CENTRIFUGAL CHILLER USING HFO-1233zd(E)

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ABSTRACT
To reduce the environmental burden of refrigeration and air conditioning equipment there is an urgent need to transition to low-GWP refrigerants. HFO-1233zd(E) is a low-GWP alternative refrigerant in the centrifugal chiller sector. It is considered an excellent alternative as it has a low environment burden (global warming potential, GWP = 1), is low toxicity, and is nonflammable. The performance of a chiller with HFO-1233zd(E) was found to be improved over one with HFC-134a, and the installation space required for both was almost the same.

Keywords: HFO, R1233zd(E), GWP, Centrifugal chiller, COP

INTRODUCTION
In December 2015, the 21st Session of the Conference of the Parties to the United Nations (UN) Framework Convention on Climate Change (COP21) adopted the Paris Agreement, requiring action on worldwide decarbonization to be taken by each country over the long term. In relation to refrigeration and air conditioning equipment, F gas regulations in Europe and the Act for Rationalized Use and Proper Management of CFCs and HFCs in Japan aimed to reduce environmental impacts.

Therefore, HFC refrigerants with high global warming potential (GWP), such as R410A and R134a, have given way to a new type of low-GWP refrigerant. These low-GWP refrigerants must be verified in relation to aspects such as their stability, safety, economical efficiency, and availability in comparison with existing refrigerants. In particular, flammable refrigerants, which require more time for their safety assessment, hamper refrigerant conversion in chiller heat source systems whose refrigerant charge amount is greater than that used for industrial purposes.

In considering these aspects, our team developed a centrifugal chiller that used the low-GWP refrigerant HFO-1233zd(E), which is nonflammable and low toxicity.

SELECTION OF ALTERNATIVE REFRIGERANT
The following were taken into consideration when selecting alternative refrigerants.

Environmental conditions: ODP ≤ 0.001, GWP ≤ 150, long term toxic exposure ≥ 800 ppm
Composition: Single. For a centrifugal chiller that applies flooded type evaporator, the mixing ratio of nonazeotropic refrigerant gases in the inlet of a compressor varies, leading to performance issues.
Physical properties: Cycle efficiency is equivalent to that of existing refrigerants. Designed pressure must not to be excessively high.
Safety: Low toxicity and low flammability.

Economical efficiency: Used for purposes other than as a refrigerant for centrifugal chillers; thus increasing the potential for its wider sale.

Certain HFO refrigerants are considered to meet such requirements. Table 1 shows a comparison of HFC and HFO refrigerants. The GWPs of the HFO refrigerants range from 0 to 1 (i.e., very low), and the cycle efficiencies are equivalent to those of the existing refrigerants. It is not also applied to fluorocarbons prescribed in Act for Rationalized Use and Proper Management of CFCs and HFCs.

HFO-1233zd(E) is nonflammable and of low toxicity. It can be used for a forming agent, and it is excellent in in terms of safety, availability, and economical efficiency. The working pressure of centrifugal chillers used for air conditioning is lower than 0.2 MPa(G), the high pressure gas safety law does not apply to the refrigerant. Its physical properties are similar to HFC-245fa.

On the other hand, the refrigerant gas specific volume of HFO-1233zd(E) is about five times greater than that of HFC-134a. This requires a greater amount of space to accommodate units such as the compressor, evaporator, condenser, and gas piping. Refrigerant HFC-134a is a major refrigerant for centrifugal chillers. A more advanced and compact design would allow for the adoption of HFO-1233zd(E) as an alternative.

DESIGN OF CENTRIFUGAL CHILLER USING HFO-1233zd(E)
Equipment was designed to improve efficiency and make chillers more compact.

