Deployment of a New Series of Eco Turbo ETI Chillers

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The use of inverters in heat source equipment has expanded significantly since the release of the eco Turbo ETI Series of centrifugal chillers, which are equipped with inverters (as standard equipment) for energy savings and user-friendliness. In particular, application of inverters contributes to energy savings in heat source systems subjected to widely varying operating conditions such as cooling water temperature and load factor. Mitsubishi Heavy Industries, Ltd. (MHI) is expanding the eco Turbo ETI Series in order to reduce the environmental burden of these units. This paper explains the possibility of further series expansion in terms of characteristics, energy saving effects, and the usefulness of performance enhancements and functional improvements, as well as technologies for reducing the environmental burden, including the adoption of new refrigerants.

1. Introduction

In response to increasing social concerns for energy savings and reduction of CO_2 emissions, high-performance centrifugal chillers are currently being widely used in industrial facilities (such as heat source systems) as well as for residential air conditioning systems. Although centrifugal chillers are highly efficient heat pump machines, their energy consumption is greater because of their high capacity. Thus, the development of technologies and products focusing on performance enhancement is essential in terms of reduction of CO_2 emissions. In addition, because centrifugal chillers are now widely used in many heat source systems, simplicity of installation and user-friendliness have become important customer needs.

This paper provides a background on the current trends and customer needs in heat source equipment and describes the evolution and characteristics of the eco Turbo ETI Series of centrifugal chillers, which are equipped with inverters (as standard equipment) and were first released in May 2008.[1]

2. Further Performance Enhancements

For the ETI series of centrifugal chillers, all technical factors for performance enhancement have been proven in the field of large, high-performance centrifugal chillers, and downsizing and performance enhancement have both been accomplished through review and refinement of these technical factors. We have expanded the ETI series and achieved further performance enhancements. The technologies required for these performance enhancements are described below.

2.1 Performance enhancement for expansion of the series

The ETI-20 series and ETI-40 series, released in 2008, were designed in response to the capacity range of the adsorption chillers to be replaced. However, the demand for general air conditioning applications has continued to increase. In order to handle the primary demand for a

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capacity zone of 700 USRt (1 USRt = 3.516 kW), and to improve the performance of the ETI-20 series and ETI-40 series in the capacity range of 250 to 350 USRt, in 2011 we added the ETI-30 series and the ETI-60 series, which attains a capacity of 300 USRt with a single compressor. At the same time, the following technologies have been applied for overall performance enhancement.

- Refinement of the shape of the impeller for performance enhancement
- Refinement of the shape of the 2nd inlet guide vane for performance and controllability enhancement
- Further reduction of bearing loss
- Reduction in the size, weight, and loss of gear
- Optimization of the suction and discharge flows of the compressor for further reduction of suction and discharge losses

Table 1 lists representative specifications for the ETI-30 series and the ETI-60 series, to which the above technologies were applied. The rated COP (Coefficient of Performance) evaluated for electric power consumption including the inverter input power, oil pump power and control power was increased to a maximum of 6.2, a performance enhancement of approximately 3% in comparison to the maximum COP of the previous ETI series. The refinements in the shape of the impeller and the 2nd inlet vane enabled significant performance enhancement around the maximum capacity. The rated COP around the maximum capacity of the new series exceeds 6.0, a performance enhancement of approximately 5% or more in comparison to the previous ETI series (the rated COP is 5.7). As with the previous ETI-20 series and ETI-40 series, the new series do not require a separate panel because the inverter is installed on the chiller as standard equipment. As a result, the footprints of these units decreased by approximately 45% in comparison to the equivalent-capacity models of the previous AART series, thus simplifying the installation procedure.

