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ABSTRACT

Reciprocating refrigerant compressors, designed exclusively for refrigerant vapor duty, are inherently weak under liquid slugging conditions. When handling large volumes of liquid refrigerant/oil, cylinder pressures can approach 3000 psi (20.68 mPa). Obviously, components can be designed to handle these high pressures, although this is not cost effective. By reducing cylinder pressures, excessive stress levels and high costs can be avoided, and enhanced reliability can be achieved.

Establishing a proper relief plate design required extensive system transient testing under severe liquid slugging conditions. This paper will review a reciprocating compressor design that has incorporated a relief plate with adequate flexibility to deflect under liquid slugging conditions, while maintaining excellent sealing during normal operation. The experimental test results including cylinder pressures and component stress levels will be reviewed. The system test set up rationale will be discussed.

INTRODUCTION

With the continuing emphasis on compressor reliability, it is imperative that compressors be designed to withstand large quantities of liquid refrigerant/oil for a significant number of start up sequences. Now that this is understood, new products can be designed to meet these demands with minimal effort. However, existing products are at a disadvantage in that there may be physical limitations that preclude cost effective design improvements to enhance the ability to repeatedly ingest large volumes of liquid refrigerant/oil.

Such was the case with a Carlyle compressor that was designed in the 1960's and in need of improvement to meet the performance and reliability requirements of the future. Several of the loaded components were "beefed up" to withstand the high pressures in the cylinder and cylinder head experienced during liquid slugging. A relief valve was added to each cylinder head to reduce the slugging pressures and maintain acceptable stress levels in the cast iron head. These measures were adequate to meet the requirements for the present generation systems.

The average residential condensing unit today has a Seasonal Energy Efficiency Ratio (S.E.E.R.) of about 8.5 and uses 2 lbs (.91 kg) of refrigerant/nominal ton. With the enactment of the 1992 Federal energy standards, the minimum S.E.E.R. is mandated at 10.0 which will require about 2.5 lbs. (1.13 kg) of refrigerant/nominal ton with compressor efficiencies of 10.5 at A.S.R.E./T. This is a 25% increase in the amount of refrigerant in the typical system. All other things being equal, the compressor must be able to handle this increased volume of liquid refrigerant under liquid slugging conditions to keep costs competitive.

In response to the need to handle increasing refrigerant charge levels with these systems, the relief plate concept was developed. The relief plate would serve as a multi-functional structural member. During normal operation it would provide a sealing function to separate discharge and suction plenums. Under liquid slugging conditions, it would function as a calibrated relief device, deflecting to relieve excessive pressures. Refer to Figure 1 for details of the overall design. Successful application of this concept will provide a reciprocating compressor that can be applied to systems without the need for liquid handling devices at charge levels of 12 lbs. (5.44 kg) of refrigerant.

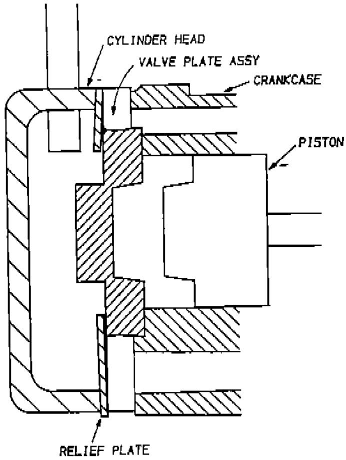

Figure 1

Relief Plate Concept

Incorporation of the relief plate design has reduced the cylinder head pressures by 50% at the 2.5 lbs. (1.13 kg) of refrigerant/ton charge level. At the same time, we have increased the liquid handling ability by up to 50%. With the lower pressure levels, we are able to make reductions in component strength and eliminate the relief valves. This design approach allows the usage of thinner suction valves, which improves the efficiency and eliminates suction valve deformation previously experienced during liquid slugging. Implementation of the relief plate design is expected by the end of 1988.

BACKGROUND

Reliability

In an increasingly competitive Industry, it is clear that the success of a compressor manufacturer is measured by their ability to achieve the highest standards of quality and reliability.

Reliability is frequently measured by the first year failure rate and is influenced by many variables. Those most notable are compressor design, system configuration and field service technique. There is also a considerable time lag between compressor production and field failure based on seasonality, build and deliver lead times and inventory levels. With decreasing field failure rates, it is more difficult to determine and respond to the dominant failure modes due to the quantity of machines available.

