High-Performance Absorption Chiller for District Heating and Cooling

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An efficient absorption chiller for district heating and cooling was developed. This chiller is an epoch-making chiller which was developed by full use of the state-of-the-art high performance technology of heat exchanger utilizing CFD, and an efficient cycle. And it has reduced the rate of steam consumption by 10% of the conventional chiller, and 14% to 25% in installation space. Moreover, this absorption chiller is highly reliable in design, manufacturing, and verification. It can contribute to the environmental preservation by efficient use of energy.

1. Introduction

The effective use of energy in measures to counter global warming and address various energy problems is a critical issue of human activity. At the same time, the ever-greater desire for comfort in the living environment highlights the importance of air conditioning. Accordingly, the demand for ever-more efficient air conditioners has become increasingly intense year after year.

Absorption chillers are heat driven type air coolers that can be driven by a low enthalpy heat source. They are the most suitable chillers for the effective use of energy to generate cold using waste heat generated from power generators or other facilities. The introduction of large-scale systems in urban areas, where air conditioning loads are most concentrated, for district heating and cooling is becoming a common way to achieve efficient heating and cooling. Large-scale absorption chillers play a major role in district heating and cooling systems. In this regard, Mitsubishi Heavy Industries, Ltd. (MHI) has developed an epoch-making, high efficiency absorption chiller that makes full use of the state-of-the-art high performance technology of heat exchangers utilizing cutting edge computational fluid dynamics (CFD). The absorption chiller thus developed has been operating smoothly at the Minato Mirai 21 District Heating and Cooling Service Co., Ltd. located in Minato Mirai 21 District, Yokohama. It is the world’s largest scale system of its type at 5000 USRt and achieves a steam consumption rate that is 10% lower than that of conventional absorption chillers used for district heating and cooling. In addition, MHI has also developed a new high efficiency MDUE Series absorption chiller based on this technology. The MDUE Series provides epoch-making absorption chillers that achieve 3.9 kg/h-USRt, representing a 10% reduction in the rate of steam consumption compared with conventional units.

This paper summarizes the technology that has been adopted in these high efficiency absorption chillers and describes their operation and verification of their performance.

2. Development of 5000 USRt absorption chillers

2.1 General

MHI has developed the largest capacity steam-drive absorption chiller in the world, which has a capacity of 5000 USRt (2500 USRt was previously the largest capacity absorption chiller in existence). The newly developed absorption chiller enhances efficiency by 10% in terms of the rate of steam consumption compared with that of conventional district heating and cooling units. The new absorption chiller was installed at the No.2 Plant of Minato Mirai 21 District Heating and Cooling Service Co., Ltd. in Yokohama City, and test operations were conducted for one year prior to commercial operation.

2.2 Specifications and features of the newly developed absorption chiller

Table 1 shows a comparison of the specifications between the newly developed chiller and a conventional chiller. The newly developed chiller is an absorption chiller that occupies 25% less space and consumes 10% less steam than a conventional chiller or a high-efficiency and space-saving absorption chiller.

<table>
<thead>
<tr>
<th>Specification</th>
<th>Newly developed chiller</th>
<th>Conventional chiller</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refrigeration capacity</td>
<td>5 000 USRt</td>
<td>2 500 USRt X 2 unit</td>
</tr>
<tr>
<td>Steam consumption</td>
<td>19 500 kg/h</td>
<td>21 500 kg/h</td>
</tr>
<tr>
<td>Rate of steam consumption</td>
<td>3.9 kg/h-USRt</td>
<td>4.3 kg/h-USRt</td>
</tr>
<tr>
<td>Chilled water temperature</td>
<td>13°C/6°C</td>
<td>13°C/6°C</td>
</tr>
<tr>
<td>Cooling water temperature</td>
<td>32°C/40°C</td>
<td>32°C/40°C</td>
</tr>
<tr>
<td>Installation space</td>
<td>74.1 m²</td>
<td>98.1 m²</td>
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Fig. 1 shows an external view of the chiller, while Table 2 shows the main features of the chiller, along with the methods used to achieve each respective feature. In addition to the high-efficiency and space-savings provided by the system, other features of the chiller include improvements in efficiency under partial loads at which ordinary chillers generally operate, shortened start-up and shut-down times, and improvements in follow-up performance to load variations.

