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DEVELOPMENT OF A MULTISTAGE CAPACITY ROTARY COMPRESSOR

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ABSTRACT

In this paper, we will introduce a novel variable capacity rotary compressor, named Digital Rotary Compressor (DRC), which provides continuous capacity modulation mechanically without using any electronic frequency modulation. The vane control method is adopted to modulate the capacity of the twin rotary compressor. The major difference from the typical variable capacity rotary compressor is its continuous capacity modulation characteristics. Continuous capacity modulation of the DRC is achieved by controlling the vane motion with PWM control. In this paper, we will present the structure, operation mechanism and performance test results of DRC. Also we will briefly present the reliability test result of DRC.

1. INTRODUCTION

In order to reduce the indirect global warming contribution and to meet the energy regulation, efforts to improve the efficiency of refrigeration systems are being continued. Conventional air-conditioner having a single capacity consumes much larger electric power compared to a variable capacity air-conditioner. The power consumption of a single capacity air-conditioner doesn't change according to the variation of the temperature around the indoor unit. To enhance the efficiency, it is essential to develop a capacity modulation compressor. Recently, a variable capacity compressor has been increasingly used in refrigeration systems, such as air conditioners or refrigerators, to vary cooling capacity as desired, thus accomplishing an optimum cooling operation and saving energy. The capacity modulation is a key technology in the improvement of efficiency of refrigeration systems. The variable capacity compressor can provide the solution for the variable capacity air-conditioner. Samsung developed a novel rotary compressor, which provides continuous capacity modulation without using any electronic frequency modulation. It is named DRC, abbreviation for Digital Rotary Compressor. Capacity modulation of DRC is achieved by controlling the vane motion with PWM control. To control the vane, some key components of twin rotary compressor are redesigned. The inventive solution tool, TRIZ, is used to develop reliable vane control mechanism of DRC. The experimental results show that DRC could be used to increase the efficiency of air-conditioning systems to a considerable extent. This paper mainly focuses on the introduction of the capacity control mechanism of DRC and its experimental results.

2. STRUCTURE OF DRC COMPRESSOR

2.1 Description of Capacity Control

DRC is composed of two pumps like a conventional twin rotary compressor, as illustrated in Figure 1. The capacity modulation is accomplished by controlling the vane of the upper pump. To control the vane motion, we provide a hermetic pressure chamber at the back of the upper vane to control the vane motion by controlling pressure of that chamber.

Fig. 1 shows the operating mode of DRC which is settled by pressure of the vane chamber. The pressure of the vane chamber is selectively applied by 3 way valve. As shown in the Fig. when the suction pressure (P_s) is applied into the vane chamber, the vane is separated from rolling piston by pressure difference. As a result, the division between compression chamber and suction chamber in upper pump disappears and the upper pump idles. In that case, the displacement of lower pump determines the compression capacity of DRC. In the other hand, if the discharge pressure (P_d) is applied to the vane chamber, DRC works like conventional twin rotary compressor, both upper and lower pump works together.