These reliability variables make it necessary to resort to "rules of thumb" regarding the application of compressors to systems. Obviously, there must be adequate test data to support any "rules of thumb" on a very broad basis. The data must reflect the current field practices and be applicable to the existing compressor designs and generic system configurations.

Establishment of application "rules of thumb" can be accomplished using accelerated bench tests provided that the above criteria are considered. To insure overall cost effectiveness, the tests must be representative of abusive conditions, but repeatable to a high degree to avoid adding excessive costs to the compressor design.

To insure the highest compressor reliability in Carrier products, we have established an accelerated liquid slugging test that can simulate the compressor design life in about ten weeks. A photograph of a typical slugging test stand is shown in Figure 2. Although the test represents the environment of a worst case application, we apply this test to all of our compressors. Initial efforts have been concentrated on establishing test repeatability and improving the reliability of Carrier compressors. All compressors used in Carrier products will be subjected to this test at a threshold charge level and applied based on their ability to complete the required number of cycles, pass a calorimeter test and show no damage upon teardown analysis.

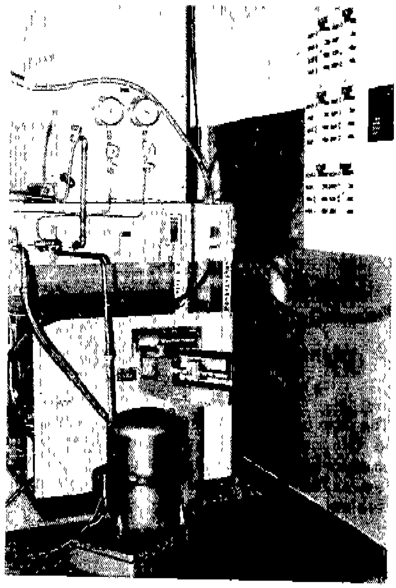

Figure 2

Slugging Test Stand

Summary

As stated earlier, a minimum target charge level of 2 lbs. (.91 kg) of refrigerant/nominal ton is appropriate for cost effective residential condensing units. Successful completion of testing at higher charge levels and greater number of cycles will allow application without liquid handling devices, such as crankcase heaters and suction accumulators.

The compressor is the largest single cost item in a residential condensing unit. The addition of liquid handling devices to protect the compressor against liquid abuse can add up to 10% to the unit cost.

A reduction in cylinder and cylinder head pressures during liquid slugging was of prime importance in improving reliability, increasing the ability to handle liquid, and providing opportunities to further reduce costs.

RELIEF PLATE DESIGN

Design considerations

The envelope dimensions of the existing cylinder head were determined by the shell, crankcase and motor. Head bolt quantity and location were part of the capital equipment dedicated to the compressor line. Our objective was to achieve the reduced pressures while maintaining the required envelope dimensions. The challenge was to optimize the plate deflection to seal under normal operation and relieve excessive pressures through leakage to the suction side under liquid slugging. This became the starting point for our design analysis and subsequent prototype work.

Critical design areas

Two areas were identified as critical to the successful implementation of the relief plate concept. The relief plate thickness/material optimization and the cylinder head bolt strength. Refer to Figure 3 for the details of the relief plate and related components.

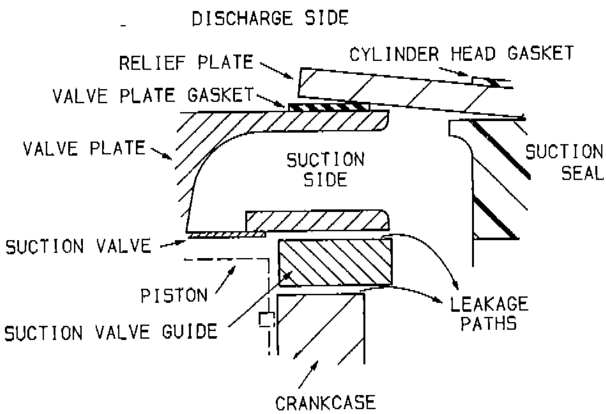

Figure 3

a) Relief plate - The maximum thickness of the relief plate was limited by the envelope available and the need to maintain existing plenum volumes and clearances. The critical parameter in the proposed design was the leakage rate as a function of deflection. We calculated stress as a function of the target cylinder head pressure neglecting leakage. The following assumptions were used:

