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## A SCROLL COMPRESSOR FOR AIR CONDITIONERS

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### ABSTRACT

A series of scroll compressors for air conditioners with revolutionary high efficiency have been developed and put into commercial production. This development was accomplished through the development of a controlled thrust force mechanism to support the orbiting scroll in the axial direction with the lowest frictional force and wear yet achieved, and through a precise production technique for mass production. The scroll compressors have been mounted on a heat pump-type air conditioner and marketed since 1983. This paper describes the series of scroll compressors which have a number of useful features in application.

### INTRODUCTION

To cope with the energy crisis, energy conservation is one of the most important problems in the world. The demand for high-efficiency air conditioning equipment is increasing year by year. Under these conditions, Hitachi has been working on improving the efficiency of compressors, heat transfer elements and refrigeration cycles through an optimum combination of each component. The electric power consumption of a compressor accounts for about 90% of the total electric power consumption of an air conditioner, and improvement in compressor efficiency has a remarkable effect on improvement in the efficiency of an air conditioner.

Recently, to meet the demand for high efficiency, small-size, light-weight, low-noise, conventional reciprocating compressors have been replaced by a rotary-displacement type compressor. The efficiency of various types of compressors for air conditioners and refrigerators is shown in Figure 1. As shown, Hitachi has adopted a rolling piston-type compressor under the range of 1.1kW nominal capacity, and a screw-type compressor over the range of 22kW nominal capacity. But in the nominal capacity range of 1.1kW to 15kW, no rotary displacement-type compressor with higher efficiency has appeared, due to the improvement in reciprocating compressor efficiency. The recent history of reciprocating compressor efficiency improvement is shown in Figure 2. As shown, reciprocating compressor efficiency has been

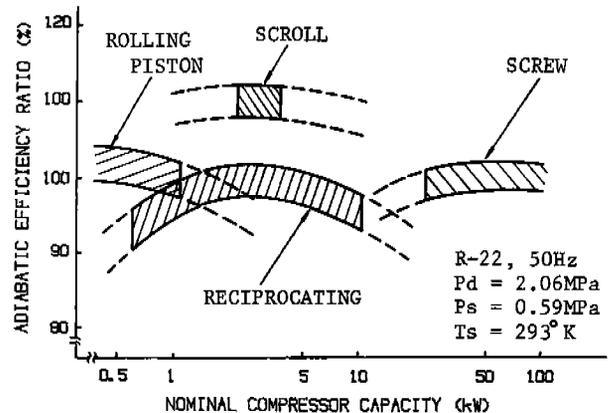


Figure 1 Adiabatic efficiency ratio of various types of compressors for air conditioners and refrigerators (Efficiency of 2.2kW reciprocating compressor is taken as 100%)

improved by more than 20% over the last several years. During these years of progress, almost all effective means of improving reciprocating compressor efficiency were applied<sup>4),5)</sup>, and further significant improvement at an acceptable cost did not seem likely. Therefore, the development of a new type of high efficiency compressor was required. With this in mind, a new type of compressor with scroll wraps was developed and put into commercial production in 1983. The scroll compressors are mounted on heat pump-type air conditioners of 2.2~4.4kW nominal capacities.

The concept of a scroll fluid machine is very old. It was first described in a U.S. patent in the 1900s<sup>1)</sup>, but not fully developed for practical application because of a lack of precise production techniques and component wear due to large axial gas force. To solve these problems, Hitachi developed a controlled thrust force mechanism to support the orbiting scroll in the axial direction with the lowest frictional force and wear yet achieved, and also developed a precise machining technique for mass production. In addition, computer simulation programs were frequently utilized to predict