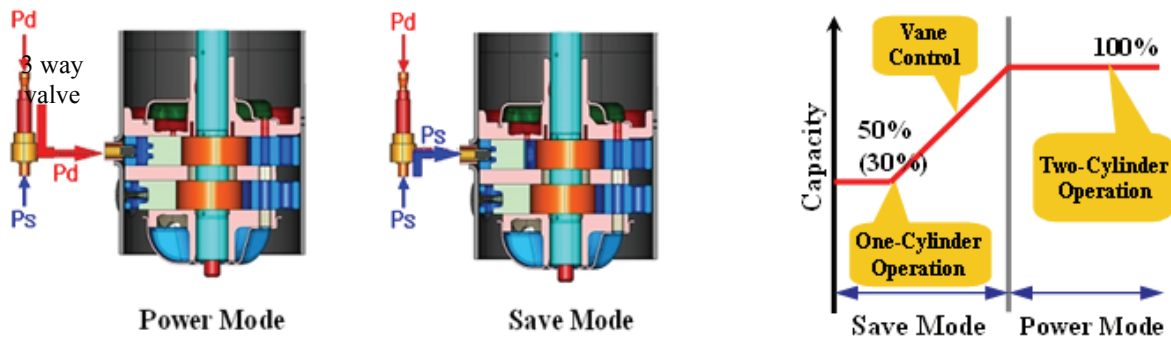


Figure 1: Operating mode of DRC

Fig. 1 also shows capacity variation characteristics of DRC. As described previously, basically DRC modulate the capacity in two steps, power mode for both pumps working or save mode for only lower pump working. When the upper cylinder working, DRC generates full capacity and if the upper cylinder idling DRC generates minimum capacity which is equal to the capacity of lower pump. The minimum capacity of DRC is equal to the lower pump capacity. For an example if we design the DRC having same compression volume for upper and lower pump, then the minimum capacity will be 50% of total capacity. In this paper, the minimum capacity is designed to 30% of total capacity, by making two pumps having different compressing volume. The intermediate capacities between minimum to the total capacity can be obtained by PWM control of each mode. For example, DRC which has total cycle time 20 seconds, 70% capacity can be made by working DRC 11.4 seconds in power mode and 8.6 seconds in save mode. After this manner 30%~100% continuous capacity modulation is possible.

2.2 Vane Control Mechanism

Fig. 2 shows the working mechanism of DRC and the dual stage compressor which was developed by Toshiba. Both compressors modulate the capacity by controlling the vane motion, but the control mechanism is different. DRC controls the pressure of vane chamber but dual stage compressor controls the inlet pressure of the pump. According to the working mechanism, each method has merits and demerits as listed in table 1. The main reason of DRC take the vane chamber pressure control method is because it's more appropriate to the PWM control.

Table 1: Vane Control Mechanisms of rotary compressor

	DRC	Dual stage
Efficiency	Good at Power Mode	Good at Save Mode
Structure	Relatively complex	Simple
Application	Easy for PWM	Difficult for PWM