Table 1 Representative specifications for the ETI series

Type	ETI-20	ETI-40	ETI-30A	ETI-60A
Cooling capacity	200 USRt	400 USRt	300 USRt	600 USRt
	703 kW	1,407 kW	1,055 kW	2,110 kW
Chilled water temperature	Inlet 12°C/Outlet 7°C			
Cooling water temperature	Inlet 32°C/Outlet 37°C			
Electric power consumption	116.3 kW	232.6 kW	172.9 kW	340.2 kW
COP	6.0	6.0	6.1	6.2
Refrigerant	HFC-134a			

2.2 High-performance ES series

An improved high-performance centrifugal chiller, ETI-40ES, has been released.[2] Based on the ETI-40 series, the ETI-40ES uses a double cooling cycle, which was previously applied to large-capacity chillers (1,000 USRt or higher). This system has two series-connected refrigerant cycles, as shown in **Figure 1**. Because the compression ratio of the compressor is shared, the power required for compression decreases, and thus the performance is enhanced. In addition, the unit's capability for handling large temperature differences allows power reduction at the chilled water pump. As a result, the rated COP has reached 7.0.[2]

Table 2 lists representative specifications of the ETI-40ES, and **Figure 2** shows its part load characteristic. The optimized fine inverter control of the two separate compressors for high and low pressure side allows the maximum COP of 29.1 to be attained during part load operation, which is an improvement of approximately 22% compared with the existing ETI-40 series. Based on this improvement of the maximum COP, the IPLV (Integrated Part Load Value) increased to 11.7, approximately 15% better than the ETI-40. As a result, improvements in both economic efficiency and CO_2 emissions are expected; specifically, yearly CO_2 emissions and electricity costs will be reduced by approximately 68% in comparison to our previous model, the ART.

Although the standard load control range is 100% to 10%, 0% load operation is also available as an optional function for enhanced convenience of operation. As with the ETI series, ETI-40ES has a wide capacity control range. Its inverter is installed on the chiller as standard equipment, in a manner similar to the ETI-40 series, thus providing a compact design.

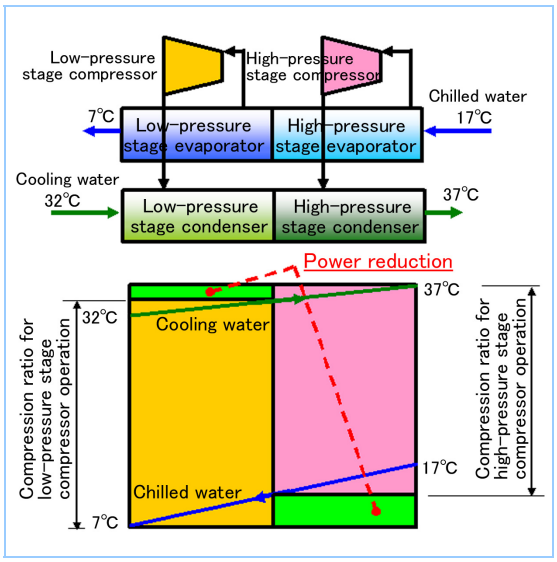

Figure 1 Principle of the double cooling cycle

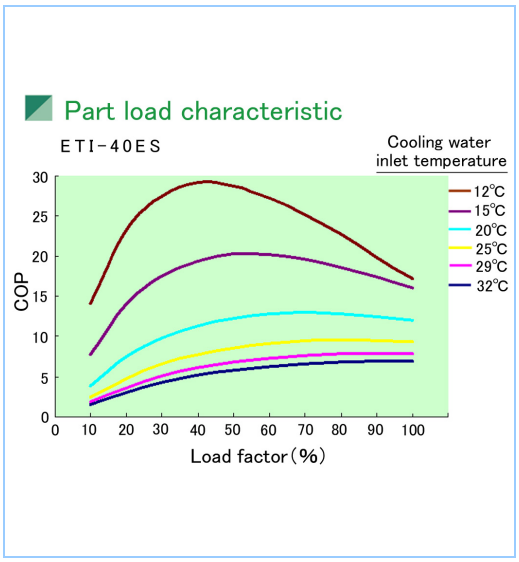

Figure 2 Part load characteristic of ETI-40ES

Table 2 Representative specifications for the ETI-40ES

Cooling capacity	400 USRt	
	1,407 kW	
Chilled water temperature	Inlet 17°C/Outlet 7°C	Inlet 12°C/Outlet 7°C
Cooling water temperature	Inlet 32°C/Outlet 37°C	
Electric power consumption	202 kW	213 kW
COP	7.0	6.6
IPLV (ARI)	11.7	

3. Further Functional Improvements

In the technical development of centrifugal chillers, we have focused on functional improvement as well as performance enhancement, thereby allowing users to always make the best use of the high performance of their machines. Specifically, we provide 1) indication of real-time COP and the target COP, 2) indication of the load zone in which optimal operation occurs, and 3) a function that continuously responds to variations in load and temperature to maintain high performance.