1. Flat circular plate (a) of constant thickness (t) with a central hole (r_o)
2. Plate fixed at outside edge
3. Inner edge simply supported
4. Load concentrated (p) along edge of central plate
5. Poissons ratio = .30

$$\sigma_{max} = k_1 p/t^2 = 121.5 \text{ ksi } (837.7 \text{ mPa})$$

σ = stress

a = plate radius

r_o = hole radius

k_1 = stress coefficient (from table based on a/r_o ratio)

t = thickness

p = plate loading

This indicated that we would require a high strength material if the target pressures were met or exceeded. Since the goal was to limit deflection and the resulting high stress by achieving leakage, we needed to establish a baseline to work from. We selected the maximum thickness and used cold rolled steel due to its availability, for our initial prototype work. We planned to instrument the first machine to determine the actual pressures, stresses and deflections at various charge levels. The optimization of material and thickness was based on the strain gage test results.

b) Cylinder head bolt - The present cylinder head was a one piece design that had an internal force balance except for the cylinder bore area. This subjected the bolts to the load from the area represented by the cylinder bore diameter at the high pressure. The new design utilized an open head which now subjected the bolts to the pressure load of the full head area. This increased the bolt loads from about 900 lbs. (408.24 kg) in the old design to 4000 lbs. (1814.4 kg) in the new design. This required that a larger diameter and higher strength bolt be used.

Target charge level

To insure that the cylinder head redesign would stand up to all future requirements, a charge level target of 12 lbs. (5.44 kg) was established. At this charge level, the compressor shell would be completely full of liquid on start up. Even though the suction inlets are a few inches from the top of the shell, they would be completely full with this amount of refrigerant. As shown in Figure 4, successful qualification at this charge level would allow application of the relief plate design to all residential condensing units without the need for liquid handling devices at the 2.5 lbs. (1.13 kg) of refrigerant/ton level.

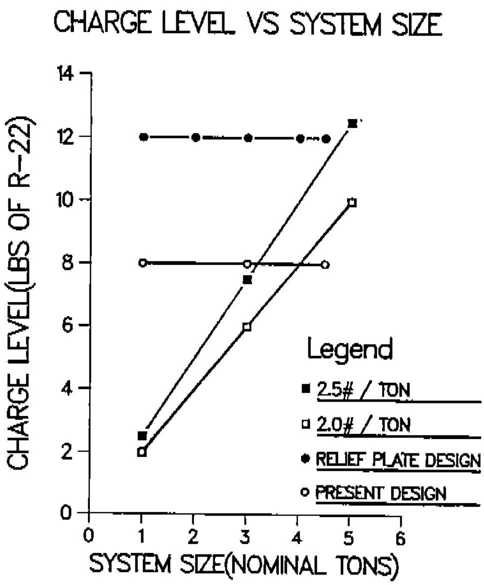

Figure 4

TEST PROGRAM

Instrumented compressors had cylinder pressure transducers, cylinder head pressure transducers and strain gages on the relief plate. Electronic scales were used to accurately measure the charge level in the instrumented compressors on start up and throughout the test.

The test program was conducted on liquid slugging test stands with strict adherence to procedures developed to minimize variations between stands and over time. Stands were monitored daily relative to charge level in the compressor on start up and compressor pumping performance. The characteristics of the actual slug cycle were recorded for comparison with the present design to quantify the long term improvement expected in reliability.

TEST RESULTS

The test results show a significant reduction in cylinder, cylinder head and muffler pressures at all charge levels with the relief plate design. Refer to Figure 5 for the cylinder head pressure reductions at various charge levels for the three designs. Reductions of 50% are indicated at the 14 lbs. (6.33 kg) charge level.

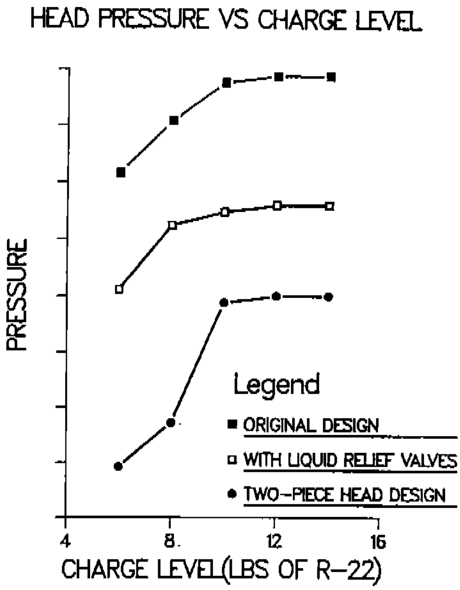

Figure 5

The testing has verified the validity of the initial design concerns. Prototype plates fabricated from cold rolled steel showed permanent deformation with the target head pressures. Attempts to use the existing cylinder head bolts at high charge levels evidenced occasional fatigue failures.

