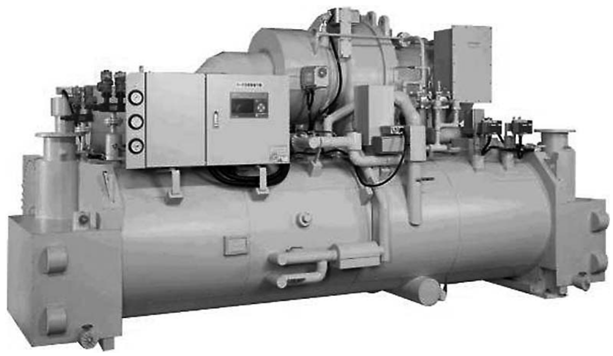

Highest-Efficiency in the World, Variable Speed Drive Turbo Chiller NART-I Series

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The NART-I series turbo chiller, developed and marketed by Mitsubishi Heavy Industries, Ltd. (MHI), utilizes as a base a highly efficient turbo chiller that uses the refrigerant HFC134a, which does not affect the ozone layer. An inverter has also been introduced in the drive source of the NART-I series turbo chiller to improve aerodynamic performance, and a newly designed optimum control capable of coping with variable speed is incorporated that has made it possible to realize remarkable savings in energy. The inverter also facilitates variable speed control of the NART series turbo chiller, thereby helping to make it highly efficient. The turbo chiller has achieved a COP of 6.1 by high performance aerodynamic characteristics, low mechanical loss, and a highly efficient heat exchanger. In addition, advanced calculation control has been incorporated in the NART series to realize optimum acceleration/deceleration and load control based on the aerodynamic characteristics of the compressor. As a result, a remarkable increase in performance could be obtained for NART series turbo chiller during periods of partial load and when cooling water temperature is low. These features have made it possible for the series to attain the highest level of efficiency in the world, achieving a COP as high as 17.8 max. (chilled water outlet temperature of 7°C). Trial-calculations of the annual energy saving effect of this machine under general plant load patterns have shown remarkable reductions in electric power consumption of as high as 45 % compared with the level of power consumption of a fixed speed machine.

1. Introduction

Turbo chillers are heat source machines used for various purposes such as air conditioning of buildings, heat storage, district heating and cooling in heat supply business, air conditioning in plants, and process cooling in chemical plants. To address problems associated with the destruction of the ozone layer, efforts have been under way in recent years to completely eliminate the use of CFCs and to abolish the use of HCFCs in the future as refrigerants. It has thus become necessary to increase the efficiency of turbo chillers using HFC134a.

As a result, since 1998, MHI has used a specific refrigerant HFC134a with an ozone depletion potential (ODP) of zero for its turbo chillers to protect the global environment, and has aimed at increasing the performance of equipment for ever greater energy savings, which has become a matter of great social concern at present.

As shown in **Fig. 1**, a turbo chiller using HFC134a was first put on the market in 1994. Since then, subsequent successors of the system have been developed in fairly quick succession. For example, the ARS series was developed in 1998, and the NART series, which had the world's highest level of efficiency with a COP of as high as 6.1 (at a chilled water outlet temperature of 7°C), was developed in the year 2000. At present, an increase in efficiency of 20 % or more compared with conventional MHI systems has been achieved. In 2003, MHI developed and marketed the AART series with a COP of 6.4, which was a turbo chiller series with the world's highest efficiency.

The NART-I series reported on this time was developed in 2002 and put in the market on January 2003. The aim of this new series has been to increase operating efficiency to even higher levels to meet the needs of users who desire

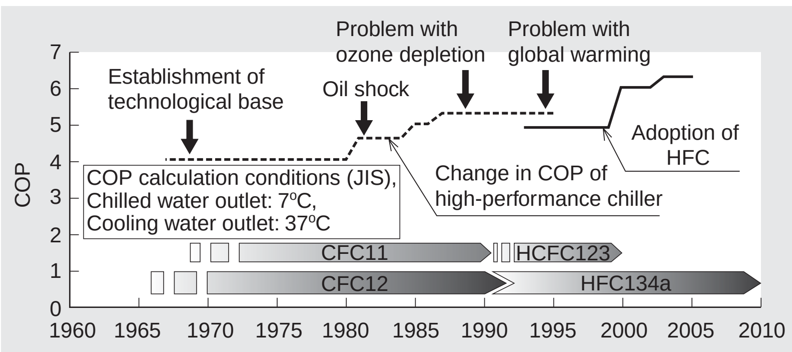

Fig. 1 Change in turbo chiller performance
Change in refrigerant and improvement in turbo chiller performance are shown.

