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Dynamic Stress of Refrigeration Compressor Reed Valve with Oval Shape

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DYNAMIC STRESS OF REFRIGERATION COMPRESSOR REED VALVE WITH OVAL SHAPE

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ABSTRACT

The purpose of this study is both theoretically and experimentally to clarify the dynamic stress of a discharge reed valve with oval shape, and to get fundamental knowledge for the design of this type valve and its related parts. The strain measurements were performed on the strain gauge bonded on the surface of the oval shaped reed valve. The stress and deformation of the valve were also calculated by the finite element method. These calculations were carried out under various differential pressures between the discharge plenum and cylinder and under the wide range of drag forces. Comparing the experimental results with the analytical results, the deformation and stress of the discharge valve with oval shape were revealed under various compressor operating conditions. The design concept on this type valve and its related parts was also discussed.

1. INTRODUCTION

The trend of refrigeration compressor toward higher and higher reliability and efficiency continually presents the designer with new and ever more intractable problems. Among those, there are the behavior and strength of the valves which govern the efficiency and performance of a compressor. Many researchers [1]~[6] have conducted a lot of studies which can solve fundamental problems related to the valve and can evaluate its design, thus eliminating the time and expense involved in the construction and bench-testing of model. Through those studies, a satisfactory mathematical model and means of simulation have been obtained. However, most of them have been carried out on the leaf-type valve.

Recently, an oval shaped reed valve is widely getting employed in the refrigeration compressor for use of low temperature applications. The major reason of this tendency is the severe demands for noise reduction and efficiency. However, the dynamic behaviors of the oval shaped reed valve have not been clarified so much [7]. This situation motivated the study described in this paper.

In this study, therefore, the experimental and analytical studies have been performed on the oval shaped reed valve in order to clarify the dynamic stress performances in compressor operations. The strain measurements were carried out on the strain gauge mounted on the valve surface over the wide range of compressor operating conditions. The results obtained showed that impact stress was negligibly small for evaluating the valve strength, and that it was adequate to calculate the valve stress statically. So, the deformation and stress of the valve were statically calculated by the finite element method. These calculations were performed during suction and discharge strokes. Through those studies, the behaviors of the discharge valve with oval shape were revealed, and its design concept was clarified.

2. TEST EQUIPMENT AND TEST PROCEDURE

2.1 Test Equipment

The configuration of the discharge valve and its related parts is explodedly shown in Fig. 1. As can be seen in Fig. 1, the oval shaped reed valve was used in this test. The valve stop was constituted with the arch at the center portion and the straight at both ends. The radius and rise of the arch were determined from the view point of the valve strength. The valve was sandwiched between the valve plate and valve stop at both ends. A certain spring force was applied to the valve by two springs which were held with two pins.

In this test, two-element rosette was used for stress measurements. It was bonded on the valve surface on the valve stop side and was located at the valve center. The

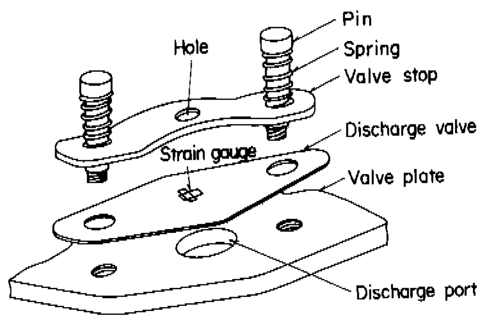

Fig.1 Exploded configuration of discharge valve and its related parts.

strain gauge was oriented so that its axis was in the plane which contained the longitudinal axis of the valve, thus providing a convenient reference for reporting the direction of the principal stresses.

As the strain gauge was bonded on the valve stop side, it might contact with the valve stop during discharge stroke. So, as shown in Fig. 1, a hole with larger diameter than gauge length was milled out at the center portion of the valve stop and the lead wires from the strain gauge were pulled out of this hole. The terminal strip was bonded on the surface of the valve stop in the vicinity of the hole. The lead wires from the strain gauge were connected to the terminal strip with loop to avoid the fatigue failure of the lead wire due to the repeated motions of the valve.

