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Compressor Capacity Control via Early Suction-Valve Closing

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INTRODUCTION

Compressor capacity control is useful as a means of increasing the efficiency of refrigeration and heat pump devices during off-peak operation, if such control can be achieved efficiently.(1) Proposed here is a new method of compressor capacity control, called early suction-valve closing or "cut-off" control, which is a potentially efficient and inexpensive means of control. The approach is efficient because it avoids throttling of gas back out of the suction valve as in other capacity reduction methods, such as valve unloaders or late suction valve closing.(2)

In the early suction valve closing (cut-off) approach, the amount of gas taken into the cylinder is reduced by premature closing of the suction valve, or a secondary valve just upstream of the normal suction valve. After the valve is closed, gas in the cylinder is expanded until the piston reaches bottom dead center (BDC), and is then recompressed. The expansion and recompression process is shown compared to a normal compressor in the P-V diagrams of Figure 1. The amount of capacity or flow reduction is controlled by controlling the time after top dead center (TDC) at which the suction valve is closed. If power to run the early suction-valve cut-off device is available, then complete capacity variation from 0 to 100 percent is possible.

The remainder of this paper gives a brief computer comparison of a large 14-ton refrigeration compressor with and without cut-off control, followed by a description of preliminary design and development tests on one type of cut-off mechanism, intended to achieve up to 70 percent capacity reduction in a small 3-ton hermetic, 3600 RPM refrigeration compressor. The latter tests demonstrate that such a cut-off mechanism can indeed perform in high speed compressors, although power requirements make the particular mechanism described more suitable to larger, lower speed (1800 RPM or less) compressors.

COMPUTER PREDICTIONS

Detailed computer simulations of a large 14-ton semi-hermetic refrigeration compressor with and without cut-off control have been performed(1),(3) and the results are briefly summarized in Table 1.

The overall efficiency with cut-off control is less than a normal unit operating between the same suction and discharge pressures, because of losses during expansion and recompression of the gas in the cylinder after cut-off. Such a comparison is misleading, however, because, in a given system, use of capacity control will cause the compressor to operate across a lower system pressure ratio than without capacity control, and hence total system efficiency will be increased. For more information the reader should consult References 1 and 3.

DESIGN AND TEST OF A CUT-OFF MECHANISM

Basic Mechanism

A simple schematic of a cut-off mechanism which has few moving parts, and which may be installed on many existing compressor designs, including hermetically sealed compressors, with little modification is given in Figure 2. The mechanism has essentially three moving parts:

1. Timer-spool valve,
2. Power piston, and
3. Slide valve.

The slide valve is a secondary valve installed as close as possible upstream of the normal suction valve, and which is closed sometime during the intake stroke to limit the amount of gas taken into the cylinder. The slide valve has essentially "bang-bang" motion, to avoid throttling losses through the valve during closing, and is driven directly by the power piston. Energy to move the power piston is supplied directly from the pressure differential between suction and discharge sides of the compressor. Timing control of the power piston/slider combination is governed by the travel time of the timer-spool valve. The timer-spool valve operates like a normal spool valve in that its function is to reverse the flow to the power piston. Travel time of the spool, and hence timing control of the power piston and slider, is governed by the mass of the spool and the pressure differential acting across the ends of the spool. Tests have shown that frictional forces may be neglected, being significantly less than the inertia forces required to move the spool. A unique feature of the timer-spool valve is the fact that it is powered and timed directly by cylinder pressure and <u>needs no connection to the crankshaft</u>. The travel time of the timer-spool valve, and hence the closing point of the slider valve, is controlled merely by setting an appropriate control pressure, P_c, which is constant for any particular operating condition. The control pressure P_c can be supplied through a simple pressure regulator from discharge pressure, and can be actively controlled in a manner similar to thermal expansion valves to maintain a desired operating condition, such as constant condensing pressure. Operation of the above cut-off mechanism through one complete cycle is described in Figure 3.

Design for a Small 3600 RPM Compressor

The task of designing the cut-off mechanism becomes more difficult as the speed of the compressor is increased, and the size is decreased. Initial development efforts, therefore, have centered on a device to achieve up to 70 percent capacity reduction in a small 3-ton, 2-cylinder 3600 RPM hermetic refrigeration compressor.(4) Figure 4 shows the discharge valve, the suction/discharge manifold, and the manifold side of the head plate of the above compressor. The suction valve is on the opposite (cylinder) side of the head plate, concentric with the discharge valve, although larger in diameter. Figure 5 shows how the cut-off mechanism is designed to fit into the compressor. A separate cut-off mechanism is required for each cylinder, but only one control pressure regulator is required, and it may be located either inside or outside of the hermetic shell. Note that the actual mechanism is very small, and therefore is easily added to the compressor. The only changes required are a new head plate, and a slightly modified suction/discharge manifold. The normal valves in the above compressor, which remain intact, are of the ring-plate type. The slide valve has therefore been designed as a semi-ring valve, and would have a rotary sliding motion.