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to operate the system at high efficiencies throughout the year and who seek to reduce power consumption so as to reduce air conditioning costs throughout the year.

2. Details of technologies for realizing increased efficiency

In general, the relationship between ambient air temperature and power consumption can be summarized as follows: decrease in outside air temperature → decrease in cooling water temperature → decrease in condensing temperature and pressure → decrease in compression ratio of compressor → decrease in power. In short, power consumption drops as the temperature of the cooling water becomes lower. Since turbo chillers use a centrifugal compressor, unlike positive-displacement types of systems (reciprocating type, screw type, etc.), their compression ratio and power are determined by the rotational speed of the compressor. Hence, notable energy savings can be realized throughout the year by optimizing the control of the rotational speed of the compressor in accordance with variations in load.

In NART-I series, MHI newly designed an advanced microcomputer panel capable of high-speed calculations, adopted an inverter for the motor power, and has mounted a rotational speed controller. As a result, MHI could solve the technical problems of suitable speed control with the upgraded series. The details of the new technologies are explained for each element below.

2.1 Increase in aerodynamic performance

In NART series, the design of the profile of the impeller forming the moving blade and the side shape of the stationary flow passage were optimized with the assistance of a three-dimensional CFD and based on a database of the results of aerodynamic verification tests. The design also contributes to greater optimization through three-dimensional accurate cutting machining operation of the impeller by an advanced five-axis NC machine. The applicable rotational speed of a fixed speed compressor comes to within 85 to 115 % of the design point, whereas it comes to within 50 to 115 % for the variable speed compressor. Namely, the off-design region is increased remarkably. During the development phase of the NART series, efficiency is increased at the design point with the assistance of a CFD. This has made it possible to develop an impeller with excellent performance characteristics, even in a rotational speed range wider than the region of the fixed speed compressor. Through these improvements, a high level of performance could be achieved in the NART-I series in a wide rotational speed range.

Fig. 2 shows the results of the examination of the performance obtained using the CFD when the inlet guide vane, called an inducer, shown in the figure is both present and absent. When the impeller with an inducer is applied to the variable speed chiller under operating conditions of low flow rate and low rotational speed, it causes gas flow to peel off from the leading edge to produce a region of reverse flow. On the other hand, the impeller without an inducer produces a slight reverse flow on the downstream side of the leading edge. As can be seen in the lower portion of Fig. 2, the efficiency on the small flow rate is higher in the impeller without a diffuser than in the other system. Accordingly, an impeller without a diffuser was adopted in the design.

It is well known that the surge limit increases to the low airflow rate side from the design point toward the lower speed region. In this case, the stable region was increased up to the region of minimum airflow rate at 50 to 70 %, with the result that region of high efficiency operation could be increased remarkably. From the above examinations, it was found that a compressor efficiency of 80 % or higher could be maintained stably, even in a low Mach number region.

On the other hand, since the rotational speed range is increased under variable speed operation, adequate care must be taken into account in the design of both the shaft resonance and blade resonance. It could be confirmed by analysis and actual measurement of the characteristic frequency concerned that resonance is sufficiently avoided in a wide rotational speed range.

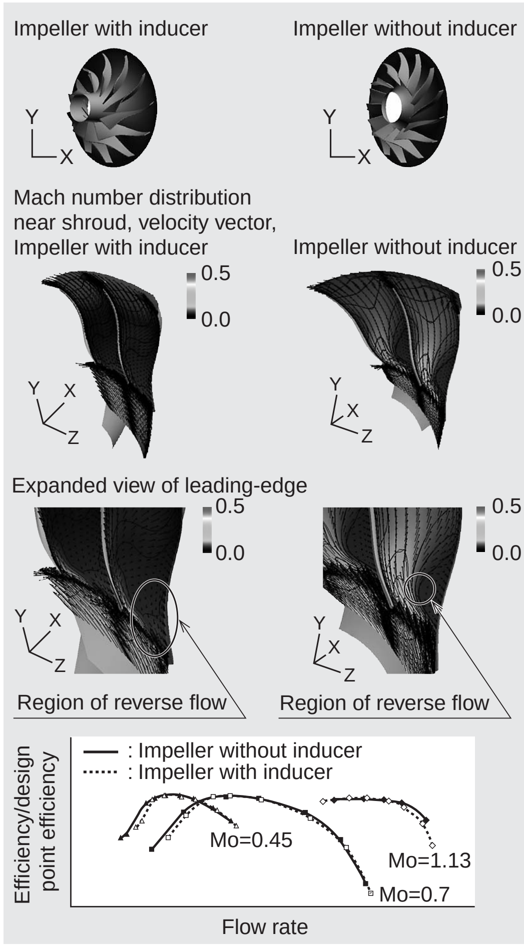

Fig. 2 Analysis of impeller flow by CFD
Effect of inducer on impeller flow is studied. The six figures show velocity-vector distribution at Mo=0.45.