2.2 Test Procedure

(1) Test under Compressor Operating Conditions

The block diagram of refrigeration cycle is shown in Fig. 2. As can be seen in Fig. 2, it operated on a combined ideal refrigeration and hot gas cycles. After refrigerant was compressed by the compressor, the hot gas was branched into two cycles. Part of the discharge gas was passed through the condenser while remainder of the gas was

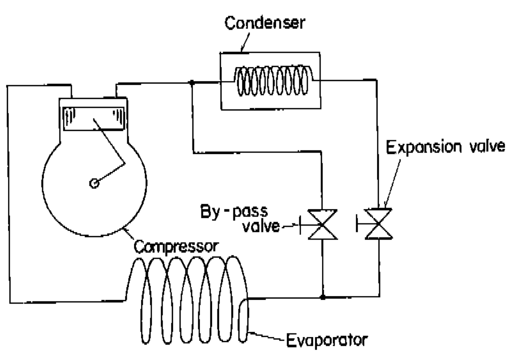

Fig.2 Block diagram of refrigeration cycle.

throttled through the by-pass valve at constant enthalpy. The condensed refrigerant was also throttled by the expansion valve and two parts of refrigerant were again mixed. Mixed refrigerant was passed through the evaporator, bringing the final state to the compressor suction condition. R-22 was used as refrigerant in this test.

By changing two valve settings and the refrigerant charge in the system, the operating conditions of the compressor were adjusted to any required operating condition. These operating conditions were determined monitoring the indications of the pressure gauges and thermocouples which were installed in the suction and discharge plenums.

In this test, the strain measurements were carried out under the wide range of compressor operating conditions. The suction pressure was changed in the range from 1.1 kg/cm^2 to 3.6 kg/cm^2, and the discharge pressure was changed in the range from 12.2 kg/cm^2 to 15.8 kg/cm^2. The outputs of the strain gauge were amplified by the dynamic strain indicator with the flat frequency of 14 kHz and then were simultaneously recorded on the oscilloscope with the top dead center position of the piston, which was detected by the electromagnetic pick-up attached at the end of the crank shaft.

(2) Static Test under Pressure Difference between Discharge Plenum and Cylinder

This test was carried out to clarify the strain induced in the valve during suction stroke. In order to simulate the pressure difference between the discharge plenum and cylinder during suction stroke in compressor operation, the cylinder of the compressor used in this test was opened to the air and compressed air was supplied to the discharge plenum from an air compressor. So, the pressure difference could be obtained from the pressure in the discharge plenum. The strain was measured under the pressure difference within 8 kg/cm^2. The outputs of the strain gauge were simultaneously recorded on the oscillograph paper with the pressure in the discharge plenum.

3. STRESS ANALYSIS

Fig. 3 shows a finite element idealization for a quadrant of the valve. As shown in Fig. 3, the origin was taken at the valve center, and the longitudinal and transverse directions of the valve were defined as x and y directions, respectively. The valve was subdivided into a number of quadrilateral elements which were defined by the corner nodal points as shown in Fig. 3. To improve accuracy, smaller elements were used in zone where rapid variations in stress were anticipated.

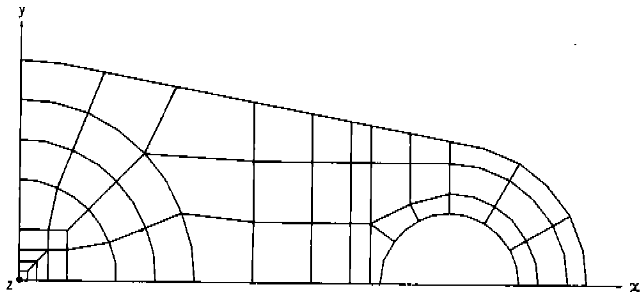

Fig.3 Finite element idealization for a quadrant of valve.

Fig. 4 shows the cross sectional view of the valve deformation and the mathematical model for stress analysis during suction stroke. As can be seen in Fig. 4, the valve is sandwiched between the valve plate and valve stop at both ends subjected to a certain spring force. When the lateral uniform load of p applies to the center portion within radial distance r, the valve deforms as supported at the periphery of the discharge port. The valve deflection at both ends seems to be negligibly small because the valve was sandwiched between the valve plate and valve stop at these portions. The assumptions were made in this analysis, therefore, that the valve deflection at these portions were restricted to zero but the valve were movable to the longitudinal direction.

