

1984

Over-Reexpansion as a Means of Compressor Capacity Modulation

K. W. Yun

L. Reese

Follow this and additional works at: <https://docs.lib.purdue.edu/icec>

Yun, K. W. and Reese, L., "Over-Reexpansion as a Means of Compressor Capacity Modulation" (1984). *International Compressor Engineering Conference*. Paper 435.

<https://docs.lib.purdue.edu/icec/435>

This document has been made available through Purdue e-Pubs, a service of the Purdue University Libraries. Please contact epubs@purdue.edu for additional information.

Complete proceedings may be acquired in print and on CD-ROM directly from the Ray W. Herrick Laboratories at <https://engineering.purdue.edu/Herrick/Events/orderlit.html>

OVER-REEXPANSION AS A MEANS
OF COMPRESSOR CAPACITY MODULATION

K. W. Yun, Product Manager-Semi-Hermetic Engineering
Copeland Corporation, Sidney, Ohio

Lothar Reese, Director of Engineering
DWM-Copeland, Berlin, West Germany

ABSTRACT

The purpose of this paper is to introduce the development of a unique compressor capacity modulation concept which utilizes reexpansion volume as a means of capacity reduction in hermetic air conditioning and refrigeration system. While there are various methods of compressor capacity modulation in use, each particular method is limited in its application or appeal for different reasons such as cost, vibration, performance, reliability or limited compressor range because of high operating temperature.

This paper compares this over-reexpansion method with other common methods, and presents its thermodynamic and operating performance characteristics. Then, actual performance data obtained from prototype hardware are compared with actual data of other capacity modulation methods. The comparisons show that this over-reexpansion concept offers unique advantages including a wider compressor application range.

INTRODUCTION

Typical refrigerating loads are seldom constant, and also deliberate oversizing of the system capacity is common. A disparity between load demand and capacity supply is therefore inevitable. Thus, for both operational and economic reasons, it is desirable to provide for some means of the capacity control of the system to achieve equalization of capacity and load.

A number of methods of capacity modulation are in use today, but they all have benefits and drawbacks. In addition to improved system efficiency, there are other important reasons, such as vibration or range of application, for striving to produce a better capacity modulation method.

The concept of reducing compressor capacity by providing an additional clearance volume under an unloaded mode of operation is not new. However, the application of the concept in the past has been limited to low speed compressors, and it cannot readily be applied to today's compressor.

METHODS OF COMPRESSOR CAPACITY MODULATION

A significant number of capacity modulation methods can be found in the literature [1] [2] [3] or in practical usage. Though each method is selected for a particular application for different reasons (including availability), the method is limited for one reason or another.

These methods include blocked suction, hot (discharge) gas bypass, suction line throttling, cylinder bypass, suction valve lift, variable displacement compressor, speed control, either using multiple speed or variable speed motor, and compressor paralleling. Control or manipulation of gas flow is the most common approach. Multiple compressors offer another widely used approach.

FUNCTIONAL REQUIREMENTS OF CAPACITY MODULATED COMPRESSOR

There are certain characteristics of compressors which are sought after when the capacity modulation feature is built in the compressor. Brief descriptions of these characteristics are as follows:

Unloading Steps - Infinitely variable control is ideal, but incremental steps such as 1/4, 1/3, 1/2, 2/3 and 3/4 unloading steps are commonly accepted.

Efficiency - A one-to-one reduction of power to capacity reduction is ideal, but practically the cost effectiveness of capacity modulation usually determines the method used.

Vibration - Torque unbalance caused by certain modulation methods can severely limit their application.

Application - The majority of methods is not applied to medium or low evaporating temperature applications because of excessive compressor operating temperatures. Even at high evaporating temperature (air conditioning) application, the minimum evaporating temperature allowed when operating in the unloaded mode is quite limited.

Reliability - Generally speaking, added components, more complex piping or control scheme, and high compressor operating temperature reduce overall compressor reliability.

Miscellaneous - Other factors such as cost, sound, serviceability, manufacturability, interchangeability with standard non-modulated models are also considered for comparison.