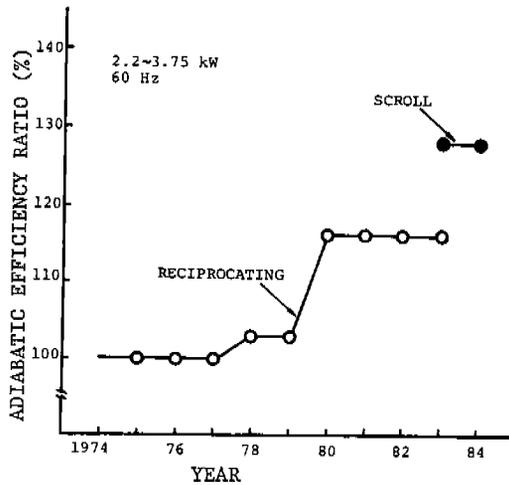


Figure 2 History of reciprocating compressor efficiency improvement (Efficiency of 2.2~3.75kW reciprocating compressor in 1975 is taken as 100%)

compressor efficiency, to optimize the spiral scroll profile, and to analyze the strain and stress occurring in compressor components such as scroll wrap, frame member, Oldham ring, and crank shaft. In the controlled thrust force mechanism, the back pressure acting on the orbiting scroll is adjusted automatically by means of gas introduced through small apertures on the orbiting scroll plate. As a result, a high efficiency scroll compressor was developed which is 40% smaller, 15% lighter in weight, has 10% higher compressor efficiency and a noise level 5dB(A) lower than a conventional reciprocating compressor.

This paper outlines this revolutionary new scroll compressor for air conditioners which has a number of advantages for practical application.

### OPERATION

The main elements of a scroll compressor are the two identical involute spiral scrolls shown in Figure 3. They are assembled at a relative angle of 180°, so that they touch at several points and form a series of crescent-shaped pockets. One of the scroll members is fixed and the other orbits around the centre of the fixed scroll wrap. The orbiting scroll member is driven by a simple short-throw crank mechanism. The pair of contact points between the two spiral walls are shifted along the spiral curves. The relative angle of the two scroll members are maintained by means of an anti-rotation coupling mechanism located between the back of the orbiting scroll plate and the stationary part. The compression process is shown in Figure 4. The inlet port of the compressor is at the periphery of the scrolls. As the crank shaft rotates clockwise, gas is drawn in at the periphery, trapped in a pair of pockets, and compressed by volume reduction while moving toward the center of the spiral. The compressed gas is exhausted through the outlet port at the center of the fixed scroll. Since a new pair of compression pockets are formed with every shaft rotation, the same process goes on in sequence with the preceding process. The discharge flow is relatively continuous and no valves are required.

### CONTROLLED THRUST FORCE MECHANISM BY SELF-ADJUSTING BACK-PRESSURE

Several forces and moments act on the orbiting scroll due to the compression of gas as shown in Figure 5. One of the reasons why the scroll fluid machine has not been fully developed for practical application is the component wear resulting from the large axial gas force.

There have been several mechanisms to support the orbiting scroll in the axial direction, such as

