

(2) Volumetric flow rate (equipment size)

Compared to conventional refrigerants, the equipment design pressure of the refrigerant to be selected shall not be significantly higher and the cooling capacity that can be output by the same equipment size shall not be significantly smaller.

When the equipment design pressure is significantly increased, the thickness increases for securement of strength, and when the cooling capacity that can be output is decreased, the equipment size increases. As a result, the volume of materials used and CO_2 emissions in manufacturing also increase. Furthermore, the size of a compressor or a heat exchanger is generally determined by the volumetric flow rate (m^3/s) of the refrigerant gas. Even with the same cooling capacity, as the latent heat of evaporation is lower, the mass flow rate (kg/s) and the volumetric flow rate (m^3/s) become higher. Even with the same mass flow rate (kg/s), as the specific volume of saturated gas (m^3/kg) is larger, the volumetric flow rate (m^3/s) becomes higher.

→ The saturation pressure of HFO-1234yf is very close to that of HFC-134a (**Figure 1**) and the equipment design pressure can be the same as that of the conventional chiller. In addition, since the latent heat of evaporation of HFO-1234yf is about 80% of HFC-134a and the specific volume of saturated gas is about 85% of HFC-134a, the volumetric flow rate of HFO-1234yf is about 106% of HFC-134a, allowing output of an equivalent cooling capacity by equipment of the same size as a chiller using HFC-134a. As for HFO-1234ze(E) used for the conventional GART-ZE series, since the latent heat of evaporation is about 95% of HFC-134a and the specific volume of saturated gas is about 120% of HFC-134a, the volumetric flow rate is about 130% of that of HFC-134a. Therefore, the cooling capacity that can be output by the same equipment size tends to become lower.

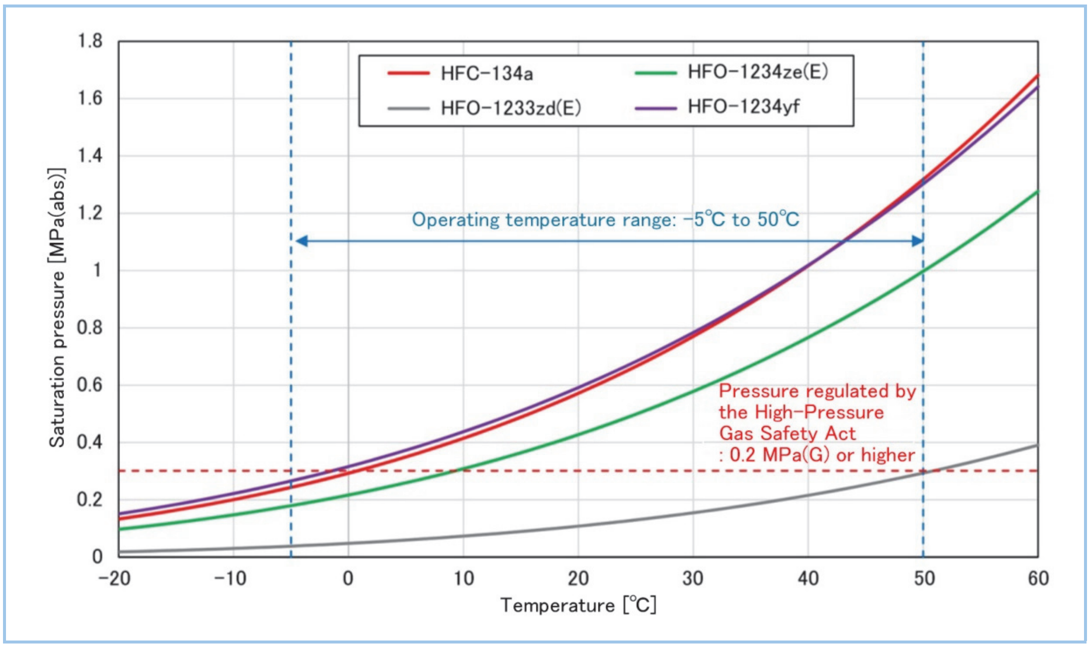

Figure 1 Relationship between temperature and saturation pressure in various refrigerants

2.3 Availability

The refrigerant to be selected shall be used for applications other than as a refrigerant for centrifugal chillers to ensure a certain volume of production.

Compared with multi-air conditioners for buildings, centrifugal chillers use a smaller amount of refrigerant per unit of cooling capacity and are manufactured in smaller quantities. Therefore, the amount of refrigerant used by centrifugal chillers in the whole market is smaller compared with other air conditioning systems (multi-air conditioners for buildings, automotive air conditioners, etc.). In view of stable supply and prices, it is desirable that the refrigerant to be selected should be used as a refrigerant for other air conditioning systems, a foaming agent, etc., and be widely available in significant quantities.

