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Over 81% of domestic passenger cars produced in 1977 were equipped with factory installed air conditioning systems. Additionally, 1.4 million air conditioning kits are manufactured annually for after-market installation on U.S. vehicles. The popularity of this accessory plus current concerns for energy conservation, weight and space limitations, and pending regulation of refrigerants are placing new application requirements on mobile air conditioning components. This paper will review the application requirements of automotive air conditioning compressors and present the operating characteristics of a rotary vane compressor developed by York Automotive Division of Borg-Warner Corporation.

APPLICATION CONSIDERATIONS

Design and application requirements of refrigerant-12 automotive air conditioning systems are unique. The following parameters present some of the more difficult aspects of automotive compressor design:

Speed Vs. Load- Automotive compressors are belt driven directly from the engine and therefore, operate through engine speed ratios of 10:1. For example, engine idle speed may be 600 rpm and the maximum speed may be 6000 rpm. Automotive cooling loads frequently vary inversely with compressor speed; i.e. maximum cooling requirements can be encountered when the vehicle is tied up in urban traffic with the engine operating at idle, and minimum cooling requirements can exist while the vehicle operates on the open highway. In addition, condensing capacity is severely limited under engine idling conditions because condenser air flow depends on engine cooling fan speed and vehicle speed.

Temperature Range- Automotive systems operate in ambient temperatures from 35° F minimum to in excess of 110°F in order to provide the cooling and/or dehumidification needs of the occupants. Temperature under the hood surrounding the compressor and refrigerant lines may reach 250°F under high ambient idle conditions.

Space Limitations- The current trend of automobile manufacturers is toward smaller cars with lower hood lines and engines crowded by pollution controls. The automotive compressor must fit in a tight space between the engine and the radiator fan. With small frontal areas, the size of the automotive condenser is also sacrificed. Therefore, under high ambient idle operation, the refrigerant-12 pressure may reach 400 psig (197°F saturation).

Liquid Slugging- During low ambient, low load operation, the refrigerant entering the compressor may be a mixture of saturated gas and liquid which can be damaging to the internal parts of the compressor.

System Controls- Automotive compressors may be applied on either of two basic types of automotive systems. Cycling clutch systems are controlled by a variable thermostat mounted on the evaporator coil, which cycles the compressor clutch on and off to satisfy the comfort requirements of the occupants. Cycle rates under low loads may only be of a few seconds duration. There are also several types of evaporator pressure regulating controls in use today. However, they all require that the compressor operate continuously when the air conditioning selector is in the A/C mode and the ambient temperature is above 35-40°F. Operation below 35°F ambient is avoided because water vapor may condense and freeze on the evaporator coil.

Leakage- Automotive compressors are of the open-type as opposed to hermetic compressors which are sealed in a steel shell. Therefore, automotive compressors require mechanical shaft seals on the driven end and gaskets or O-rings to seal all exterior joints. Vibrations transmitted from the engine also place additional loads on gasketed joints. Regulations currently under consideration by the Environmental Protection Agency may produce lower limits than the current 1.0 ounce/year leakage rate which the industry has maintained for compressors.

