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An Experimental Study of Frequency-Controlled Compressors

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AN EXPERIMENTAL STUDY OF FREQUENCY-CONTROLLED COMPRESSORS

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ABSTRACT

This report describes a study regarding the performance and reliability of frequency-controlled compressors combined with power frequency inverters, which are considered to be one of the strongest means of providing energy saving for air conditioners.

Items Related to Performance

Compressor capacity is available in proportion to a change in operating frequency. Moreover, since reduction in efficiency based on a change in operating frequency is very low, frequency-controlled compressors provide an ideal means of capacity control.

When the rotary compressor is operated at a relatively high frequency range (such as 30 Hz - 90 Hz) and the reciprocating compressor is operated at a relatively low frequency range (25 Hz - 75 Hz), the capacities of these compressors in proportion to a change in operating frequency can be obtained with low input and at high efficiency.

Regarding frequency-controlled compressors equipped to air conditioners, the improvement of EER at low load and the reuction of work loss due to ON/OFF cycling become possible. Especially, the difference in required capacity between cooling and heating can be eliminated in heat pumps, and a 20% - 40% improvement in SEER can be realized in comparison to the general ON/OFF control method.

Items Related to Reliability

For rotary compressors, the countermeasures to reduce the amount of oil discharged from the compressor in high operating frequency areas and to reduce the wear of the sub-bearing valve seat were performed.

For reciprocating compressors, an improvement of oil pump performance in low operating frequency areas and the prevention of resonance in the discharge piping over the full operating range were obtained.

INTRODUCTION

In air conditioners, various energy-saving countermeasures have progressed based on recent changes in the energy environment. Regarding an evaluation method for efficiency, not only energy efficiency (EER) during rated operation, but also seasonal energy efficiency (SEER) under actual operating conditions have received a considerable amount of attention.

On the other side, in the field of small-sized air conditioners for households, offices and residences, an ON/OFF control system, which is a cheap and simple method, is generally utilized as a capacity control system. However, since the rated capacity of air conditioners is selected based on the maximum capacity throughout the year at the installation location, there is a disadvantage regarding the ON/OFF control system in that a reduction in SEER could not be avoided due to the large loss caused by frequent ON/OFF cycling under actual loaded conditions.

Therefore, compressors for which the capacity can be controlled according to the load to the air conditioners have come to be requested in order to improve the reduction to this ON/OFF control. In order to perfectly perform this capacity control, the following items are considered as conditions.

Capacity control shall be continuously performed under loaded conditions.

When the capacity decreases, motor input decreases at the same time. During such a partial load operation, the efficiency of the compressor shall not be decreased.

The efficiency under a fully-loaded condition shall not decrease due to the capacity control device.

The reliability of the compressor shall not decrease.

There are various types of actuallyutilized capacity control systems, as shown in Table 1, but the system which optimally matches the conditions described above is the frequency-controlled compressor method. Moreover, an inverter which is applicable to air conditioners has become possible regarding practical utilization from the standpoint of cost and size due to recent rapid progress in the field of electronics, and the continuous capacity control system based on a combination with the inverter has become a very strong method of energy saving.

The authors performed study and development of the frequency-controlled compressor, and this type of reciprocating type compressor has been mass-produced since 1980, while this type of rotary type compressor has been mass-produced since 1981. Since it appears that the frequency-controlled compressor will be a strong method for improving SEER in the future, the following report is submitted.

TEST MODEL

The compressors utilized in this study are based on the compressors manufactured by TOSHIBA CORPORATION, and two-pole induction motors, newly-developed for inverter drive, were utilized in the compressors. In order to ensure sufficient reliability over a wide operating frequency range, various measures were incorporated. The outline for these compressors is given below.

Rotary Compressor

The rotary compressor is a hermetic type compressor where the mechanical structure and motor assembly are directly fixed in the same shell, and where the shell is sealed by means of welding.

For the compression mechanism, the rolling piston type, equipped with a roller which rotates in an eccentric manner, was adopted. Additionally, suction gas is sucked directly into the cylinder, and compressed gas is discharged into the shell.

The aforementioned type of compressor system provides the following superior features.

The rotary compressors are highly-efficient because there is no wire-drawing due to the suction valve, in addition to minimum heating of the suction gas.

The compressors employ a comparatively simple lubrication system for lubrication of the mechanical structure, and possess high lubricating performance.