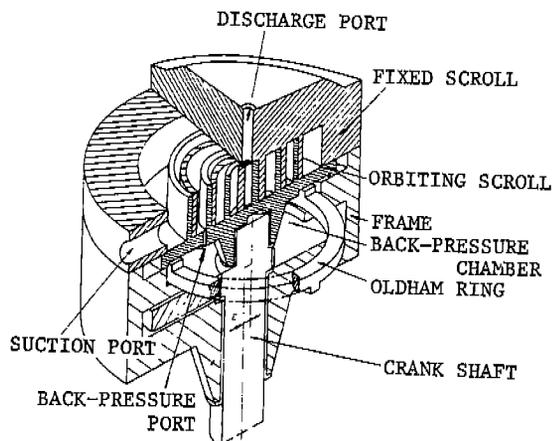


Figure 3 Basic configuration of scroll compressor

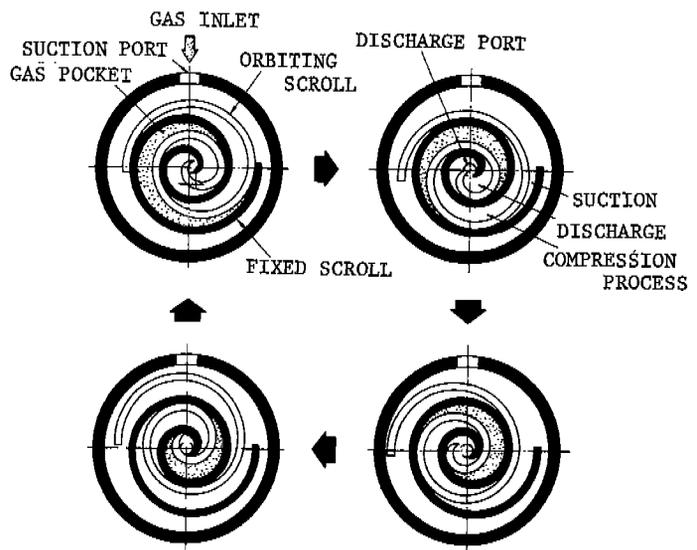


Figure 4 Principle of compression

arranging the thrust bearing on the back of the orbiting scroll, or forcing the orbiting scroll to the fixed scroll by means of mechanical spring or fluid pressure. The mechanism using fluid pressure on the back of the orbiting scroll has the lowest frictional loss<sup>2)</sup> among them. Since the condensing pressure and evaporating pressure for air conditioners and refrigerators undergo with refrigeration load, it is hard to maintain the fluid pressure in the proper range on the back of the orbiting scroll. Therefore, a controlled thrust force mechanism by self-adjusting back-pressure was developed.

The fundamentals of this mechanism are shown in Figure 6. Behind the orbiting scroll, so-called back-pressure chamber is provided. The periphery of the orbiting scroll plate fits between the fixed scroll plate and frame member with small axial clearance, which provides a sealing arrangement with axial compliance to maintain the seal between the back pressure chamber and suction chamber, and stabilizes the orbital motion of the orbiting scroll during the transient conditions when the operating pressure changes instantaneously (such as during start-up, shut-down, and switching of the cycle from cooling or heating to defrosting).

On the orbiting scroll plate, small apertures (back-pressure port) are located in positions opened to the intermediate compression gas pockets. The back-pressure chamber is pressurised automatically at a level between the suction and discharge pressure by means of gas introduced through the small apertures, and provides axial pneumatic force against the back of the orbiting scroll. The pneumatic force supports the orbiting scroll in the way of reacting the axial force and moment, and maintains an axial seal at the tips of the scroll

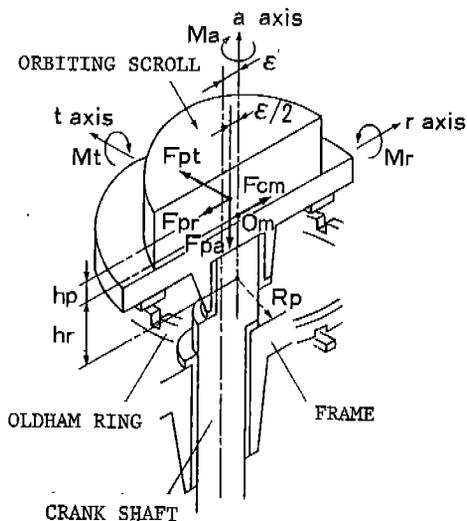


Figure 5 Forces acting on the orbiting scroll

wrap with minimum friction and wear. This mechanism provides several advantages as follows:

- a) The axial sealing at the tip of the scroll wrap is maintained without the influence of assembling tolerance.
- b) The axial pneumatic force on the back of the orbiting scroll is obtained automatically at a proper range level, and supports the orbiting scroll with lowest frictional force over a wide operating range.
- c) A sealing arrangement with axial compliance permits the orbiting scroll to move upward and downward either in response to gradual wear, or to compensate for the temporary presence of noncompressible material (such as a slug of liquid refrigerant or lubricating oil) and avoid excessive compression.