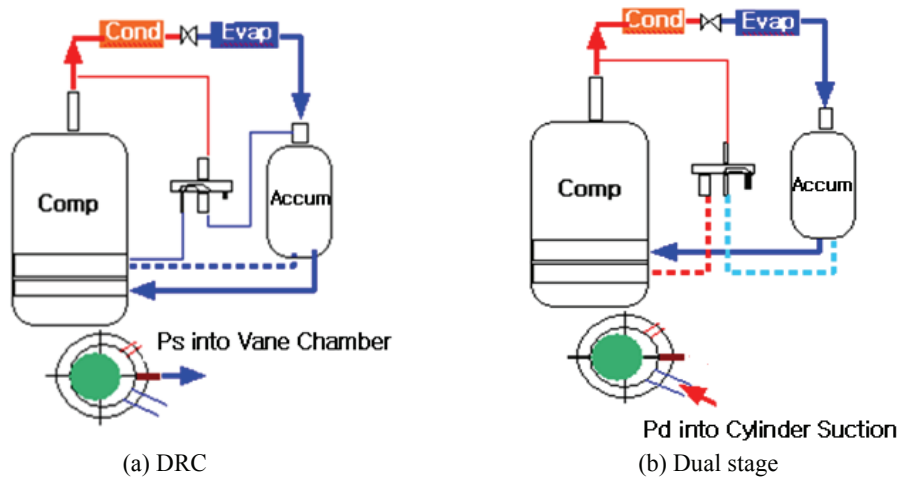


Figure 2: Vane control mechanism

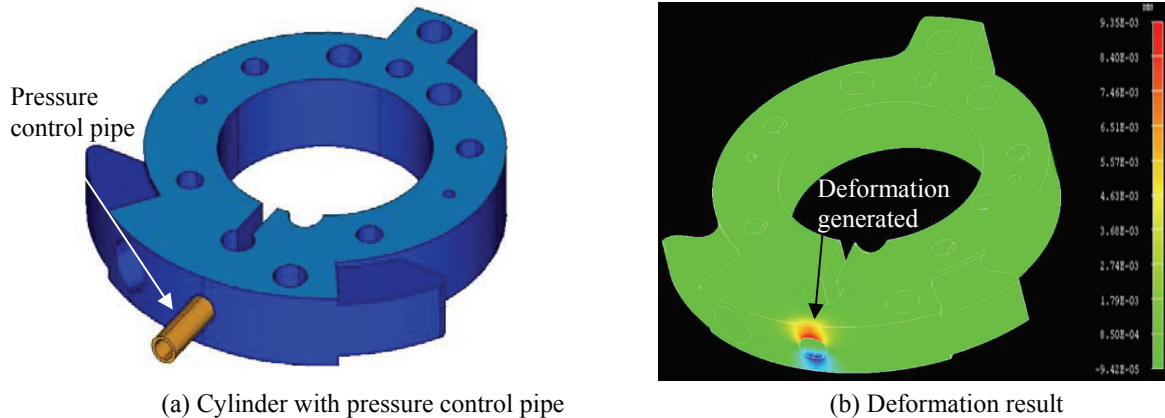


Figure 3: Deformation of Cylinder

2.3 Design of Vane Room

For conventional rotary compressor, back side of vane is generally open so the vane back pressure is always equal to the discharge pressure in operating condition. On the other hand, as described previously, DRC has hermetic chamber include the vane to control the vane motion. Because of the vane is isolated, precautions must be taken against reliability problems that can happen because oil supply to the vane is not enough. In early development stage, we designed DRC vane chamber that directly inserting pressure control pipe into the back of cylinder, and in this case, the surface of cylinder was deformed by the interference. Fig. 3 shows deformation of cylinder due to the interference between the pressure control pipe and the cylinder, which is obtained by FEM analysis. We obtained similar results by actual deformation measurement. The deformation is about $5\sim 8\ \mu\text{m}$ according to the interference. This deformations cause the leakage of refrigerant gas and low EER. This paper presents the design procedure of vane control chamber, which is making possible the control of vane motion. The inventive solution tool, TRIZ is adopted to design the vane control chamber. We will briefly introduce the TRIZ procedures used for optimum design of vane control chamber of DRC. The main goal of the first part of TRIZ is the transition from an indefinite inventive situation to the clearly created and extremely simple model of the problem. TRIZ helps to resolve conflicts between parameters of a product routinely guiding to a complete set of breakthrough solutions. A Technical contradiction is a situation in problem solving where improving something in the system causes the deterioration of something else. The technical contradictions for vane control chamber of DRC are defined as follows; the technical contradiction 1 is: "If the interference between the pressure control pipe and the cylinder is too big, then the reliability of vane control chamber is good but the deformation of cylinder get large." The technical contradiction 2 is: "If the interference between the pressure control pipe and the cylinder is too small, then the deformation of cylinder is small but the reliability of vane control chamber get worse. Figure 4 shows the defined contradictions graphically. Secondly, a physical contradiction is defined, which is the two mutual exclusive requirements to the same parameter of a component of the system. The physical contradiction of the vane control chamber of DRC is defined as follows. "The interference between the pressure control pipe and the cylinder should be large for guarantying the reliability and the interference between the pressure control pipe and the cylinder should not be large for preventing the deformation of cylinder." Figure 5 shows the defined physical contradiction graphically.