The compressors are small in size, light in weight and possess low-noise characteristics.

Additionally, the basic items incorporated to ensure reliability over a wide operating frequency range are as follows.

Adoption of a Liquid Injection System Due to Prevention from Overheating in the High Operating Frequency Range

Adoption of a Disc to Separate the Oil Due to Prevention of Rapid Increase Amount of Discharged Oil in the High Operating Frequency Range

Increase in Discharge Valve Seat Contact Area Due to Prevention of Increase in Valve Seat Wear in the High Operating Frequency Range

Reciprocating Compressors

The reciprocating compressor, for which the sectional view is shown in Fig. 2, is a fully-enclosed type where the mechanical structure and motor assembly are fixed through a spring in the same shell, and where the shell is sealed by welding. For the compression system, a connecting rod system consisting of a connecting rod to convert the rotating movement to the reciprocating movement and a piston to perform reciprocation, are adopted. Additionally, the low side case type was adopted, where suction gas is sucked into the case to cool the motor portion, then introduced to the cylinder, and the compressed gas is discharged directly out of the shell.

The aforementioned reciprocating compressors possess the following superior characteristics.

Very Little Work Loss Due to Sliding Friction of the Bearing, and High Efficiency

High Reliability Under Various and Severe Utilization Conditions

Less Vibration Because the Compression Mechanism is Supported Inside the Shell

The basic items incorporated to maintain the reliability over a wide operating frequency range are as follows.

Adoption of a Two-Stage Oil Pump Due to Increase in Lubricating Capacity Over the Low Operating Frequency Range

Adoption of Ring Valve Due to Prevention of Decrease in Capacity Over the High Operating Frequency Range

Adoption of Damper Due to Prevention of Resonance in Discharge Piping Over Wide Operating Frequency Range

Experiment

The performance was measured by a secondary refrigerant system calorimeter, the pressusre in the cylinder was measured by a piezo type pressure transducer, the valve motion was meausred by a gap sensor, and discharge piping stress was measured by a strain gauge. R-22 was utilized as the primary refrigerant. The cardinal specifications and frequency operating range are as shown in Table 2.

Description of Symbols

η; Viscosity
N; Rotational Speed
r; Shaft Radius
c; Radial Clearance
U_o; Constant Depending on $\ell/2r$
U_m; Macky's Friction Factor
ℓ; Shaft Length
U; Tangential Velocity
F; Load
W_f; Lost Work Due to Bearing Sliding Friction
A; Length of Leakage Portion
ΔP; Pressure Difference
Q; Amount of Leakage per Revolution
γ; Specific Weight
g; Gravitational Acceleration
$C_d A_d$; Effective Flow Area
V; Cylinder Volume
ω; Angular Velocity
W_L; Compression Loss

ANALYSIS OF EFFICIENCY CHARACTERISTIC DUE TO FREQUENCY CHANGE

The energy flow of the compressor is in the order of electric input, motor shaft output, operation of compression structural drive, gas suction, compression and discharge (refer to Fig. 3). Efficiencies influencing these processes are motor efficiency (including inverter efficiency), mechanical efficiency, volumetric efficiency and compression efficiency.

Table 3 was comprised based on theoretical analysis and experiments, and shows the curve characteristics in the respective efficiencies and the overall efficiency related to frequency.

The motor efficiency and the volumetric efficiency of rotary compressors are improved when the operating frequency is increased. Conversely, the mechanical frequency, compression efficiency and volumetric efficiency of the reciprocating compressor are improved when the frequency is reduced. The overall compressor efficiency, which is the synthesis value of these respective efficiencies, decreases only slightly in the low operating frequency range, is approximately flat, and shows ideal characteristics.

The results of the experiments and theoretical investigation are explained hereunder.

Motor Efficiency

The block diagram of the inverter for the test motor is shown in Fig. 4, and the inverter control system in the test is PWM control of V/F = constant control.

This system possesses the highest efficiency as an induction motor control system, and rotation is possible at high speed. The general output loss characteristics are shown in Fig. 5, and the actual measured characteristics are shown in Fig. 6. Regarding motor efficiency, the higher the operating frequency becomes, the more the motor efficiency is improved.