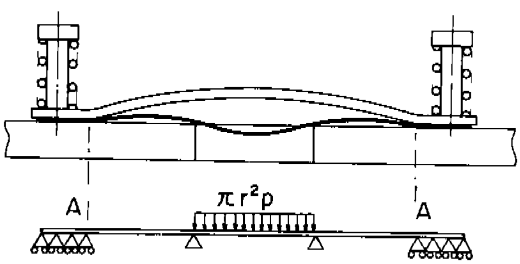

Fig.4 Cross sectional view of valve deformation and mathematical model for stress analysis during suction stroke.

Fig. 5 shows the schematic diagram of the valve deformation and the mathematical model for stress analysis during discharge stroke. When the lateral uniform load of p applies to the center portion of the valve within radial distance r, the valve deforms as supported at both ends of the valve and subjected to the external force $F = k\delta + F_0$ corresponding to the valve deflection at point A, where k, F_0, and δ are spring constant, initial spring force, and deflection of the valve at point A, respectively. Therefore, the assumption was made that the valve was simply supported at both ends. The stress calculation was performed changing the drag force until the valve touched the valve stop.

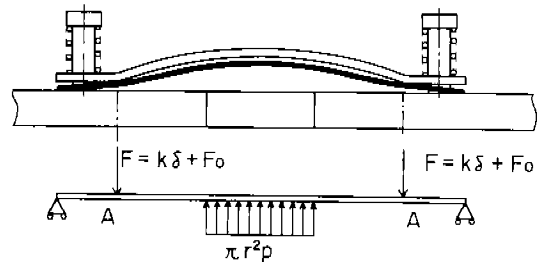

Fig.5 Cross sectional view of valve deformation and mathematical model for stress analysis during discharge stroke.

The outputs of the finite element computer program included the deformation and stress in the x and y directions for each node. These outputs were plotted on the sheets by the plotter. That is, the outputs of the deformation were plotted with the overall view of the three dimensional model for a quadrant of the valve, and the outputs of the stress were plotted with the contour plots of stress intensity for the plane stress.

4. EXPERIMENTAL RESULTS

Fig. 6 shows a typical record of the strain variations under the suction pressure of 12.3 kg/cm^2 and the discharge pressure of 1.1 kg/cm^2. During expansion, suction, and compression strokes, the strains in both the x and y directions are compression and are almost same amplitude. During discharge stroke, the strain in the x direction is also comparatively large tension, but that in the y direction is negligibly small.

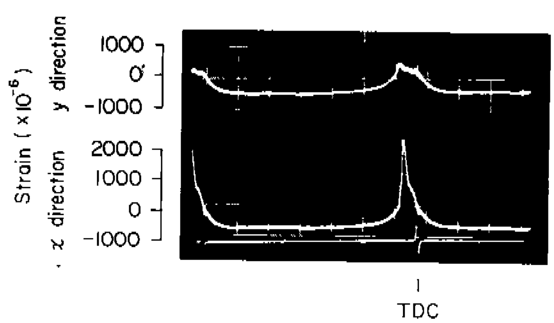

Fig.6 Strain vs. time
Suction pressure: 1.1 kg/cm^2
Discharge pressure: 12.3 kg/cm^2
Sweep time: 5 ms/div.

Fig. 7 shows another typical record of the strain variations when the discharge pressure got increased from 12.3 kg/cm^2 to 15.8 kg/cm^2, and the suction pressure got kept the same level as shown in Fig. 6. Comparing Fig. 7 with Fig. 6, the strain amplitudes in the x and y directions increase with increasing discharge pressure during expansion, suction, and compression strokes. However, the strain amplitudes during discharge stroke are almost same even if the suction pressure increases. This seems to illustrate that the strains during expansion, suction, and compression strokes are ruled with the pressure difference between the discharge plenum and cylinder, and that the strains during discharge stroke depend on the valve deformation restricted by the valve stop.

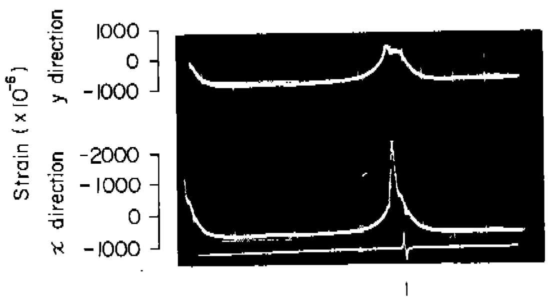

Fig.7 Strain vs. time.
Suction pressure: 1.1 kg/cm^2
Discharge pressure: 15.8 kg/cm^2
Sweep time: 5 ms/div.