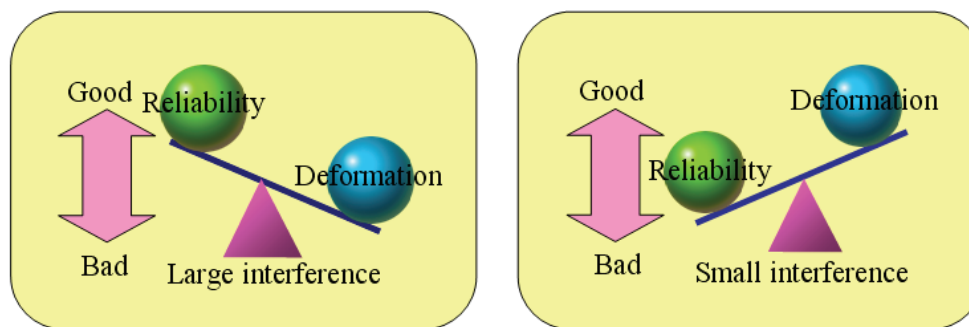


Figure 4: Technical contradictions

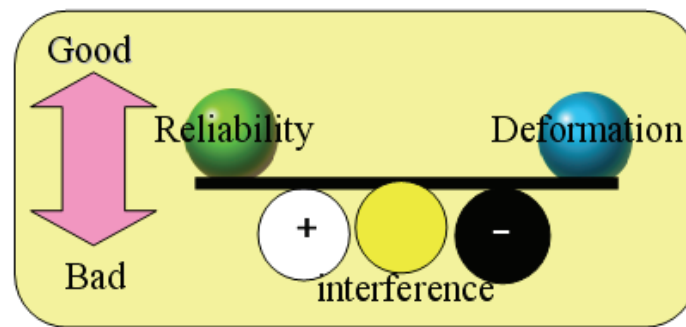


Figure 5: Physical contradiction

The goal of second part of TRIZ is inventory of available resources, which may be used to solve problems. To solve the contradiction, TRIZ recommends using the resource of the system and solving the problem. In this project the pressure difference between discharge and suction is used to solve the problem. The ideal final result for vane control chamber can be expressed as follows: “The vane control chamber itself provides the hermetic seal when the suction pressure is applied without make any deformation to the cylinder.” TRIZ recommends applying principle of separation in case contradiction of problem is defined. We applied time separation for DRC vane control chamber design problem. When the suction pressure is applied to the vane control chamber hermetic seal is necessary, when the discharge pressure is applied there is no needs for sealing for vane control chamber. So we invent the valve structure for vane control chamber. The valve is closed when suction pressure is applied to the vane control chamber, because of the pressure difference between both valve sides. When the discharge pressure is applied to the vane control chamber, pressure difference of valve in front and in rear get small then the valve is easily open so oil is supplied to the vane. Figure 6 shows the invented structure of DRC vane control chamber. As shown in the picture the vane control chamber is composed with a valve. The valve is hold by magnet but not solidly attached to the cylinder. It is semi-hermetic structure. When the suction pressure applied to the vane control chamber it becomes hermetic structure by pressure difference. When the discharge pressure is applied to the chamber the valve is easily open by pressure generated by vane motion so the oil can be applied to the control vane. Because there is no interference between the pipe and the cylinder there is no deformation.

We confirmed that oil was supplied for working vane in above semi-hermetic chamber with visualizing experiment, and inspected reliability of vane with various tests including field test. We compared the wear of various parts of DRC to that of the conventional twin rotary compressor. As shown in next section, there is no difference in wear between conventional twin rotary compressor and DRC. Especially the control parts like upper vane, upper roller and upper cylinder show similar wear characteristics to that of conventional twin compressor.

