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Development of a Compact Horizontal-Type Scroll Compressor for Alternative Refrigerants

by
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ABSTRACT

A program for total abolition of refrigerants using HCFCs has been adopted and a selection of alternative refrigerants to HCFC is an urgent task, thus enhancing an absolute necessity to develop a reliable and high efficiency scroll compressor for alternative refrigerants. In the present market in Japan, furthermore, a competition to be a leader in energy saving technology for air conditioners is now highly intensified and there appears an increasing demand for the scroll compressors to be ever more reliable and efficient. Under such circumstances, based on a compact horizontal-type scroll compressor that has been popular in the market since its release in 1992, we have developed a scroll compressor for an alternative refrigerants, R410A, which is a mixed refrigerants of R32 and R125. R410A is inferior in lubrication performance, because of no chlorine(Cl) in its composition, thus inducing a severe sliding condition in each pair of the compressor elements, compared with the present refrigerant, R22. Furthermore, since the pressure is 1.5 times larger in R410A than in R22, we have to modify basic design factors of compressors. This paper describes the details of development of basic technologies.

1. INTRODUCTION

Protection of the global environment has recently become a top-priority issue throughout the world. Given this imperative, total abolition by 2020 of HCFC22 (R22) refrigerant presently in use for room air-conditioners was widely agreed upon to prevent the destruction of the ozone layer. This decision has triggered energetic studies for switching the currently used refrigerant to alternative HFC refrigerants that have an ozone destruction factor of zero.

R410A (R32/R125=50/50wt%) is a promising candidate for an alternative refrigerant: it exerts a high pressure of approximately 1.5 times that of R22 and it has a refrigeration capacity of approximately 1.4 times that of R22. However, before we can adopt R410A, basic design factors of compressors such as cylinder capacity and pressure—resistance must be modified. Also, from the tribological viewpoint, R410A provides weaker lubricating action than R22 due to the absence of chlorine atom in its molecular structure. This makes lubrication of sliding parts extremely difficult. Furthermore, development of refrigerator oils appropriate for the environmentally-friendly new refrigerant is required. Consequently, assuring the reliability of compressors is essential technologies for adopting the new refrigerant, thus developing a compact horizontal-type scroll compressor for R410A. This paper reports on the selection of refrigerator oil, our evaluation of compressor reliability, and the relationship between the changes made in the compressor to adapt to the new refrigerant and the resulting performance of the compressor.
2. CONSTRUCTION and MAJOR SPECIFICATION

The construction of the compact horizontal-type scroll compressor under development (hereafter termed "new compressor") is shown in Fig.1. The new compressor is based on the compact horizontal-type scroll compressor presently installed in conventional types of the R22 room air-conditioner. The shape of the scroll vane remains unchanged, but the height of the vane was reduced to accommodate the high-capacity refrigerant R410A.

The new compressor is a high-pressure shell type. The main shaft is supported at both ends; the compression-mechanism side is supported by a sliding bearing and the other end is supported by a ball bearing.

Compression mechanism
The compression mechanism consists of the fixed scroll and the orbiting scroll, performing orbiting motion on the fixed scroll. The fixed scroll is made of cast iron. It has a check valve and a bypass valve integrated in a single structure. The check valve in the discharge part of the fixed scroll prevents reverse flow of the discharged refrigerant. The bypass valve leads to a bypass hole positioned near the final compression chamber. The bypass prevents the super-compression phenomenon, which is peculiar to the scroll compressor with its inherent volume ratio. The bypass valve opens and closes so as to prevent loss due to super-compression. The orbiting scroll has a driving shaft in the center of its end plate. The scroll performs in orbiting motion by the combined action of the eccentric bearing on the main shaft and the Oldham ring behind the end plate. The orbiting scroll has a tip seal on the top of the vane for sealing the compression chamber in the axial direction. The orbiting scroll is made of an aluminum alloy to withstand high-speed operation by the inverter drive and to reduce weight.

Oil supply route
The new compressor has a positive displacement oil pump in one end of the main shaft. It pumps the oil accumulated in the shell and supplies it to the compression mechanism via the channel in the center of the main shaft, providing stable lubrication on the driving shaft bearing and the main bearing. Some of the oil is led from the driving shaft bearing through the oil pressure reducer in the orbiting scroll to the back pressure chamber. After lubricating the backside of the orbiting scroll and the thrust face, the oil flows into the compression chamber, where it serves to seal the chamber.

3. EXAMINATION for LUBRICATING OIL

Development of an appropriate lubricating oil is essential for assuring the reliability of the compressor for the alternative refrigerant. We selected esters compatible with HFC refrigerants as candidate lubricating oils for the R410A compressor and studied their lubrication performance.

3.1 Measurement of viscosity
Viscosities of oils in the compressor and quantities of discharged oil were both measured under standard conditions. As a result of the observation of transient heating, it was concluded that the performance of VG68 ester with R410A is comparable to that of lubricating oils used in current compressors.

