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DESIGN CRITERIA AND PERFORMANCE OF AN ADVANCED RECIPROCATING COMPRESSOR

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ABSTRACT

The reciprocating compressor has been the work horse for air conditioning and heat pumps over a large range of capacities, with reliability being one of its prime attributes. Most notably, this reliability has been achieved in varied applications and over a wide range of compression ratios, despite the fact that many systems are field-erected where control over cleanliness and refrigerant charge are sometimes wanting.

In recent years, refined rotary compressor designs have commanded attention because, with improved manufacturing techniques, very high efficiency performance is achieved. However, its design is inherently limited to smaller sizes for air conditioning and the reliability in split-system heat pump applications is unproven. The scroll compressor does not have the size limitations of the rotary and has many desirable attributes, but its long-term field reliability (say, 20 years or more) is as yet unproven, and high manufacturing costs may limit its usage.

The dream of any compressor designer would be a compressor with the gas dynamics of the rotary in both large and small capacities and embodying a mechanism capable of perfect vibrational balance. This paper describes the design concepts and resulting mechanism, the Quadro-Flex compressor, which comes close to just this vision.

INTRODUCTION

In recent years, newer compressor technologies, such as the rotary and scroll, have become the references to which the performance of air conditioning and heat pump compressors are compared for evaluation. At the same time, it is expected that any advanced compressor systems would continue to exhibit the same reliability as achieved by reciprocating compressors in a wide range of applications.

This paper will present some design criteria which were used to develop an evolutionary reciprocating compressor intended primarily for unitary air conditioning and heat pump applications. Performance features which we have come to expect from reciprocating compressors are discussed, together with the unique adaptation of technological improvements developed in recent years. Performance data are presented for the new compressor and are compared to similar data for rotary, scroll, and conventional reciprocating compressors. Performance is evaluated in terms of the capacity at low temperature ambients (as encountered by heat pumps) as well as the energy efficiency ratio under the same conditions.

In determining the suitability of a compressor for a given application, the choice is usually based upon a compromise among such factors as performance, energy efficiency, sound level, field reliability and cost of application to a system. When these factors are considered, it is apparent that the new design should be a good match for the air conditioning and heat pump requirements of the 1990's.

Design Features - Conventional Reciprocating Compressor

Various design features of the new compressor are discussed in terms of the following attributes which have been associated in the past with conventional reciprocating compressors:

Piston Reliability. Reciprocating compressors have developed a reputation of extreme reliability in such applications as refrigerators for which useful running lives of 20-30 years are not uncommon. The high reliability has been associated with the relatively simple design of the reciprocating mechanism and also to the fact that it can be packaged in a hermetic housing, thus minimizing contamination from leaks and dirt.

Wide Range of Applications. In addition to refrigeration applications, reciprocating compressors have found use in room and unitary air conditioners, water coolers, heat pumps, and a broad range of other uses. These varied applications require an ability to function successfully over a wide range of pressure ratios and the resulting ranges of temperature and internal loading of the mechanisms. Successful designs exist for compressors which range in size from several hundred BTU/hr for refrigerators to many thousands of BTU/hr for air conditioning. In contrast, the rotary compressor is limited to about 1.5 tons capacity for air conditioning, while the scroll compressor appears practical only in capacities larger than the maximum for the rotary design.

Field Erection-Proof. Larger size split-system air conditioning and heat pump systems are required by their very nature to be assembled in the field. Under these conditions, the controls over cleanliness, the size of the refrigerant charge, and the pressure tightness are substantially reduced over those achievable under factory white-room conditions. Despite these drawbacks, reciprocating units continue to show remarkable reliability in field-installed split systems. Currently, rotary compressors are not acceptable for such field-installed systems, although they do offer exceptional reliability when the systems are factory assembled where control of cleanliness can be maintained.

Cost of Manufacture. Because the basic reciprocating mechanism is rather unsophisticated, and since this technology is shared by automotive and other engine applications, the technologies to mass produce the components are rather advanced. As a consequence, the manufacturing cost is lower than that for other mechanisms. Other factors which contribute to this cost advantage include the higher machining precision required for rotary compressor components and the fact that machining the complex geometry of the scroll is both difficult and time-consuming.

Innovative Features Incorporated in the New Design

The new compressor design incorporates several innovations which, when taken in combination, produce significant performance improvements:

Optimum Compressor Balance. The piston arrangement in the new design is shown in Fig. 1 and features two double pistons powered by a scotch-yoke mechanism which in this paper is referred to as the Quadro-Flex compressor.