The following is a summary of the necessary design conditions for a cut-off mechanism capable of achieving 70 percent capacity reduction in the above 3-ton compressor:(1)

1. Compressor speed 3600 RPM,
2. Minimum required travel time of timer-spool valve .0005 sec.,
3. Maximum required travel time of timer-spool valve .0055 sec.,
4. Maximum allowable travel time of power piston and slide valve .0016 sec.,
5. Required travel of power piston and slide valve .187 in.,
6. Suction and discharge pressures at maximum cut-off 96 psia and 260 psia, and
7. Suction and discharge pressures at minimum cut-off 36 psia and 260 psia.

Initial Development Tests

The purpose of the initial development tests was to show that a cut-off mechanism could indeed be constructed, which would meet the necessary performance criteria for the small 3600 RPM compressor. Tests of the cut-off mechanism were performed under simulated compressor conditions on a compressed air test system. The test parts are shown in Figures 6 and 7. The spool valve material was nylon, and the power piston consisted of a steel disk silver soldered to a piece of .032 in. O.D. stainless steel tubing. The slider was spring steel, and was also silver soldered to the stainless tubing. All of the former parts ran on low carbon steel surfaces.

The tests showed that the spool met or exceeded its specifications, although some spool bounce was noted when running on steel end walls. Performance of the power piston was also satisfactory, although testing was not complete due to failure of the tubing at the solder joint with the disk. The latter problem, however, should not occur with a properly manufactured one-piece piston.

POWER CONSUMPTION

The cut-off mechanism, as designed to function in the 3-ton compressor described above, is estimated to consume about 16 percent of the total reduced mass flow from the compressor under the 70 percent capacity reduction condition. This high power consumption is felt to be unacceptable, and indicates that either less capacity reduction or a different cut-off mechanism are in order for small compressors. The forces required to actuate the cut-off mechanism are strongly dependent on compressor speed, and, in addition, as displacement per cylinder is increased, the percentage of mass flow required to operate the cut-off mechanism decreases. Therefore, large, low speed compressors require considerably less power to run the cut-off mechanism than do small, high speed compressors.

CONCLUSIONS

Preliminary tests have demonstrated that it is possible to design a cut-off mechanism to successfully meet requirements for application in a small 3-ton hermetic, 3600 RPM refrigeration compressor with 70 percent capacity reduction. Power requirements, however, are quite high, and the particular type of mechanism presented would be more suitable to larger, lower speed (1800 RPM or less) compressors. Moreover, considerable development is still required before reliability of the cut-off mechanism can be assessed in actual compressor operation.

REFERENCES:

1. Hiller, Carl C., and Glicksman, Leon R., Improving Heat Pump Performance Via Compressor Capacity Control - Analysis and Test Vol. I & II, (Energy Laboratory Report Nos. MIT-EL 76-001 & 002, Massachusetts Institute of Technology, Cambridge, Massachusetts, 1976).

2. Proceedings of the 1972 and 1974 Purdue Compressor Technology Conferences (Purdue Research Foundation, 1972 and 1974).

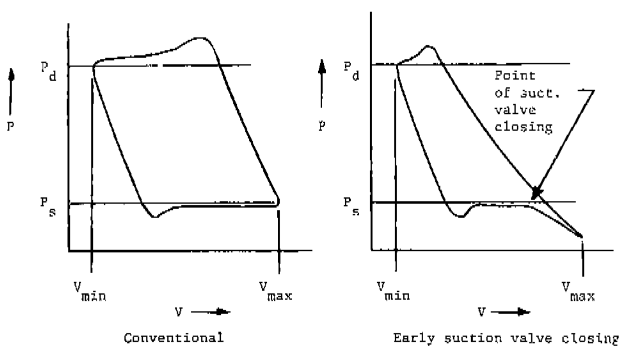
3. Hiller, Dr. Carl C., and Glicksman, Dr. Leon R., "Detailed Modeling and Computer Simulation of Reciprocating Prefrigeration Compressors," Proceedings of the 1976 Purdue Compressor Technology Conference (Purdue Research Foundation, 1976).