#### HERMETIC TYPE SCROLL COMPRESSOR

A cross-sectional view of the Hitachi hermetic type scroll compressor is shown in Figure 7. The scroll assembly is housed in the top of the cylindrical hermetic case. The drive motor is a 2-pole refrigerating compressor motor and is located below the scroll assembly. The fixed scroll and motor stator are mounted on frame member which is attached to the inner wall of the hermetic case. An Oldham coupling fits between the back of the orbiting scroll plate and frame member. This coupling prevents rotation of the orbiting scroll and maintains its angular alignment during orbital motion. Behind the orbiting scroll, a back-pressure chamber is provided. A rotary sealing arrangement is provided at the bearing where the crank pin drives the orbiting scroll and where the crank shaft passes through the

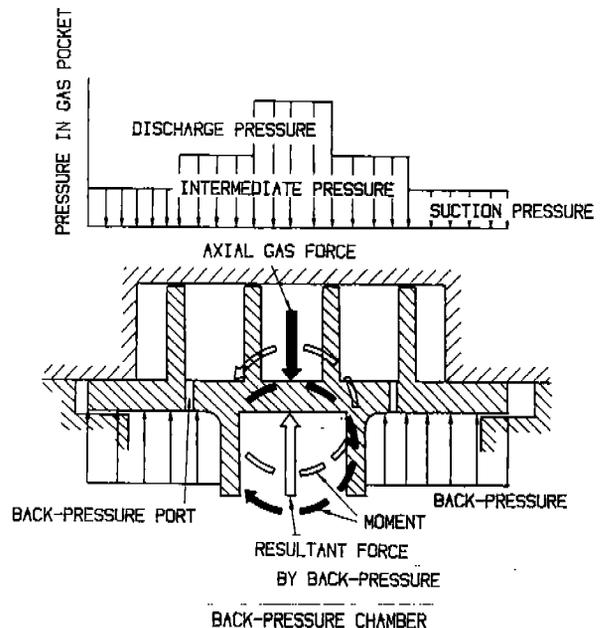


Figure 6 Controlled thrust force mechanism by self-adjusting back pressure

frame member to maintain a seal between the back-pressure chamber and the interior of the hermetic case.

Refrigerant gas flows directly into the periphery of the scrolls where it is trapped, then compressed, and discharged from the centre of the fixed scroll to the interior of the hermetic case. The discharged gas flows downward over the coil of the driving motor and finally is exhausted through the discharge pipe, so the interior pressure of the hermetic case is maintained at the discharge pressure level. Lubricating oil is supplied to the bearings from the bottom of the hermetic case through a path machined in the crank shaft by the force caused by the pressure difference between the interior of the hermetic case and the back-pressure chamber. Oil is finally introduced into the compression gas pockets through the back-pressure ports and lubricates the spiral walls. A large portion of oil is separated in the hermetic case and drains back to the bottom.

#### Specifications

General specifications of scroll compressors are shown in table 1. Each type of scroll wrap has the same profile but a different axial height (i.e., the displacement volume is different). In addition to the standard type 2.2kW, 3.0kW, 3.75kW series, the 2.5kW, 3.3kW, 4.4kW series with a gas injection system have been developed. In the gas injection system, cooling and heating capacity are enlarged by 10% to 15%. The gas injection system can be applied to scroll compressors with little difficulty. The outer dimensions and weight of scroll compressors are reduced by 40% in volume and 15% in weight compared with conventional reciprocating compressors.

#### General features

The Hitachi scroll compressor has a number of useful features for practical application derived from the unique compression mechanism. These include:

- 1 High efficiency - due to
  - a) Refrigeration gas flowing directly into the suction chamber, which avoids the addition of heat to the suction gas. There is no process analogous to the re-expansion in a reciprocating compressor. The pressure difference between the two neighboring compression gas pockets is much smaller than the total pressure difference of the discharge and suction pressure. The unique mechanism also provides good axial sealing in the compression pockets with the help of lubricating oil. Thus a very small gas leakage loss and high volumetric efficiency is performed.
  - b) All points in the orbiting scroll moving in a synchronization with the small radius, which results in low friction loss due to low rubbing speed.
2. Low vibration / noise level - since
  - a) No valves are required and discharge flow is relatively continuous.
  - b) The compression process is performed slowly and two to three compression processes go on simultaneously as shown in Figure 8. This results in a smooth operation and little

fluctuation in shaft driving torque. The instantaneous driving torque variation is shown in Figure 9. The fluctuation of driving torque in scroll compressors is about one-tenth that in rolling piston-type and the reciprocating-type compressors.