Since the four coplanar pistons are separated by 90 deg. in both time and space, they produce an unbalance force which can be exactly nullified by a single pair of counterweights. The crankshaft counterweights are specifically sized and located to achieve this result. In contrast, conventional reciprocating compressors in sizes for unitary heat pump usage generally have two or more in-line pistons. Since the shaking forces in this configuration cannot be completely compensated by counterweights, unbalance forces are usually found which give rise to vibrations. The time-varying amplitude and direction of such forces can be calculated, as shown in Fig. 2. At any time instant, the shaking forces can be represented by the arrow which rotates as the crankshaft rotates. For the new design, the coplanar piston arrangement allows one to shrink the amplitude of the arrow to zero by making the proper choice of counterweights. Consequently, the limiting factor for balance is the tolerance to which the dynamic components can be machined.

Improved Thermodynamics. The unique layout of the new compressor is shown in Fig. 3. This configuration allows the suction gas to flow directly into a cavity located behind the pistons and from there directly into the compression chamber. "Rotary-like" thermal characteristics and efficiencies are thus provided in a reciprocating unit and are accomplished by minimizing the opportunity for precompression heat pickup by suction gas.

Inertia-Assisted Suction Valve Closing. The newly-developed suction valve is mounted on the piston and the valve geometry is selected to yield a strong, yet light and flexible member capable of sustained operation under the most severe conditions. An optimum combination of deformation characteristics and impact resistance allows this design to succeed where other designs have failed.

The inertia forces developed in the valve as a result of piston motion give rise to a very definite and optimally-timed closing action. This is particularly advantageous during low temperature heat pump conditions where conventional valves often exhibit erratic closing patterns. The latter result from the combined effects of pressure-actuated flapper valves which, in turn, are forced open or closed by gas pressures. At low ambient temperature, where suction gas pressures are low, valve action may be erratic because the low forcing pressures are often overridden by gas pulsations in the compressor passages, as shown in Fig. 4.

Improved Mechanism Efficiency. The layout of the new Quadro-Flex compressor is shown in Fig. 3. The mutually perpendicular opposed-pair piston-yoke assemblies provide a compact and efficient means of transforming rotary motion into reciprocating motion. This provides a superior ability for self-alignment under load and also minimizes the resistance to motion which is generated within the compression mechanism. This concept is best understood when the piston side wall forces are contrasted with those in a conventional pump, as shown in Figs. 5 and 6.

For the conventional compressor, the side wall forces shown in Fig. 5 are a result of the connecting rod pushing on the piston at an angle, with the result that a significant force can be generated. In practice, this system can also generate additional frictional forces due to misalignment of any of the members of the slider-crank mechanism. In contrast, the calculations for the Quadro-Flex shown in Fig. 6, indicate that wall forces are reduced to one-third of their former value, and because the piston is free to rotate somewhat, no additional forces are generated due to cocking or binding of the mechanism. As a result, frictional forces are reduced and less electrical energy is required per unit of output.

Variable Speed Capability. Since the vibrational forces will be minimal because of the perfect balance capability of the design, the Quadro-Flex mechanism can run equally well at any speed. When taken in combination, the pure sinusoidal motion of the pistons and the precise timing of the piston-mounted suction valve provides for a smooth and efficient gas flow during compression over a wide speed range. The result of this unique design is a heat pump compressor capable of variable speed operation. This feature can be extremely valuable in extending the range of heat pump capability, as discussed in the next section.

Heat Pump Requirements

The use of air-source heat pumps as a primary heating system in Northern climates in the United States is hindered by a well-known phenomenon: heating capacity is reduced as the ambient temperature decreases. A typical heat load capacity curve for an average home is shown in Fig. 7 on which capacity curves for a conventional air-source heat pump are superimposed. The reduced capacity of the air-source pump at lower temperatures is exactly opposite of that required since heating load increases as the ambient temperature decreases. A number of schemes have been proposed to improve the load-matching capabilities of the air-source heat pump, such as a super-charged cycle compressor or a variable speed compressor. However, another means would be to change the slope of the compressor capacity curve so as to enhance the low temperature capabilities. The design concept discussed in this paper shows just such characteristics. This results in a compressor offering significant advantages in retaining capacity when both the ambient temperature and the evaporating temperature of the heat pump system decrease, as next discussed.