Fig. 8 shows the strain variations of the valve when the compressor is operated under the suction pressure of 2.1 kg/cm^2 and the discharge pressure of 12.3 kg/cm^2. The abscissa of Fig. 8 is exaggerated 5 times ones of Figs. 6 and 7. From this figure, no remarkable impact stress is induced in the valve when it touches the valve stop or valve seat.

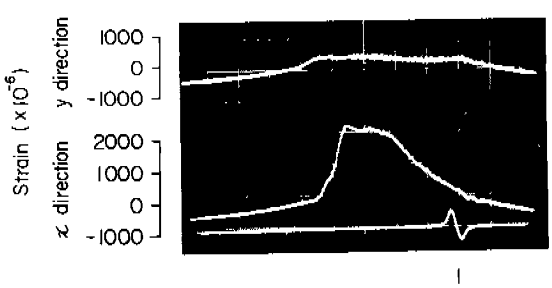

Fig.8 Strain vs. time.
Suction pressure: 2.1 kg/cm^2
Discharge pressure: 12.3 kg/cm^2
Sweep time: 1 ms/div.

Many previous researchers(1)∿(6) have performed the strain measurements on the leaf-type reed valve, and have revealed that the strain variations of these type valves are fluctuation. However, it is clear from Figs. 6 and 7 that the strain variations of the valve used in this test are alternation of tensile and compressive stresses. This phenomena is the dominant difference between the strain variations of the leaf-type reed valve and oval shaped reed valve. This leads to the conclusion that from the view point of bending fatigue, the oval shaped reed valve moves in more severe conditions in comparison with the leaf-type reed valve in compressor operation, and that the alternating stresses must be taken into consideration for the design of the oval shaped discharge valve.

5. DISCUSSION

5.1 Stress during Suction Stroke

(1) Comparison between Analytical and Experimental Results

Fig. 9 shows the relationship between the strains in the x and y directions and the pressure difference between the discharge plenum and cylinder. The plots shown with marks -o- and -●- were obtained from static test below the pressure difference of 8 kg/cm^2, and the plots shown with marks o and ● were obtained from the test under compressor operating conditions. It is clear from Fig. 9 that the plots obtained from the test under compressor operating conditions are located on the lines extending the plots for the static test. This means that the strains obtained from two tests are produced in accordance with the same mechanism, and that the static test is successful to simulate the strain of the valve during suction stroke in compressor operating condition.

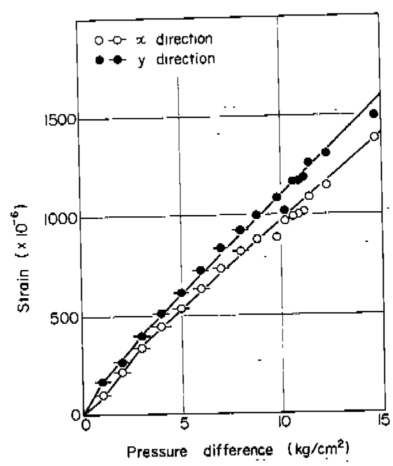

Fig.9 Relationship between strains in x and y directions and pressure difference between discharge plenum and cylinder.

From Fig. 9, the both lines seem to have a knee below the differential pressure of about 3.0 kg/cm^2. The cause of this phenomena is considered to be the warping of the valve or the presence of a clearance between the valve and valve seat leading to a change in the stress state. These factors may lead to dangerous abrupt aggravation of the stress if they are large.

This result seems to mean the requirement that the clearances between the valve and the load-bearing collar of the valve seat should be as small as possible.

To eliminate the strain caused by the above phenomena from the data shown in Fig. 9, the test data are replotted with the pressure difference of above 3.0 kg/cm^2. These results are shown in Fig. 10 in comparison with the analytical results shown with the solid and dotted lines. On the basis of the good correlation between the results of the analytical and experimental values, the analytical result seems to have been quite satisfactory from the stand point of having achieved conditions described in the section of stress analysis.

