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Introduction to
Capacity Control and Thermodynamic Design

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Contents

- Why capacity control?
- Operating principle
- Capacity control options
- Effects on thermodynamics

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Why capacity control?

Capacity control is required in case of:

- Variations in process conditions (e.g suction pressures, molweight, suction temperature, etc.)
- Margin in capacity (over-design)
- Different needs for gas

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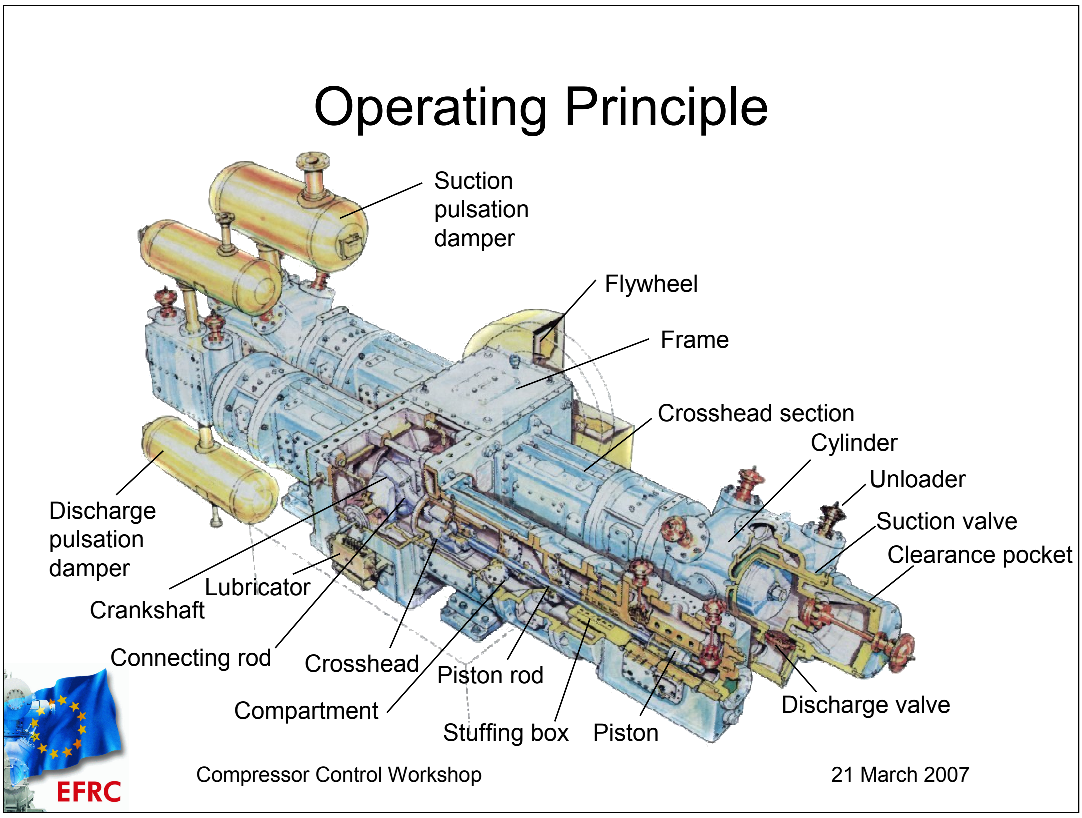
Controlling the compressor capacity has everything to do with controlling the capacity in the process where the compressor is operating. The process system is important, the compressor is just one of the components in a complex process system. With capacity control of the compressor the process pressures and process volume- or mass flow can be kept constant or can be adjusted to the process requirements. Capacity is the amount of gas drawn into the cylinder and therefore the amount of gas taken out of the suction header of the compressor.

Capacity control is required in case of:

- Variations in process conditions (e.g suction pressures, molweight, suction temperature, etc.). Example depletion compressor with decreasing well (or suction) pressure over the years and requirements that differ over time and season.