3. High reliability at acceptable cost due to its simplicity, few moving parts, low vibration, and low rubbing speed, coupled with the fact that it requires no valves. Furthermore, the controlled thrust force mechanism provides the compliance, which avoids damage or failure resulting from heavy liquid slugging.

#### TYPICAL PERFORMANCE

Several examples of scroll compressor performance are shown as follows.

The relation between volumetric efficiency and adiabatic efficiency is shown in Figure 10. These results are measured by various compressors with different axial and radial clearances in scroll wrap.

It is obvious from this figure that the adiabatic efficiency strongly depends on volumetric efficiency. On the other hand, volumetric efficiency depends on clearances in scroll wrap, especially axial clearance (between the tip of the scroll wrap and scroll plate). The precision production technique and unique controlled thrust force mechanism provide volumetric efficiency higher than 95%.

An example of a p-v diagram of the compression process provided by pressure transducer measurement in comparison with analytical results is shown in Figure 11. With the scroll wrap configuration of this type, three pressure transducers are mounted on the fixed scroll to indicate the entire compression process in a particular gas pocket. As shown in this figure, a small amount of gas drawing in and out through the back-pressure port expands the pressure line outward during the compression process when the gas pocket open to the back-pressure port, and results in compression power loss.

The p-v diagram is used to determine the effective gas compression power and losses. Almost all of the power losses of compressor are due to mechanical friction loss, followed by motor loss and thermo-fluid loss. These losses are outlined in Figure 12. In this figure, power loss of a conventional reciprocating compressor is taken as 100%. The total power loss of a scroll compressor is reduced by 27% as compared with a reciprocating compressor. In particular, thermo-fluid loss related to gas leakage loss, passage pressure loss and additional heat to the compression gas is found to be less than half that of a reciprocating compressor.

Computer simulation programs are utilized to determine the effect of leakage within compression gas pockets and the small amount of gas drawing in and out through the back pressure ports on the compression efficiency and pressure level in the back pressure chamber.

Some computed results are shown in Figure 13. In this figure, adiabatic efficiency under normal conditions (no gas flow through back pressure ports) is taken as 100%. As is evident from this figure, the larger the effective flow passage area at the back pressure ports, the lower the compression efficiency and the higher the pressure level in the back-pressure chamber are. But under practical operating condition, the effective flow area at the back-pressure port is considerably small, and the resulting efficiency reduction is negligible.

The volumetric efficiency and adiabatic efficiency in comparison with that of a reciprocating compressor is shown in Figure 14. In this figure, efficiency of a reciprocating compressor at the pressure ratio of 3.5 (design pressure ratio) is taken as 100%. A great improvement of volumetric efficiency is seen over a wide range of operating pressure ratios. The resulting adiabatic efficiency is about 10% at the design operating pressure ratio, and at the range of high pressure ratio the improvement in adiabatic efficiency is more remarkable. Therefore, a scroll compressor is suitable for application to a heat pump-type air conditioner.

The sound pressure spectrum of the scroll compressor at a distance of 1m from the surface of the hermetic case is shown in Figure 15. Sound pressure level of the scroll compressor is lower over the whole range of frequencies, and overall sound pressure level is lower by 5dB(A).

#### CONCLUSION

A high efficiency hermetic type scroll compressor with unique controlled thrust force mechanism was developed and put into commercial production in 1983. The scroll compressors are mounted on heat pump-type air conditioners with nominal capacities of 2.2~4.4kW. The development program results in a number of advantages, as listed below:

- 1) 10% higher compressor efficiency.
- 2) 40% smaller outer dimensions and 15% lighter weight.
- 3) smooth operation and 5dB(A) lower noise level.