CAPACITY MODULATION BY OVER-REEXPANSION

A. The Concept

The over-reexpansion (henceforth, abbreviated as ORE method) is based on the concept that compressor capacity reduction can be accomplished by increasing the clearance volume, under a partially loaded mode of compressor operation. When the clearance volume is increased, the following consequences result:

1. The reexpansion of gas trapped in the larger clearance volume takes more of the cylinder volume which otherwise is taken up by suction gas from the evaporator. This delays the opening of the suction valve, resulting in reduced volumetric efficiency. Also, since capacity is directly proportional to the proportion of the suction stroke available for induction of gas through the suction valve, the refrigerant mass flow handled or compressor capacity is proportionally decreased.
2. The opening of the discharge valve is also delayed because the rate of pressure rise in the cylinder is slower. This lessens the refrigerant mass flow through the discharge valve.
3. The trapped high temperature gas in the clearance volume superheats the intake suction gas in the cylinder. This further lowers the volumetric efficiency.
4. Energy recovery during the reexpansion process increases. The increased clearance volume ideally has no effect on the power consumption, because the alternate compression and expansion of a fixed quantity of gas theoretically requires zero power, as in the alternate compression of a spring and expansion which recovers the work done during compression. Mechanical friction and flow losses moving gas in and out of the clearance pocket, however, result in a net increase in power.

B. Prior Approaches

The broad concept of reducing compressor capacity by providing a greater clearance (reexpansion) volume can be found in several articles. However, these are impractical for modern hermetic compressors because:

1. The hardware designs are much too bulky and impractical for modern high-speed compressors which are often limited in outline dimensions or space to accommodate the compressor.
2. The clearance volume is often controlled by manual adjustment which may have been adequate for a few large low-speed compressors in a given plant. This type of control mechanism in modern air conditioning or refrigeration compressor is just not practical, especially when many small compressors are used to carry a load and complex automatic controls are intertwined.

C. Special Characteristics of ORE Capacity Reduction

Since the amount of suction gas brought into the cylinder depends on the pressure in the clearance pocket, capacity reduction of the ORE method for a given pocket size is not constant at different operating conditions. This is the characteristic of the ORE method which distinguishes it from other modulation methods.

As shown in the following, the higher compression ratio reduces the capacity further. In other words, a major factor affecting capacity reduction with a given clearance pocket size is evaporating temperature. This is even more true at low evaporating temperature, because of sensitivity of compression ratio to suction pressure. Let's examine this in a simplified theoretical form.

The clearance volumetric efficiency η_{cv} , the ratio of actual volume of suction gas from the evaporator to the piston displacement and its relation to compression ratio, becomes the total volumetric efficiency when flow losses, the effect of cylinder heating and the effect of piston and valve leakage are neglected.

The classical analysis of a Pressure-Volume diagram (Fig. 1) results in the following relationship:

$$\eta_{cv} = \frac{V_c - V_b}{V_c - V_a} \dots \dots (1)$$

The clearance ratio

$$C = \frac{V_a}{V_c - V_b} \dots \dots (2)$$

Since reexpansion from a to b (P_d to P_s) is polytropic

$$\frac{V_b}{V_a} = \left(\frac{P_d}{P_s} \right)^{\frac{1}{n}} \dots \dots (3)$$

From (1), (2) and (3),

$$\eta_{cv} = 1 + C - C \cdot (R)^{\frac{1}{n}} \text{----- (4)}$$

Where R is compression ratio, P_2/P_1 .

From this equation, it is shown that both clearance volume and compression ratio have marked effects on η_{cv} .

These particular inherent characteristics are worth further discussion. If it is not desirable to have too wide a range of capacity reduction over a particular range of compressor operating conditions (for example, in low temperature application), the clearance pocket size can easily be varied by limiting travel of the unloader plunger with a simple sleeve of different heights. This approach is possible because the normal compressor operating range in a given application is rather predetermined, especially when product or comfort space has to be controlled within the narrow range of evaporating temperature.