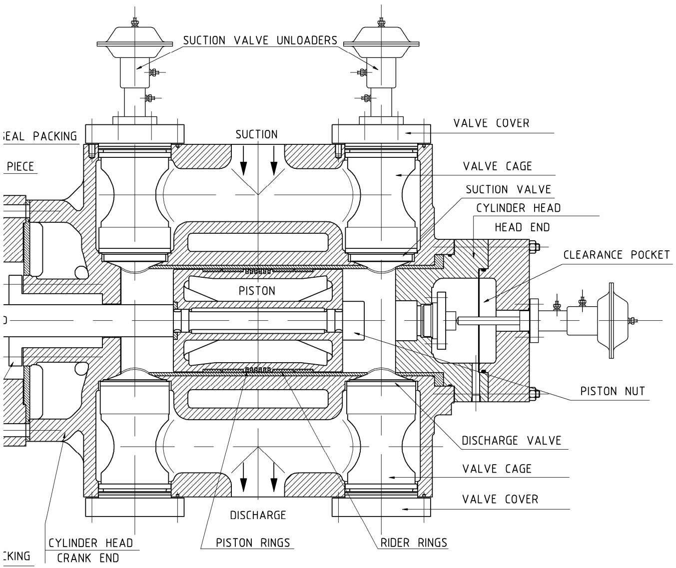
- Margin in capacity (over-design). Some specification require an additional margin in the capacity. Required capacity is most often for worst case conditions.

- Different needs for gas. Maximum capacity is not always required, e.g. in summer more PET bottles, less gas for heating, etc.



The main components of a horizontal, balanced opposed, reciprocating compressor are indicated in this figure.

Operating Principle



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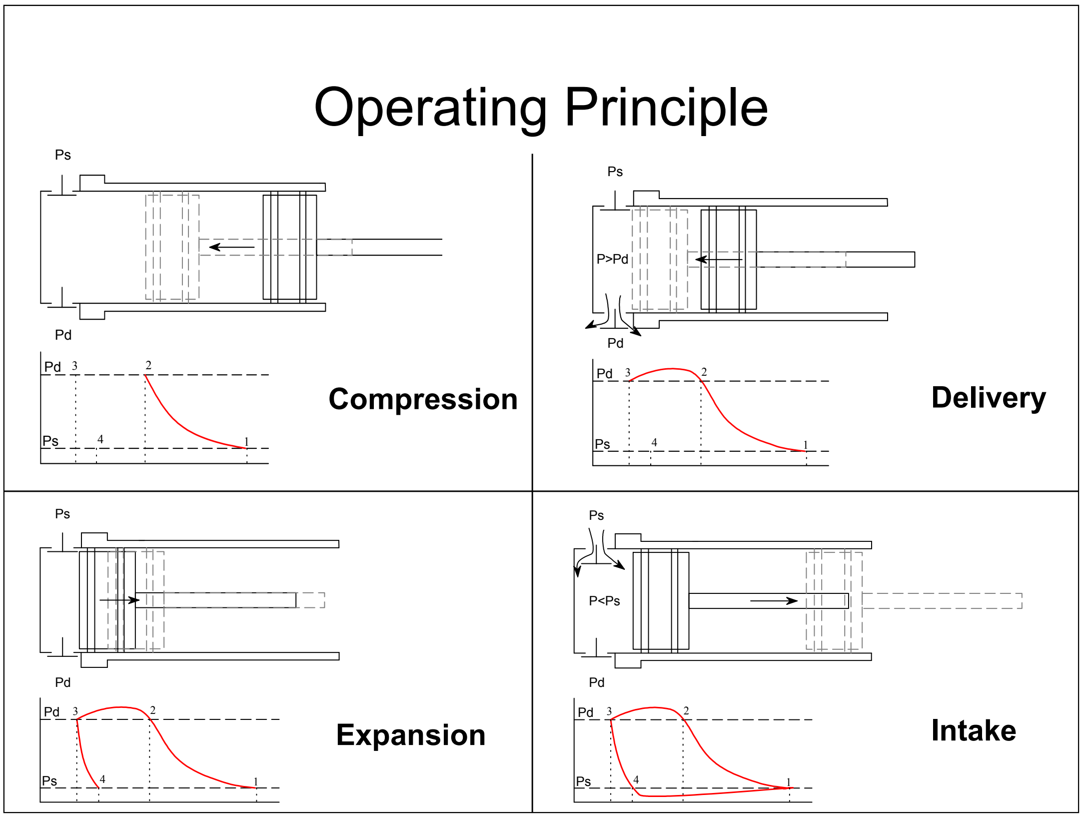
The most common cylinder is the Double Acting (DA) cylinder with compression on the head end and the crank end side (two compression strokes per revolution). The figure shows a DA cylinder with the main parts.

Unloaders can be used to unload one or two sides of the cylinder. An unloader is a device mounted on the suction valve (normally air operated) to keep the suction valve open when the compressor is in operation.