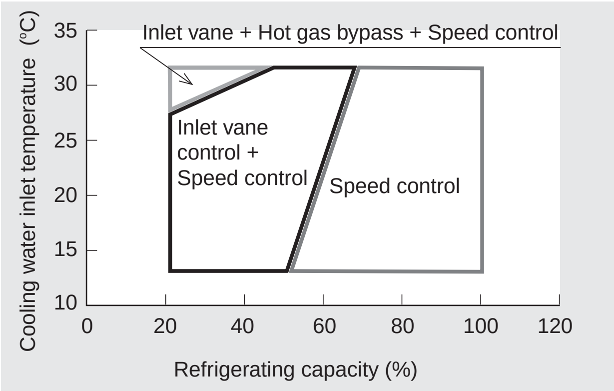

Fig. 3 Control range map
Optimum control method at each range determined by refrigeration performance and cooling water inlet temperature.

2.2 Optimum control of variable speed

In a centrifugal compressor, inlet guide vane control and hot gas bypass valve control are adopted for load control. In inlet vane control, since resistance loss at the inlet of the compressor increases in a small opening area, the control must be performed at a large opening area to reduce loss. In the hot gas bypass valve control used in a low load region, a cyclic loss is produced in the opening direction and, therefore, the control must be performed in such a way that the opening is minimum.

Based on operational data obtained from plant verification tests, it was possible to prepare a control map shown in **Fig. 3**. In addition, the limit conditions for surging occurring on the small air flow rate side of the compressor were calculated, and operation control was performed at the optimum rotational speed to minimize the lowering of performance by the hot gas bypass, while inlet vane control was performed throughout the entire operating range to allow highly efficient operation in a wide load range.

2.3 Microcomputer control panel and high functional communication technology

The characteristic equations used for realizing optimum control are very complex and the number of detection points is also large. Thus, a high-speed calculation capacity is required in order to perform calculations without delay in the temperature control of the chiller. For this purpose, MHI adopted a high performance CPU in the heart of the next-generation control panel. Also, a seven-inch TFT LCD device was furnished as a standard to increase visibility and ease of operation.

In addition, a 24-hour monitoring function has been installable in the control panel for optimum operational control and enhanced servicing. The following functions can also be incorporated, as needed.

- Routine monitoring of operation data
- Storage of data when an abnormality occurs and automatic notice to the service person
- Sampling of data in real time

Table 1 Communication data from turbo chiller

Type of data	Quantity, item, etc.
Analog data	32 items
	Temperature, pressure, etc.
Digital data	128 items
	Indication of state, trouble, etc.
Cumulative data	48 items
	Operating time, number of starts, etc.

Fig. 4 Appearance of high-voltage inverter panel (L 2.4 m x W 2.6 m x H 2.7 m)

The data shown in **Table 1** can be outputted for each equipment device so that, by making use of the standard communication function, the heat source machines of the user can be administrated easily. This function can be realized by connecting up to a maximum of six chillers to the MHI smart communication tool, or SCT, (additionally installed) through the RS485 cable.

2.4 High-voltage inverter panel

For a large capacity machine with a class capacity exceeding 800 USRt, the input voltage of the turbo chiller's motor reaches a high-voltage class of 3 kV to 6 kV. Therefore, the introduction of inverters in these classes was requested. In the NART-I series, MHI was the first in the industry to realize the driving of the inverter for all capacities through the adoption of a 3 kV to 6 kV class high-voltage inverters (**Fig. 4**).

3. Results of performance verification

In order to verify the cooling water temperature follow-up control and the partial load follow-up control of the inverter machine, the test equipment at the MHI plant was improved so that cooling water of 11°C could be produced, even in summer. The verification tests were performed once these improvements were satisfactorily completed. A flow chart of the equipment loop is shown in **Fig. 5**.