Performance Characteristics

The design objective for the Quadro-Flex compressor was to improve low temperature capacity thereby enhancing the performance characteristics for heat pump applications. Most heat pump compressors are used primarily for air conditioning or else in the dual roles of heating and cooling. As such, these compressors are sized with the air conditioning rating point in mind (130°F condensing temperature, 45°F evaporating temperature). The best measure of the heat pump adaptability of a compressor is to compare rating point capacity with performance at both the high heat pump and low heat point rating conditions (110°F condensing, 30°F evaporating temperature for the high heat pump and 95°F condensing, 5°F evaporating for the low heat point). Such comparison is made in Table I which includes comparative data for the Quadro-Flex compressor and conventional reciprocating, commercial rotary and scroll compressors. Since each of these compressors has a different nominal capacity, the data in Table I are most easily compared by normalizing the capacities about the air conditioning rating point and reporting the heat pump capacities as a percentage of that rating. For easier visualization, the data are plotted in Fig. 8 where it is seen that the Quadro-Flex offers significantly-improved low temperature capability over the conventional reciprocating compressor and is virtually equivalent to the commercial rotary and scroll compressors.

Of increasing importance is the energy efficiency ratio for compressors in heat pump systems. The energy efficiency ratio for each of the four compressor types is shown in Table II at the same rating points discussed above and is presented graphically in Fig. 9.

Here, it is seen that in terms of the energy efficiency ratio, the Quadro-Flex compressor offers significant improvements over the conventional reciprocating compressor and is again comparable to the rotary and scroll compressors.

CONCLUSIONS

The design features and performance data have been presented for a new Quadro-Flex compressor. The design retains many of the desirable attributes long-associated with the conventional reciprocating compressor such as service reliability, adaptability to a wide range of sizes and compression ratios, ability to survive the environment of field erection, and at the same time reflecting a reasonable manufacturing cost. The performance of the Quadro-Flex is enhanced by taking advantage of unique design features which allow for complete balance of the reciprocating mechanism, direct suction of the refrigerant gas, and unidirectional flow through the compression chamber made possible by the design of a new-concept suction valve. When combined with the improved frictional characteristics of the scotch yoke mechanism, the Quadro-Flex design provides performance characteristics which are on par with contemporary rotary and scroll designs as well as allowing adaptability to variable speed operation.

Table I. Comparison of Compressor Capacity

Temperature, °F:	Rating Conditions - % BTU/Hr (Normalized)		
	130/45	110/30	95/5
Mechanism:	Air Conditioning	High Heat Pump	Low Heat Pump
Quadro-Flex	100	82.6	48.8
Reciprocating	100	80.0	41.9
Rotary	100	82.9	51.8
Scroll	100	82.2	50.2

Table II. Comparison of Energy Efficiency Ratio

Temperature, °F:	Energy Efficiency Ratio		
	130/45	110/30	95/5
Mechanism:	Air Conditioning	High Heat Pump	Low Heat Pump
Quadro-Flex	11.0	11.4	8.57
Reciprocating	9.83	10.0	7.25
Rotary	10.8	11.5	9.37
Scroll	11.4	11.7	8.60

