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Rotary Compressor: P-V Diagram and Investigation Into Power Requirements

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ABSTRACT

Pressure-volume diagram in an air compressor is a tool for study of funadmaental principles. It provides valuable information for optimizing design parameters. This paper describes a method adopted to measure and record pressure-volume changes within a rotor segment as the segment completes the air induction-compression-discharge cycle. Measurements were also done for the input power to the air-end as well as power to the complete plant package enabling study of the elemental contribution to power. An attempt began to understand the P-V relationship and to the study of the effect of various design parameters on the pressure-volume diagram.

INTRODUCTION

The principle of operation of rotary air compressor, whether vane twin or single screw is well known. An amount of air automatically induced into the rotor segments at the inlet conditions and progressively compressed as the segment reduces in size as it completes each compression cycle. At the end of the compression cycle the compressed air is channeled out of the rotor segment by a suitable discharge mechanism. As the rotor segment completes a revolution, air induction process repeats and so does the compression cycle. Measurement of pressure within a rotor segment by placing transducer in a static condition is relatively easy. But that only measures the pressure while the transducer is in communication with the rotor volume and will thus record pressure only for part of the compression cycle. To arrive at Pressure-Volume diagram however requires measuring/recording the pressure continuously through the complete cycle and correlating the changes in rotor segment volume with the recorded pressure. Work to that end was done within the Chicago Pneumatic organization. The instrumentation was on a rotary vane compressor but the technique, approach and result analysis are equally applicable to the twin and single screw compressors, as all share similar fundamental design characteristics. This paper will outline:

(a) a method adopted to record a complete pressure-volume diagram as the compressor operated.

(b) ways of separating elemental power due to various components/parameters of a compressor.

(c) study and scope of interpreting the P-V diagram for refinement of compressor design.

EQUIPMENT

The equipment used consisted of a electric motor driven single stage rotary vane compressor modified to take a torque transducer between the electric motor drive and the compressor air end. The rotor was modified internally in order to mount a pressure transducer on the rotor surface. The transducer was of strain gauge type with its flat outside surface exposed to the rotor segment air, and flush with the rotor surface. The output wires from the pressure transducer is taken inward into the center of the rotor, and then through a central hole in the rotor onto a slip ring unit mounted at the end of the rotor shaft. Output from the slip ring unit was fed to Y axis of a cathode ray oscilloscope. This provided a pressure trace on the C.R.O. screen as the compressor operated.

A cam was made with radial distances presenting the volumetric displacements for one rotor segment as it completes one revolution. The cam was mounted at the end of the extended rotor shaft and was positioned in such a way that the maximum cam radial distance was aligned to the transducerized rotor segment in its maximum displacement position. A displacement transducer was instrumented to follow the cam as the compressor ran, the output from the displacement transducer was fed to the X axis of the C.R.O. to provide a trace proportional to the volume of the rotor segment. As the compressor operated, the C.R.O. traced the pressure-volume curve of the transducerized segment.

Input power to the air-end was instrumented by providing a torque transducer in between the air end and the electric motor drive. A D C. generator mounted directly onto the extended rotor shaft provided an electrical signal proportional to the speed. Signals from the torque transducer and the D.C. generator were connected to an X-Y plotter to provide a simultaneous measure of torque and speed for the air end.

Simultaneously measurement of input electrical power to the motor drive was also done with kilowatt-meter-voltmeter set up.

Presentation of Results:

A. The results are being presented at the end of this paper. Traces were taken to record the P-V curves at receiver pressures of 70, 85, 100 and 125 psig respectively, the compressor was in unloaded condition. A typical photograph in this paper shows a very interesting pattern. The suction took place at 3-4 psia. Point "O" shows the start of oil injection into the rotor segment. Oil injection to the segment continued until point "L", at this point, the segment has passed over the oil injection port. Compression of the air-oil mixture took place until the leading blade reached point "F" when the auxillary discharge ports were uncovered. At that instant, the discharge manifold pressure being higher than the segment pressure, a surge of air entered the segment from the discharge manifold. Due to inertia effect of air, the pressure inside the segment rose to above the pressure in the discharge manifold, at point "A". The pressure then dropped slightly. At point "B" the main discharge ports were uncovered by the leading edge of the segment and we noted a slight increase in pressure, again this time due to small inrush of air from the discharge manifold back to the segment. Air then flowed out of the segment at nearly constant pressure until at point "C", the rotor segment just behind was open to the discharge manifold through the auxillary discharge port and the air suddenly rushed out of the transducerized cell to the cell just behind. That was the reason for the sharp drop in pressure at "C", the pressure level stablizing momentarily but again rising sharply to "E" due to a small volume of air oil trapped as the segment went inside the minor bore.

B. In this series of tests, the plant was run at full load condition, at three different discharge pressures, 70 psig, 85 psig and 100 psig. A typical trace shown [7 at 85 psig full load discharge. Note that the line representing suction, "SU", was uniform at 13.5 psia. At "O" oil injection into the segment started and continued until point "L". Compression of the air-oil mixture taken place up to point "F" (at 76 psig) until the auxillary discharge ports were uncovered. At that instant, the pressure at the discharge manifold being above the segment pressure, there was an inflow into the segment raising its pressure due to inertia effect. Segment pressure then stabilized and the discharge was at uniform pressure.