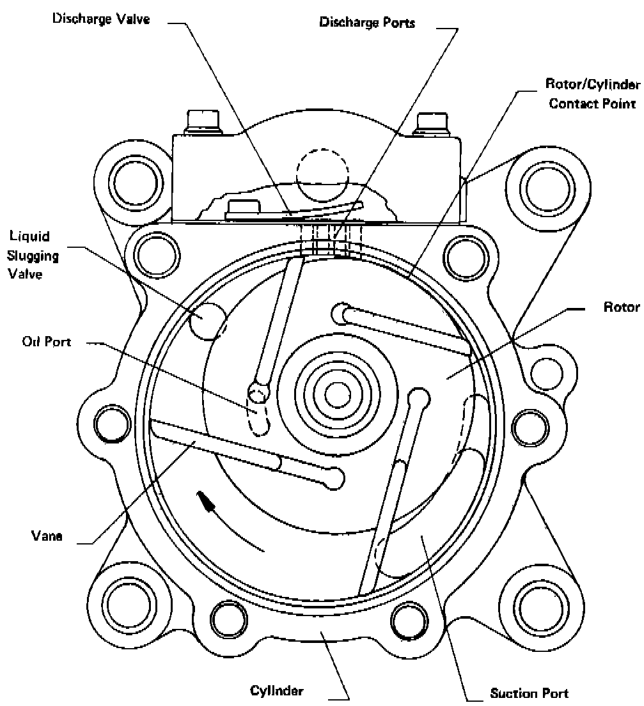


FIG. 1 MODEL 4912 ROTARY VANE COMPRESSOR

APPLICATION CHARACTERISTICS OF THE ROTARY VANE COMPRESSOR VERSUS THE TWO CYLINDER RECIPROCATING COMPRESSOR

York Automotive Division has developed a rotary vane compressor designated the Model VR4912 which has a 9.2 cubic inch displacement and four forward canted vanes (Figure 1). This compressor was designed to meet the application requirements of intermediate and full size passenger cars, trucks, off-highway and agricultural equipment. A smaller 7.0 cubic inch displacement compressor, Model VR4709, of a similar design was developed for applications on compact through intermediate size vehicles. Both models are designed for operation at drive ratios from 0.9:1 to 1.6:1 (compressor rpm to engine rpm), with a maximum operating speed of 9600 rpm. The compressors have an integral oil separator and do not require any external components such as suction line accumulators or discharge mufflers. They may be applied on systems with cycling clutch control or with evaporator pressure regulating control.

York Automotive Division has been producing automotive compressors of the two-cylinder reciprocating type for over twenty years. In this paper various characteristics of the rotary vane compressor, specifically the model VR4912, are compared to those of the York two-cylinder Model 210 design.

Cooling Capacity And Efficiency- There is no standard rating condition for automotive compressors which has industry-wide acceptance. In conjunction with its customers, YORK has used the following condition to rate the 4912 compressor:

Discharge Pressure	-	240 PSIG
Suction Pressure	-	20 PSIG
Suction Temperature	-	55 °F
Compressor Speed	-	Applied drive ratio times engine rpm

This rating condition is intended to represent a point at which a system stabilizes at 20 mph in a 110°F ambient temperature and is only approximate since the stabilized condition is dependent on the compressor, the system design, the vehicle and other ambient conditions in addition to temperature. Table 1 compares the Model

TABLE 1

	210 RECIPROCATING COMPRESSOR	4912 ROTARY COMPRESSOR	4912 ROTARY COMPRESSOR
Engine Speed	930	930	930
Drive Ratio	1.25	1.40	1.60
Compressor Speed	1160	1300	1485
Displacement-Cu. In.	10.3	9.2	9.2
Displaced Volume-CFM	6.9	6.9	7.9
Capacity-BTU/HR	9,100	11,000	12,400
Horsepower	2.1	3.0	3.4
Horsepower/Ton	2.7	3.3	3.3
Volumetric Efficiency-%	67	81	81

FIG. 2 CAPACITY

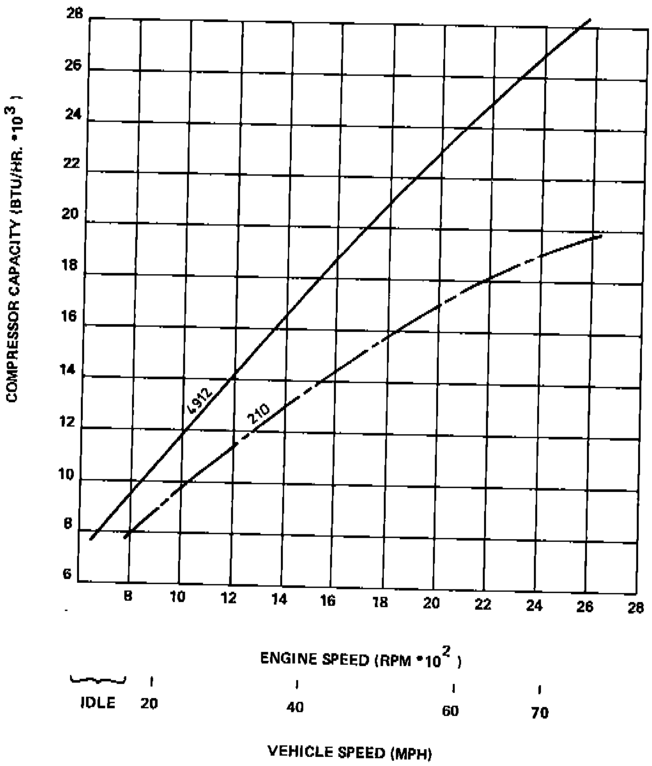
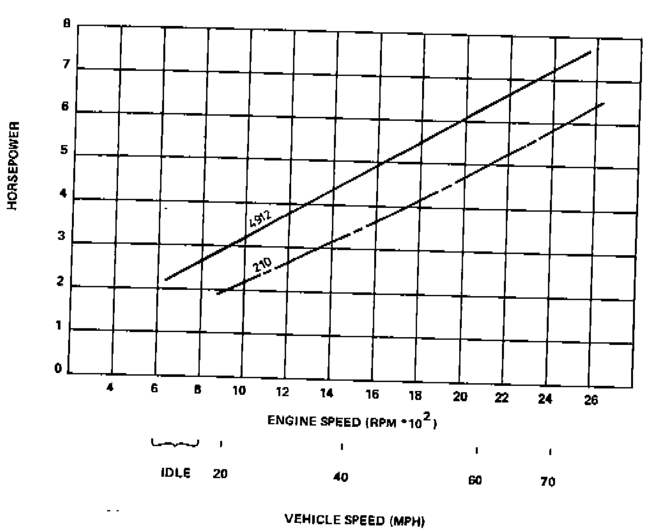


