High-efficiency Turbo Chiller (NART Series)

Wataru Seki*1 Kenji Ueda*1
Jyou Masutani*2 Yoichirou Iritani*2

Turbo chillers are widely used for district heating and cooling, heat storage (regeneration) and plant process cooling, in large-capacity air conditioning facilities. The NART series of HFC134a high efficiency turbo chiller targets the world’s highest efficiency with performance 20% or more higher than that of conventional units. Development was extended to aerodynamic performance improvement of the key compressor component, heat exchanger performance, system design, and control to upgrade performance.

1. Introduction

The HFC134a refrigerant used in the turbo chiller described here has been used in various chilling equipment as a substitute refrigerant for CFC12, HCFC22, and HCFC123 since about 1994. At present, HFC134a is a refrigerant that has been mostly used since it was adopted for use in car air-conditioners. In addition, because of recent concerns about global warming, improving the efficiency of thermal equipment that consumes large amounts of electric energy is considered as the most important and first priority subject. This is especially the case in the application of such refrigerant to plant process-cooling equipment with a product life cycle of 20 years or longer. In addition, 2001 has seen the introduction of strict statutory requirements for the recovery and destruction of refrigerants in order to control the emission of chlorofluorocarbons. As a result, chillers are now required to use refrigerants that have a guaranteed stable supply and further, are required to be highly reliable and have noticeable energy-saving performance. Hence, newly developed chillers are designed to attain the world’s highest efficiency level of COP 6.1.

2. Optimized refrigerant cycle

The more compression and expansion stages there are, the closer one can come to achieving the ideal refrigerant cycle. In the chiller developed at this time, however, a two-stage compression cycle was adopted taking into consideration the characteristics of the HFC134a refrigerant, optimum impeller design, compact equipment design, and cost-savings. For four typical refrigerant cycle systems shown in Fig. 1, the coefficients of performance (COPs) were compared. As a result, it was known that, in a two-stage compression cycle, a two-stage expansion could diminish the first stage recirculating flow rate and a subcooling could minimize the second stage recirculating flow.

*1 Air-Conditioning & Refrigeration Systems Headquarters
*2 Takasago Research & Development Center, Technical Headquarters

Mitsubishi Heavy Industries, Ltd.
rate. Accordingly, both two-stage expansion and subcooling were added. A two-stage compression, two-stage expansion subcooling cycle is theoretically about 10% superior to a single stage cycle.

3. Improvement of compressor aerodynamic performance

When a two-stage compression design is adopted, the impeller inlet Mach number becomes subsonic. Therefore, the following aerodynamic designs were taken in order to raise efficiency by improving the flows in the impeller inside and the outlet downstream. Fig. 2 shows a cross section of the compressor for the chiller developed this time.

(1) Design of high efficiency subsonic impeller
- Both the first and second stages of the system were designed to have large specific speeds, respectively, taking a discharge coefficient that is larger than that commonly used for conventional two-stage type impellers.
- In order to minimize secondary flows inside the impeller, the distribution of the blade angle and blade inclination angles were determined by using the newest CFD (Computational Fluid Dynamics). Fig. 3 shows an example taken during this study. It shows the state in which the second-
ary flows and boundary layer thickness on the negative-pressure blade surface are declining.
- Flow distortion in the impeller outlet downstream diffuser could be improved by improving the flows inside the impeller. Fig. 4 shows an example of the computed fluid distortion analysis based on an integrated analysis of the impeller and diffuser.
- Since the secondary flows in the impeller could be reduced, the number of blades was optimized, in order to reduce the wetted area, increase the inlet throat area, and reduce the tailing vortex due to the rear edge thickness of the blades. The optimized number of blades was also determined using the results of CFD.

(2) Adoption of open impeller

A comparison was made between both open and closed impellers during development of the chiller system. Flow analysis and practical unit performance tests showed that they have about the same level of performance. The open impeller was adopted for the practical units in order to permit:
- precise machining using a five-axis NC machine;
- excellent surface finishing at a several micron level;
- reduction on weight, so that the weight of the compressor shaft and the size of the impeller can be reduced to a compact size in a rotor dynamics design; as well as
- cost reductions owing to advances in machining technology.

Fig. 5 shows a comparison in the flow analysis results of both open and closed impellers. In the open impeller, both the boundary layer and flow deviation increase due to the influence of the clearance between the blade tip and the shroud. Thus, the shroud form was determined in the practical unit according to the tip shape deformed in the operating state in order to minimize the clearance so as to reduce gas leakage.

As mentioned above, very careful attention was paid to this point, so that differences in performance between the open and closed impellers could be successfully eliminated.

(3) Shaft system evaluation

The impeller shaft is longer than conventional two-stage shafts because of designing larger specific speed impellers. As a result, the shaft length extruded from the bearing position also becomes longer. Accordingly, the soundness of the shaft strength was verified by rotor dynamics analysis. Furthermore, the natural frequencies of the rotor blades installed on the shaft were measured to confirm the avoidance of coupled vibration of the rotor blades with the shaft and resonance of the rotor blades with the upstream stator blades. In addition, it was also confirmed in practical unit verification tests that no irregular vibration was generated under various operational states, including surging, with the shaft and casing vibrations monitored.