The partial load performances of the NART standard machine and the inverter machine (NART-I series) against

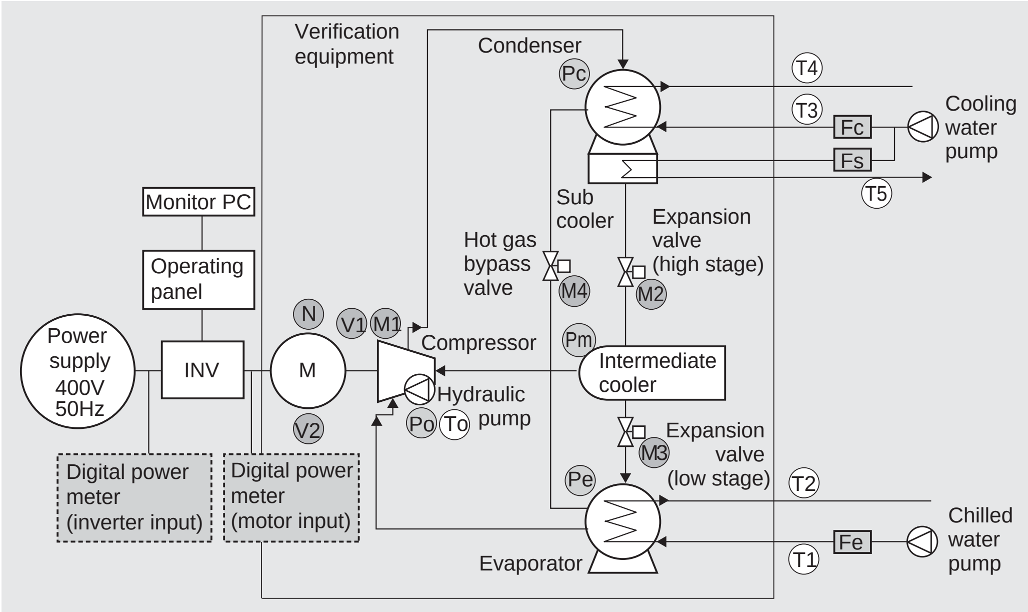

Fig. 5 Flow chart of verification equipment at MHI plant
Detailed control of cooling water inlet temperature is realized even in summer by connection to another heat source machine.

Table 2 Main specification of verification unit

Item	Specification value
Type of chiller	NART-401
Refrigerant	HFC134a
Refrigerating capacity	1 407 kW
Chilled water temperature	7 °C out/14 °C in
Cooling water temperature	32 °C in/37 °C out

Table 3 The lineup of NART-I series

NART- (Refrigerating capacity)	40 I (400 RT)	50 I (570 RT)	70 I (800 RT)	100 I (1 130 RT)	145 I (1 610 RT)	200 I (2 000 RT)
400 V	→	→	→			
3 kV class	→	→	→	→	→	
6 kV class		→	→	→	→	→

cooling water temperature are shown at the upper portion of **Fig. 6**. The performances shown in Fig. 6 indicate the actual performance values measured using the NART-40I specified in the specifications of **Table 2**. Control of the performance measurements was performed automatically as shown in the previous section.

As can be seen in Fig. 6, performance could be increased remarkably in the cooling water temperature region of 20°C or below where the control could not be performed sufficiently by the inlet vane control of the conventional fixed speed standard machine. Moreover, stable control was possible. The cooling water inlet temperature was allowed to drop to approximately 13°C. The maximum COP reached 17.8 for the machine having a chilled water outlet temperature of 7°C, which is the operating condition of general chillers in Japan, and surpassed 20 for the machine using a chilled water temperature of 9°C.

4. Energy savings effect on operation throughout the year

The calculation results of the energy saving effect during variable speed operation by the inverter drive throughout the year are shown in the lower portion of Fig. 6.

The general air conditioning load pattern and outdoor air temperature conditions in the Tokyo area were used as the requirements for calculation. When the effect is converted into annual power consumption and the volume of CO_2 discharge, they are reduced by 40 % compared with the high-efficiency standard machine (fixed speed). This is equivalent to 22% in terms of electricity charges.

In the plant loading pattern, the effect reduced is equivalent to 45 % in terms of the power consumption and the volume of CO_2 discharge and 35 % in terms of electricity charges, respectively.

The increased amount of investment in terms of initial cost resulting from the addition of the inverter can be recovered within approximately one year for a machine that is operated throughout the year in a plant process. The increased amount can be recovered within about three years even for a general air conditioning machine that is only operated during the summer.

In terms of maintenance, the overhaul period is extended to 50 000 hours or longer, and the load on the rotation system during operation can be reduced by rotation control. In addition, a longer overhaul period could be possible through operation control in which the communication function of the advanced microcomputer control panel is used. The lineup of NART-I series by voltage level is shown in **Table 3**.