4. Manufacturer wishes to remain unidentified.

Table 1

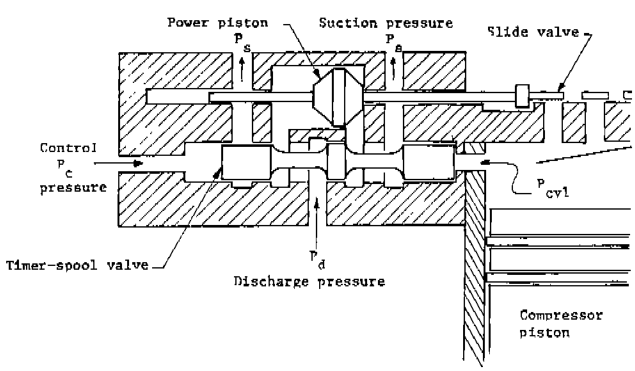
Comparison of a 14-ton Refrigeration Compressor With and Without Cut-Off Control (Refrigerant 22)

	Conventional	Cut-Off Capacity Controlled
Sat. Suct. Temp.	44°F	44°F
Sat. Suct. Press.	89 psia	89 psia
Suct. Superheat	15°F	15°F
Sat. Disc. Temp.	116°F	116°F
Sat. Disc. Press.	261 psia	261 psia
Disc. Temp.	200°F	212°F
Mass Flow	2748 lbm/hr	843 lbm/hr
Power Input	15.8 kw	5.6 kw
Overall Efficiency	60%	52%



P-V DIAGRAMS FOR CONVENTIONAL AND CAPACITY CONTROLLED COMPRESSORS

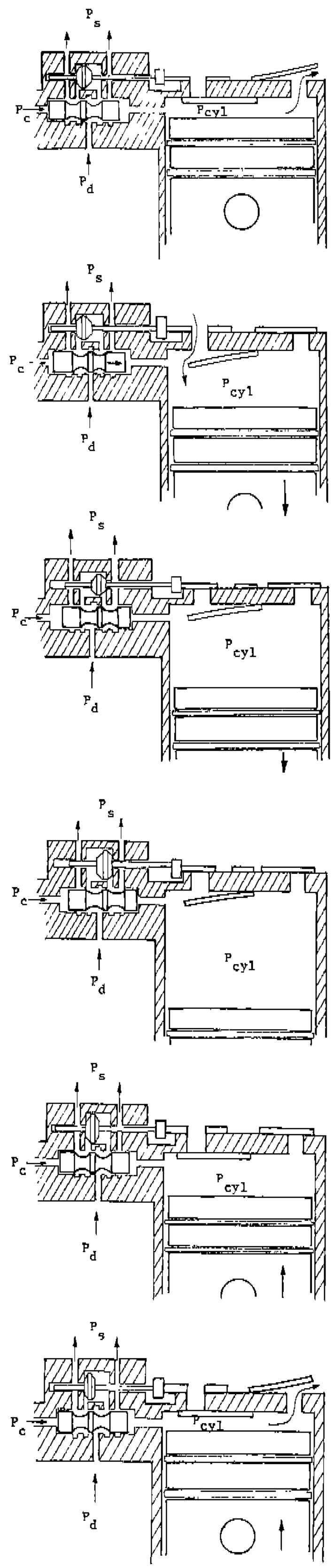
Figure 1



SCHEMATIC OF THE EARLY SUCTION-VALVE CUT-OFF MECHANISM

Figure 2

OPERATION OF THE CUT-OFF MECHANISM THROUGH ONE COMPLETE CYCLE



(a) At top dead center cylinder pressure is approximately at discharge pressure, the slide valve is open, and the timer-spool valve is to the left as shown, because $P_{cyl} > P_c$

(b) After TDC cylinder pressure falls rapidly to suction pressure, at which time the normal suction valve opens and admits gas into the cylinder. At some point during the rapid drop in pressure the control pressure P_c becomes greater than the cylinder pressure P_{cyl}, and the timer-spool valve begins to move.

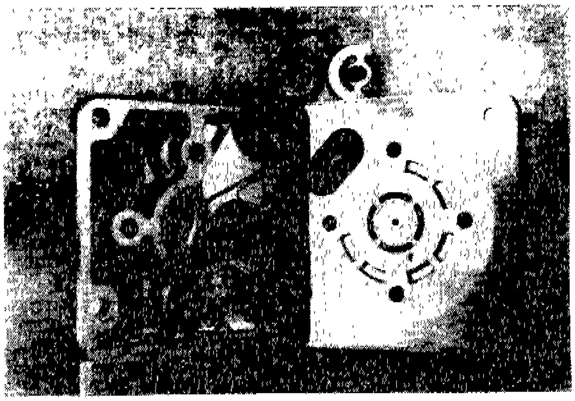
(c) After a travel time determined by the mass of the timer-spool valve and the applied pressure differential ($P_c - P_{cyl}$), the timer-spool valve reverses the pressure differential across the power piston, causing the slide valve to snap closed.