A clearance pocket can be used to reduce the capacity of cylinder side. A clearance pocket is an extra volume normally located on top of the head-end cover as shown in the figure. Incidentally this can be used on the CE side as well.

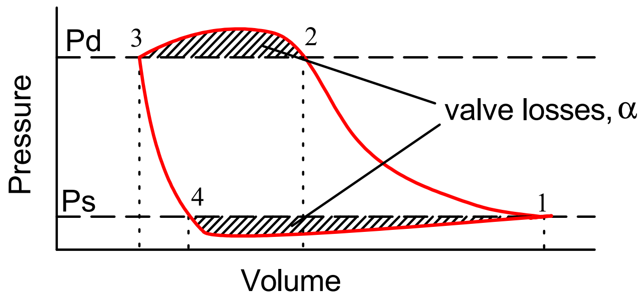


A reciprocating compressor is a positive displacement compressors which all follow a cyclic operation. The gas to be compressed is:

1. Isolated within an enclosed volume.
2. Compressed by reducing the enclosure.
3. Released into the discharge piping.

A complete compression cycle (one crankshaft revolution) is shown in diagrams. The diagrams show the indicator diagram and a cylinder illustration showing the poston movement and valve position. To begin the cycle refer to point 1 in the first figure where the piston is at the lower end of the stroke (bottom dead center). At this point the cylinder is filled with gas at the suction or intake pressure p_s and the valves are both closed. The compression cycle is illustrated by path 1-2 and the piston moves to the left. When the piston reaches point 2 the discharge valve starts to open and the gas will be delivered in the discharge piping as indicated by path 2-3. Due to valve losses and spring forces of the valves the pressure inside the cylinder will increase above the discharge pressure, p_d, when the gas is discharged into the line. When the piston reaches point 3 it has traveled to the upper end of its stroke (top dead center) and the discharge valve will close again. Physically, at this point in the stroke, there is a space between the piston face and the head. This space results in a trapped volume and is called the clearance volume. Next in the cycle, the piston reverses direction and starts to expand the trapped gas. Path 3-4 shows this part of the cycle. Note that the discharge valve has closed and the suction valve is still closed. At point 4 the expansion is complete and the suction valve opens. The intake part of the cycle is indicated by path 4-1. The cylinder fills with gas and due to valve losses and spring forces the pressure inside the cylinder drops below the suction pressure p_s. When the piston reaches point 1 the cycle is complete and starts again.

Operating Principle



$$T_d = T_s \cdot \frac{p_d}{p_s}^{\frac{k-1}{k}}$$

$$W_i = \text{area} = \int_{p1}^{p2} v \cdot dp \quad \Rightarrow \quad N_i = W_i \cdot speed$$

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The work per cycle, W_i, for one compression side of the cylinder can be measured by the pV diagram (or indicator diagram) whose area is equivalent to the integral as indicated above. The valve losses on suction and discharge side can also be measured in the pV diagram as indicated above. These losses are usually indicated by a percentage of the adiabatic work or power.

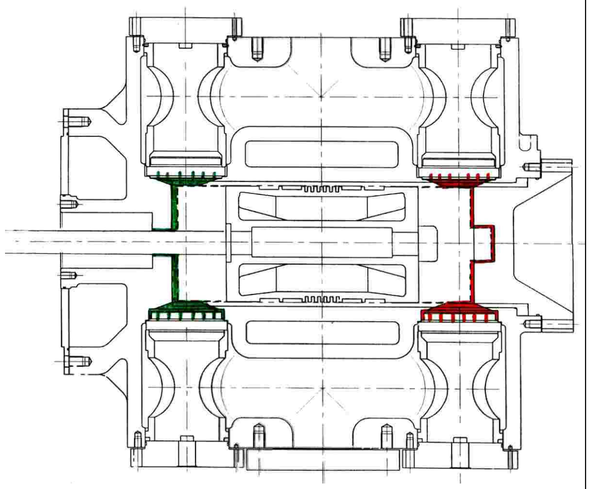
The power, N_i, can be calculated by multiplying the work per cycle by the compressor speed.

A high pressure ratio will result in higher temperatures then allowed by API and therefore the total pressure ratio has to be split up in stages.