2.3 Component Development

2.3.1 Tests of absorber and evaporator components

A two-dimensional slice model was prepared to simulate the evaporator and absorber, which was then used to evaluate and verify the performance of the evaporator and absorber of the system. In an actual chiller, longitudinal temperature distributions exist that are mainly caused by temperature variations in the chilled water and cooling water. The impact of these longitudinal temperature distributions was evaluated in component tests under varied temperature conditions of chilled water and cooling water. In addition, an estimation of the three-dimensional distribution and resulting impact was obtained using a CFD combined with a heat transfer model, which is described hereunder.

2.3.2 Simulation of dynamic characteristics

In developing the world's largest capacity absorption chiller, MHI carried out a simulation of the dynamic characteristics of the system. The dynamic characteristics simulator that was adopted was prepared by modeling individual components by concentrated approximation. The model was verified with a small-scale chiller. Through the analyses carried out, it was confirmed that the start-up time could be shortened to 15 minutes by optimizing the concentration of the solution during the stop period.

2.4 Results of on-site test operation

Verification tests carried out over a period of one year demonstrated that the chiller met designed performance levels for both static characteristics, such as full and partial load performance, and dynamic characteristics, such as start-up time. Fig. 2 shows the performance observed during the performance test period. The tests demonstrated that the unit is capable of maintaining a sustained capacity of 5000 USRt or more for a period of five days.

2.5 Summary

MHI has developed an ultra-large and high efficiency absorption chiller that has the world's largest single-unit capacity and that reduces the rate of steam consumption by 10% from that of conventional dis-

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**Table 2: Features of 5000 USRt absorption chiller**

<table>
<thead>
<tr>
<th>Features</th>
<th>Method for attaining features</th>
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<tbody>
<tr>
<td>Improved efficiency</td>
<td>1. Adoption of high performance heat transfer tubes for the evaporator and low-pressure generator.</td>
</tr>
<tr>
<td></td>
<td>2. Adoption of high performance solution heat exchanger.</td>
</tr>
<tr>
<td></td>
<td>3. Reduction in power at partial loads through the adoption of an inverter.</td>
</tr>
<tr>
<td>Size and weight reduction</td>
<td>1. Minimizing steam pressure drop by optimizing the arrangement of heat transfer tubes in the absorber.</td>
</tr>
<tr>
<td></td>
<td>2. Adoption of two-stage cycle for the evaporator and absorber.</td>
</tr>
<tr>
<td>Improvements in operability</td>
<td>1. Improvement in efficiency under low load conditions through half-unit operation.</td>
</tr>
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<td></td>
<td>2. Shortening start-up time through optimum concentration control while stopping condition.</td>
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strict heating and cooling units. The newly developed absorption chiller was shown to achieve designed performance levels for both static characteristics, including rated and partial loads, and dynamic characteristics through on-site operations.

3. Development of MDUE Series

3.1 Objective

In 1993, MHI developed the MDA Series of absorption chillers for use in district heating and cooling facilities and industrial plants. Seven years after the introduction of the MDA Series to the market, MHI developed the MDUE Series, a new series of high performance, high reliability absorption chillers for use in district heating and cooling as well as industrial plant service, based on the 5000 USRt absorption chiller described above.

(1) Reduction of operating costs

- Steam consumption rate: 3.9 kg/h-USRt (Comparison with prior conventional system: 10% increase in efficiency)
- Reduction in auxiliary equipment power
- Accommodation of specifications for large temperature differences between inlet and outlet of chilled water and cooling water

(2) Improved reliability

- Adoption of high performance extracting unit of non-condensible gas
- Reduction in the number of welding sections

3.2 Product Features

3.2.1 High efficiency and space-savings

District heating and cooling absorption chillers are expected to be highly efficient and occupy compact installation spaces because they are designed in large scale and are adopted by urban districts where large demand exists. In this regard, the MDUE Series of chillers is a high efficiency and space-saving series of chillers that reduces the rate of steam consumption by 10% and realizes an average space savings of about 14% when installed. These notable achievements have been made possible by the application of the high efficiency cycle and high performance technology of heat exchangers as described above.

3.2.2 Reduction of running costs

Since the chillers for district heating and cooling as well as for industrial plant service are operated for long hours each year, they significantly contribute to a reduction in running costs for users not only by achieving reductions in the rate of fuel consumption, but also by reducing the need for power from auxiliary units.