COMPRESSOR・MOTOR
Improvement of aerodynamic design
The, compressors were designed to compress the large gas flow rate. Since a large gas flow rate tends to lower adiabatic efficiency, CFD analysis was performed to optimize the leading/trailing edges of the impeller, the blade angle distribution, the path form of the
Table 1 Comparison of refrigerants

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<tbody>
<tr>
<td>HFC-245fa</td>
<td>858</td>
<td>0</td>
<td>non</td>
<td>toxicity</td>
<td>B1</td>
<td>7.6 years</td>
<td>300</td>
<td>15.1</td>
<td>−32.1</td>
<td>1389</td>
<td>0.241</td>
<td>6.86</td>
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<tr>
<td>HFC-134a</td>
<td>1300</td>
<td>0</td>
<td>non</td>
<td>toxicity</td>
<td>A1</td>
<td>13.8 years</td>
<td>1000</td>
<td>−26.1</td>
<td>260.7</td>
<td>1275</td>
<td>0.056</td>
<td>6.58</td>
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<td>HFC-32</td>
<td>677</td>
<td>0</td>
<td>slightly</td>
<td>low</td>
<td>A2L</td>
<td>5.2 years</td>
<td>1000</td>
<td>−51.7</td>
<td>879.8</td>
<td>1034</td>
<td>0.021</td>
<td>6.38</td>
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<td>HFO-1234yf</td>
<td>1</td>
<td>0</td>
<td>slightly</td>
<td>low</td>
<td>A2L</td>
<td>10.5 days</td>
<td>500</td>
<td>−29.4</td>
<td>283.9</td>
<td>1137</td>
<td>0.014</td>
<td>6.31</td>
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<tr>
<td>HFO-1234ze(E)</td>
<td>0</td>
<td>0</td>
<td>slightly</td>
<td>low</td>
<td>A2L</td>
<td>16.4 days</td>
<td>1000</td>
<td>−19.0</td>
<td>866.4</td>
<td>1157</td>
<td>0.018</td>
<td>6.31</td>
</tr>
<tr>
<td>HFO-1233zd(E)</td>
<td>1</td>
<td>0</td>
<td>non</td>
<td>low</td>
<td>A1</td>
<td>26 days</td>
<td>800</td>
<td>−39.1</td>
<td>624.3</td>
<td>1119</td>
<td>0.026</td>
<td>6.93</td>
</tr>
</tbody>
</table>

*1: 5th IPCC  
*2: ASHRAE34  
*3: RefProp Ver9.1  
*4: Single stage cycle; evaporating temperature of 6℃, condensing temperature of 38℃, compressor efficiency of 90%

Compared with HFC-134a, the gas flow rate for the same impeller diameter was increased by approximately 30% and the compressor efficiency was improved by 3%. The compressor capacity was increased by approximately 40%.

Direct-connected motor

For HFC-134a, the impellers are rotated by a motor via a step-up gear; whereas for HFO-1233zd(E), the impellers are directly mounted on the motor shaft, because the rotation speed of HFO-1233zd(E) is lower than that of HFC-134a (in other words, since the vapor sound speed of HFO-1233zd(E) is lower than that of HFC-134a, the impeller diameter and the circumferential velocity is larger) even if the same capacity is provided. This enables the development of a machine with a compact motor (by speeding up the rotation speed), a compact compressor unit and improved performance (by eliminating the step-up gear), and reduced losses (by reducing the number of compressor bearings).

EVAPORATOR-CONDENSER

The shell & tube type heat exchanger is adopted. Since the specific volume is larger, and the differential pressure between the condenser and evaporator is smaller, than for HFC-134a, flow loss should be designed such that it does not increase, for example, due to (i) low temperature losses caused by refrigerant depth during boiling, (ii) suppression of dry-out caused by the large gas flow rate, (iii) a lack of carry-over to the compressor caused by the large velocity of the gas burst from the liquid surface in the evaporator, and (iv) low equivalent temperature losses caused by the pressure loss of refrigerant gas into the condenser. To suppress the losses described above, it was considered during the early stages of the design process that reducing the gas velocity in the tube bundle, and direction of water flow, should be estimated by analysis and measurement of the actual chiller to help achieve a smaller size and a higher efficiency performance.