Operating Principle

Clearance volume:

1. Volume corresponding to necessary clearance between piston and end of cylinder
2. Volume in the suction and discharge valves
3. Volume between the suction and discharge valves and the cylinder
4. Possible dead spaces



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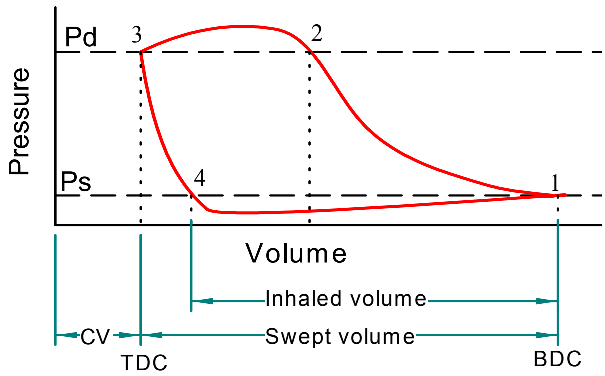
In an ideal cycle, the volume at the end of a stroke would be zero. and the compressed-gas flow per cycle would be equivalent to the piston displacement during the suction run (also called swept volume). However, not all of the gas is delivered at the end of the compression stroke, because of a residual or clearance volume, which includes the following:

1. Volume corresponding to necessary clearance between piston and end of cylinder
2. Volume in the suction and discharge valves
3. Volume between the suction and discharge valves and the cylinder
4. Possible dead spaces (e.g. around nut and stuffingbox)

Operating Principle

Definition of Volumetric Efficiency:



$$\eta_V = \frac{\text{inhaled volume}}{\text{swept volume}}$$

$$\eta_v = 1 - CV(\varepsilon - 1)$$

$$\varepsilon = \frac{V_s}{V_d} = \left(\frac{p_d}{p_s}\right)^{\frac{1}{k}} \cdot \left(\frac{Z_s}{Z_d}\right)$$

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After the delivery part (in point 3) the clearance volume (CV) is filled with gas at discharge pressure and will expand from discharge pressure to suction pressure during the return run of the piston (path 3-4). This means that the volume of gas swept through the compressor during the course of each cycle is can not be equivalent to the displacement volume of the piston.

The volumetric efficiency, ηv, is defined as the inhaled volume divided by the swept (or displacement) volume per cycle. The formula for calculating the volumetric efficiency is indicated in the sheet.

The delivery capacity or flow is reduced as the clearance volume is increased. But, in theory, the work of the compressed gas in the clearance volume will be recovered during expansion. In general the volumetric efficiency has hardly any effect on the energy efficiency (or required power).

Operating Principle

Definition of piston displacement:

$$Q_{piston} = (A_{HE} + A_{CE}) \cdot s$$

A_{HE}	= Piston area Head End = $\pi/4 \cdot D^2$
A_{CE}	= Piston area Crank End = $\pi/4 \cdot (D^2 - d^2)$
D	= Cylinder diameter
d	= Piston rod diameter
s	= Stroke

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The calculation of the cylinder displacement is a straightforward geometric procedure. It is the product of two factors, the total piston area and the stroke of the compressor. The total piston area is dependent on the number of active sides (on a single acting compressor only A_{HE} has to be taken into account) and the presence of a piston rod on the crank end.

Operating Principle

Definition of suction capacity:

$$Q_s = Q_{piston} \cdot n \cdot \eta_v \cdot \lambda$$

Q_{piston} = Piston displacement
n = Speed
η_v = Volumetric efficiency
λ = Factor for leakage

Definition of capacity at normal conditions:

$$Q_0 = Q_s \cdot \frac{Z_0}{Z_s} \cdot \frac{T_0}{T_s} \cdot \frac{P_s}{P_0}$$

$Z_0 = 1$
$T_0 = 273.15$ K
$P_0 = 101325$ Pa

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To determine the actual suction capacity of a cylinder, the calculated displacement must be corrected to include the volumetric efficiency and a factor for leakage. This factor for leakage is dependent on a lot of factors like molweight, pressure ratio, diameter, etc.

To determine the capacity of a cylinder at normal conditions the suction capacity at actual conditions must be recalculated to normal condition using the equation as given. Care should be taken that the suction condition is taken at one point. Usually this is the cylinder connection.

Capacity Control Options

Stepped Control

- Cylinder unloading
- Volumetric Control (fixed clearance pocket)

Step-less Control

- Speed Control (VSDS)
- Volumetric Control
  - Manually operated variable clearance pocket
  - Hydraulically operated variable clearance pocket
- Reversed Flow Control (i.e. Hydrocom)
- By-pass control
- Suction throttling

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The reciprocating compressor is a fixed displacement compressor in its basic configuration but the capacity can be controlled by using the following options which are divided in two groups, stepped control, in which the capacity can only be changed in fixed discrete steps, and step-less control, in which the capacity can be controlled smoothly within a certain range.