- 4) simple construction with fewer moving parts and high reliability.
- 5) low cost and high productivity.  
(compared to a conventional Hitachi reciprocating compressor)

The scroll compressor contributes to energy conservation in air conditioning and refrigerating, and leads the way to the compressors of tomorrow.

#### ACKNOWLEDGMENT

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Table 1 Scroll compressor specifications

DESCRIPTION		MODEL	300RH	330RH	400RH	450RH	500RH	600RH
NOMINAL OUTPUT		kW	2.2	2.5	3.0	3.3	3.75	4.4
DISPLACEMENT VOLUME		cc/rev	45.0		62.4		78.0	
OUTER DIMENSION	DIAMETER	mm	177.0		177.0		177.0	
	HEIGHT	mm	378.0		430.0		430.0	
WEIGHT		kg	31.0		36.0		37.0	
GAS INJECTION ATTACHED			NO	YES	NO	YES	NO	YES

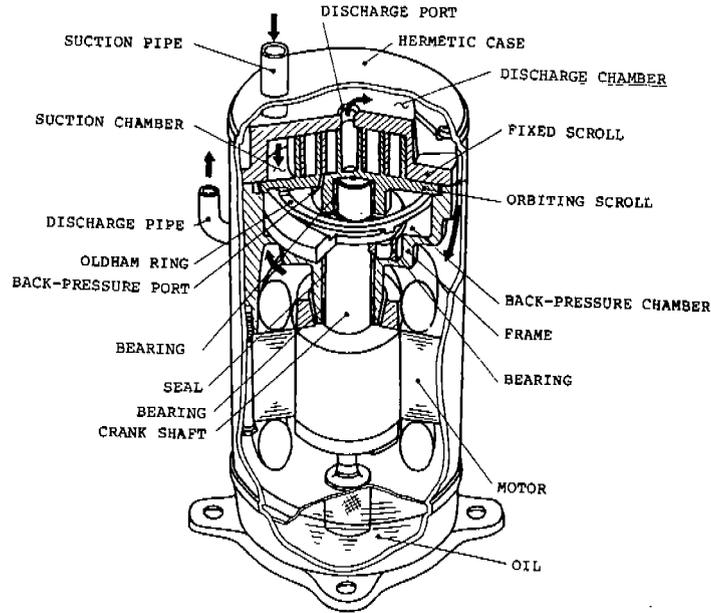


Figure 7 Cross sectional view of 3.75kW hermetic type scroll compressor

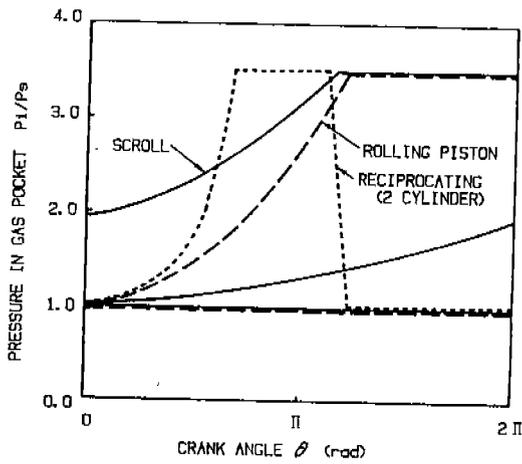


Figure 8 Pressure in gas pocket vs. crank angle

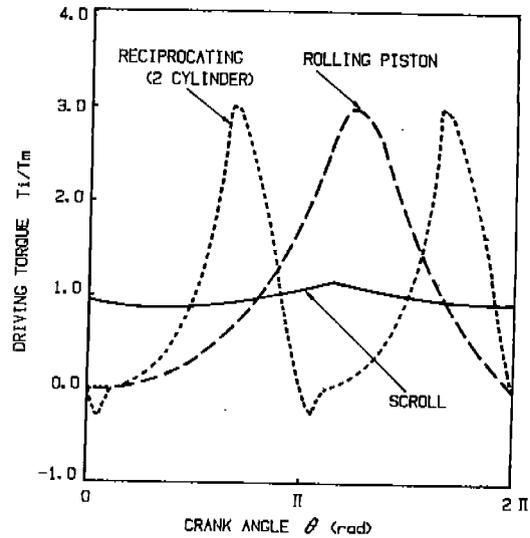


Figure 9 Driving torque vs. crank angle

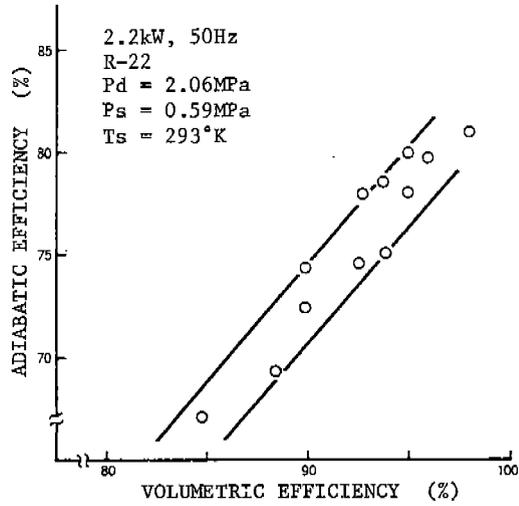


Figure 10 Relation between volumetric efficiency and adiabatic efficiency

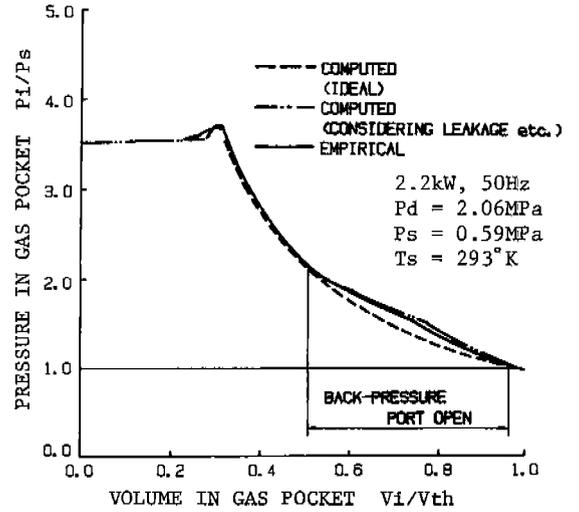


Figure 11 Pressure-volume diagram

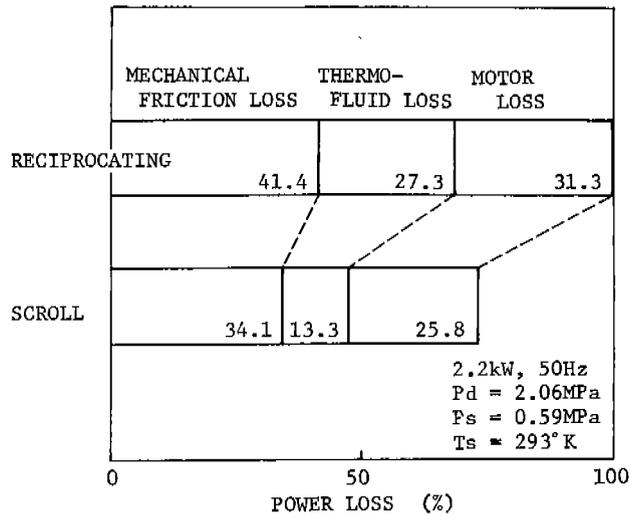


Figure 12 Comparison of power loss  
(Total power loss of reciprocating compressor is taken as 100%)