FIG. 3 HORSEPOWER



210 compressor and the Model 4912 compressor at the 20 mph rating condition. Model 210 data are given at a 1.25:1 drive ratio, the most common drive ratio for this compressor. Model 4912 data are given at a 1.4:1 drive ratio since the displaced volume of the 4912 at this drive ratio is equal to that of the 210 compressor at 1.25:1. Model 4912 data are also given at a 1.6:1 drive ratio, the maximum permissible drive ratio for the 4912. Curves

Test Conditions For Figures 2,3,4 and 5:
240 PSIG Discharge Pressure
20 PSIG Suction Pressure
55°F Suction Temperature
Compressor Drive Ratios:
Model 210 - 1.25:1
Model 4912- 1.40:1

FIG. 4 HORSEPOWER/TON

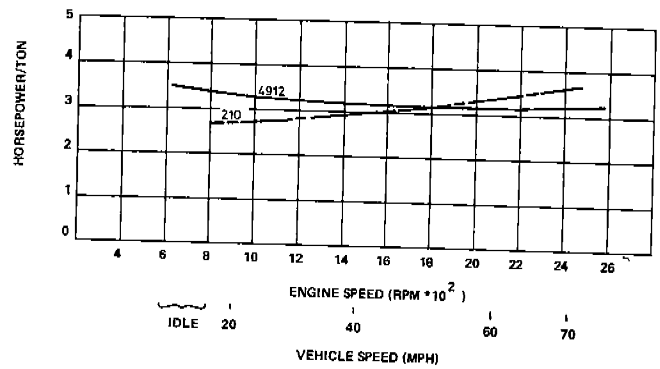
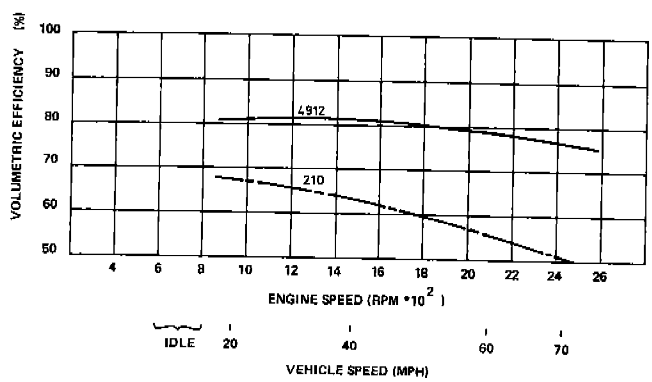


FIG. 5 VOLUMETRIC EFFICIENCY



comparing 4912 and 210 performance at the 240/20 psig rating point as a function of vehicle speed are shown in Figures 2, 3 4 and 5.

The horsepower/ton referred to in Table 1 is a measure of the operating efficiency of the compressor and is defined as the horsepower required to produce one ton (12,000 BTU/HR) of refrigeration. The compressor efficiency of the Model 210 is representative of the highest efficiency available in automotive compressors and, therefore, provides a challenging objective for the 4912.