(d) The gas in the cylinder after the slide valve is closed is then expanded until the piston reaches BDC, while the slide valve remains closed. The small volume between the slide valve and the normal suction valve is also reduced in pressure.

(e) The gas in the cylinder is compressed. The normal suction valve is closed because of the pressure differential across it. When the cylinder pressure rises above P_c, the timer-spool valve moves back to its original position, causing the slide valve to reopen.

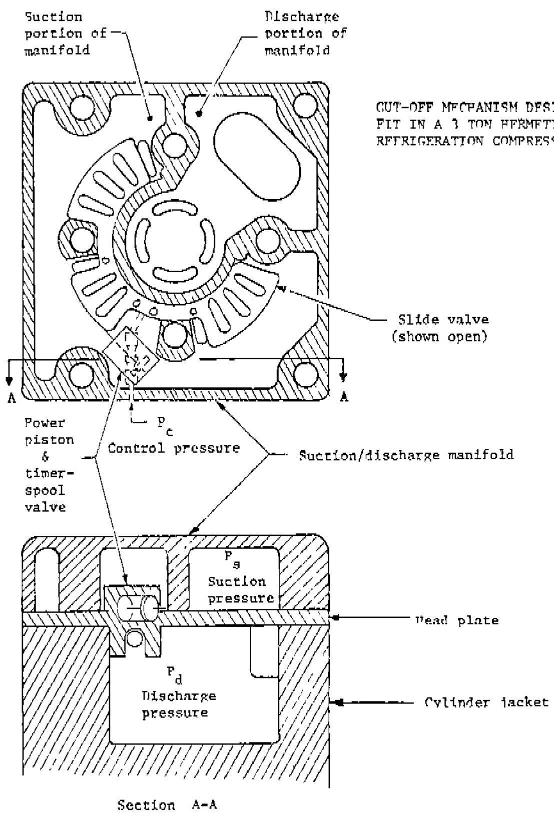
(f) The gas in the cylinder is discharged and the cycle is repeated.

Figure 3



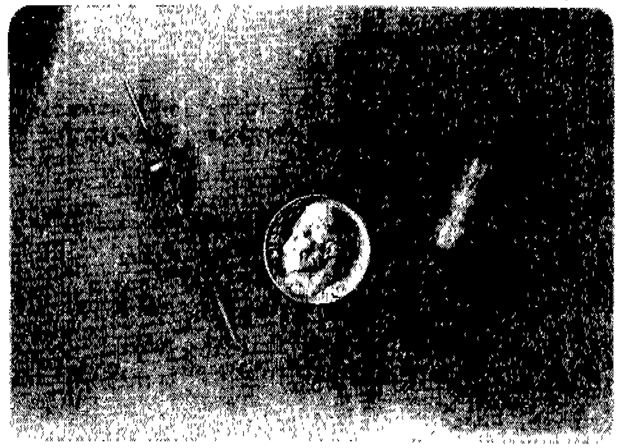
DISCHARGE VALVE, SUCTION/DISCHARGE MANIFOLD,
AND MANIFOLD SIDE OF HEAD PLATE - 3 TON COMPRESSOR

Figure 4



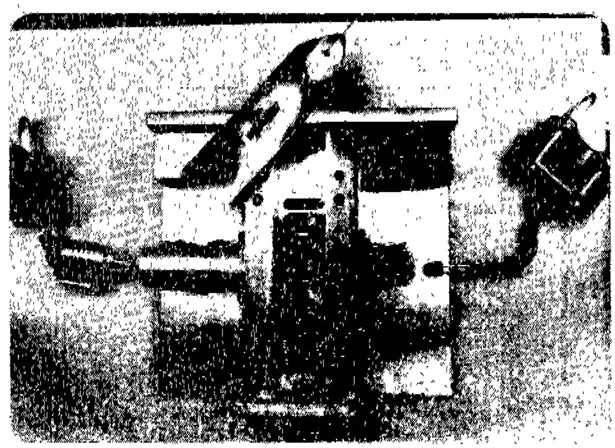
CUT-OFF MECHANISM DESIGN TO FIT IN A 3 TON HERMETIC REFRIGERATION COMPRESSOR

Figure 5



EXPERIMENTAL POWER PISTON (LEFT) AND SPOOL VALVE (RIGHT)

Figure 6



SLIDE VALVE & SLIDE VALVE CHAMBER, SHOWING
PHOTO-SENSING SYSTEM & MASK ON SLIDER

Figure 7