→ HFO-1234yf is adopted mainly for automotive air conditioners, vending machines, etc. An automotive air conditioner is designated as a regulated product under the Fluorocarbon Emissions Control Act and will be regulated from fiscal 2023 (starting April 1, 2023). Therefore, it is expected that the mainstream refrigerant will be switched from HFC-134a, which is subject to the regulation, to a low-GWP refrigerant HFO-1234yf and the production volume of HFO-1234yf will significantly increase.

2.4 Safety

The refrigerant to be adopted shall have low toxicity and be inert (poses no risk of fire when used in a machine room). If safety cannot be secured, legal restrictions shall be provided and necessary measures shall be taken.

→ The toxicity of HFO-1234yf is classified as Class A (low toxicity) in the ASHRAE Standard 34. The flammability is classified as 2L (lower flammability), and it is classified as a specific inert gas under the High Pressure Gas Safety Act. In Japan, the Refrigeration Safety Regulation under the High Pressure Gas Safety Act was revised in 2016 and the legislation for safe use of A2L (lower flammability/lower toxicity) refrigerants, HFC-32, HFO-1234ze(E) and HFO-1234yf, was implemented first in the world. Accordingly, these refrigerants can be safely used equivalently to conventional refrigerants such as HFC-134a if they satisfy the following requirements stipulated by the "Exemplified Standards for the Refrigeration Safety Regulation" and "KHKS0302-5(2020) Facility criteria of refrigeration and air conditioning equipment (Facilities of specific inert gas)."

- The installation site of a chiller shall have a structure to prevent the refrigerant gas from stagnating in the event of leakage of gas. When a chiller is installed in a place such as the inside of a building where the refrigerant gas may stagnate, a continuous mechanical ventilation system having a specified ventilation capacity shall be provided and an interlocking mechanism for the chiller and the ventilating equipment shall be also provided (to prevent the chiller from starting up when the ventilating equipment stops.)
- A leakage detection and alarm device shall be provided, which has a leakage detecting element installed at a place where gas leaking from a chiller may stagnate. The alarm equipment shall be periodically inspected to check the alarm operation.

As described above, HFO-1234yf satisfies all the selection criteria and has many features similar to those of HFC-134a, and it was selected as a refrigerant for the new series.

3. Applied technologies

The volumetric flow rate of HFO-1234yf is equivalent to that of HFC-134a, but the ideal refrigeration cycle COP is 96% of that of HFC-134a. Therefore, to achieve the performance equivalent to the conventional chiller, a chiller using HFO-1234yf requires a mechanical design that allows an increase in efficiency. In order to increase the performance while maintaining the compact design equivalent to that of the conventional chiller, we conducted the development and design described below.

3.1 Downsizing and performance enhancement of compressor

(1) Large gas flow and compact aerodynamic design

In the JHT-Y series, the blade technology for a large gas flow, which is proven in the ETI-Z series, was adopted. Based on the blade shape for the ETI-Z series, the CFD (Computational Fluid Dynamics) analysis in which the equation of a flow is solved on a computer to visualize the flow was used to optimize the leading and trailing edge shapes of the impeller blade, blade angle distribution, shape of the inlet guide vane, etc. As a result, compared with the conventional chiller using HFC-134a, the gas flow was increased by about 20% while the adiabatic efficiency was maintained with the same impeller diameter and the compressor was downsized. With the downsized compressor, the bearings, sealing, gears, etc., were also optimized for the reduction of loss and improvement of reliability.

(2) Optimum selection of compressor

A compressor achieves the highest efficiency around the design point gas flow rate and the efficiency is reduced at a gas flow rate other than the design point. The existing series covers the cooling capacities ranging from 550 to 2,700 USRt (in the case of a single unit with one compressor installed in one chiller) with 5 compressor models, and for the cooling capacities in the transition zone of models, a model having a gas flow away from the design point gas flow where the highest efficiency is delivered has been selected. The number of compressor models was increased from 5 to 11 in the JHT-Y series and for all cooling capacity zones, a high-efficiency model can be selected.

3.2 Performance enhancement and downsizing of heat exchanger

A shell and tube heat exchanger was adopted in the evaporator and the condenser, while a plate heat exchanger was adopted in the sub-cooler and the economizer. As is the case with the conventional series, a compact design was made for the heat exchangers. In selection of a model in the conventional series, a heat exchanger is uniquely determined based on a compressor selected according to the specification. Therefore, a heat exchanger having excessive specifications may be selected. In the JHT-Y series, with the increased number of compressors, the lineup of heat exchangers was also expanded so that an optimum heat exchanger can be selected in any cooling capacity zone. As a result, the number of chiller models in the JHT-Y series is 17 models, which doubled the number of models (9 models) in the conventional series, and chillers that meet customer specification requirements can be offered.