Since the evaporator pressure of refrigerant HFO-1233zd(E) is below atmospheric pressure, incoming noncondensable gas and atmospheric air should be considered. The low velocity area was determined to set the bleeding pipe.

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Figure 4 and 5 show the heat exchanger performance results. Compared with the existing heat exchanger for HFC-134a, performance at rated conditions is lower by 10% for the evaporator and by 20% for the condenser. The volume of the evaporator and the condenser suppress up to 20% increase.

SUB-COOLER

A shell & tube type, rather than a blazing type, heat exchanger is adopted to reduce pressure loss on the refrigerant side. The degree of super cooling was expected to be equal to that of HFC-134a, and the heat
capacity of the sub-cooler is 20 kW (200Rt machine). Space can be saved by installing a refrigerant pit under the condenser and laying out tubes for the sub-cooler.

Fig.1 Void fraction distribution of evaporator

Fig.2 Gas flow velocity distribution of evaporator

Fig.3 Gas flow velocity distribution of condenser

Fig.4 Overall outside heat transfer coefficient of evaporator

Fig.5 Overall outside heat transfer coefficient of condenser

ECONOMIZER

A flash tank type heat exchanger (rather than a plate type, which leads to larger pressure loss) is adopted. The larger volume than that of the HFC-134a chiller is necessary; however, the form of the tank can be changed freely because of the low designed pressure. Space can be saved by sharing the wall between the condenser shell.

OIL TANK

By reducing pressure of oil tank, e.g., at start-up, the necessary volume of the gas phase area in the oil tank is larger because the gas volume emitted by the formation of lubricant oil in the oil tank is more than that of the HFC-134a machine. Space can be saved and the necessary capacity secured by combining the oil tank with the condenser and the economizer.

PIPE JOINT

The saturated vapor temperature for HFO-1233zd(E) is 18.3°C. The pressure is negative in the evaporator of a chiller operated under standard air conditions, leading to the ingress of ambient air. However, by minimizing the number of joints, the risk of air ingress is reduced.

MODEL MACHINE VERIFICATION

A centrifugal chiller was manufactured and verified based on each element described in the former
sections. Table 2 shows the centrifugal chiller specifications and Fig. 6 shows the test machine appearance.

Figure 7 shows the performance results under the conditions given in Table 2 and by capacity. Under the rated capacity conditions in Table 2, the COP was 6.3 and the performance was improved by 3% compared with an existing HFC-134a type that had the same capacity.

Table 3 shows a comparison of specifications between the developed machine and an existing HFC-134a machine. The specific volume of refrigerant gas is approximately five times greater than that of the existing HFC-134a type, and the installation area is approximately 105% that of the existing type.

### Table 2 Centrifugal chiller specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tr>
<td>Rated capacity</td>
<td>200 USRt (703kW)</td>
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<tr>
<td>Chilled water temperature</td>
<td>12.0°C → 7.0°C</td>
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<tr>
<td>Chilled water flow rate</td>
<td>120.7 m³/h</td>
</tr>
<tr>
<td>Cooling water temperature</td>
<td>32.0°C → 37.0°C</td>
</tr>
<tr>
<td>Cooling water flow rate</td>
<td>139.6 m³/h</td>
</tr>
<tr>
<td>Power supply voltage</td>
<td>400V</td>
</tr>
<tr>
<td>Starting method</td>
<td>Inverter</td>
</tr>
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</table>

**CONCLUSIONS**

A centrifugal chiller using HFO-1233zd(E), which is equivalent to CO2 (GWP = 1), was developed. Except for a centrifugal chiller using HFO-1233zd(E), there are no alternatives offering large heat source equipment with low-GWP, nonflammable, low toxicity refrigerants.

The developed machine using HFO-1233zd(E) achieved an integrated performance equal to, or higher than, an existing machine using HFC-134a. Performance was improved by 3% compared with the existing type and the installation area was suppressed by up to approximately 5% despite differences in the physical properties.

**REFERENCES**


