The design of slide valve unloaders for refrigeration screw compressors in air conditioning applications

S. P. Engineer **J. Sauls,** USA

Zusammenfassung

In der vorliegenden Arbeit wird eine Methode für die Konstruction eines in Klimaanlagen gebrauchte Schraubenverdichter Regelshiebers beschrieben. Zuerst ist einen Überblick über allgemeine Grundsätze der Konstruction gegeben. Dann ist die Optimierung die in dieser Bericht so genannten "slide stop" Länge mit hilfe eines thermodynamischen Simulationssystems für Schraubenverdichter als auch der Kreisprozess dargestellt. Schließlich ist ein Vergleich der gemessenen und berechneten Teillastverhalten für Luft- und Wassergekühlten Betriebsbedingungen gegeben.

Summary

This report describes a method of design for slide valve unloaders in screw compressors used in air-conditioning applications. General design considerations are reviewed and an optimization study of the slide stop length using an integrated computer simulation of the screw compressor and refrigeration cycle is presented. Finally, a comparison between computed and tested performance of a refrigeration compressor designed using the methods of this report is made for operation at both air- and water-cooled system operating conditions.

1.0 Introduction

Although the single-piece slide valve unloader is a geometrically simple device, it requires careful design in order to provide good performance in air-conditioning equipment. This means that the designer must have the ability to study the effect of variations in geometric parameters on both full- and part-load performance. In addition, it is necessary to do the design studies taking into account the actual operating conditions that will be imposed on the compressor by the air-conditioning system. Air-conditioning equipment can use either water- or air-cooled condensers, imposing full load pressure ratios of 3:1 and 4:1 respectively. More importantly, the systems will impose a variation in pressure ratio that is a function of the capacity. An air-cooled system will run at a pressure ratio of about 2.3 at 50% capacity while water-cooled system pressure ratio falls to a value of 2:1.

In the following, the use of a screw compressor computer simulation model integrated with a refrigeration cycle analysis in optimizing slide valve unloader design for specific air-conditioning applications is discussed. The computer program used is described in general terms in /8/. The computation of the compression process within the rotors is similar to that described by other authors /1/, /2/, but the mathematical formulation is for real gas properties to more accurately reflect the nature of refrigerants. Air-conditioning system performance is integrated into the cycle analysis segment of the program to allow the variation in evaporator and condenser saturation temperatures with system capacity to be included in the overall simulation...the program iterates between compressor and system calculations until the load and the saturation temperatures used are consistent with the system's operating characteristics.

Symbols and terminology are described in the Nomenclature section at the end of the report. Figures 9 and 10 are in this section.

2.0 **General Considerations in Slide Valve Unloader Design**

The parameters that the designer can use to adapt the slide valve to the system operating requirements are (see Figures 9 and 10):

- Slide stop length. The slide stop is the section of housing that determines the location of the suction end of the slide valve when the compressor is at maximum capacity. The length of the slide stop is Zstop and the slide valve length is then Lr - Zstop.
- Slot width. This is controlled by the slide valve angles $\alpha 1$ and $\alpha 2$. These angles will also determine the diameter of the slide valve and the total slide valve surface adjacent to the rotors, an important factor in internal leakage.
- Axial and radial discharge ports. These are chosen to set the full- and part-load volume ratio characteristics of the screw compressor.
- Unloader gallery. This is the passage in the housing between the rotor space exposed by moving the slide valve and the suction side of the compressor. Pressure drop in the gallery increases as the compressor unloads. Excessive gallery pressure drop can cause poor performance in the lower capacity range of operation.

Elements of the slide valve that work together to determine the capacity of the compressor are:

- Axial location of the suction end of the slide valve, Zsv. Moving the slide valve away from the slide stop and towards the discharge end of the compressor reduces the effective length of the rotors. This effect alone provides a capacity variation that is directly proportional to the value of Zsv.

- Open area of the unloader slot. The slot area is equal to the slot width times the unloader displacement (Zsv-Zstop). The slot represents a resistance to the refrigerant leaving the rotors to recirculate for load reduction. Thus, for a given slide valve position, increasing values of Zstop result in higher capacities than represented by the reduced effective length of the rotors as determined only by the value of Zsv.