The curves in Figure 4 compare horsepower per ton of the 4912 and 210 compressors at the 240/20 psig operating condition. Within the applied speed range and at the rating conditions described above, the horsepower per ton of the rotary compressor ranges between 3.1 and 3.4 while the 210 reciprocating compressor ranges between 2.7 and 3.6 horsepower per ton. At the drive ratios shown, the 4912 requires greater horsepower per ton than the 210 at vehicle speeds below 50 mph and less horsepower per ton at vehicle speeds above 50 mph. The rotary vane compressor is applied at higher drive ratios because the compressor efficiency generally peaks at a higher speed for the rotary compressor than for reciprocating compressors and because mechanical features may allow the rotary compressor to be operated at a higher maximum operating speed. The high drive ratio results in a more compact, lighter weight design.

The true measure of capacity of an automotive compressor is not what it does at a specific rating point, but how quickly it can cool a vehicle. As with calorimeter ratings, no standard pulldown test has been accepted by the industry. Generally, most pulldown tests are representative of operation under desert conditions. For example, YORK's test is run by soaking the car under a sun load (real or artificial) in a 110°F ambient temperature. Here the average inside car temperature stabilizes near 140°F. The vehicle speed is then established at 20 mph and the air conditioning system, adjusted to the maximum cooling setting, pulls down the inside car temperature. The average inside car temperature achieved at specified intervals during the pulldown is a measure of the pulldown capability of the system. The compressor begins operating with the system balanced and the operating pressure ratio continually increases throughout the test. For this reason, evaluating compressor pulldown capability by comparing compressors at one standard rating point may be misleading.

A comparison of pulldown data for the 4912 and 210 compressors at 20 mph is shown in Figure 6. For this test the drive ratio for the 4912 was 1.4:1 and for the 210 was 1.25:1 in order to compare the compressors on the basis of equal displaced volume. Figure 5, the volumetric efficiency curve, shows that the 4912 compressor cools the vehicle better because it is generally operating with a higher volumetric efficiency than the 210 compressor.

Compressor Reliability- To satisfy YORK's concern for a quality product, new automotive compressor designs are subjected to a variety of vehicle and laboratory endurance tests. The following tests have been selected to satisfy both the specifications of automotive manufacturers and the requirements of the International Mobile Air Conditioning Association.

A 636 hour laboratory endurance test is used to qualify a compressor for evaporator pressure regulating control systems. This test consists of 260 hours of continuous running at high speed; 150 hours of continuous running at high load idle speed; 15 hours of cycling at average speeds; 200 hours of cycling at high speed with saturated suction gas and four cycles of three minutes duration at the limiting speed of 9600 rpm.

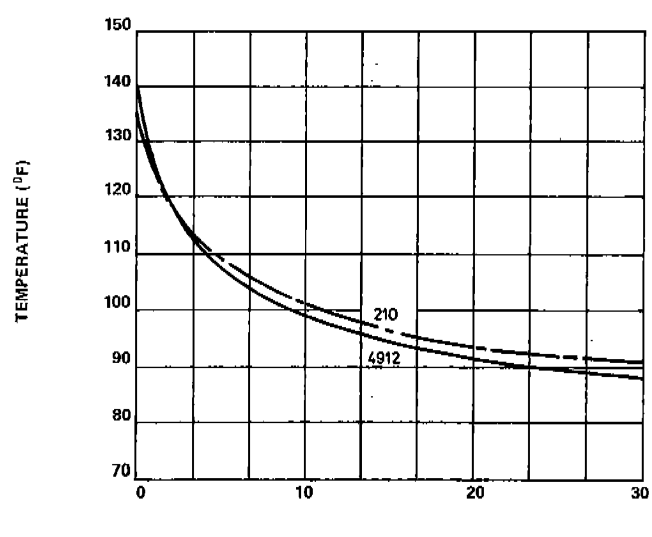
A 300 hour traffic simulation test, is used to simulate the automotive application. The compressor speed profile is controlled by magnetic tape to duplicate both city and highway driving, including downshift conditions to 8400 rpm. 75 hours are run at low evaporator loads, 75 hours at average loads and 150 hours at high loads.

For cycling clutch applications, YORK has initiated an 800 hour test which is similar to the previous 636 hour test, but with additional clutch cycling. The clutch is required to cycle 78,000 times during this test.