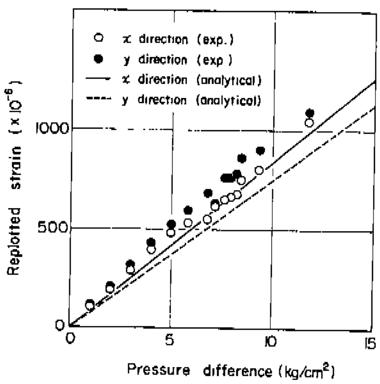

Fig.10 Comparison between strains obtained analytically and experimentally.

(2) <u>Deformation and Stress Distribution</u>

Fig. 11 shows the output of the deformation plotted with the overall view of three dimensional model for a quadrant of the valve. Figs. 12 and 13 show the outputs of the stress intensity in the x and y directions for a quadrant of the valve, respectively. From Fig. 10, it is clear that the deformation of the valve is three dimensional at the center portion, which takes place as

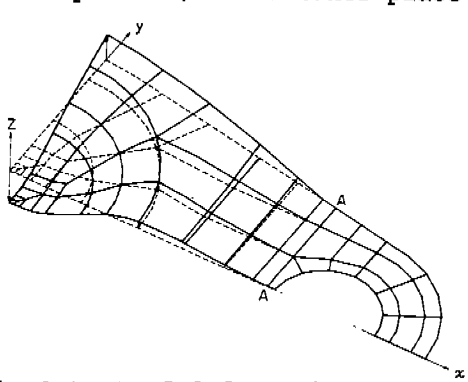

Fig.11 Output of deformation plotted with overall view of three dimensional model for a quadrant of valve during suction stroke.

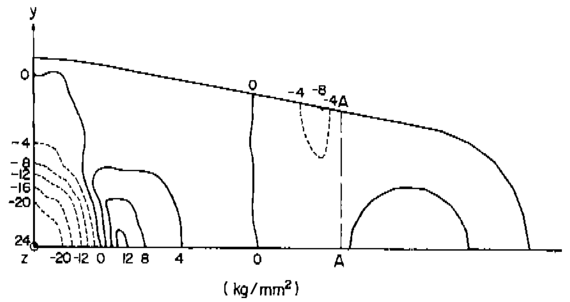

Fig.12 Contour plots of stress intensity of valve in x direction during suction stroke.

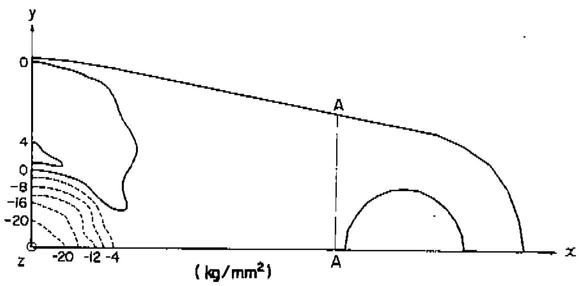

Fig.13 Contour plots of stress intensity of valve in y direction during suction stroke.

simply supported at the periphery of the discharge port. Deviating away from it to the x direction, the deformation of the valve gradually changes to two dimensional deformation in the plane contained in the plane of the valve. As can be seen in Figs. 12 and 13, the stress becomes maximum at the valve center in both the x and y directions. The stress in the x direction becomes comparatively large in the vicinity of the periphery of the discharge port, but that in the y direction gradually decreases with deviating away from the valve center.

Summing up these results, it is noticed that the dominant strain which may effect on the valve strength is produced at the center of the valve during suction stroke, and is caused by the pressure difference between the discharge plenum and cylinder. The presence of this phenomena has already been predicted and discussed by the previous researchers(7)∿(10), but they are limited within qualitative discussion. Two out of authors have also revealed the presence of this phenomena on the ring valve in the previous paper(11) from both experimental and analytical points of view. Through this study, the same phenomena has also revealed on the oval shaped reed valve, and it has made possible to estimate quantitatively the stress of the valve during suction stroke.

5.2 Deformation and Stress During Discharge Stroke

(1) Comparison between Analytical and Experimental Results

The purpose of the valve stop is to allow the use of a more flexible valve while preventing excessive strain by restricting the maximum opening. The span and radius of the valve stop of this type are generally determined from the view point of the valve strength. In order to make a study of the valve dynamics, and to understand the effects of various design considerations on the valve strength, it is necessary to determine under what loading conditions the valve is striking the valve stop and how much maximum stress is produced. This was accomplished most conveniently by finding the plateau level of the maximum strain.