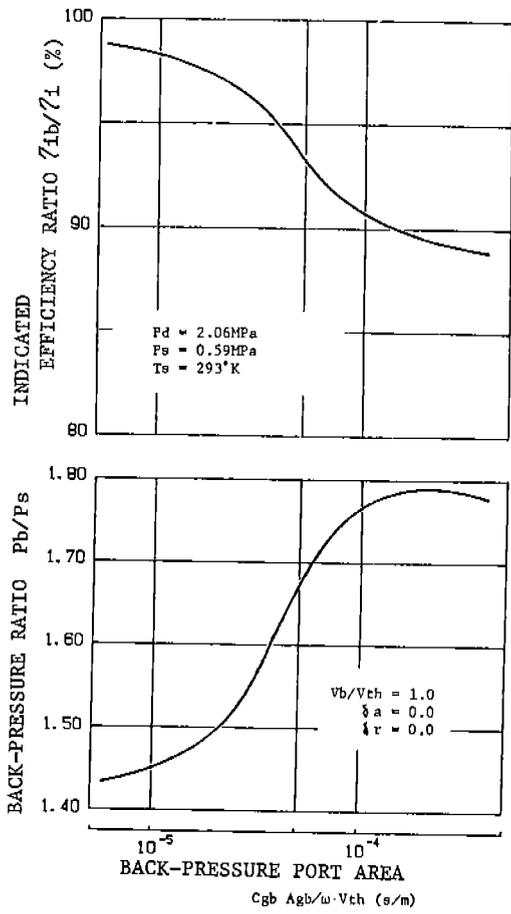


Figure 13 Variation of compressor efficiency and back-pressure with effective back-pressure port area

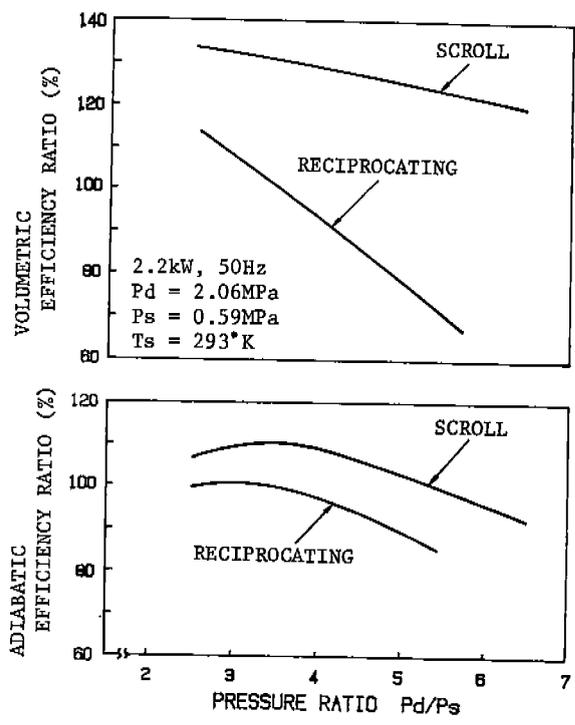


Figure 14 Volumetric efficiency and adiabatic efficiency (Efficiency of reciprocating compressor at pressure ratio of 3.5 is taken as 100%)

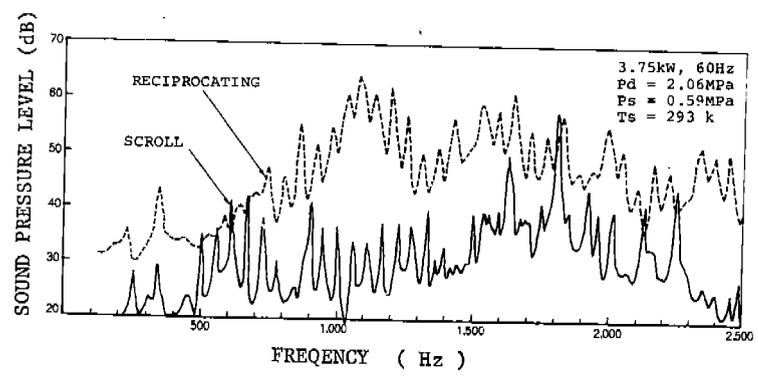


Figure 15 Comparison of sound pressure spectrum