3.3 Downsizing and performance enhancement of operation panel

For the microcomputer control panel, a state-of-the-art board, which allows an increase in the speed and precise control of CPU (Central Processing Unit), was adopted and the usability and viewability were improved with the following functions. **Figure 2** shows an image of the screen of the control panel.

- The liquid crystal display size was increased from the conventional 10.4 inch to 12.1inch to improve the viewability.
- The touch panel allows intuitive operation.
- In the event of a failure or when the chiller detects any abnormality, the cause of the failure and measures to be taken are displayed for the enhancement of user support.
- The function of automatically notifying the maintenance time was added for the improvement of convenience.

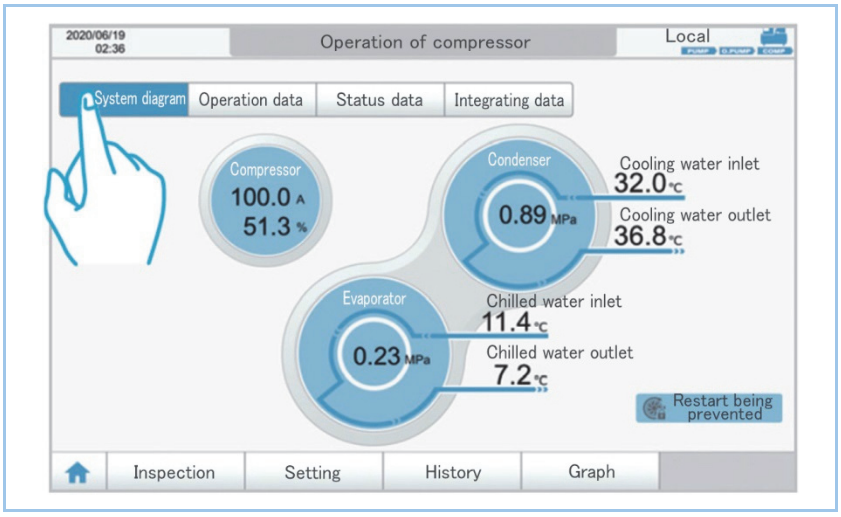

Figure 2 Screen of control panel

3.4 Customer portal site

We provide all customers who have purchased our centrifugal chillers with various information on the customer portal site "MHI Centrifugal Chiller Club". **Figure 3** shows the image of the customer portal site. The portal site conducts integrated management of the information possessed by customers on the cloud to allow customers to search or download the materials on their chillers and view the maintenance plans, etc., through a PC, smartphone or the like and check the conditions of their chillers anytime and anywhere.

In addition, the remote monitoring service "M-CONNECT" is available on a chargeable basis and contracted customers can use the additional functions of checking the operation conditions and preparing automatic reports on operation data. The customer is notified of any abnormality detected by the chiller by email to the designated address.

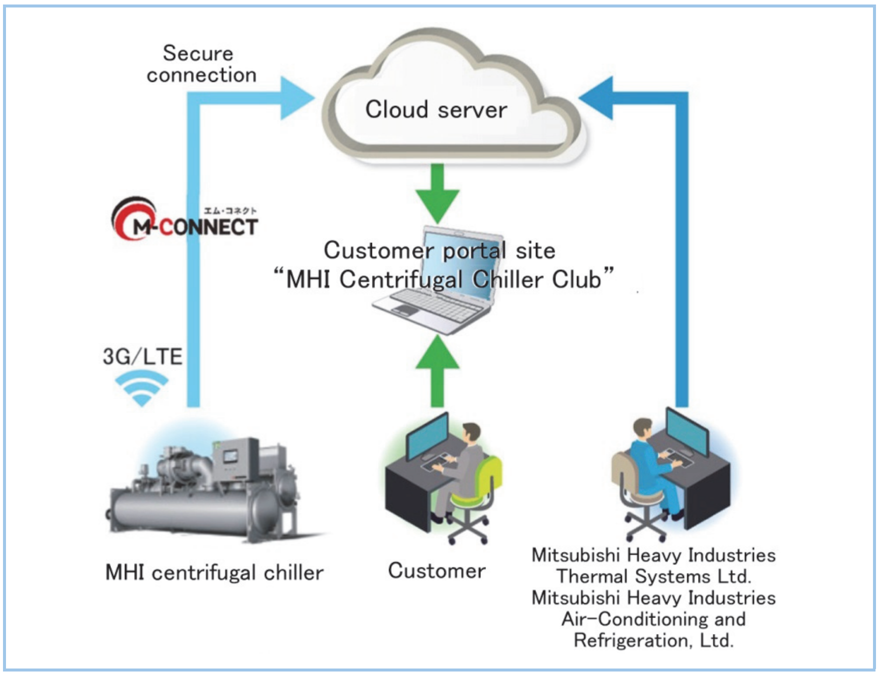

Figure 3 Image of customer portal site "MHI Centrifugal Chiller Club"