Fig. 14 shows the relationship between the maximum strain and suction pressure as a parameter of the discharge pressure. Fig. 14 also shows the calculated maximum strain with the solid line. Below the suction pressure of 2.0 kg/cm^2, the maximum strain tends to increase with increasing suction pressure. Since the rate of gas flow increases with increasing suction pressure, it seems that this region referes to conditions for no contact. Beyond the suction pressure of 2.0 kg/cm^2, as expected, the maximum strain becomes the plateau level in spite of increasing suction pressure. This means that the valve motion is more restricted by the valve stop beyond the suction pressure of 2.0 kg/cm^2, and that the strain signal could be a reliable indicator for valve contact.

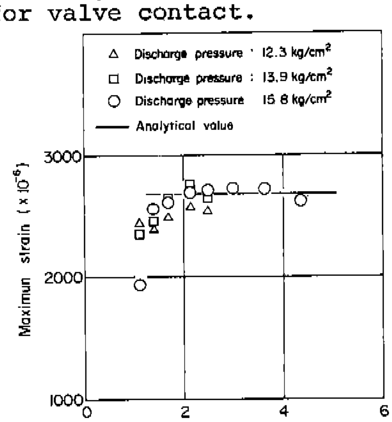

Fig.14 Maximum strain vs. suction pressure during discharge stroke.

On the basis of the good correlation between the maximum strains of the analytical and experimental values beyond the suction pressure of 2.0 kg/cm^2, the analytical result seems to have been quite satisfactory from the stand point of having achieved conditions described in the section of stress analysis.

(2) Deformation and Stress Distribution

Fig. 15 shows the output of the deformation plotted with the overall view of the three dimensional model for a quadrant of the valve. Figs. 16 and 17 show the outputs of the stress intensity for a quadrant of the valve in the x and y directions, respectively. These results are calculated under unit pressure.

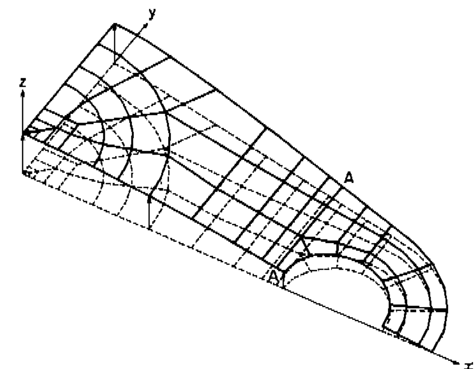

Fig.15 Output of deformation plotted with overall view of three dimensional model for a quadrant of valve during discharge stroke.

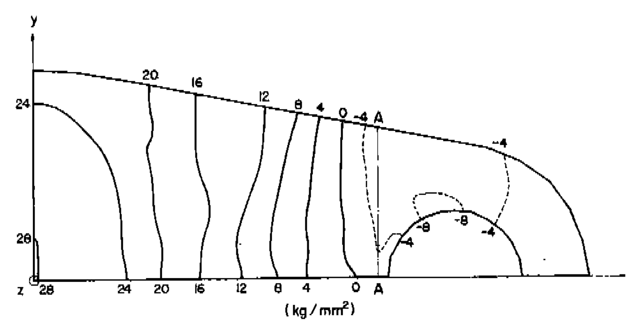

Fig.16 Contour plots of stress intensity of valve in x direction during discharge stroke.

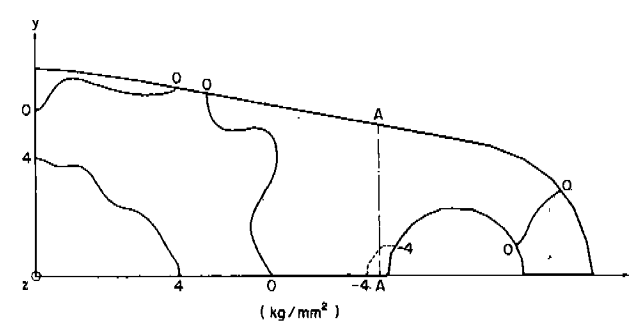

Fig.17 Contour plots of stress intensity of valve in y direction during discharge stroke.

As can be seen in Fig. 15, two dimensional deformation is observed in the valve during discharge stroke, that is, the valve deforms like a beam simply supported at both ends, admitting the refrigerant gas into the discharge plenum. Figs. 16 and 17 show that the maximum stress in the x direction occurs at the valve center while the stress in the y direction is comparatively small. This leads to the conclusion that the valve stress during discharge stroke is caused by the flexural deformation of the valve subjected to the drag force.