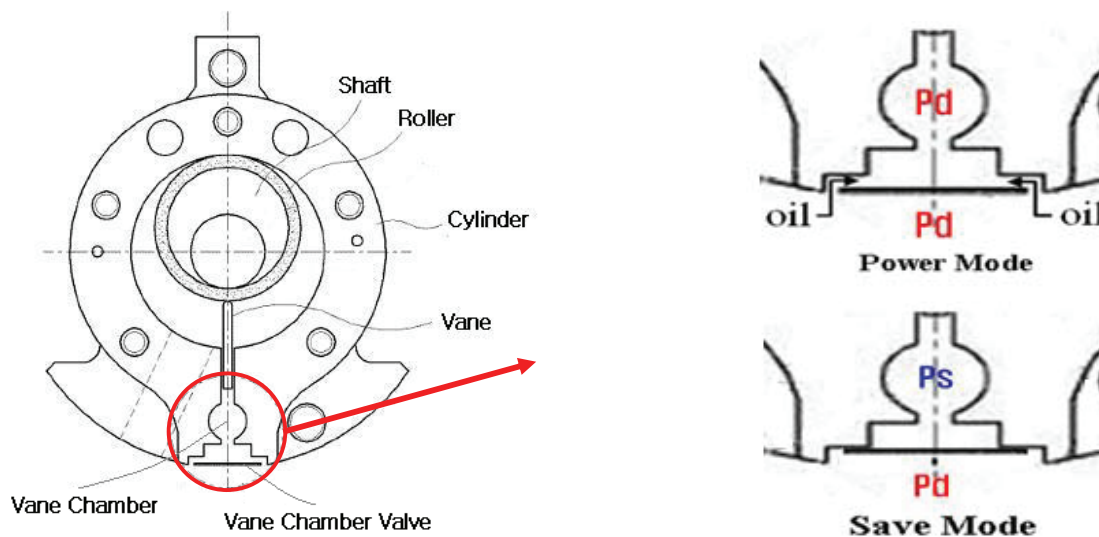


Figure 6: Semi-hermetic vane chamber structure

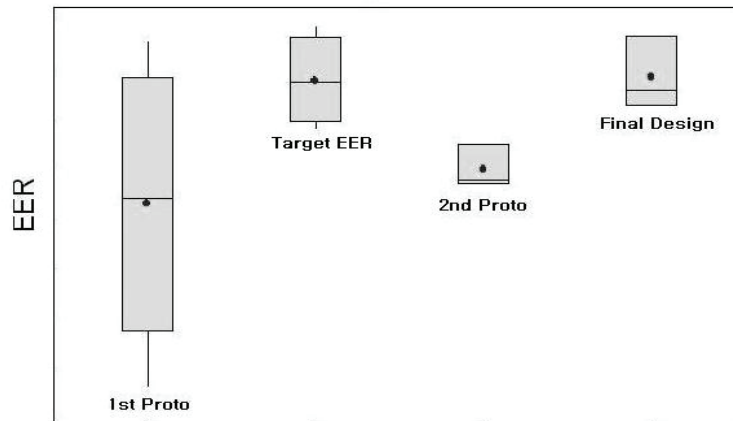


Figure 7: Performance history

3. EXPERIMENTAL TEST RESULTS

Figure 7 shows the performance history of the DRC from early stage prototypes to the recent optimized products. Figure represents the EER of DRC at the power mode. As shown in Fig., in the case of early proto samples, the efficiency was low and data variation is too large. From the experimental investigation, this was caused by the leakage due to the deformation of the upper cylinder. The deformation is caused by the interference between pressure control pipe and cylinder which makes possible the mode control of DRC. The vane chamber was not completely sealed because of the deformation of cylinder, so high pressure gas leaks into the pump. We tested the conventional twin compressor to set the performance target for the DRC that has no deformation. The second box plot represents EER of conventional twin rotary compressor which has the same dimension with DRC. In our project, we have set our DRC performance target on these results of the conventional twin compressor. The third box plot shows the test result of the modified prototypes of DRC that has semi-hermetic vane chamber as stated previous chapter. Compared with the early prototype DRC, the performance data show small variance but mean value of EER is still not enough compare to the target EER. This was because the compressor input of DRC was a little higher than conventional twin compressor due to frictional loss of the vane. The last box plot is the test result of the latest DRC that reduce frictional loss of the vane by optimum design of vane slot and vane chamber. Figure shows DRC satisfy the target EER, which is based on the conventional twin rotary compressor that has no vane chamber.

Figure 8 shows the performance curve of DRC that continuously modulated capacity from 30% to 100% capacity by PWM control. The performance data is obtained in the ASHRAE-T condition with R410A refrigerant. The upper and lower pump shares the capacity with 7:3 ratios. The minimum capacity is 30% of the total capacity of DRC; the minimum capacity is equal to the lower pump capacity. The 100% capacity is generated when the both pump works together. The modulation between 30% capacity to 100% capacity is obtained by PWM control of vane. The follow equation can be used to expect the capacity of DRC. For example, if we want 70% capacity for the system that has 20 seconds of total PWM cycle, it can be obtained by operating 11.4 seconds in power mode and 8.6 seconds in save mode.

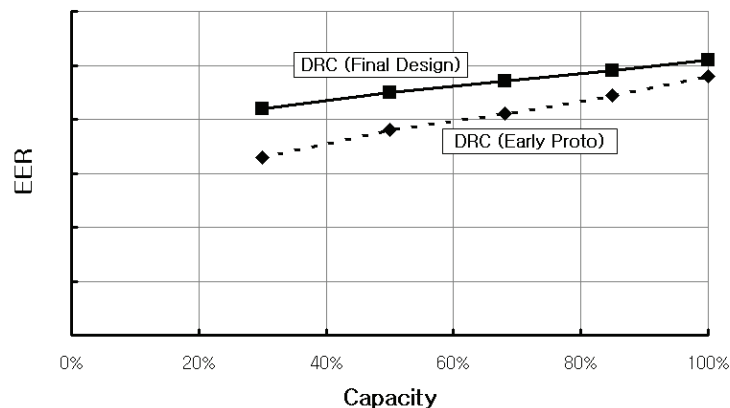
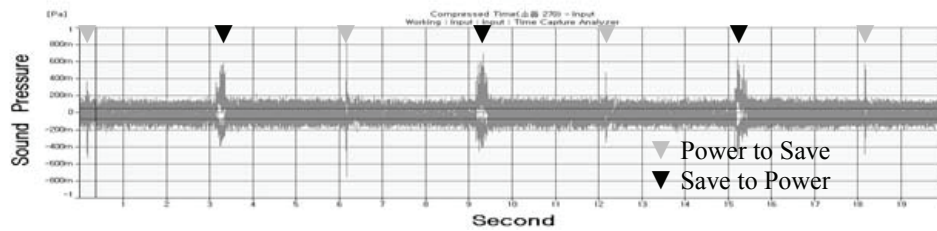
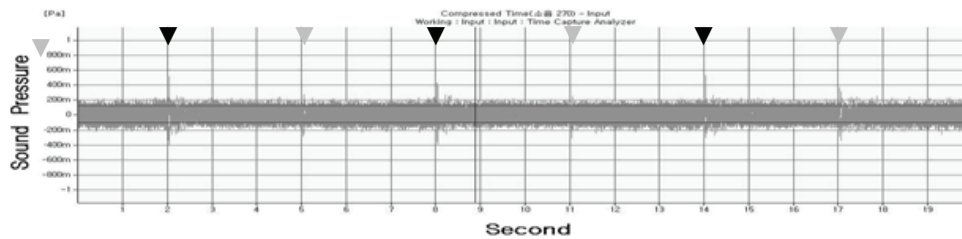