Mechanical Efficiency

Since the quantity of lubricating oil was increased so that the proper lubricating conditions could be obtained, the lubricating conditions of the respective sliding surfaces are the same. If the lubricating conditions are the same, friction work loss will decrease further, and the mechanical efficiency will be improved, as shown below, when the operating frequency decreases.

The friction coefficient of the hydrodynamic lubrication area is theoretically obtained, and it can be sufficiently investigated by means of Macky's empirical formula.

$$\mu_M = 33.3\left(\frac{\eta N}{P}\right)\left(\frac{r}{C}\right)\times 10^{-10} + \mu_o \qquad (1)$$

$$W_f = 38.2\,\eta l U^2\left(\frac{r}{C}\right)\times 10^{-7} + 60\mu_o F U \qquad (2)$$

The first term of equation (2) is proportionate to the frequency raised to the second power, and the second term is proportionate to the product between the frequency and the load.

The work loss of the boundary lubrication area is proportionate to Coulomb's friction; that is, the product between the frequency and the load.

Volumetric Efficiency

In capacity-controlled compressors, volumetric efficiency is very important, and it is necessary that the volumetric efficiency shows good values over the respective operating frequencies.

$$Q = \frac{AB^2 \Delta P}{12\eta l N} \qquad (3)$$

Rotary Compressor

The volumetric efficiency of the rotary compresor is determined primarily according to the leakage from the sliding surfaces. If this leakage is assumed to be a steady incompressible viscous flow, the flow per revolution will be according to the following formula. That is to say, the formula shows that the volumetric efficiency becomes high when the frequency becomes high. The experimental values are shown in Fig. 7. A higher volumetric efficiency was obtained according to a higher operating frequency.

Reciprocating Compressor

The volumetric efficiency of the reciprocating compressor is primarily determined according to the top clearance, heating of the suction gas and opening/closing delays of the suction/discharge valves. The opening/closing delays vary according to the frequency. Ring type valves were adopted for the valve assembly, with the intention of improving the increase in gas flow area and opening/closing delays of the valves.

The volumetric efficiencies of the ring valve and the leaf valve are shown in Fig. 7. The ring valve shows a higher volumetric efficiency than the leaf valve.

Compression Efficiency

The compression efficiency is significantly related to work loss in gas suction and discharge (wire-drawing when gas is sucked into the cylinder and overcompression caused when the compressed gas is discharged out of the cylinder). This work loss is determined according to the gas flow area and the piston speed (volumetric variation rate of the cylinder chamber). The piston speed is shown in Fig. 8, and the work loss is shown in equation (5).

$$\Delta P = \frac{\gamma}{2g}\left(\frac{1}{C_d \cdot A_d}\right)^2 \cdot \left(\frac{dV}{dt}\right)^2 = \frac{\gamma}{2g}\omega^2\left(\frac{1}{C_d A_d}\right)^2 \cdot \left(\frac{dV}{d\theta}\right)^2 \quad (4)$$

$$W_L = \int \Delta P \, dV \quad (5)$$

Equation (5) shows that the compression efficiency becomes higher when the frequency is lower.

Calorimeter Test and Input Contents

The refrigerating capacity and overall efficiency (including inverter efficiency) of the compressor are shown in Fig. 9. The refrigerating capacity increases approximately in proportion to the operating frequency. The refrigerating capacity of the reciprocating compressor is slightly out of proportionate relation in the high frequency range due to the influence of the suction valve. The compressor overall efficiency shows an approximate flat line and a high value in the approximate 75% frequency range, and is the ideal characteristic.

The relation among electric input, motor output and net work is shown in Fig. 10.

SEER

The characteristics of an air conditioner equipped with the frequency-controlled compressor are shown in Fig. 11.

The significant feature among these is that the compressor can be operated at a high EER under partial load. The degree of high EER increased at lower loads (corresponding to the case of low operating rate in ON/OFF control). Additionally, this compressor can reduce the loss in cycling debit from starting to the stable condition in conventional ON/OFF control.

According to the calculation and experiments for SEER, the SEER of the set equipped with the frequency-controlled compressor is improved by 20% - 40% in comparison to ON/OFF control.

CONCLUSION

Frequency-controlled compressors display a capacity which is proportionate to the frequency, high compressor overall efficiency in almost all frequency ranges and ideal characteristics as capacity controlled compressors.