Interesting that in all three cases of discharge pressure conditions, the compression of air-oil mixture took place up to 76 psig, the pressure set by the design compression ratio. At "C", the pressure started to drop due to the fact that the trailing segment which at a lower pressure than the (transducerized) segment was open to it through the auxillary ports. As the segment volume shrinked further and the segment went inside the minor bore, the pressure dropped to "S" and the whole cycle repeated.

C. This was with oil flow reduced by 25%. There was no basic change in the P-V curve. The only small change that we observed was that the pressure point "E" was markedly lower which meant that in normal oil flow conditions the pressure rose at "E" due to greater amount of oil squeezed through the minor bore. Test was also carried out without blades inside the air end to determine the power needed to drive the air end against mechanical friction.

ANALYSIS OF THE RESULTS

From the knowledge of rotor segment volumetric displacements and the area under the P-V curves, the power requirement of the air end to compress the air-oil mixture and deliver at the outlet manifold pressure was calculated. Power obtained from this was then compared with the power consumption of the air-end as obtained from the torque-speed measurement from the X-Y plotter. The later is a measure of power to compress the air-oil, plus additional components such as mechanical friction (at air end).

Simultaneous measurements of input power to the electric motor gave a measure of the power consumed by the entire plant, that is, air end electric motor and the fan. Compare this to the power consumed by the air end as obtained from torque and speed measurements, we can now separate the power consumed by the prime mover itself. Test without blades gave a measure of power required exclusive of power to compress air. The P-V diagram also enabled us to calculate the index of compression. Computing of the net leakage air into the segment was also possible.

DISCUSSION:

The energy required to drive a rotary compressor consists of pumping power, mechanical losses in the compressor as well as in the motor drive, and power to drive the fan. The pumping power consists of power required to:

a) Compress and deliver air at the outlet manifold pressure,

b) carry oil through the system,

c) provide power for internal air and oil leakage losses.

The instrumentation used enabled a direct recording of the P-V trace. The changes in pressures due to such factors as undercompression, overcompression, discharge port position were clearly noticeable on the trace. Attempt was made to establish elemental power requirements. The method has tremendous potential for a complete study and design optimization for the compressor air end. The scope includes study of:

a) effect of changes in inlet port size and location, discharge port size and location and areas of excessive power loss due to overcompression or undercompression.

b) effect of air leakage between rotor segments or lobes.

c) effect of altering running speed.

d) effect of mismatch in actual pressure ratio vs air end design pressure ratio.

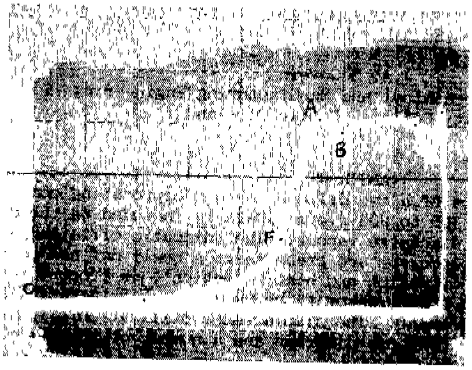
e) direct computation of pdv using a digital C.R.O. and an on-line computer.

f) establishing elimental power consumption.

g) effect of change in oil flow quantity or method.

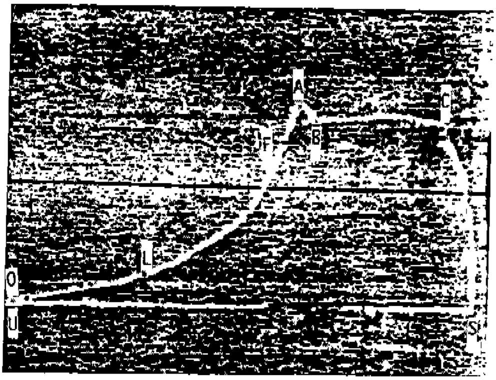
h) value of index of compression.

i) effect of changes in the design of screw lobes or blades.



TRACE T 1

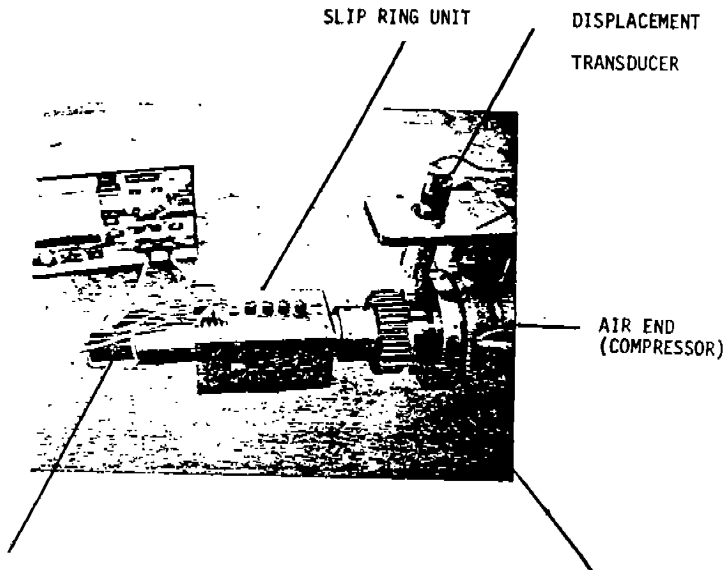
No Load
100 PSIG Rec. Pres.
F – 30 psig
B – 95 psig
A – 102 psig
E – 107 psig
Discharge at about 101 psig



TRACE T 2

85 PSIG Full Load
F – 76 psig
A – 95 psig
B – 86 psig

Discharging from the segment at nearly 87 psig



INSTRUMENTATION