Figure 8: PWM control test Result



(a) Noise of early proto type



(b) Noise of optimized design

Figure 9: Modulation noise of DRC

The averaged capacity shows 70% capacity of total capacity. With this manner the continuous variation of capacity from 30% to 100% is possible. As shown from the figure, the EER decline is not large compare to the similar mechanical modulation compressor, the EER difference between power mode and save mode is less than 15%. This is because, for DRC the lower cylinder, which is not controlled, is always working.

Fig. 9 shows the result of modulation noise of DRC which is generated when the operating mode is changing from power mode to save mode or vise versa. The modulation noise is consists with the valve noise, the refrigerant flow noise and the vane and roller impact noise. For DRC the refrigerant flow noise is negligible because the volume of vane chamber is very small, the valve and vane impact noise is dominant source of modulation noise. Fig. 9 (a) shows modulation noise of early stage DRC, as shown from the figure there is chattering of vane when the mode change is made. This vane chattering yields noise and reliability problem. We have improved this problem by optimum design of the valve and vane chamber. Fig. 9 (b) is the modulation noise for modified DRC, from the figure it is shown that there is no vane chattering during mode change, and the modulation noise level is much improved. The detail works on reducing the modulation noise is presented in the other paper.

To verify the reliability of DRC, we have operated the DRC in many reliability test conditions include Field Test. Fig. 10 shows the one of the reliability test result; it shows the wear of major parts of pump after 2000 hours acceleration life reliability test. The dotted line is represents the results of conventional twin rotary compressor, and the solid line for DRC after the same reliability test condition. As shown Fig. 10, there is no difference in wear between conventional twin rotary compressor and DRC. Especially the control parts like upper vane, upper roller and upper cylinder show similar wear characteristics to that of conventional twin compressor.

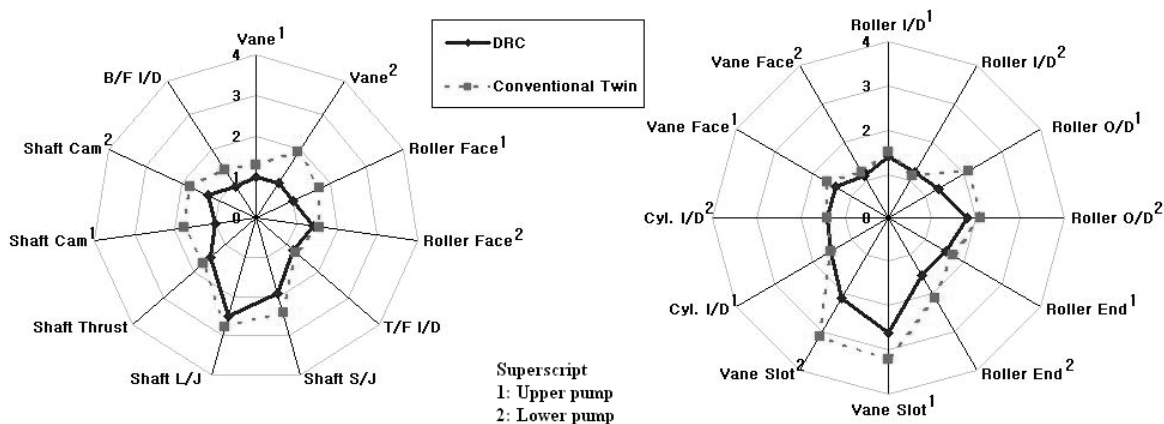


Figure 10: Reliability test Result

We have developed a rotary compressor that controls variable capacity mechanically and achieved competitive performance and confirmed that there wasn't any reliability problem.

4. CONCLUSIONS

In this paper we introduce the DRC that controls capacity mechanically without using any electronic frequency modulation. The vane control method is adopted to modulate the capacity continuously. Continuous capacity modulation of the DRC is achieved by controlling the vane motion with PWM control. The unique semi-hermetic vane chamber has been developed with the aid of TRIZ. From the experimental results of the performance and reliability test of the new rotary compressor, DRC could be used to increase the efficiency of air-conditioning systems to a considerable extent.

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