4. Comparison with existing chillers

Compared with the conventional series using HFC-134a and HFO-1234ze(E), the JHT-Y series achieves an equivalent or higher performance and cooling capacity range and is more compact in size. **Table 2** shows the comparison of specifications and performance between the JHT-Y series and the conventional series.

Table 2 Comparison of rated specifications and performance in domestic large chillers

Series	GART	GART-ZE	JHT-Y
Refrigerant	HFC-134a	HFO-1234ze(E)	HFO-1234yf
Capacity range of each series	400-5, 400USRt	300-5, 000USRt	300-5, 400USRt
Chiller model	GART-270	GART-ZE250	JHT-Y245
Cooling capacity	1, 830USRt (6435 kW)		
Chilled water temperature	12.0°C → 7.0°C		
Chilled water flow rate	1,104 m^3/h		
Cooling water temperature	32.0°C → 37.0°C		
Cooling water flow rate	1, 288 m^3/h	1, 291 m^3/h	1, 290 m^3/h
Power consumption	995 kW	1, 014 kW	1, 005 kW
COP	6.46	6.35	6.40
L×W×H	6.2m×3.4m×3.4m	6.2m×3.5m×3.4m	6.2m×3.5m×3.3m
Installation area	21.08 m^2	21.70 m^2	21.70 m^2
Shipping weight	33.0 ton	33.6 ton	31.4 ton
Operating weight	43.4 ton	43.9 ton	40.8 ton

In the JHT-Y series, the constant-speed model (2, 000 USRt class) has a rated COP of 6.4 and the variable speed model has a maximum COP with partial load of 24.9 and an IPLV (Integrated Part Load Value) of 8.8. The series delivers the world's top class performance and energy saving efficiency.

The JHT-Y models for air conditioning can be operated for the cooling capacities ranging from 300 to 5,400 USRt, which are equivalent to those of the conventional series using HFC-134a, and the maximum cooling capacity is about 20% larger than that of the conventional series using HFO-1234ze(E). As is the case with the conventional series, the new series can be applied to the low-temperature, heat-recovery and heat pump specifications.

In the chiller unit, a shell and tube heat exchanger equivalent to that of the GART series using HFC-134a was adopted, and in the sub-cooler and the intercooler, a plate heat exchanger was adopted. For the GART series, an optimum arrangement of a heat exchanger was considered and compared to the chillers developed 10 years ago, the installation area was reduced by about 30% and the spatial volume was reduced by about 40%. The JHT-Y series follows the compact design of the GART series and furthermore, the downsizing of the compressor described in Chapter 3 allowed the compressor weight to be reduced by about 15% at maximum, and the optimum selection of a heat exchanger allowed the total weight of the condenser and evaporator units to be reduced by about 9% at maximum. Of the whole chiller unit, the height was reduced by about 4% at maximum and the mass was reduced by about 10% at maximum.

5. Conclusion

We developed and launched the centrifugal chiller JHT-Y series using the low-GWP refrigerant HFO-1234yf, which has a lower GWP than CO_2. The newly developed JHT-Y series and the small-capacity centrifugal chiller ETI-Z series using HFO-1233zd(E) cover cooling capacities of 150 to 5,400 USRt. Accordingly, all the cooling capacities of the centrifugal chillers using the HFC-134a refrigerant can be covered by the centrifugal chillers using low-GWP refrigerants. In the JHT-Y series, state-of-the-art design technologies were used and the performance equivalent to or higher than the GART series using HFC-134a, downsizing and weight reduction were achieved. Therefore, the customer can select centrifugal chillers while checking in more detail according to their specification requirements.

We will continue to focus our efforts on developing high-performance products using low-GWP refrigerants in order to spread the use of such products in the global market, thereby contributing to the conservation of the global environment.

References

(1) Intergovernmental Panel on Climate Change (IPCC), Fourth Assessment Report (AR4), (2007), https://www.ipcc.ch/assessment-report/ar4/
(2) Intergovernmental Panel on Climate Change (IPCC), Fifth Assessment Report (AR5), (2014), https://www.ipcc.ch/assessment-report/ar5/