3.2 Lubrication performance
The lubrication performance of oils was evaluated with the high-pressure atmosphere wear tester shown in Fig.2. The wear tests were conducted in the same refrigerant atmosphere as that in the actual compressor, and the lubrication performance of oils was evaluated by measuring the wear of the vane and the disk. The wear test
conditions are given in Table 1. As all HFC refrigerants—R32, R134a and R125—were found generally comparable in wear characteristics, R134a was adopted for the following study. The vane and disk are made of a special cast iron alloy. Hardness/initial surface roughness values were HRC 65/Ra 0.07 for the vane and HRC 51/Ra 0.09 for the disk.

The results of wear tests are shown in Fig.3, respectively, where the base oil is a mixture of mineral oil and synthetic oil. The ester A is based on branched fatty acids, and the ester B, which is based on a mixture of linear and branched fatty acids. In a nitrogen atmosphere, esters provide lubrication performance comparable to that of the current base oil/R22 combination; in an R134a atmosphere, however, a considerably higher degree of surface roughness of the wear than observed with the current base oil/R22 combination is due to the dissolution of R134a. Specifically, the ester B shows an increased degree of surface roughness of the wear face. Esters characteristically show lower viscosities than the current mineral oil under high pressure, and further lowering of the high pressure viscosity when refrigerants are dissolved in esters has been reported. The above unsatisfactory lubrication performance compared with that of the current base oil/R22 combination is considered to be caused by the severe lubricating condition resulting from a decrease in high pressure viscosity by dissolution of the R134a. Consequently, key requirements for esters are to improve lubrication performance and to enhance viscosity effect.

<table>
<thead>
<tr>
<th>Table 1 Test Condition</th>
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<tr>
<td>Refrigerant</td>
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<td>Oil Temperature</td>
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<tr>
<td>Vessel Pressure</td>
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<td>Load</td>
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<td>Speed</td>
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<td>Time</td>
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<th>Table 2 Effect of Moisture on Wear</th>
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<tr>
<td>Vaccum Heating</td>
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<tr>
<td>Moisture</td>
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<tr>
<td>Wear</td>
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<tr>
<td>Disk</td>
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<tr>
<td>Roughness</td>
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<td>Ra</td>
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<tr>
<td>Coefficient of Friction</td>
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3.3 Presumption of wear mechanism

The results of studying the relationship between moisture in the material and wear are given in Table 2. This study indicates that as the moisture content of the material increases, the slide face smoothens and the wear of the vane (the higher hardness side) increases. The result of FT–IR analysis of the sediment around the vane’s slide face is shown in Fig.4. Absorptions implying the presence of metallic soap appear at 1423 and 1532 cm⁻¹. Presumably, the ester hydrolyzed by the moisture in the material reacts with the iron surface to form iron soap, which is a form of chemical wear. The smoothening of the slide face and the wear of the vane, which is exposed to high temperatures, are considered the result of this chemical wear.
When moisture in the material has been reduced by vacuum heating, wear of the disk (the lower hardness side), surface roughness and the friction coefficient are found to increase; that is, the lubricating condition is more formidable than when the material contains a greater amount of moisture. FT-IR analysis of the sediment around the slide face of the vane again indicated the presence of iron soap. In this case, however, the formation of iron soap is attributable not to hydrolysis but to thermal decomposition at a higher temperature level.

Consequently, iron soap formed by hydrolysis, one of the causes of capillary clogging, can be controlled by reducing moisture in the material, but the occurrence of thermal decomposition will worsen the lubricating condition.

### 3.4 Improvement of lubrication performance

#### 3.4.1 Chemical structure of fatty acid

We studied the relationship between the chemical structure of fatty acids and wear (Fig.5). Results were obtained by using materials whose moisture had been thoroughly removed by vacuum heating.

It has been reported that linear fatty acids are less stable than branched fatty acids. Hardly any viscosity effect is obtained even at VG100, presumably because the lubricating condition is worsened by the thermal decomposition of linear fatty acids.

With branched fatty acids, the results show that the content of \( \text{C}_9 \), which is branched at the beta position, increases with wear of the vane, which is hard but structurally exposed to high temperature. \( \text{C}_9 \) component enables high VG but is subject to thermal decomposition due to chemical instability. \( \text{C}_8 \) component, which is branched at the alpha position, is chemically stable and resistant to thermal decomposition, and controls wear even with low VG.

Consequently, esters comprising the fatty acids branched at the alpha position show superior lubrication performance and restrict the formation of iron soap.

#### 3.4.2 Additives

Wear tests were conducted to study the effects of acid absorbers, oiliness improvers and extreme pressure agents in restricting iron soap formation (Fig.6). It was found that acid absorbers and oiliness improvers, both of which form physical adsorption films, are effective in blocking moisture in the material but are incapable of limiting thermal decomposition. It was also found that the use of oiliness improvers having strong polarity is effective in reducing the wear in the vane. Furthermore, the use of extreme pressure agents, which form chemical adsorption films, proved to be the most effective approach. Density characteristics of extreme pressure agents are shown in Fig.7. Extreme pressure agents containing phosphorus demonstrate a wear-prevention effect through the formation of phosphates. Specifically, phosphoric esters, which can be used in a wide range of additive quantities,
Phosphorous esters and acidic phosphoric esters, only in minute quantities, are considered effective in accelerating the initial stages of operation. Even with phosphoric esters, caution should be exercised for using adequate quantities as an excessive amount may cause corrosive wear.