Laboratory tests of the 4912 compressor to the above specifications have demonstrated the durability of the design and its suitability for automotive applications. In addition to the laboratory tests, the rotary compressor has compiled more than six million miles of fleet testing on sales vehicles, taxi fleets and at a

FIG. 6 20 MPH PULLDOWN

AVERAGE INSIDE CAR TEMP.



commercial vehicle test facility in San Antonio, Texas. Typically, fleet tests are run for 50,000 miles. However, twenty rotary compressors were run for 100,000 miles and three of these test compressors were continued for 200,000 miles.

Noise And Vibration- As with the capacity rating condition, industry standards do not specify noise and vibration levels for automotive compressors. YORK, however, has a continuing program aimed at reducing the noise and vibration levels in its production and development compressors.

Evaluation tests are performed on laboratory test facilities using: strain gages to measure the shaft torque pulsations and linear force fluctuations (vertical, lateral and longitudinal); pressure transducers to measure suction and discharge gas pulsations; and a traveling microphone and rotating diffuser to measure airborne sound. These parameters are measured and recorded at two pressure ratios and throughout the compressor speed range.

The rotary vane compressor is inherently quieter and smoother in operation than the two-cylinder design[1]. For this reason, the operating characteristics of a six cylinder, axial piston compressor with a swash plate drive were selected as the comparison for the noise and vibration criteria for the rotary vane compressor. Several of these swash plate compressor designs are currently in production in the U.S.A. and Japan and are noted for their quiet, smooth operation. The following is a comparison of noise and vibration characteristics of these two compressor designs:

Shaft torque pulsations- In general, the rotary compressor exhibited lower peak to peak torque pulsations (10 to 22 ft.lb) than the swash plate compressor (9 to 33.5 ft. lb.) except at frequencies in the vicinity of 4000 rpm which is the torsional resonance frequency of the rotary vane compressor and clutch assembly (34 ft. lb. peak to peak amplitude). The swash plate compressor has a resonance point of greater amplitude (48 ft. lb. peak to peak) at 2100 rpm. These resonant frequencies are difficult to detect without the use of instruments.

Discharge gas pulsations- The rotary compressor peak to peak discharge gas pulsations are below 3.5 psi at all conditions tested, while the swash plate compressor ranges from 6 to 28 psi.

Suction gas pulsations- The swash plate compressor has lower overall peak to peak suction gas pulsations (3.5 psi maximum for the swash plate versus 12 psi maximum for the rotary compressor). While this feature is desirable, its importance is secondary to discharge gas pulsations because the magnitude of the suction gas pulsations is low and thus, less capable of creating disturbances in system lines and components.

Linear vibration- In these comparisons, the swash plate compressor has a resonant vertical response of 345 lb. at 4100 rpm as compared to a maximum 110 lb. force fluctuation for the rotary. Both compressors exhibited vibrations of low and relatively constant magnitude in the lateral direction (all below 150 lb). In the longitudinal direction and below 3600 rpm, both compressors were again equal and consistently low (50 lb). Above 3600 rpm, the swash plate compressor begins to increase and peaks at 410 lb. at 5900 rpm. The rotary compressor remains below 60 lb. throughout the speed range.

Airborne noise- This is the noise level one would experience when listening to an automobile engine and compressor from the front of the car with the hood up. The recorded sound pressure level, measured at 3 feet and 4000 compressor rpm was 94DBA for the swash plate compressor and 79DBA for the rotary compressor.

Size And Shape- Size and shape characteristics should be considered together. It is desirable to mount the compressor as close to the centerline of the engine as possible to limit the effect of compressor vibration. This can be accomplished by mounting the compressor in the space between the engine block and the cooling fan. For this reason, compressor length is probably the most critical dimensional requirement. Overall length for domestic automobiles is limited to about nine inches. Foreign vehicles may have less space available.