When the rotary compressor is compared with the reciprocating compressor regarding the frequency control range of frequency-controlled compressors, capacity which is proportionate to the frequency and high compressor overall efficiency are obtained from reciprocating compressors operated in the lower frequency range (25 Hz - 75 Hz) because of the equipped suction valve, the capacity is proportionate to the frequency, and high compressor overall efficiency is obtained from rotary compressors operated in the higher frequency range (30 Hz - 90 Hz), because there is no suction valve.

Improvements were performed regarding the following items, in order to ensure the reliability of frequency controlled compressors.

Rotary Compressors

Prevent Overheating During High-Frequency Operation

Decrease the Amount of Discharge Oil Out of the Compressor

Prevent Wear of Sub-Bearing Valve Seat

Reciprocating Compressors

Increase the Quantity of Shaft Lubricating Oil

Prevent Resonance in Discharge Piping

In air conditioners equipped with frequency-controlled compressors, 20% - 40% of SEER improvement was realized.

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Table 1. Capacity Control Method in Small-Sized Compressors for Air Conditioners

Control Method	Features
ON/OFF Operation	Control of the Capacity According to Operating Time Because of the simple structure and low pricem this method is generally utilized in small-sized air conditioning equipment. The work loss under partial load and at the time of starting is large, and the efficiency is decreased.
Cylinder Unloader (2 Cylinders)	Converting the Number of Operated Cylinders According to the Load Two-stage capacity control is possible, and capacity control of as much as 50% can be performed. Reduction of efficiency under partial load is small.
Twin Compressors	Converting the Number of Operated Compressors According to the Load Two-stage capacity control is possible, and capacity control up to 50% can be performed. The reduction in efficiency under partial load is zero.
Gas Injection	Controlling the Quantity of Discharged Gas According to the Load Two-stage capacity control is possible, but the capacity range is narrow and is between approximately 10% - 20%. The more the release is increased, the lower the efficiency becomes.
Two-Speed Motor (Two-Pole Four-Pole)	Converting the Number of Poles of the Motor According to the Load Two-stage capacity control is possible, and capacity control of as much as 50% is possible, but motor efficiency under partial load is decreased.
Inverter Drive	Controlling the Operating Frequency of the Motor According to the Load Stepless capacity control over optional ranges is possible, and optimum capacity control can be performed.

Table 2. Cardinal Specifications

	Stroke Volume	Rated Capacity (60 Hz)	Operation Frequency Control Range
Rotary	13.1 cc/rev.	2,300 kcal/h	30 Hz - 90 Hz
Reciprocating	69.7 cc/rev.	9,100 kcal/h	25 Hz - 75 Hz

Table 3. Efficiency vs. Frequency

	Rotary Compressor	Reciprocating Compressor
Motor Efficiency (Including Inverter)	Level ↗ Frequency	↗
Mechanical Efficiency	↘	→
Volumetric Efficiency	↗	→
Compression Efficiency	→	→
Overall Efficiency	↗→	↗→
	(30 Hz - 90 Hz)	(25 Hz - 75 Hz)