The slide valve design factors that affect the part-load efficiency:

- Volume ratio - Vi changes considerably as the slide valve moves. Figure 1 shows the volume ratio change as capacity is reduced for compressors with full load radial Vi's = 2.2 and 2.9 with an axial Vi = 4.5. As the compressor unloads, the Vi drops in response to a relatively large reduction in effective suction volume (reduced rotor length), then rises as the radial port size is reduced as it moves out of the housing. The axial and radial port Vi's are the same at Zsv' = 0.47 load for the 2.2 Vi compressor and Zsv' = 0.35 for the 2.9 Vi compressor. For Zsv' above these crossover points, the axial port determines the Vi. As the slide valve continues to move, the effective length of the rotor is reduced and Vi drops.

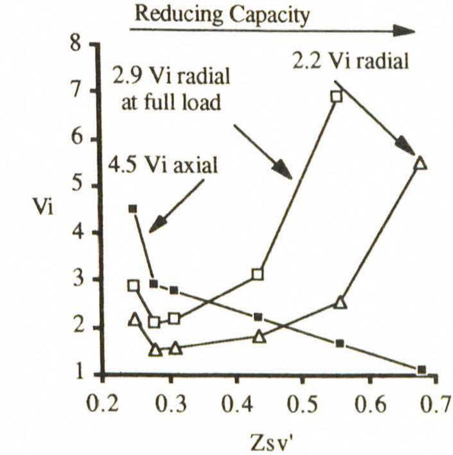

Figure 1: Part-Load Volume Ratio Characteristics

Bild 1: Teillast Volumenverhältnis Verlauf

The effect that variation in volume ratio has on the efficiency depends on how the operating pressure ratio imposed on the compressor by the refrigeration system varies /3/, /4/, /7/. For air-conditioning systems this is a significant factor in part-load performance.

- Compression over the slide stop - The slide stop forms a closed part of the rotor housing regardless of the position of the slide valve. As the rotor pocket passes over the stop, some compression takes place with this 'pre-compression' work increasing with slide stop length.

- Slot size - This is the open area that flow passes through as it leaves the rotors. The area is the product of the slot width, determined by the design angles α, and the slide valve displacement, Zsv - Zstop.

- Unloader gallery pressure drop. This is determined by the cross-sectional area of the gallery, the shape and roughness of the passages and the flow rate through the gallery. As the slide valve moves farther from the slide stop, flow through the gallery increases, resulting in increased gallery pressure drop. This resistance causes a higher pressure in the rotors, resulting in increased work and reduced unloading capabilities.

Slide stop length plays a major role in affecting the compressor's part-load performance. Variations in both capacity and efficiency with slide valve position will be influenced by the choice Zstop. The basic slide stop effects are illustrated in Figure 2. These schematics show long and short slide stops, respectively, along with a representation of the rotor's internal pressure characteristic.

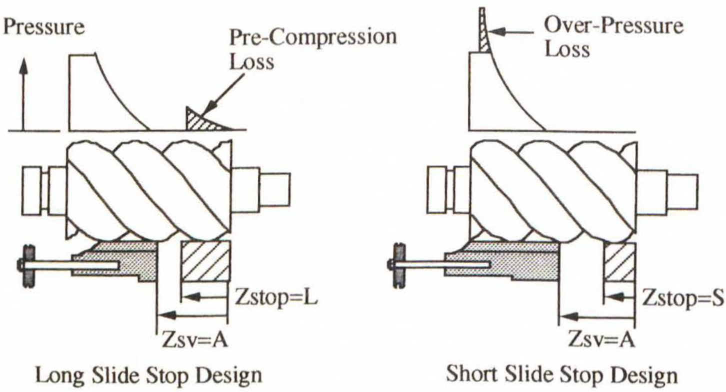

Figure 2: Effect of Slide Stop Length
Bild 2: Wirkung der “Slide Stop” Länge

For the long slide stop, positioning the slide valve at Zsv = A requires less movement than for the design with the short slide stop so the radial discharge port is not moved as far. Thus, the long slide stop design has a lower Vi and less slot area than the short slide stop design. There is also more pre-compression work with the long slide stop, a performance loss at any condition.