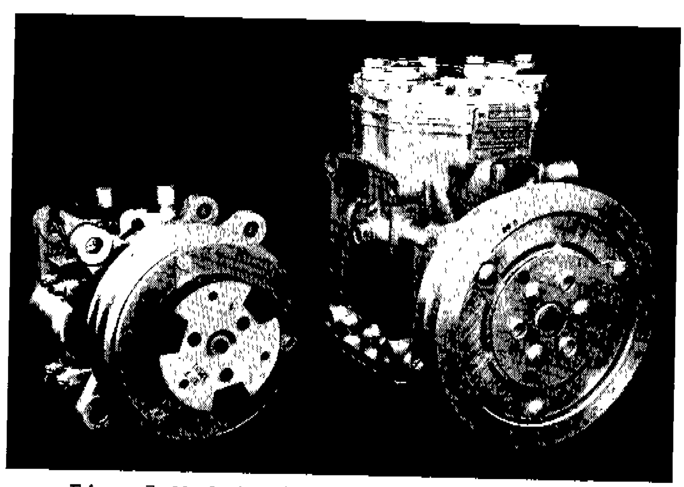


Fig. 7 Models 4912 and 210 Compressors

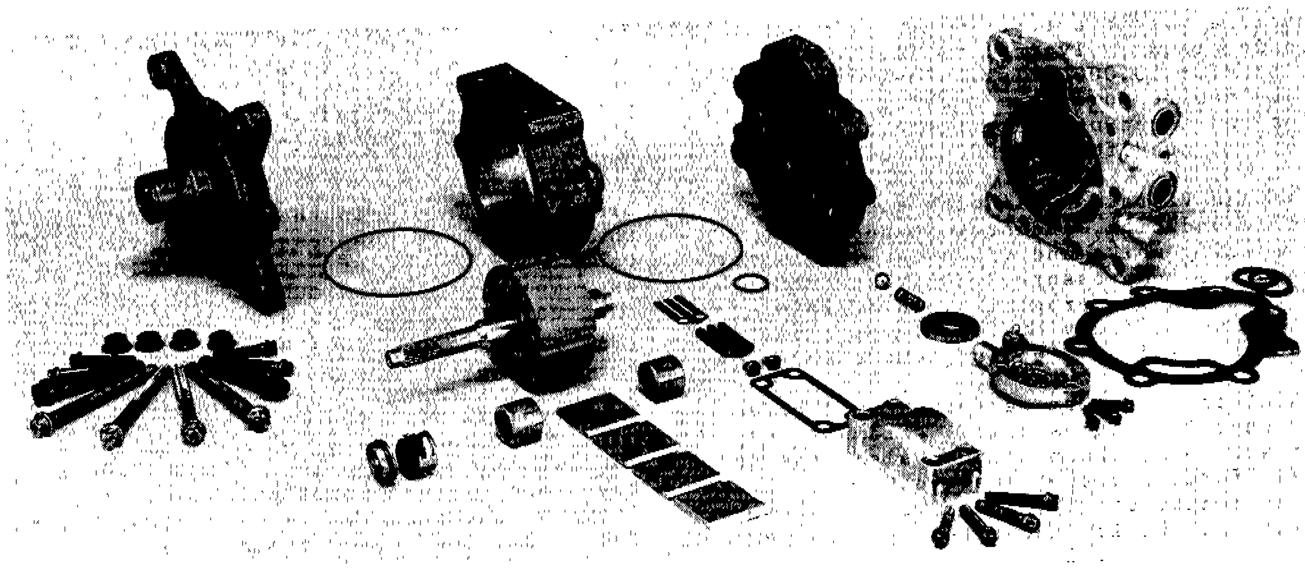


Fig. 8 Model 4912

The rotary vane compressor is inherently compact. It also has a cylindrical shape oriented in the direction of the engine shaft. This is the preferred shape for engine accessories such as the alternator, power steering pump, air pump, and starter. The 4912 compressor is 8.2 inches in length and easily meets the length requirements of most vehicles, both domestic and foreign. A size and shape comparison of the 4912 compressor with the 210 reciprocating design is shown in Figure 7. Both compressors are shown with electromagnetic clutches. The 210 clutch is larger because it is usually applied at a lower drive ratio.

Weight- Rotary vane compressors are usually constructed of ferrous metals for reasons of dimensional stability. The 210 reciprocating compressor is primarily constructed of aluminum. Due to the compactness of the rotary design and in spite of the material weight disadvantage, the rotary remains competitive in weight and at a moderate advantage when considered as a compressor-clutch package. The 4912 compressor with clutch weighs 20.4 pounds. The 210 reciprocating compressor with clutch weighs 24.1 pounds. Considered on a pound weight per ton of refrigeration basis, the 4912 is 22.3 and the 210 is 31.8.

Ease Of Manufacture- The rotary compressor requires tighter running clearances than a reciprocating compressor, but through selective assembly of the rotor, vanes and cylinder, machining tolerances are comparable to the reciprocating components. Assembly operations are fewer for the rotary compressor by virtue of the number of separate parts; 61 for the 4912 versus 93 for the 210 (Figure 8).