Within this experiment, the stress during discharge stroke is larger than that during suction stroke. This means that the oval shaped reed valve is subjected to mean stress in addition to alternating stresses in tension and compression. Since these stresses seem to be the most significant in affecting life prediction of this type valve, it is considered desirable to take them into consideration for the design of the oval shaped reed valve.

5.3 Recommendation for Stress Reduction

As mentioned above, the stress during discharge stroke is ruled with the deformation of the valve which is restricted by the valve stop. The reduction in stress during discharge stroke, therefore, may easily be attained by determining the suitable shape and dimension of the valve stop.

On the contrary, the stress during suction stroke depends on the diameter of the discharge port. The stress reduction, therefore, is also attained by decreasing the diameter of the discharge port. However, this leads to increasing the resistance to admit the refrigerant gas into the discharge plenum, following to reduction in efficiency. To avoid this problem, another way is considered, in which the multi ports are located on the valve line of synmmetry. However, with multi port design, gas flowing from the side of the port which is adjacent to the other port is confined between the valve and valve plate, and collides with the gas flowing from the other port. This interaction of the gas flowing from the two ports may reduce the flow rate of refrigerant gas from both ports.

In order to cope with this inconsistent problem, an oval shaped discharge port is developed of which the major axis is oriented to the direction of the valve line. The area of this port is designed to be equivalent to that of the multi port so that compressor performance is not affected. With the single discharge port with oval shape, the gas expands transversely to the valve line between the valve and valve plate. As a result, the pressure of the gas between the valve and the valve plate is caused to be lower.

Fig. 18 shows the relationship between the maximum stress and the ratio of the length of the major axis to that of the minor axis, keeping the discharge port area constant. As can be seen in Fig. 18, the stress in the x direction gradually decreases with increasing the length of the major axis and then reaches to a plateau level. While the stress in the y direction at first tends to increase slightly with increasing the length of the major axis but later becomes almost constant with it. This means that the deformation of the valve becomes to be ruled with the only deformation in the y direction at the region beyond a given length of the major axis.

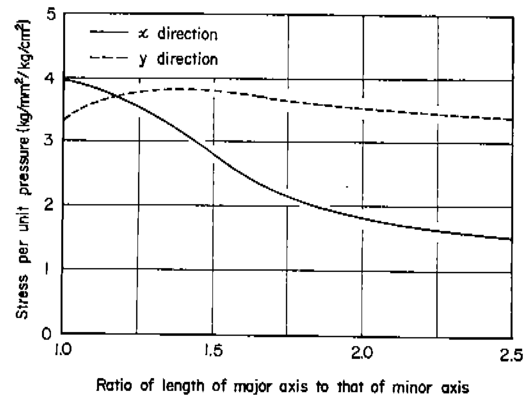

Fig.18 Relationship between stress and ratio of length of major axis to that of minor axis.

This result illustrates that if suitable length of the minor axis is determined from the view point of the valve strength, larger effective flow area of the discharge port could be expected, leading to higher efficiency.

6. CONCLUSION

The results obtained from this investigation are as follows.

(1) The alternating stresses in tension and compression are produced in the oval shaped discharge valve during every suction and discharge strokes. The impact stress, however, is negligibly small for evaluating the valve strength.

(2) The mean stress is also produced in the valve due to difference between the stresses during discharge and suction strokes. In the design of this type valve, therefore, it is considered desirable to take both alternating and mean stresses into consideration.

(3) The stress during suction stroke is caused by the flexural deformation of

the valve subjected to the pressure difference between the discharge plenum and cylinder. This stress depends on such design parameters as the diameter of the discharge port, the flexural stiffness of the valve, and the external restriction to the valve deformation at both ends.

(4) The stress during discharge stroke is caused by the flexural deformation of the valve subjected to drag force. This stress is ruled with such design parameters as the flexural stiffness of the valve, the valve length, the radius and height of the valve stop, and the external restriction to the valve deformation at both ends.

(5) Reduction in stress during discharge stroke is easily attained by determining the suitable shape and dimension of the valve stop. However, reduction in stress during suction stroke accompanies with some hard problems such as loss of gas flow area and interaction of gas flow. To cope with this problem, the oval shaped discharge port has been proposed in this paper.

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