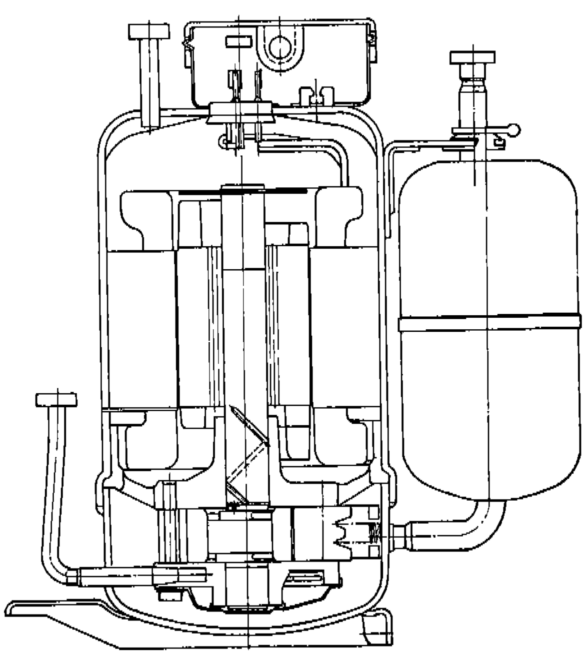

Fig. 1. Rotary Compressor

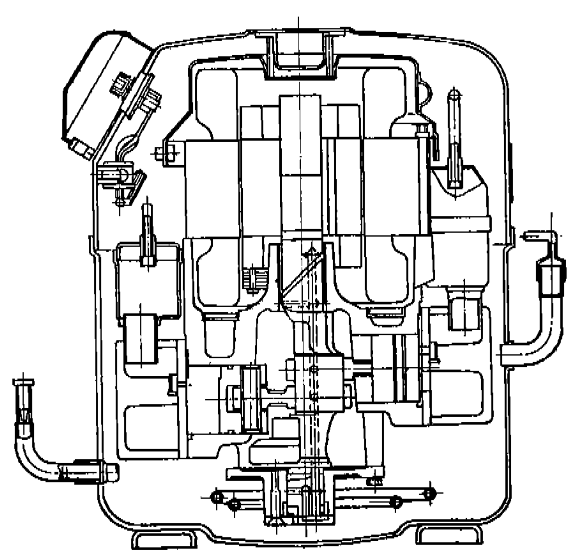

Fig. 2. Reciprocating Compressor

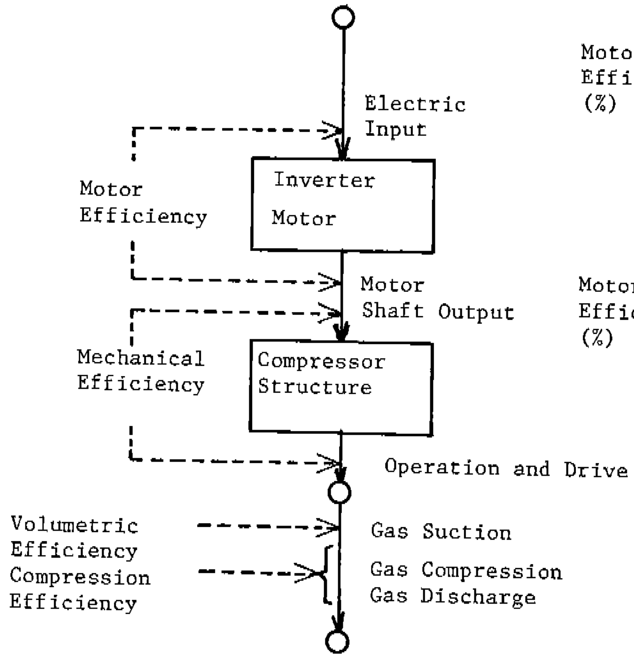

Fig. 3. Flow of Energy in Compressors

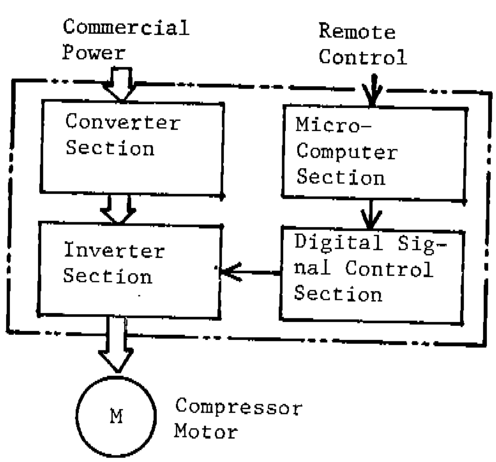

Fig. 4. Block Diagram of Inverter

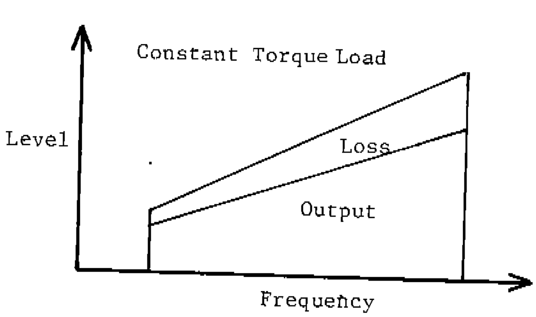