3.1 Real-time indication of target COP

It is important to be able to judge the appropriateness of current operations to ensure that the centrifugal chiller operates at high performance. Under rated conditions, such a judgment can be made by comparison with specifications. In actual operations, however, the load and cooling water temperature differ from the rated specifications, so that the expected performance (COP) is different from what is expected under rated conditions. Although it is possible to estimate the performance (COP) accurately via a computer simulation based on actual measured operating data, this technique is not always applicable due to the complexity. Thus, we have established a performance estimation procedure, using simple formulas based on theoretical principles.[3]

Different performance estimation procedures are established for the inverter-driven centrifugal chiller with variable speed control and the fixed-speed centrifugal chiller. The reason for this is that the two differ in their capacity control methods: one uses a compressor speed control, while the other does not. For the fixed-speed centrifugal chiller, part load performance is estimated based on the inlet vane control, taking control of the capacity and the loss characteristic, along with the hot gas bypass control. For the inverter-driven centrifugal chiller, a performance estimation formula was created to reflect compressor characteristics for all chilling capabilities and chilled water and cooling water temperatures, using an index based on theoretical properties of the pneumatic equipment in the centrifugal compressor. This procedure is more general because losses at the inlet vane and the hot gas bypass valve can be identified. For both centrifugal chiller control types, the difference between the estimated and measured values was less than 3% of the rated power equivalent, and hence (in view of the measurement accuracy) the electric power consumption of the chiller can be determined with adequate precision (**Figure 3**).

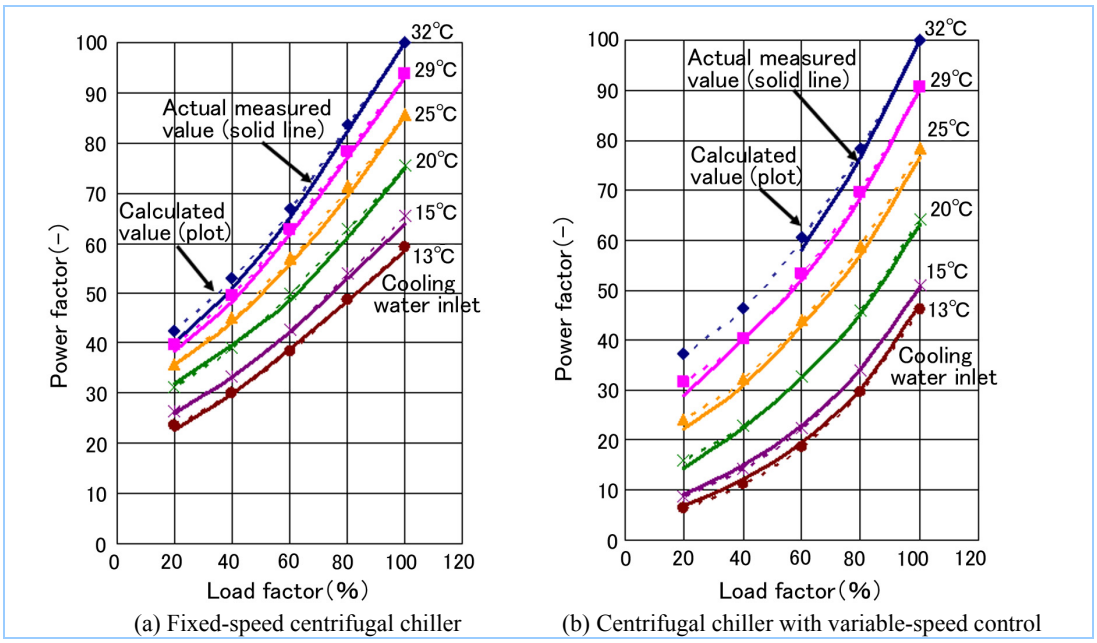

Figure 3 Comparison of estimated and measured values of part load COP

The performance estimation procedure can be installed on a microcomputer board (with less computing power than a typical personal computer) mounted on the chiller and can indicate the target COP on the display screen of the chiller operation panel in real time for comparison with the actual measured COP. Comparison of the results should lead to improved chiller operation and early detection of abnormalities.