The short slide stop is desirable since it provides a large slot flow area and little pre-compression work. However, the part-load volume ratio characteristics of the short slide stop compressor...generally high volume ratio at low loads...may not be consistent with the actual operating conditions. Thus, even for a relatively simple geometric feature such as the length of the slide stop, selection of an optimum dimension is a complex process, requiring studies of the interaction between all of the slide valve design parameters and a knowledge of the actual operating conditions at which the compressor must run.

3.0 Slide Valve Optimization with the Simulation Program

3.1 Evaluation Criteria

Before presenting the design studies, it is necessary to define the operating conditions to be used and the method by which the various alternatives will be compared. The slide valve design should be analyzed for the conditions in which it must perform in the air-conditioning system. In the examples, designs are studied in systems with relief. That is, the condenser and evaporator temperatures vary with capacity such that operating pressure ratios are reduced as the compressor unloads. Two systems, one with air-cooled condensing and one with a water-cooled condenser, are considered. Typical variations in operating temperatures and pressure ratios are illustrated by the data below:

		Air-Cooled	Water-Cooled
100% Capacity	Condenser Temperature:	130°F /54.4°C	105°C / 40.6°C
	Evaporator Temperature:	35°F / 1.7°C	35°F / 1.7°C
	Pressure Ratio (R-22):	4.1:1	3.0:1
50% Capacity	Condenser Temperature:	93°F /33.9°C	83°C / 28.3°C
	Evaporator Temperature:	39°F / 4.0°C	39°F / 4.0°C
	Pressure Ratio (R-22):	2.3:1	2.0:1

It is also well known that air-conditioning systems operate at part-load conditions much of the time, with a different number of operating hours at different capacities /7/. Thus, the measure of power or COP must be a time-integrated value. The Integrated Part Load Value (IPLV) is used for this purpose. The IPLV, a load-weighted, annual average COP, is defined in /5/; its usefulness in evaluation of various unloading methods for air-conditioning equipment has been described in /6/ and /7/.

3.2 Calculation of Slide Stop Length

In order to illustrate the process of slide valve design, the compressor simulation program was used to select the optimum slide stop length for an air-conditioning screw compressor. The method is illustrated on the design of a compressor for water-cooled systems with full load volume ratios of 2.2 (radial) and 4.5 (axial). The compressor is a 60 Hz, male rotor drive, semi-hermetic screw using a rack generated rotor profile /9/. The slide valve angles $\alpha 1$ and $\alpha 2$ are 40° . Other compressor data is given in the table below:

Design Dimensions		
Rotor Lobes		5:7
L/D		1.25
Vi -	radial	2.9 A/C or 2.2 W/C
	axial	4.50

Full Load Performance (R-22)		
	A/C	W/C
Capacity (KW)	294	343
Power (KW)	113	88
COP	2.6	3.9

The procedure for optimization involves computing performance at several slide valve positions (Zsv' = constant). For each value of Zsv', performance for several slide stop lengths (Zstop' = constant) is computed.

Figure 3 shows the computed performance for one slide valve position. For these calculations, Zsv' was held at a constant value of 0.31 and Zstop' was varied from 0 to 0.31. The power vs. capacity characteristic shows a distinct minimum power condition. This is the optimum value of Zstop' for this slide valve position.

The reason for the increase in capacity with increasing slide stop length is the reduction in the slot width. Since Zsv' is fixed, increasing Zstop' reduces the slot size and subsequently the amount of refrigerant that can be recirculated. Continuing to increase the slide stop length until Zstop' = Zsv' just fully loads the compressor as shown in Figure 3.

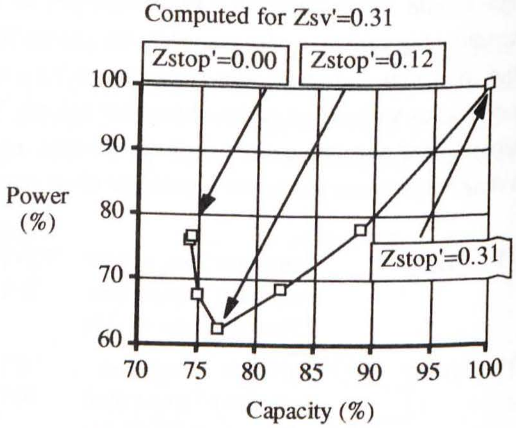

Figure 3: Power Characteristic for Zsv' = Constant
Bild 3: Leistungsverfahren für Zsv' = Konstant

The reduction in power as the slide stop length is reduced from a value of 0.31 is due to the reduced capacity and the system head relief. In the range from Zsv' = 0.31 to Zsv' = 0.12, the compressor volume ratio matches system pressure ratio fairly well and the operating efficiency is good.