Fig. 5. Characteristics of Motor of V/F-Constant Control

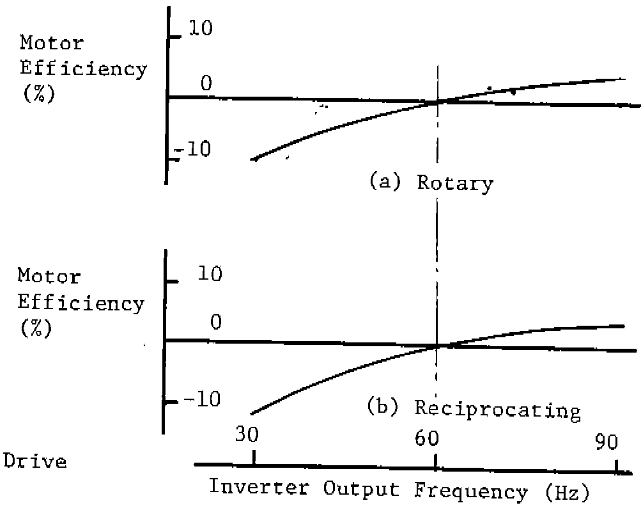

Fig. 6. Motor Efficiency Curve; Inverter-Driven Motor

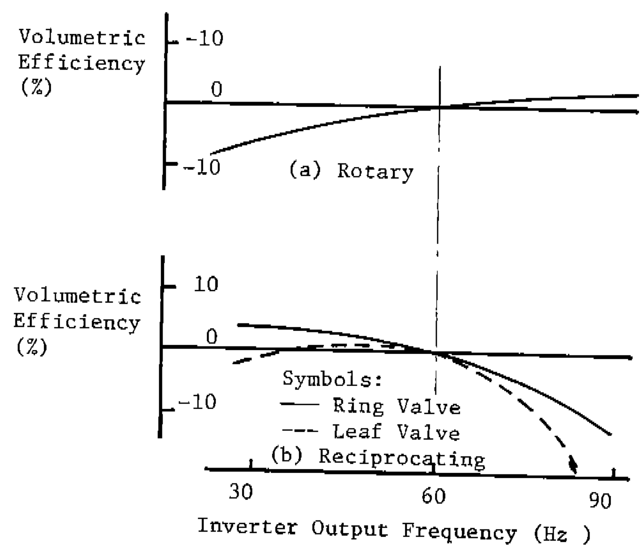

Fig. 7. Volumetric Efficiency vs. Frequency

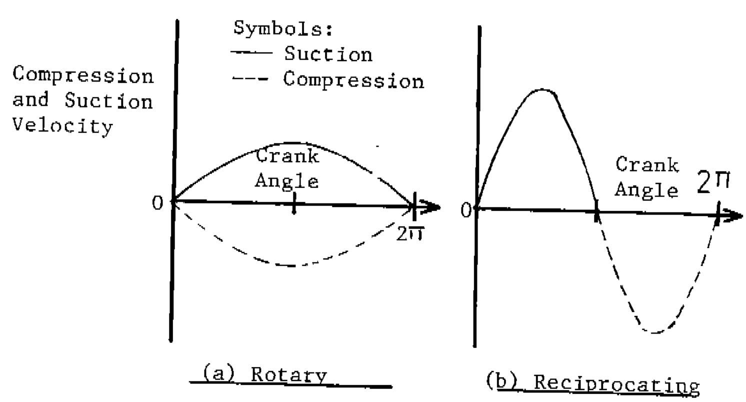