It is also quite possible to design a clearance pocket which can be varied in volume by multiple step control or infinitely variable volume. Of course, this approach, which appears to be an attractive control scheme, is bound to be more expensive and more complicated. Simple fixed clearance pocket volume for a given application is worth its simplicity.

The inherent characteristics of the ORE can also be conceivably advantageous. As the system load decreases, the evaporating temperature decreases which, in turn, requires more reduction in compressor capacity, and this can be accomplished because of anticipated higher capacity reduction at higher compression ratio.

D. Sizing the Clearance Pocket

The size of the clearance pocket is the key to the extent of capacity reduction for a given compression ratio [4].

Defining the terms:

V_{cp} = Volume of clearance pocket

Q_f = Full load capacity

Q_u = Unloaded (minimum partial load) capacity

f = Fraction, unloaded range/full load capacity, $(Q_f - Q_u)/Q_f$

C = Fraction, clearance volume/piston displacement or clearance ratio

D = Piston displacement or $(V_c - V_a)$

R = Compression ratio

The portion of displacement not used for suction through suction valve is piston displacement multiplied by the fraction f .

$$\text{Then, } V_{cp} = D \cdot f \cdot \left(\frac{V_a}{V_b - V_a} - \frac{V_a}{V_c - V_a} \right)$$

Substituting (2) and (3),

$$V_{cp} = D \cdot f \cdot \left[\frac{1}{(R^{\frac{1}{n}} - 1)} - C \right] \text{----- (5)}$$

For the purpose of illustrating the effect of compression ratio on clearance volumetric efficiency (η_{cv}) and on volume of clearance pocket (V_{cp}), take the following compressor:

2 7/16" bore x 2 1/2" stroke, or
D = 11.66 in.

Capacity reduction range of 33% or f
= 0.33

C = 0.01

Then, equation (5) now becomes:

$$V_{cp} = 3.85 \left[\frac{1}{(R^{\frac{1}{n}} - 1)} - 0.01 \right] \text{----- (6)}$$

Since many other factors besides compression ratio affect V_{cp} in an actual compressor, the equation should be used as a guide only.

In Fig. 2, volume of the clearance pocket in percent of the piston displacement is plotted as a function of compression ratio. The actual development test data is also indicated on it.

PERFORMANCE AND ADVANTAGES OF THE ORE MODULATION

The ORE method of capacity modulation offers several key advantages over other commonly used methods. The following discussions describe them on the basis of theoretical basis as well as actual development test results.

A. Balanced Torque/Vibration

One of the major drawbacks of certain modulation methods is induced torque imbalance when one or more cylinders operate under different loading. This happens when the suction flow to the designated cylinder is prohibited partially or completely. A three-cylinder compressor is a case in point, for example. As long as clearance volumes of all cylinders are increased at the same time and amount, torque balance is maintained.

B. Energy Efficiency Ratio (EER)

Evaluation of compressor performance under the partially loaded mode can be made by comparing

EER ratio* (EER fully loaded divided by EER partially loaded) at the identical operating condition.

Over a range of evaporating temperature, capacity reduction and EER ratio are depicted in Fig. 3, comparing ORE and blocked suction methods for a given compressor. It can be seen from the data that performance of the ORE method is at least comparable to blocked suction method, which is often favored for its high efficiency.

C. Operating Temperature/Application Range

The most critical limiting factor in the application of capacity modulation is high compressor operating temperature under unloaded mode. This is due to overheating under reduced mass flow for motor/compressor cooling. Therefore, the application range in the unloaded mode is typically quite restricted in order to keep compressor operating temperature under the critical design limit. The critical limit may be discharge temperature, motor temperature or oil temperature. Under a given suction gas temperature, as compression ratio increases, the operating temperature increases, this limits range of operation under high compression ratio.

For a given unloading method, limit of compressor operating range can readily be defined by constructing points (combination of evaporating/condensing temperature) at which certain operating temperature (discharge, oil, or motor temperature) exceeds the design limit (Fig. 4). At all points on any given line, operating temperature reaches the critical design limit. This clearly illustrates a significant advantage of the ORE method in compressor operating temperature, especially for low evaporating temperature application. Note that this is a theoretical curve, and actual applications would be restricted beyond these points.