However, for Zstop' < 0.12, the power required rises rapidly. This is a result of the change in the effective volume ratio to higher values while the system pressure ratio remains almost constant (capacity is changing very little). For shorter slide stops, the slide valve has to move farther to reach the Zsv' = 0.31 unloaded position so the radial discharge port moves farther, thus increasing the operating Vi. At the constant system pressure ratio, the result is an increase in over-pressure losses with higher power and reduced efficiency.

These calculations at one slide valve position show that there is a minimum power point. However, it is necessary to repeat the process described for other slide valve positions to establish the unloading characteristics over the entire capacity range of interest.

Figure 4 shows the complete set of slide valve design curves computed for the water-cooled screw compressor in a system operating with relief. Performance was computed for four slide valve positions and for each slide valve position, calculations were made with several slide stop lengths. Again, the curves show the distinct minimum power point seen in Figure 3. The envelope of these minimums would in theory be the best performance achievable. However, the minimum points for each value of Zsv'=constant may not occur at the same Zstop' value.

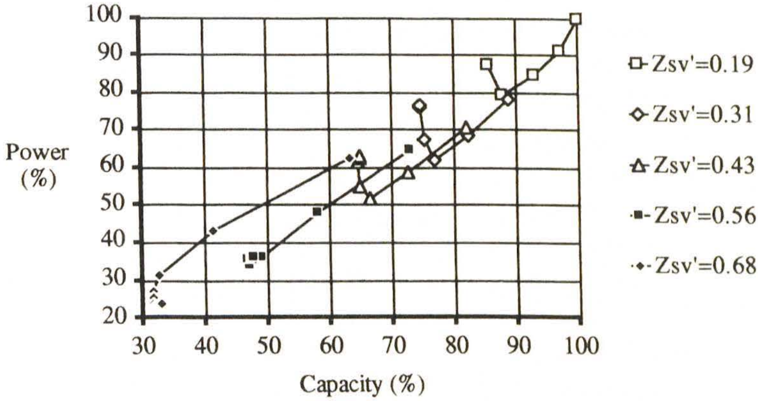

Figure 4: Part-Load Characteristics for Water-Cooled Systems with Zsv' as the Design Parameter

Bild 4: Teillastverfahren für Wassergekühlten Anlagen mit Zsv' als Parameter

To find the optimum value of Zstop' for a compressor with a fixed slide stop length, the data shown in Figure 4 is presented in a different format as shown in Figure 5. Here, the optimization data is presented with lines of constant Zstop'.

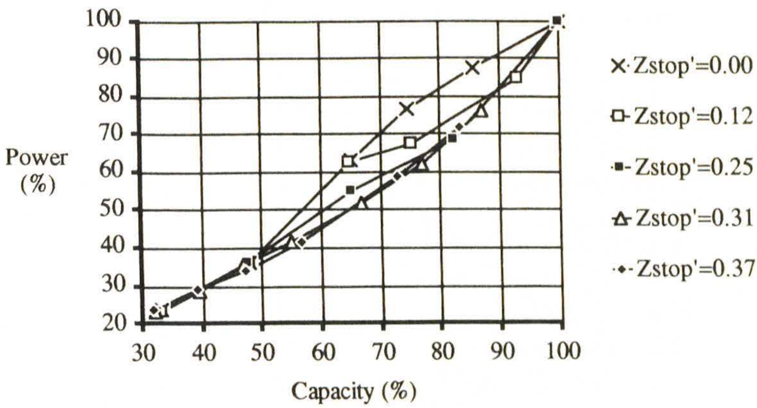

Figure 5: Part-Load Characteristics for Water-Cooled systems with Zstop' as the Design Parameter

Bild 5: Teillastverfahren für Wassergekühlten Anlagen mit Zstop' als Parameter

From this data it can be seen that the short stop design is clearly a poor choice, using more power at all capacities over 50%. The longer slide stop alternatives have much better characteristics. At Zstop'=0.31 performance is slightly better at higher loads while Zstop'=0.37 is better at lower loads.