3.2 Chilled water and cooling water flow rate detectors as standard equipment

(1) Chilled water and cooling water flow rate detection

A very effective and widely used overall energy-saving technique for a heat source system employs a variable flow control for the chilled water (or brine) and cooling water to reduce the electric power consumption of the respective pumps. A variable flow control usually involves electromagnetic flow meters mounted on the water pipes to obtain flow rate signals for controlling the inverter frequencies of the motors driving the pumps. However, because a centrifugal chiller is a high-capacity heat source with large water pipes, and an electromagnetic flow meter suitable for such a pipe size is expensive, realization of variable flow control is challenging, and this stands in the way of energy conservation. Thus, the chiller is equipped with a sensor instead of a flow meter, providing chilled water and cooling water signals that can be used to control the pumps at moderate cost. Additionally, the expansion valve, the rotation speed, and the hot gas bypass valve, excluding the inlet vane (which performs PID control of the chilled water outlet temperature), are controlled on the basis of the chilled water inlet and outlet temperatures, the chilled water flow rate, the pressure at each point, and the amount of refrigerant in circulation, calculated using the cooling capacity that optimizes control of the chiller. For variable flow control of the chilled water, very fine control (and the resulting high energy-saving efficiency) can be attained using a chilled water flow rate signal to calculate the cooling capacity. Also, the relevant sensor can be used as a substitute for an electromagnetic flow meter in the system. Moreover, for systems not using variable flow control, robustness is ensured by allowing adjustable control through detection of departure or staggering by continuously monitoring the flow rate of the chilled water and cooling water, which affects the operating conditions.

(2) Detection of chilled water and cooling water stoppage

A chiller must be equipped with water stoppage detectors in both the chilled water and cooling water systems, to prevent freezing in the heat exchanger tubes of the evaporator and rapid increases in condenser pressure. In the past, the differential pressure at the heat exchanger for a specified flow rate of the chilled water (or brine) and cooling water was used as the detection criterion, and a situation in which the differential pressure reached a value equivalent to a certain flow rate was judged to be a water stoppage. However, this detection method

requires an expensive fine differential pressure detector when the flow rate is low. Thus, we used the flow rate measuring function described above to detect water stoppages under a wide range of conditions, regardless of the specified conditions. This enables a wider range of control for the heat source system. Although measurement of the flow rate and detection of a water stoppage involve the same sensor, separate arithmetical processing of each signal can ensure a quick response to both, which is essential for water stoppage detection (a function that protects the equipment) and the accuracy required for flow rate measurement.

4. Application of a New Environmentally Friendly Refrigerant

In past years, possible ozone-depleting CFC and HCFC refrigerants in refrigeration and air conditioning equipment were replaced with HFC refrigerants. However, in the wake of this replacement, there are growing concerns about the global warming effects of HFC refrigerants, which have high GWP (Global Warming Potential). In Europe, the F gas regulation, which includes restrictions on the use of HFC refrigerants in newly built automotive air conditioning systems, has been in effect since 2011. The refrigerant used in existing centrifugal chillers is HFC-134a, which has a high GWP of 1430.[4] Therefore, we have proposed the application of a low-GWP refrigerant and tested it on the ETI series.

4.1 Selection of an alternative refrigerant

In the refrigeration and air conditioning industry, the application of low-GWP refrigerants has mainly been considered for automotive and household air conditioning systems. For large-capacity centrifugal chillers, which contain large quantities of refrigerant, the application of low-GWP refrigerants has not been actively discussed because of availability issues. HFO-1234ze(E), which was developed as an alternative to SF6, is manufactured domestically, and its availability is relatively high. Furthermore, it has thermophysical properties similar to those of HFC-134a. We have therefore selected HFO-1234ze(E) as a possible low-GWP alternative refrigerant for centrifugal chillers and have discussed its application.