D. Compressor Starting Ability

One important requirement in selecting a motor for a compressor is starting ability of the compressor under low voltage condition. At the compressor start-up, the solenoid is de-energized (unloaded mode), therefore the compressor can start at a lower voltage than the case of start-up under the fully loaded mode. Less refrigerant mass brought into the cylinder through the delayed suction valve opening and moderated rate of pressure increase in the cylinder contribute to the starting improvement.

*In an actual system, operating condition changes when the compressor is switched from fully loaded to partially loaded condition. Condensing temperature drops while evaporating temperature goes up.

E. Noise

Noise is normally not of concern under the partially loaded mode, since reduced loading in the compressor reduces noise level, unless resonance or sound power level at a certain frequency becomes a problem.

Sound tests in a reverberant room showed neither increased overall sound power level nor annoying tone at a certain frequency. At the ARI test point for high temperature application (+45°F evaporating/130°F condensing/R-22), the noise level at 60% of fully loaded capacity was 2 dbA lower than that under fully loaded mode. This reduction is roughly what would be expected from the reduced capacity.

F. Reliability

Adding unloading features could affect compressor/reliability for two reasons: First, the need for added controls. Since a control scheme must be added regardless of the modulation method, we have to be concerned about making the additional hardware in the compressor as simple and reliable as possible.

Second, despite the fact that switching of a compressor running mode to a partial loading lowers compression ratio, it could also impose additional stresses on the compressor because of higher operating temperature or shock loading. Operating temperature advantages of the ORE method has already been covered in the previous section.

G. Miscellaneous Factors

In this category, cost, manufacturability, serviceability, interchangeability with or convertability to non-modulated model compressor should be considered. Due considerations were given to these factors in finalizing hardware design/development.

DEVELOPMENT OF ORE HARDWARE DESIGN

The Design Concept

The particular design from which design modifications were made to accommodate the ORE concept is the low clearance volume "Discus" valve plate assembly. This particular valving design [5] utilizes a ringed suction valve, and a conical discus-shaped discharge valve which minimizes unnecessary clearance volume.

With the given valve plate assembly, a separate clearance pocket above each cylinder bore is built in the common head casting to locate the pocket adjacent to the cylinder bore. A solenoid valve is used to either activate or deactivate the clearance pocket. The piston plunger moves up/down, depending on different gas pressure above it, which is alternated by the solenoid valve. Between the solenoid valve and the head, there is a cover plate which provides gas passages and seals the clearance pockets from each other.

CONCLUSIONS

The concept of increased clearance volume for modulation, as applied to hermetic compressors, has demonstrated its advantages in excellent energy efficiency, wide application, and low voltage starting. Reliability, cost and sound emission goals are readily achievable with this method.