The longer slide stop alternatives give better performance than the short stop designs. In order to pick the best design for this particular application however, it is necessary to use an integration procedure such as the IPLV to include the effect of operating profile. Figure 6 shows the IPLV vs. Zstop' characteristic taken from the data in Figure 5. In addition to the IPLV, the ratio of IPLV to the maximum value is shown. For this example, the best integrated performance is achieved with a slide stop that is 30% of the rotor length. Selection of Zsv' = 0.25 would result in a performance loss of more than 2%, as would a design using a longer stop of Zsv' = 0.38.

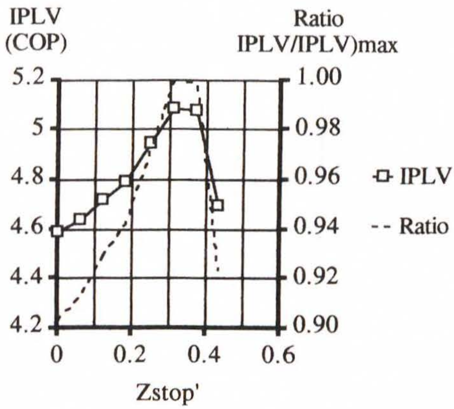

Figure 6: IPLV as a Function of Zstop'

Bild 6: IPLV in Abhängigkeit von Zstop'

Figure 7 shows the computed slide valve optimization data for the air-cooled version of the same compressor represented in Figures 3 through 6, using a fully loaded Vi of 2.9.

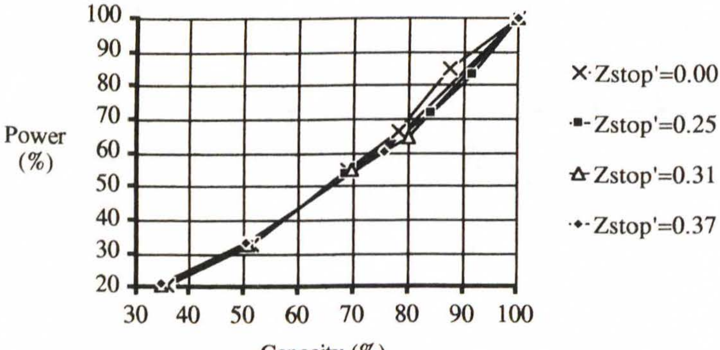

Figure 7: Part-Load Characteristics for Air-Cooled systems with Zstop' as the Design Parameter

Bild 7: Teillastverfahren für Luftgekühlten Anlagen mit Zstop' als Parameter

This higher volume ratio compressor shows less sensitivity to the variation in slide stop length, with most of the performance variation seen at capacities above 75%. This is primarily due to the fact that the radial discharge port is relatively small and allows the axial discharge port to control the volume ratio at capacities below about 80% where Zsv' = 0.35 (see Figure 1) for all but the longest slide stops studied. With the large change in pressure ratio seen in air-cooled systems during part-load operation, this falling Vi characteristic is desirable. The IPLV variation for all of the air-cooled design options was less than 2% over the entire range of Zstop' studied.

4.0 **Comparison of Computations with Data**

Figure 8 shows a comparison of measured and computed performance for three operating characteristics for a 2.9 Vir/4.5 Via screw compressor operating in R-22 at 60 Hz. Air-cooled load lines with relief and at constant saturation temperatures of 1.7°C/54.4°C as well as a load line at the water-cooled conditions of 1.7°C/40.6°C are shown (the power for the W/C data is shown as a percentage of the A/C full load power for clarity on the chart).