Fig. 8. Shape of Suction and Compression Velocity

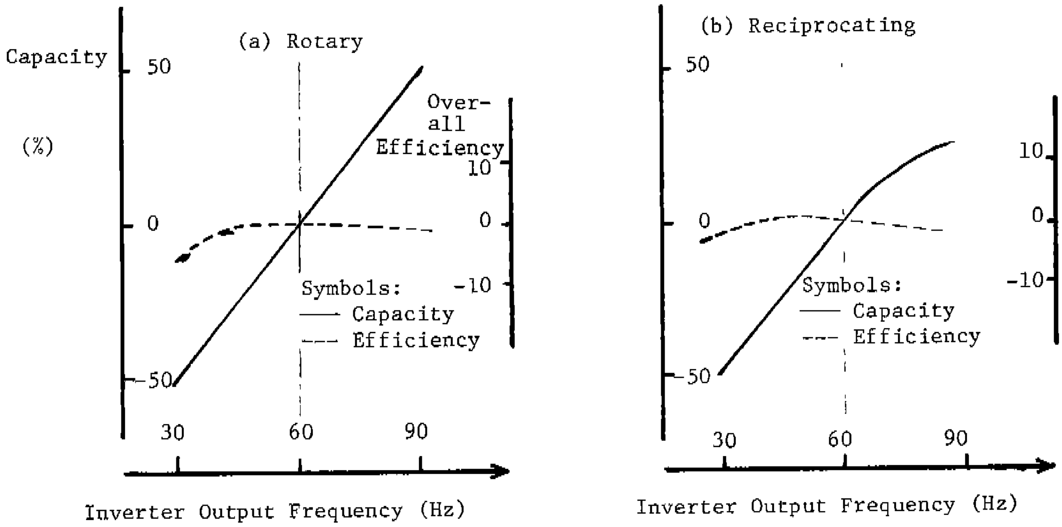

Fig. 9. Capacity and Overall Efficiency vs. Frequency

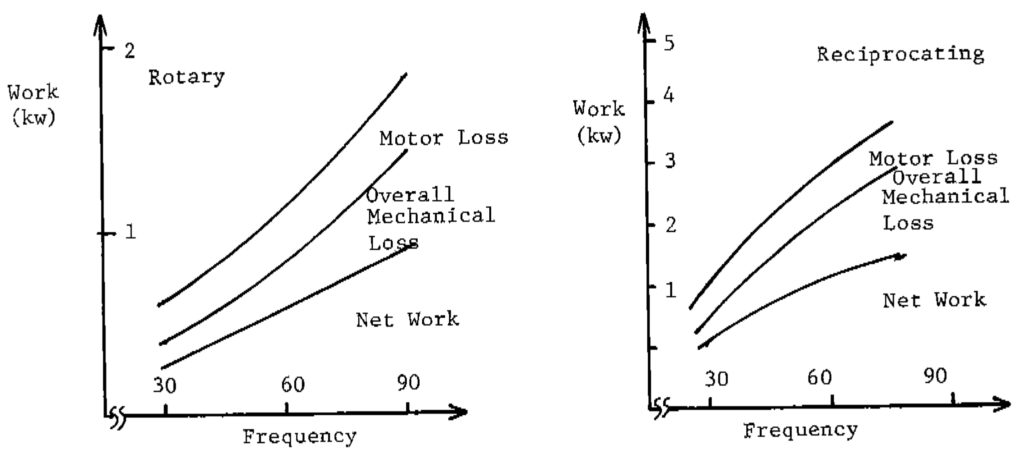

Fig. 10. Power Input, Motor Output, Net Work vs. Frequency

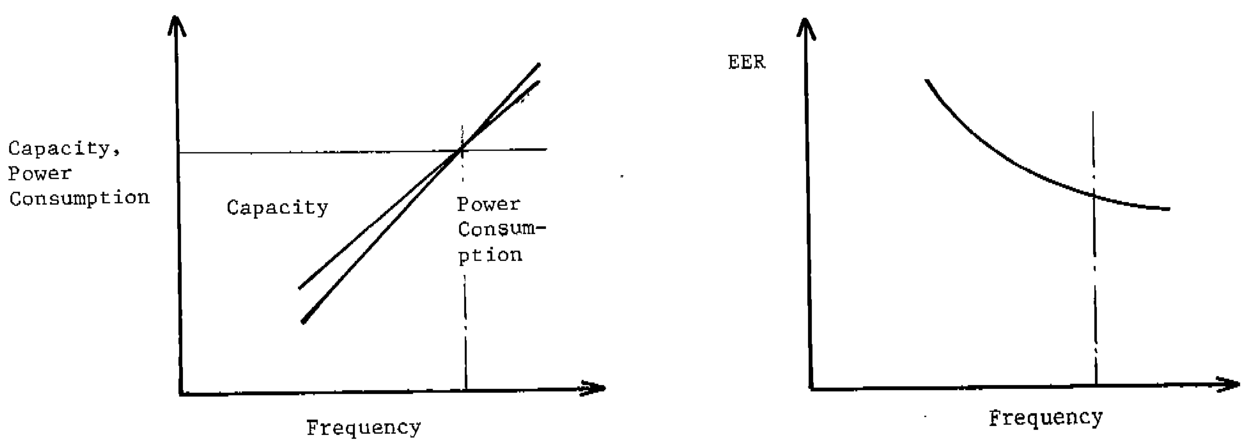

Fig. 11. Power Consumption, EER, Capacity vs. Frequency