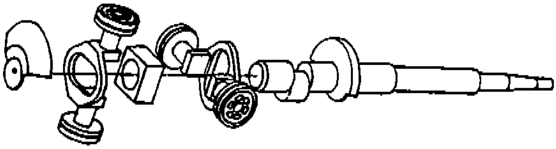

Fig. 1. Piston and Counterweight Arrangement for the Quadro-Flex Compressor

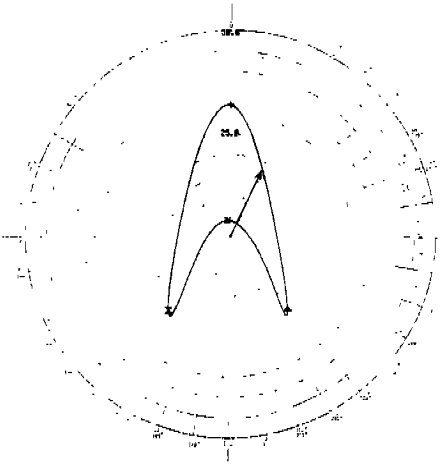

Fig. 2. Total Unbalance Forces Acting on a Reciprocating Compressor

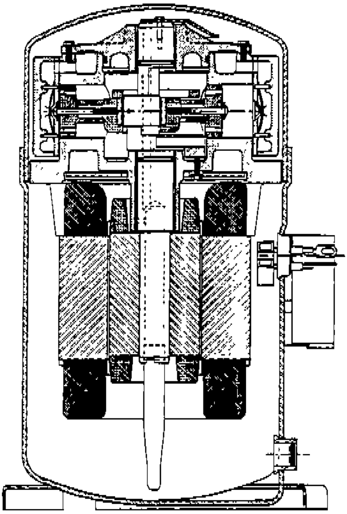

Fig. 3. Lay-Out of the Quadro-Flex Compressor

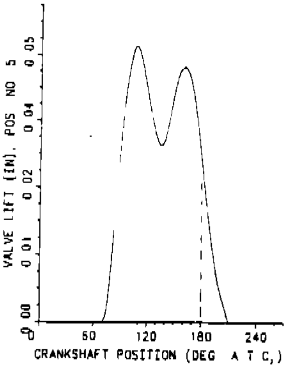

Fig. 4. Calculated Valve Closure for a Conventional Reciprocating Compressor

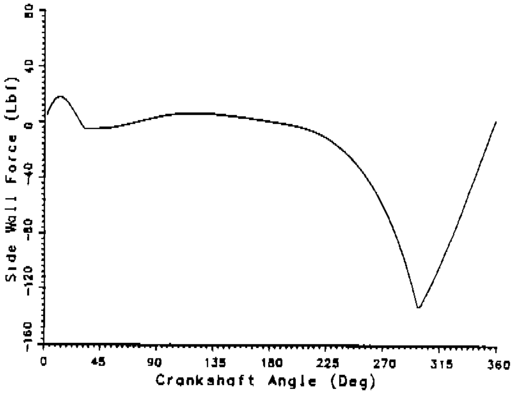

Fig. 5. Side Wall Forces on a Connecting Rod-Driven Piston

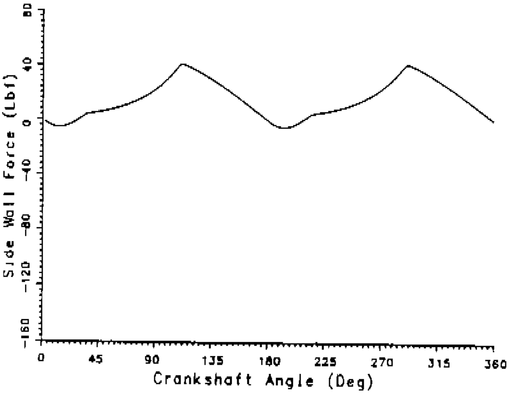

Fig. 6. Side Wall Forces on a Quadro-Flex Double Piston

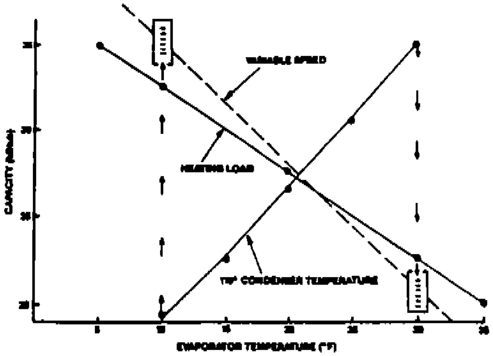

Fig. 7. Heating Load and Compressor Capacity Vs. Evaporator (Ambient -20°F) Temperature

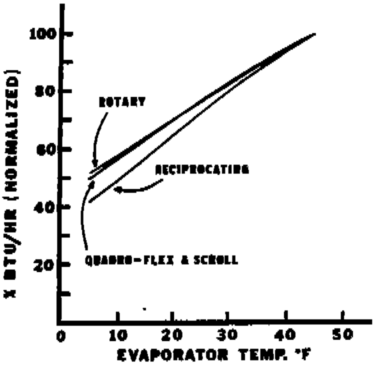

Fig. 8. Compressor Heat Pumping Capacity Normalized to Air Conditioning Rating Point Conditions for Various Design Configurations

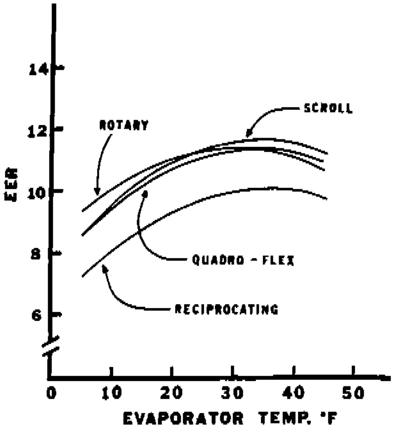

Fig. 9. Energy Efficiency Ratio Compared Between Various Compressor Types