In developing the new absorption chiller, the design focused on reducing the power of the pumps used to circulate fluids and refrigerant, as well as on reducing the fuel consumption rate. Furthermore, development was carried out assuming a large temperature variation with increased temperature differences of chilled water and cooling water between the inlet and outlet in order to reduce the power requirements of the pumps for chilled water and cooling water. Table 3 shows a comparison of the specifications between the newly developed chiller and a conventional one. The chilled water was designed to satisfy the two levels of temperature difference between the inlet and outlet of 10°C and 7°C, respectively.

The results showed significant reductions in running costs. Based on calculations for a 1500 USRt chiller, cost reductions amounting to about fifteen million yen per year can be expected, as shown in Fig. 3.

3.2.3 Improvement of reliability

District heating and cooling systems need to be used in such a way as to ensure a stable supply of chilled water to contract users. Accordingly, the development of the system necessitates consideration being given to suitable means of preventing such prob-

<table>
<thead>
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<th>Table 3 The comparison in the specification between the conventional chiller and the developed chiller</th>
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<tbody>
<tr>
<td>Refrigeration capacity</td>
</tr>
<tr>
<td>Rate of steam consumption</td>
</tr>
<tr>
<td>Chilled water temperature</td>
</tr>
<tr>
<td>Cooling water temperature</td>
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</table>

Fig. 3 The comparison in the running cost between the conventional chiller and the developed chiller. Significant reductions in running costs with the MDUE series can be clearly seen here.
lems as equipment failures and degradation of performance, and how best to enhance equipment reliability ever further as the system is directly connected with production lines.

With regard to this point, the newly developed chiller employs a high performance extracting unit of non-condensible gas and reduces the number of welded sections in pipe to improve the reliability of hermetic sealing, thereby preventing any degradation in performance or the occurrence of corrosion in the equipment caused by insufficient hermetic sealing. In addition, filter units have been added to each solution system and refrigerant system in order to prevent performance degradation triggered by the occurrence of fouling on the surface of the heat transfer tubes.

3.3 Technologies and techniques applied
Technologies to increase cycle efficiency and enhance the performance of the heat exchangers were applied to achieve the increased performance levels and space-savings of the chiller.

3.3.1 Technology to increase cycle efficiency
(1) Absorption cycle of low circulation rate and wide concentration range of solution
As shown in Fig. 4, a cycle that widens the concentration range was achieved by improving the absorption performance and regeneration performance of the system. This made it possible to reduce the circulation rate of the fluid solution, and to reduce in heat loss in individual fluid solution heat exchangers along with improvements in the performance of these heat exchangers.

(2) Two-stage absorption and two-stage evaporation cycle
As seen in Fig. 5, each of the absorbers and evaporators were divided to two sections, and absorption was conducted at different pressure levels for each. Thus the lowest temperature of the fluid solution was increased from A to B at the same concentration level, and the temperature difference between the fluid solution and the cooling water was increased in order to improve heat transfer capability.

(3) Cooling water branch cycle
As illustrated in Fig. 6, the flow of cooling water through the absorber was branched to the low-pressure side of the absorber and to the condenser, thus optimizing the relation between the inside heat transfer performance of the absorber and the condenser tube and the pressure drop so as to improve overall performance.

3.3.2 Improvement of performance of heat exchangers
(1) Adoption of high performance heat transfer tubes
High performance trapezoidal acicular fin tubes were employed in the absorber, while high performance acicular fin tubes were employed in the evaporator in order to improve heat transfer performance.

(2) Adoption of high performance tube bundle arrangement
In order to improve the performance of absorber and evaporator, CFD was applied to optimize the tube arrangement pattern. The impact of steam flow in evaporator and absorber was simulated using analytical codes taking into account the heat and mass transfer phenomena in the absorber. Using the subsequently derived codes, the impact of flow distributions in the absorber and the evaporator was evaluated. Fig. 7 shows an example results of this analysis.

3.3.3 Realization of high reliability
The verified simulation techniques of heat transfer, flow distribution, structure, and others were applied to evaluate the impact of flow distribution
inside the heat exchanger as well as to evaluate structural strength, which becomes significant in large systems, thereby attaining the high reliability of the equipment.