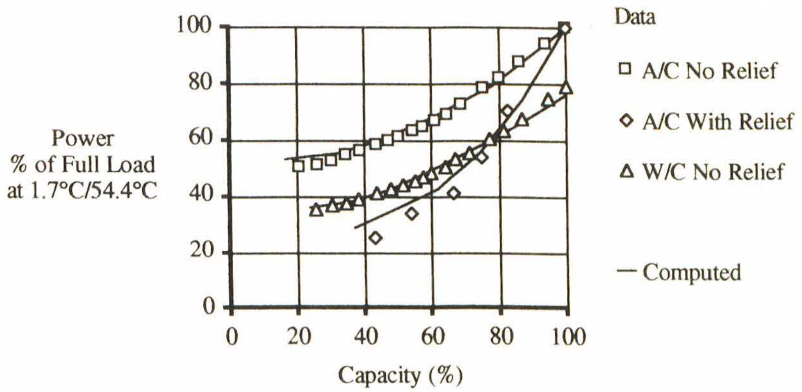

Figure 8: Measured and Computed Part-Load Characteristics
Bild 8: Gemessenen und Berechneten Teillastverfahren

Computed values of IPLV (COP) for the data in Figure 12 are tabulated below:

	Data	Computed
Air-Cooled/No Relief	1.84	1.71
Air-Cooled/With Relief	4.00	3.40
Water-Cooled/No Relief	3.03	3.15

While the actual levels of IPLV computed are not exactly the same as those measured for this particular compressor, other work has shown that the method described in this report is very accurate in selecting the geometry that will give the best performance. Examples of test and computation on the effects of slide stop length and volume ratio in earlier research programs are given in reference /8/. It is suspected that one reason why the computed performance does not agree more closely to the measured is that the unloader slot and gallery flow models are relatively simple in consideration of the complexity of the actual flow conditions.

5.0 Concluding Remarks

This report has presented a description of the slide valve unloading method and illustrated a slide valve design procedure using a computer simulation of a screw compressor and refrigerant cycle. The following conclusions can be drawn from the report:

- A slide valve for screw compressor capacity regulation has only a few design parameters, but proper selection of these parameters is necessary for achieving acceptable integrated part-load performance as measured by the IPLV parameter.
- Using the methods presented in this report, it is possible to select one value for slide stop length that gives good performance for both air-cooled and water-cooled air-conditioning systems.
- The method can be improved by better simulation of the complex fluid flows occurring during the part-load operation of the screw compressor.

6.0 References

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7.0 Nomenclature

7.1 Symbols

A/C	Air-cooled system	α	Slide valve design angle
W/C	Water-cooled system	Zstop	Slide stop length
Lr	Rotor or housing length	Zsv	Slide valve location - distance from suction end
L/D	Rotor length/diameter ratio	**Superscripts**	
Vi	Built in volume ratio	'	Relative to rotor length
Vir	Radial Port Vi		Zsv' = Zsv/Lr
Via	Axial Port Vi		Zstop' = Zstop/Lr

7.2 Definitions

Slide Stop: The part of the rotor housing that limits the travel of the slide valve towards the suction or inlet end of the compressor (see Figure 9).

Relief: The reduction in pressure ratio from changes in air-conditioning system condenser and evaporator saturation temperatures. In general, the condenser temperature will drop and the evaporator temperature will rise with reductions in capacity, imposing a lower pressure ratio on the compressor (see /7/).

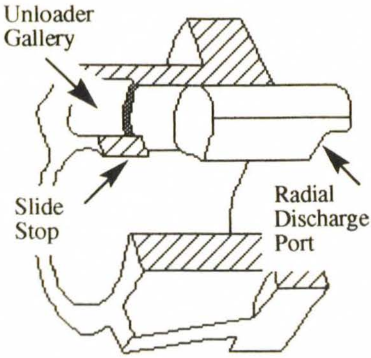

Figure 9

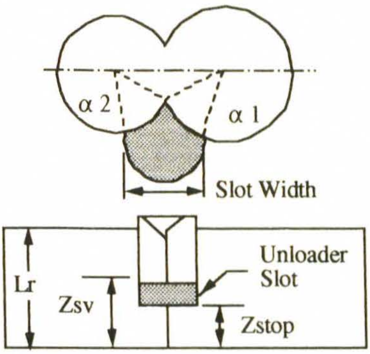

Figure 10

Slide Valve Unloader Design Features

Hauptpunkten der Konstruktion des Regelschiebers

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