DESIGN CONSIDERATIONS FOR THE ROTARY VANE COMPRESSOR

Description- The rotary compressor consists of a slotted rotor, supported on needle bearings, and eccentrically located in a round cylinder bore. The four vanes reciprocate in the forwarded canted rotor slots to provide for compression of the trapped gas between the vanes. The contact line formed between the rotor diameter and cylinder bore provides a seal between the suction and discharge sections of the compressor. During suction, as the vanes are extending, the trapped volume increases until it reaches a maximum opposite the rotor/cylinder contact point. At that point, the vanes begin retracting in the slots as the cylinder bore converges on the rotor diameter thus compressing the trapped gas. Discharge is through a reed valve mounted on the cylinder housing just prior to the rotor/cylinder contact point. The rotary compressor does not require a suction valve as the vanes function as valves to separate the suction and compression stages.

Displacement- The design objective of the 4912 rotary compressor was to match the cooling capacity of an eleven or twelve cubic inch reciprocating compressor. By ratio of volumetric efficiency and physical displacement the 9.2 cubic inch rotary suited that requirement. The 7.0 cubic inch rotary was selected for meeting the capacities of an eight or nine cubic inch reciprocating compressor. The displacement or swept volume of the rotary compressor equals the maximum trapped volume between two adjacent vanes times the number of vanes.

Clearances- The rotor, vanes, cylinder bore and end plates provide the sealing surfaces of the compression chamber. Therefore, the running clearances and oil film between these surfaces are very critical to compressor performance. The component materials and the magnitude of assembly clearances must be selected with extreme care and consideration for application requirements. For automotive applications, thermal gradients during transient periods can approach 250°F. Running clearances must therefore be small enough during stabilized operation to control these leakage paths, but large enough to provide ample expansion room during periods of extreme temperature gradients. Otherwise the compressor will either operate inefficiently with loose clearances or seize due to insufficient clearances. By optimizing the distribution of lubricating oil to the sealing surfaces the designer is allowed more generous running clearances.

Materials- Thermal stability of the components was the primary consideration in the selection of materials. The rotor, cylinder and end plates of YORK's rotary compressors are ferrous materials, which are heat treated for strength and wear resistance. In selecting a vane material, thermal stability, weight, strength and wear resistance were of equal importance. York's rotary compressor vanes are an aluminum alloy which offers strength for liquid slugging loads, light weight to reduce frictional forces and good thermal and wear properties.

Valves- A suction valve is not necessary for the rotary compressor as the vanes provide the separation of the intake and compression chambers. The discharge valve is a Swedish Steel reed valve which covers four rows of gas ports in the cylinder housing. The discharge ports are located 50° before the rotor/cylinder contact point.

A liquid relief or anti-slugging valve is located in the compression chamber to relieve hydraulic pressure due to liquid ingestion. Its construction is that of a spring loaded ball valve exposed on one side to the compression chamber and seated in the closed position by a pressure differential plus the spring load. When the compression chamber exceeds the forces of the discharge pressure and spring load, a condition which may occur during start-up if the compression chamber is filled with liquid refrigerant or oil, the liquid is relieved through the rear end plate to the oil separator volume.

Lubrication And Oil Separation- The oil reservoir is located in an aluminum housing behind the rear end plate. This housing also contains an impingement oil separator which receives the discharge flow from the compressor, separates the oil from the refrigerant gas and provides a reservoir volume for the oil. A pressure differential lubrication system provides oil flow to the rotor end faces, bearings and shaft seal. High pressure oil is directed under the sliding vanes to extend the vanes and maintain contact with the cylinder bore. The oil flows outward, radially to lubricate and cool the vanes and cylinder and is finally discharged with the refrigerant gas through the discharge valve.

SUMMARY

The feasibility of the rotary vane compressor has been proven by the qualification tests described in this paper. The 4912 compressor provides greater capacity, and more favorable noise and vibration characteristics than current two cylinder compressors. Durability test experience of YORK's rotary compressors exceeds six million miles of vehicle operation. The 4709 and 4912 rotary compressors are compact and compare favorably in weight and cost with piston compressors.

REFERENCE-[1] Moore, W. C. "Reducing Noise and Vibration in Automotive Air Conditioning Compressors, "I.I.R. Conference, Vienna, September, 1973.