Two interesting phenomenon were discovered during the test program:

Even though both cylinders were assumed to be full of liquid during the test; due to the shell being full of refrigerant, the lower cylinder pressures were consistently 15% higher than those in the upper cylinder.

Since the cylinder pressures were obviously higher than those in the cylinder head, we assumed that the maximum stress would be in the direction of the cylinder head. Testing showed the opposite to be true as the initial plates deformed in the direction of the crankcase.

An additional and not so obvious design concern was uncovered. The repeated deflecting of the relief plate, as it relieves excessive pressure, causes gasket abrasion at the valve plate and cylinder head gaskets. This led to an additional constraint of limiting the relief plate deflection to maintain gasket life.

Results from the instrumented compressors indicate a dramatic reduction of pressures as shown in Figures 6 and 7.

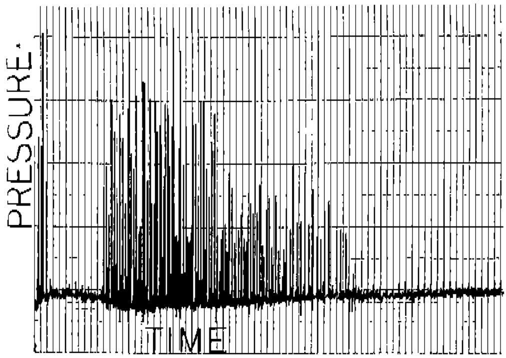

Figure 6

Original Design

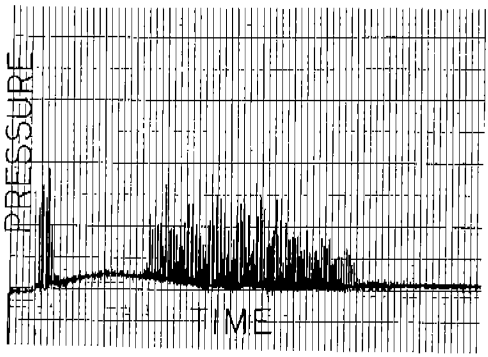

Figure 7

Relief Plate Design

Figures 8 and 9 indicate the relief plate deflection and stress determined by relief plate strain gage as the refrigerant charge level (pressure) is increased .

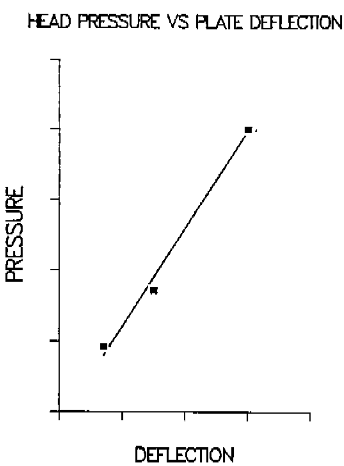

Figure 8

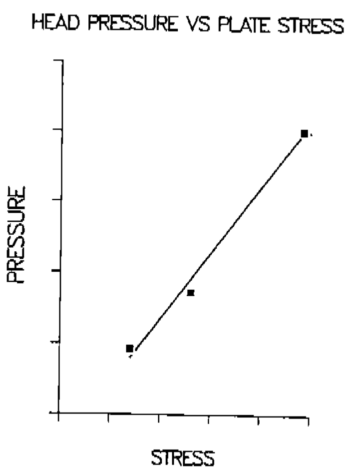

Figure 9

CONCLUSIONS

It can be seen from Figure 5 that the present compressor design is capable of meeting the refrigerant charge levels compatible with today's systems with minimal added cost. As unit efficiency levels increase to meet the 1992 Federal standards, higher charge levels would have required the added cost of liquid handling devices to maintain present reliability levels. The relief plate concept has increased the liquid handling ability of this reciprocating compressor to 12 lbs. (5.44 kg) of refrigerant, and avoided the need for added system cost to protect against liquid abuse during slugging.

Additional laboratory testing of the production configuration has validated the relief plate design approach.

A patent application has been filed on the relief plate concept represented in this paper.

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