3.5 Summary
In the scroll compressor, the face pressure produced in the sliding part is structurally low. Therefore, the lubricating oil we used was the ester composed of branched fatty acids that are chemically stable and PE. Furthermore, the oil was added with acid absorbers and anti-oxidants.

4. CHARACTERISTICS of THE SCROLL COMPRESSOR for R410A and IMPROVEMENT of EFFICIENCY

A key feature of R410A refrigerant is high pressure. However, the current scroll compressor comprises some elements functioning by the difference between the intake pressure and the discharge pressure. Therefore, in several design aspects this must be redesigned for R410A. In this regard, the oil supply to the compression chamber and the axial-direction force to support the orbiting scroll are discussed below.

4.1 Setup of the axial-direction force to support the orbiting scroll
In the scroll compressor, as shown in Fig.1, the backside of the orbiting scroll is split by a seal into two parts, and the orbiting scroll is supported by applying discharge pressure to the inside and intake pressure to the outside. Considering that these pressures always vary depending on the operation of the air-conditioner, the optimum diameter of the seal should be determined so that the compressor always generates adequate power and maintains high performance under all operating conditions.

The axial-direction force which are applied to the backside of the orbiting scroll were calculated for different seal diameters, of which values are given in Fig.8. The relationship between seal diameter and compressor performance is shown in Fig.9 (COP for phi=39.5 mm is set at 100). From these Figures, we see that under the rated condition where a large force is applied, smaller seal diameters obtain higher COP, presumably due to significant influence of the sliding loss on the thrust face. On the other hand, under the minimum capacity condition where only a small force is applied, larger seal diameters obtain higher COP. Presumably, large forces will stabilize the movement of the orbiting scroll and thus reduce the loss due to leakage.

Based on the above results, we selected the seal diameter phi=39.5 mm for best achieving high efficiency under all operating conditions.
4.2 Optimization of the oil supply to the compression chamber

The oil flow route of the new compressor has already been described. Some of the oil flows through the oil pressure reducer in the orbiting scroll to the back pressure chamber and then to the compression chamber. As the flow rate of the oil is determined by the difference in pressures across the oil pressure reducer and the viscosity of the oil, the flow rate must be readjusted in order to adopt the high-pressure refrigerant R410A.

For the three oil pressure reducers used in this study, the air flow rate (at pressure difference 0.05 MPa) and actual oil flow rate values on different operating conditions are given in Table 4. Volumetric efficiencies under different operating conditions are compared in Fig.10. Under the rated condition and medium capacity condition, the smaller the oil flow rate, the higher the volume efficiency; under the minimum capacity condition, this tendency is reversed.

The reason for this can be considered as follows. Under the rated condition, a large axial-direction force applied to the orbiting scroll serves to keep the gap in the compression chamber small; also under this condition, high operating speeds shorten the compression cycle time, thus reducing the necessity of sealing action by the oil. An increase in the oil flow rate under these conditions increases the quantity of refrigerant to be heated, which results in a reduction of the volumetric efficiency. Under the minimum capacity condition, however, a small axial-direction force and low operating speed make the movement of the orbiting scroll unstable, and thus the gap in the compression chamber tends to enlarge. In this condition, an increase in the oil flow rate provides a better sealing effect, namely higher volumetric efficiencies.

Based on the above results, the oil pressure reducer HB2 was selected in this study. It achieves high efficiencies over a broad range of operating conditions.

4.3 Performance of the new compressor

The performance of our compact horizontal-type scroll compressor for R410A is compared with that of the R22 compressor in Table 5. Here, compressor efficiency is the ratio of theoretical compression power to compressor input, which enables an evaluation of compressor performance independent of thermal characteristics of refrigerants.

In our study, as shown in the Table 5, compressor efficiencies of nearly 100% were achieved under the rated heating and cooling conditions by changing the height of the vane, which was the only marked change in the compressor's specifications. Accordingly, we could confirm that R410A can be adopted as an alternative refrigerant for R22 without substantially sacrificing the efficiency of the compressor itself.

4.4 Summary

Through this study, we could grasp the characteristics of the scroll compressor for use with R410A and ascertain that when the current refrigerant R22 is switched to the high-pressure refrigerant R410A, the efficiency of the compressor itself remains almost unchanged. We will pursue further improvement of compressor efficiency by optimizing the configuration of the vane, determined by its orbiting radius, for R410A.

5. CONCLUSION

From the present study made in developing a scroll compressor for R410A, the author and his colleagues selected esters as the appropriate refrigerator oil for R410A and obtained their characteristics. In regard to the
compressor performance, we discussed and optimized several aspects in the basic design of the compressor to address the requirement of R410A. Consequently, we succeeded in developing a scroll compressor for R410A with performance comparable to that of the scroll compressor for R22. We will continue to study further improvement of compressor efficiency by such means as the optimization of the scroll's orbiting radius, which we believe contributes to energy conservation in room air-conditioners.

7. REFERENCES