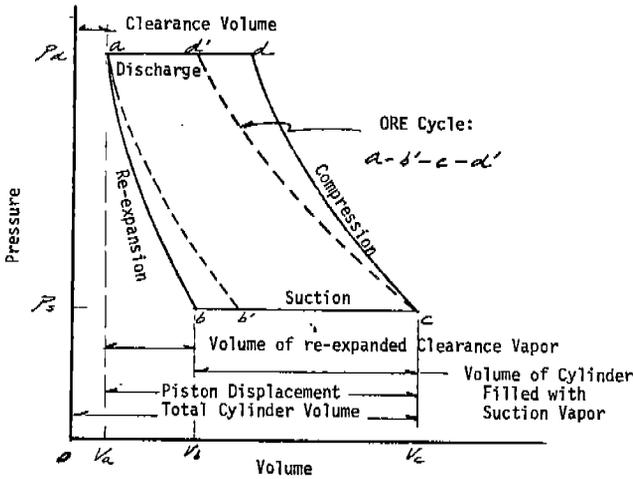


Fig. 1 Theoretical Pressure-Volume Diagram of an Ideal Compression Cycle

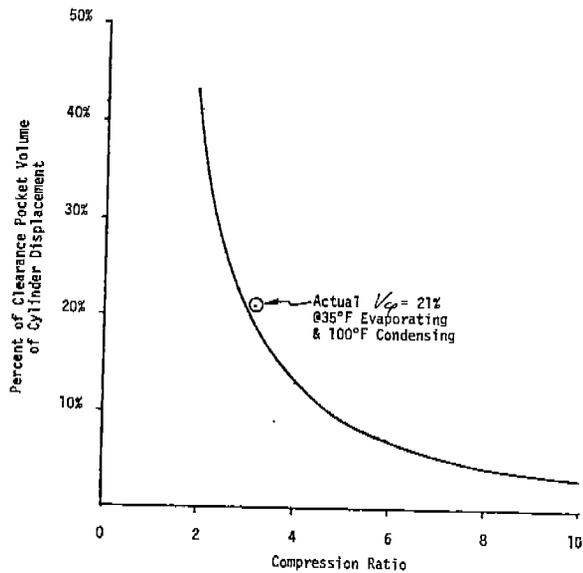


Fig. 2 Effect of Compression Ratio on Sizing of Clearance Pocket

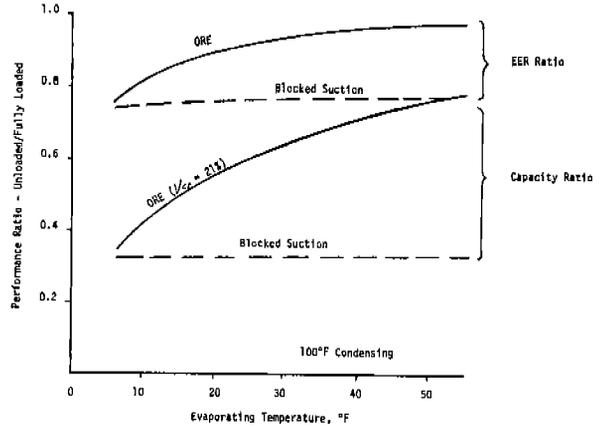


Fig. 3 Performance Comparison for ORE and Blocked Suction Modulation

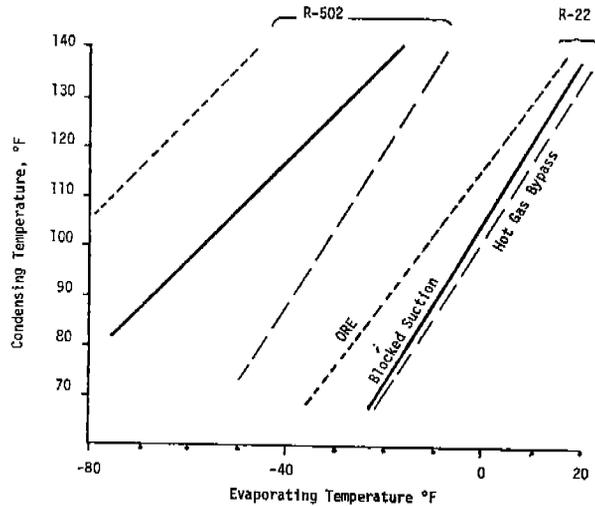


Fig. 4 Theoretical Application Limits Based on 330°F Discharge Temperature

REFERENCES

- [1] Muir, E.B., Griffith, R.W., Capacity Modulation for Air Conditioning and Refrigeration Systems, Air Conditioning Heating & Refrigeration News, May 14, 1979 Issue.
- [2] Dossat, R.J., Principles of Refrigeration, John Wiley & Sons, 1961, pp. 239-243.
- [3] Holdack, H., Kruse, J.H., Continuous and Discontinuous Capacity Control for High Speed Refrigeration Compressors, Especially Those With Few Cylinders, 1984 Purdue Compressor Technology Conference Proceedings.

- [4] Bauer, F., Molnar, K.G., Regulating Air Compressors, Fluid Power International, Vol. 33, 1968, pp. 36-39.
- [5] Chambers, D.C., Kalivoda, F.E., High Performance Valve System, 1984 Purdue Compressor Technology Conference Proceedings.