4.2 Results of the compatibility test with materials

Compatibility assessments of HFO-1234ze(E) with materials used have already been conducted.[5] In a centrifugal chiller, however, the refrigerant exists as a mixture of lubricant and refrigerant, and hence it is necessary to assess the compatibility of such a mixture with materials to ensure that no deterioration occurs in the materials, refrigerant, or lubricant. If material deterioration occurs, refrigerant leakage, operational problems, or mechanical breakdown may result. In the lubricant compatibility assessment described above, steel, copper, and aluminum materials used as catalysts have been verified to be compatible. We performed autoclave tests to assess the compatibility of a mixture of HFO-1234ze(E) and POE (Polyol Ester) with 29 high-polymer materials used as sealing or insulating materials in centrifugal chillers. For 27 of the 29 materials tested, no lubricant acid number increase, turbidity, or material mass decrease occurred, and thus their compatibility was verified. On the other hand, as **Table 3** indicates, two of the materials (CR and asbestos-free sheet) experienced an acid number increase of 0.2 mgKOH/g or more, significant turbidity, and deterioration, and hence their compatibility is dubious. However, because there was no acid number increase or turbidity for the third sealing material (HNBR), CR and asbestos-free sheet can be replaced with HNBR.

Table 3 Compatibility test results for mixture of R1234ze(E) and lubricant

Test specimen	O ring	Gasket	O ring
Material	CR (chloroprene rubber)	Asbestos-free sheet	HNBR (hydrogenated nitrile rubber)
Color (ASTM)	(L3.0) (×) 	(L5.0) (×) 	(L0.5) (○) 
Percentage of mass change	107.5% (○)	106.5% (○)	104.1% (○)
Total acid number (mgKOH/g)	0.98 (×)	1.36 (×)	0.00 (○)

4.3 Results of drop-in test[note 1]

We performed an operational assessment of an ETI-40 centrifugal chiller with the original HFC-134a replaced by HFO-1234ze(E). **Figure 4** shows an external view of the chiller. Because HFO-1234ze(E) has a specific gravity at least 20% lower than that of HFC-134a, its cooling capacity is 71% of the cooling capacity of HFC-134a, provided the volumetric inflow rate to the compressor is the same for both refrigerant gases. In order to assess the refrigerant characteristics of HFO-1234ze(E) in comparison to HFC-134a, the test was conducted under operating conditions in which the HFO-1234ze(E) volumetric inflow rate to the compressor corresponded to 350 USRt, 400 USRt, and 500 USRt of operation with HFC-134a. In addition, the measurements were taken under part load conditions, which is important for assessing the performance during actual operation. **Figure 5** shows the measurement results for rated performance, and **Figure 6** compares the test results under part load conditions.

The COP of HFO-1234ze(E) at rated performance is 94% to 97% of the COP of HFC-134a. As the load decreases, so does the performance. This is thought to result from the fact that a decrease in the Re number increases the friction loss in the compressor, and the relative percentage of mechanical loss and motor loss to cooling capacity increases because HFO-1234ze(E) has a higher viscosity coefficient than HFC-134a. In this regard, if an exclusive design is employed for optimization of compressor specifications such as impeller diameter or blade shape, performance similar to that of HFC-134a will be obtained. Under part load conditions, the COP of HFO-1234ze(E) surpasses that of HFC-134a at a load factor of 40% or lower because it shifts to a smaller load rate than HFC-134a, due to differences in compressor inlet gas density and latent heat.

Note 1: The HFO-1234ze(E) drop-in test with the centrifugal chiller was grant-aided by NEDO in 2010.