Fig. 6 shows the two-stage open impeller assembled with the shaft.

4. Design for reducing mechanical loss

The mechanical loss could be reduced to 50% or less of that of conventional units through the use of rolling bearings in place of plane bearings. A bearing life of 50,000 hours or more was ensured(2). A gear power-transferring efficiency of 99% or higher could be achieved by optimizing the pressure angle(2).

5. Improvement of heat exchanger performance

(1) evaporator

In order to improve the heat transfer performance
of the evaporator, it is essential the overall heat transfer performance be improved by optimizing the tube arrangement, since there is a limit to how much the performance of the heat transfer tubes only can be enhanced. In particular, a zone with a high void ratio is produced in the upper part of the tube bundle due to the accumulation of bubbles generated in the lower heat transfer tubes. This results in nucleate boiling being restrained and a deterioration in heat transfer performance. In order to resolve this problem, tube-removed zones are provided in the tube bundle so as to collect generated bubbles into the zones in order to eliminate them, as shown in Fig. 7\(^{(4)}\).

Furthermore, when many tube bundles are piled up, it is predicted that dry out will occur and the boiling heat transfer coefficient will be reduced since the refrigerant around the upper heat transfer tubes is blown off by bubbles with increased ascending velocities. The horizontal pitch of the heat transfer tubes was increased in order to address this problem\(^{(3)}\).

On the basis of such basic data as the correlation between heat transfer coefficients and void ratios, obtained by factor tests, the heat flow-analyzing general code was improved. This improvement made it possible to predict the distribution of heat transfer coefficients of an evaporator using HFC134a, and it was applied to a practical design. An example of the results of evaporator heat transfer analysis is shown in Fig. 8\(^{(4)}\).

(2) Condenser

In order to improve condenser heat transfer performance, it is necessary to reduce the thickness of the condensate film on the heat transfer tubes and prevent deterioration of condensing performance in the lower tube bundles due to the accumulation of descending condensate. Just as with an evaporator, in order to improve the condensing heat transfer, there is a limit to how much only heat transfer tube performance can be improved. Thus, it was intended to make the liquid film uniform, with the condenser inside flow homogenized according to the results of a single phase gas fluid analysis. Fig. 9 shows an example of the results of analysis for a condenser\(^{(4)}\).

6. Control system

Until now, multi-function color liquid crystal mi-
Microcomputer panels have been used in the control of chillers. However, an assessment of the conventional control functions was carried out with the development of the NART series, and many new functions were added. For the load control, both precise load and cooling water traceabilities were achieved by individual control of the inlet vane, diffuser width, and hot gas bypass valve. Also, control of the expansion mechanism was optimized by internal computation of the recirculating amount of refrigerant. Other additional functions were newly provided as well including scheduled operations, a function to prevent irregular or incorrect operation, BAS communication monitoring function, and operating machine number controlling function so that the equipment control system would be able to meet a wide range of needs.

**Fig. 10** View of LCD monitor on control panel
Displayed items can be selected from a menu.

**Fig. 11** Breakdown of improvements in performance
A breakdown of the various areas of improved performance is shown in the newly developed unit compared with former systems.

**Fig. 12** Partial load performance.
COPs at 100% through 20% refrigerant capacities are shown.

**Fig. 13** Performance for each capacity type
COP for each capacity type is shown.

7. Performance of practical unit
Because every individually developed element achieved its target, overall performance was improved 20% or more compared with conventional chillers. **Fig. 11** shows a breakdown of the areas in which improvements were realized.

In addition, excellent partial load performance was obtained by optimizing both the inlet vane and diffuser width controls. A graph of the partial load performance of the system is shown in **Fig. 12**.

In order to evaluate the durability of the equipment, disassembled inspections were carried out after the following continuous operations and testing to verify the soundness of the equipment. Other tests included the following:
- operation at a rotating stall point,
- operation under a surging state, and
- power failure tests.

Verification tests of all the types in the series have

*Mitsubishi Heavy Industries, Ltd
already been carried out over a range of 350 through 1,680 USRt as an overall test of the entire NART series. As a result, it was confirmed that all the types could achieve their design performance levels. Fig. 13 shows the COP for each capacity type.

8. Conclusion

(1) The commercialization of the turbo chiller NART series with the world's highest efficiency of COP 6.1 (at a chilled water base of 12°C/7°C) was realized using the HFC134a refrigerant (Fig. 14).
(2) High efficiency operation could be achieved throughout the year because of the excellent load traceability and cooling water traceability.
(3) The system was shown to have sufficient durability under practical operation states, such that the compressor did not need to be overhauled for 50,000 hours or longer.
(4) Significant expansion and improvement in control functions offer excellent operability and communication ability to the control panel.
(5) Ninety chillers have already been delivered so far, and their high performance and reliability achieved their designed goals as highly evaluated systems by their customers.

References

(4) Ueda, K. et al., Development of High Efficiency HFC134a Turbo Chiller, Proceedings of 2001 JSRAE Annual Conference, p.205
(5) Seki, W. et al., World's Highest Efficient HFC134a Turbo Chiller (NART Series), Heating Piping & Air Conditioning Vol. 39 No.2 (Feb. 2001)