(1) Heat transfer and flow analyses

The internal flow conditions in each heat exchanger in the absorption chiller were estimated quantitatively using the above-described analytical codes. This made it possible to achieve reliability of the equipment by optimizing of the extracting location of non-condensible gas in the tube bundle, reducing pressure drops across the tube bundle, and by preventing carry-over.

(2) Flow analysis

A cyclone gas-liquid separator located at solution inlet of low-pressure generator was designed in order to realize a compact low-pressure generator. The performance of the separator was confirmed using flow analysis prior to installation of the system.

(3) Structural strength analysis

Structural analysis was carried out on individual structural members, including shell sections, in order to confirm that the stress levels at each section were within the design range, thereby verifying reliability.

3.4 Verification of performance

As part of development, a prototype 1000 USRt chiller was fabricated for testing as a means of conducting a final verification of the planning and design stages. Verification was conducted on the chiller focusing on system performance, controllability, and extracting performance of non-condensible gas. Once verification of the reliability of the system had been completed, sale of the chiller began from April 2001. The first order received was for a 2500 USRt chiller, which was delivered to the customer in October 2001 after performance and verification tests were conducted. Fig. 8 shows the external appearance of the 2500 USRt chiller. Table 4 shows the results of the performance and verification tests carried out on the 2500 USRt chiller. The refrigeration capacity satis-
fied the specified 2500 USRt, and proved to give a steam consumption rate of 3.74 to 3.80 kg/h-USRt, which is 2.5 to 4.0% lower than the specified value of 3.9 kg/h-USRt. As can be seen in Fig. 9, the chiller also performed quite favorably under partial load conditions, as well. In addition, performance and verification tests were conducted on a commercially delivered 1000 USRt chiller, which was the same type as the above prototype, in order to prove the steam consumption rate was lower than the specified level of 3.80 kg/h-USRt.

As described above, confirmation of the performance of the MDUE Series was carried out on a 1000 USRt chiller and 2500 USRt chiller which proved the adaptability of the basic plan and design method.

4. Conclusion

The high efficiency and large scale absorption chiller developed for use in district heating and cooling and described in this paper is an epoch-making chiller that fully utilizes the most advanced technologies and techniques, such as the technology of high efficiency absorption cycle and techniques for improving the performance of heat exchangers using CFD. The chiller was developed on the basis of detailed plans and sufficient component tests during the development stage and through full-scale verification at the manufacturing plant. Practical applications of the chiller allows the district heating and cooling system to enjoy increased efficiency, while reducing operating costs and installation space. This, in turn, further leads to the effective use of energy, which contributes to measures that help to address the issue of global warming.

It is expected that this kind of highly energy efficient chiller will come to find ever-greater application over a wide range, and thus play a special part in contributing to conservation of the global environment. MHI will continue to develop chillers of ever-higher efficiency.

### Table 4 The performance test result of MDUE 2500 USRt model chiller

<table>
<thead>
<tr>
<th></th>
<th>Specified value</th>
<th>Observed value</th>
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</thead>
<tbody>
<tr>
<td>Refrigeration capacity</td>
<td>2 500 USRt</td>
<td>2 505 USRt</td>
</tr>
<tr>
<td>Rate of steam consumption</td>
<td>3.9 kg/h-USRt</td>
<td>3.80 kg/h-USRt</td>
</tr>
<tr>
<td>Steam consumption</td>
<td>9 750</td>
<td>9 530</td>
</tr>
<tr>
<td>Chilled water inlet temperature</td>
<td>14°C</td>
<td>14.0°C</td>
</tr>
<tr>
<td>Chilled water outlet temperature</td>
<td>6°C</td>
<td>6.0°C</td>
</tr>
<tr>
<td>Chilled water flow rate</td>
<td>945 m³/h</td>
<td>947 m³/h</td>
</tr>
<tr>
<td>Cooling water inlet temperature</td>
<td>32°C</td>
<td>32.0°C</td>
</tr>
<tr>
<td>Cooling water outlet temperature</td>
<td>40°C</td>
<td>39.9°C</td>
</tr>
<tr>
<td>Cooling water flow rate</td>
<td>1 680 m³/h</td>
<td>1 682 m³/h</td>
</tr>
</tbody>
</table>

Fig. 9 The partial load data of the MDUE 2 500 USRt chiller

It can be seen here that the partial load characteristic of the newly developed chiller is more efficient compared with that of a conventional chiller.