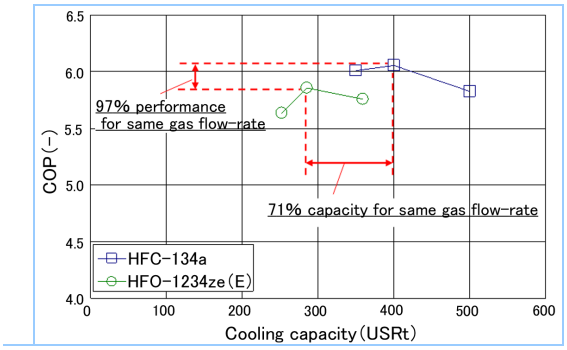

Figure 5 Measurement results for rated performance

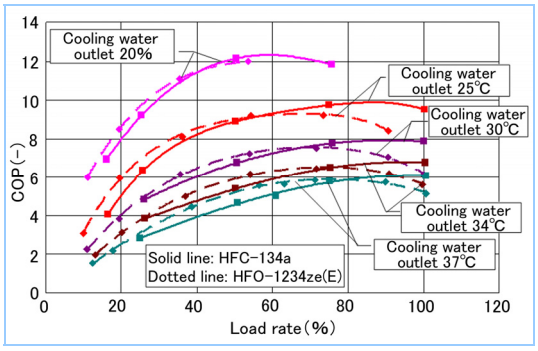

Figure 6 Measurement results under part load conditions

Figure 4 Centrifugal chiller used in the R1234ze(E) drop-in test

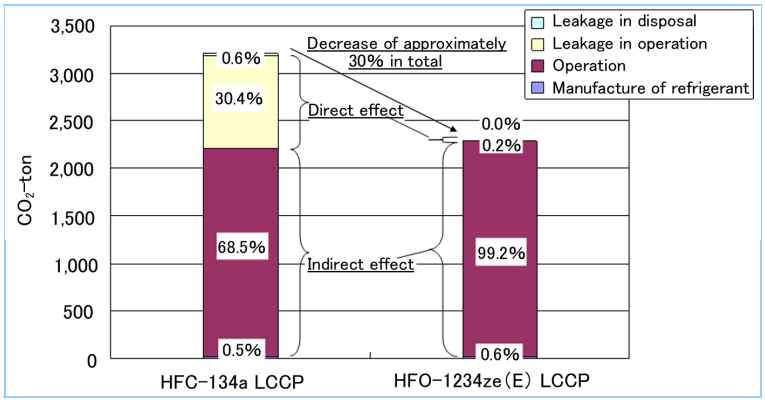

Figure 7 LCCP comparison of HFC-134a and HFO-1234ze(E)

4.4 LCCP (Life Cycle Climate Potential) assessment

Based on the performance measurement results under part load conditions described in 4.3, a comparative assessment of LCCP (the environmental load index for the entire life cycle) was conducted as shown in **Figure 7**.[note 2] The calculations indicate that although HFO-1234ze(E) has an indirect effect (CO_2 emissions due to electric power consumption during refrigerant manufacturing and chiller operation) approximately 3% higher than that of HFC-134a, due to a slight performance decrement, its low GWP can reduce overall CO_2 emissions, including a direct

effect (CO_2 leakage during operation and disposal), by approximately 30%.

Note 2: LCCP is calculated under the following conditions: 1) annual operating hours is 4,000, 2) equipment life cycle is 15 years, 3) operational electric power consumption is calculated from the IPLV load factor and the cooling water temperature, 4) the CO_2 emission factor is 0.351 kg/kWh (actual 2009 performance value reported by the Federation of Electric Power Companies of Japan), 5) CO_2 emission during refrigerant manufacturing is 23 kg per 1 kg of manufactured refrigerant (LCCP calculation factor of the Japan Refrigeration and Air Conditioning Industry Association), 6) leakage during operation is 7% per year, and 7) leakage during disposal is 2%.

5. Conclusion

The ETI series high-performance centrifugal chillers offer smaller capacity and compact size, reflecting market needs. The combination of an inverter installed as standard equipment, existing high-performance technologies, and a new design concept focused on small capacity achieves high reliability and brings significant energy savings and reduced CO_2 emissions to conventional industrial and commercial customers, as well as to customers desiring smaller capacity chillers for air conditioning and other applications. In order to expand the ETI series of centrifugal chillers, we have improved their performance, functionality, and environmental friendliness in response to market needs and have verified the results. Furthermore, we have applied a low-GWP refrigerant to advance the prospect of long-term, continuous energy savings.

It is expected that inverter-equipped centrifugal chillers will be simpler to install, easy to use, and suitable for general purposes. We would like to continue to develop products that meet market requirements, based on the technologies applied to the ETI series.

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