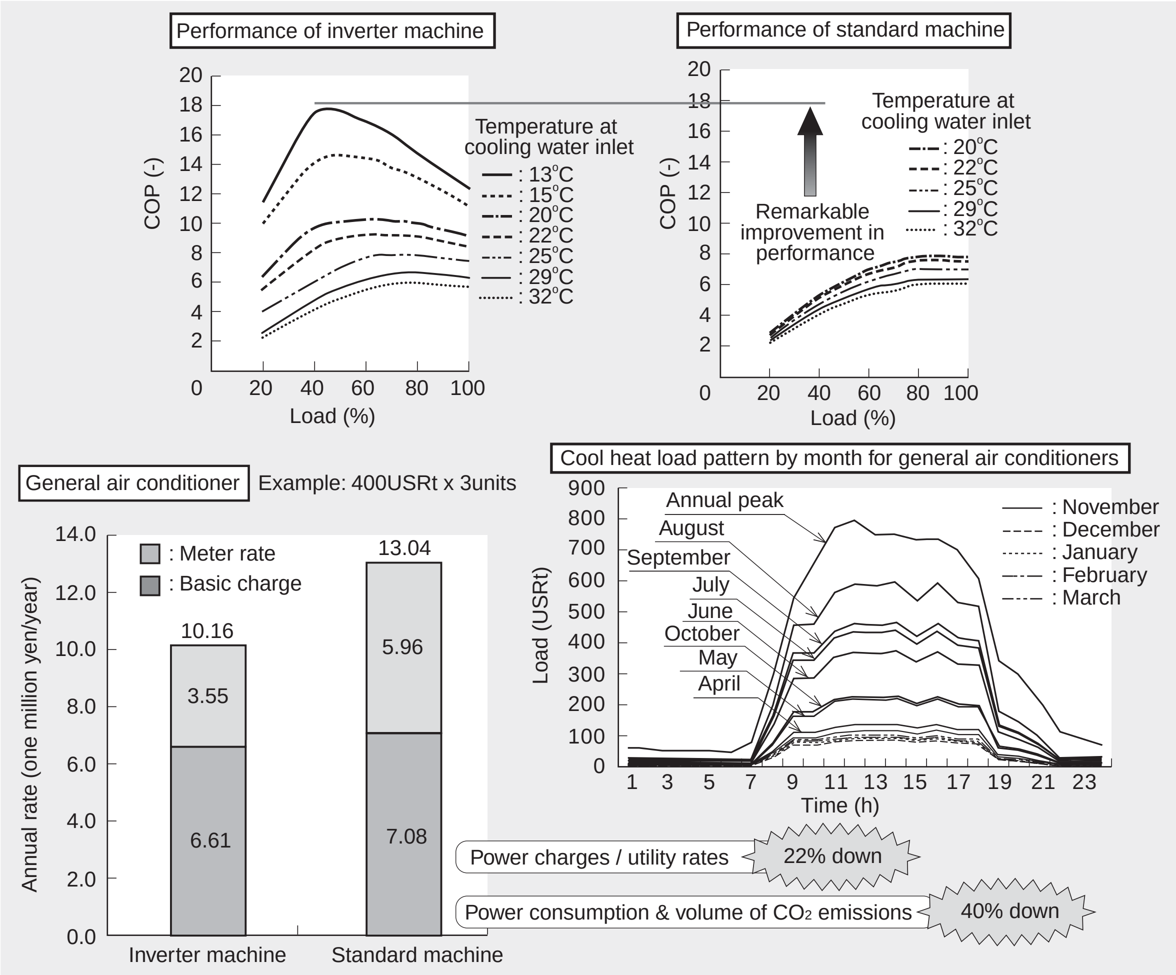

Fig. 6 Performance comparison of inverter machine and standard machine; annual energy saving effect at general air conditioning load
Inverter machine realizes remarkable improvement in performance at partial load and large annual energy saving effect.

Since it was first marketed in January 2003, the NART-I series has been well received mainly by utilities, plant heat source users. Dozens of machines are now in operation in Japan. In addition, MHI has also shipped machines in the series to overseas users, as well.

5. Conclusion

MHI has commercialized a turbo chiller capable of providing a COP of 17.8 (chilled water temperatures of 12°C/7°C) under partial loads using the refrigerant HFC134a, which has the world's highest level of performance.

Remarkably highly efficient operation has been made possible throughout the year by optimizing rotational speed control, load follow-up performance, and cooling water follow-up performance. In addition, a power reduction of 45 % (under plant load conditions) could be achieved throughout the year compared with conventional standard machines. The functions of the new NART-I series have been expanded remarkably by improving the control panel in order to provide excellent operability and communication function. As for the power source, total lineup inverter driving could be realized through the adoption of a high-voltage inverter panel that is the first to be applied as a chiller in the industry.

The NART-I series won an Energy Conservation Award by Ministry of Economy, Trade and Industry) in 2003, and is being received well for its high level of technology and performance.


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