Stepped Control

•Cylinder unloading. Unloading of a cylinder side will prevent compression on that side (the side becomes inactive and gas travels back and forth). E.g. unloading of a HE side will give a 50% load step on a double acting cylinder.

•Volumetric Control (fixed clearance pocket). Volumetric control means an increased clearance volume by opening a fixed additional volume called the clearance pocket (modifying the volumetric efficiency).

Step-less Control

•Speed Control (VSDS). Varying the speed of the driver.

•Volumetric Control. Modifying the volumetric efficiency by changing the volume in the clearance pockets. The clearance pockets can be either:

-Manually operated

-Hydraulically operated

•Reversed Flow Control (i.e. Hydrocom). Delay in closing of the suction valves with a pressure controlled (e.g. hydraulically) valve lifter.

•By-pass control. Recycling the compressed gas to the suction (over a throttle valve and a cooler).

•Suction throttling. Reducing the suction pressure of the compressor by using a throttle valve upstream of the compressor. This will increase the pressure ratio and thus decrease the volumetric efficiency. Since the pressure ratio is increased the rodloads will also increase and throttling the suction pressure can result in a lower suction temperature and probably even in condensation.

Another way of flow regulation is off course starting and stopping the compressor.

Note: It should be recognized that each of the solutions for capacity control has an influence on the characteristics of the compressor. All specified conditions should therefore be checked on cylinder performance, and especially for rodload and rodload reversal.

Capacity Control Options

<u>Indication</u> of maximum control range for DA cylinder:

Stepped Control

➢ Cylinder unloading	50%
➢ Volumetric Control (fixed clearance pocket)	75%

Step-less Control

➢ Speed Control (VSDS)	50%
➢ Volumetric Control	
• Manually operated variable clearance pocket	75%
• Hydraulically operated variable clearance pocket	75%
➢ Reversed Flow Control (i.e. Hydrocom)	30%
➢ By-pass control	0%
➢ Suction throttling	50%

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An indication of the maximum control range of each capacity control option is given below:

Cylinder unloading: With a double acting cylinder one of the cylinder sides can be unloaded which approximately gives a 50% reduced flow. In theory a 100% reduced flow is possible however can result in overheated cylinders due to valve losses. On multi-cylinder arrangements the cylinders can be unloaded one at a time providing as many steps as cylinders operating in parallel (e.g. 2 cylinders 75% and 50%).

Clearance pockets: The capacity can be reduced to approximately 25% of the full flow by the use of fixed clearance pockets. This, however, is not a fixed value since capacity control by clearance pockets may increase the discharge temperature and this could also become a limiting factor. The use of clearance pockets on cylinder head end can be limited due to the required rod load reversal. Clearance pockets on the crank-end could be an alternative, however, this is depending on the configuration of the cylinder.

Speed control: The capacity can be reduced to approximately 50% of the full flow. This number is normally limited by the lubrication of the sleeve bearings. In general reciprocating compressors are equipped with a mechanical drive lube oil pump and reducing the speed of the compressor will result in reduced capacity of the lube oil pump.

Reversed flow control: In theory the capacity could be reduced to 0% however due to increased temperature as a result of the increased valve losses this is limited. The minimum capacity that can be accomplished is approximately 30%, depending on the valve losses and the initial discharge temperature.

By-pass control: With a 100% by-pass loop, including a cooler, around the compressor the capacity can be reduced to 0%.

Suction throttling: By increasing the pressure ratio the capacity can be reduced but the maximum control range is depending on a lot of parameters such as: initial discharge temperature, rod load, driver power, initial volumetric efficiency, etc. The given value of 50% is a very rough figure.

Capacity Control Options

- Combination of capacity control options is possible e.g.
  - clearance pockets with cylinder unloading will give a 75%, 50% and 25% flow step.
  - speed control in combination with cylinder unloading will give a maximum control range of 75%.

- The type and max. range of capacity control can be restricted by a number of other factors:
  - rod load or rod load reversal
  - discharge temperature
  - condensation
  - pulsations
  - mechanical restrictions
  - ?

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Effects on Thermodynamics

Example cases to show the effects of capacity control on:

- Indicated power
- Valve losses
- Temperatures
- Pressure

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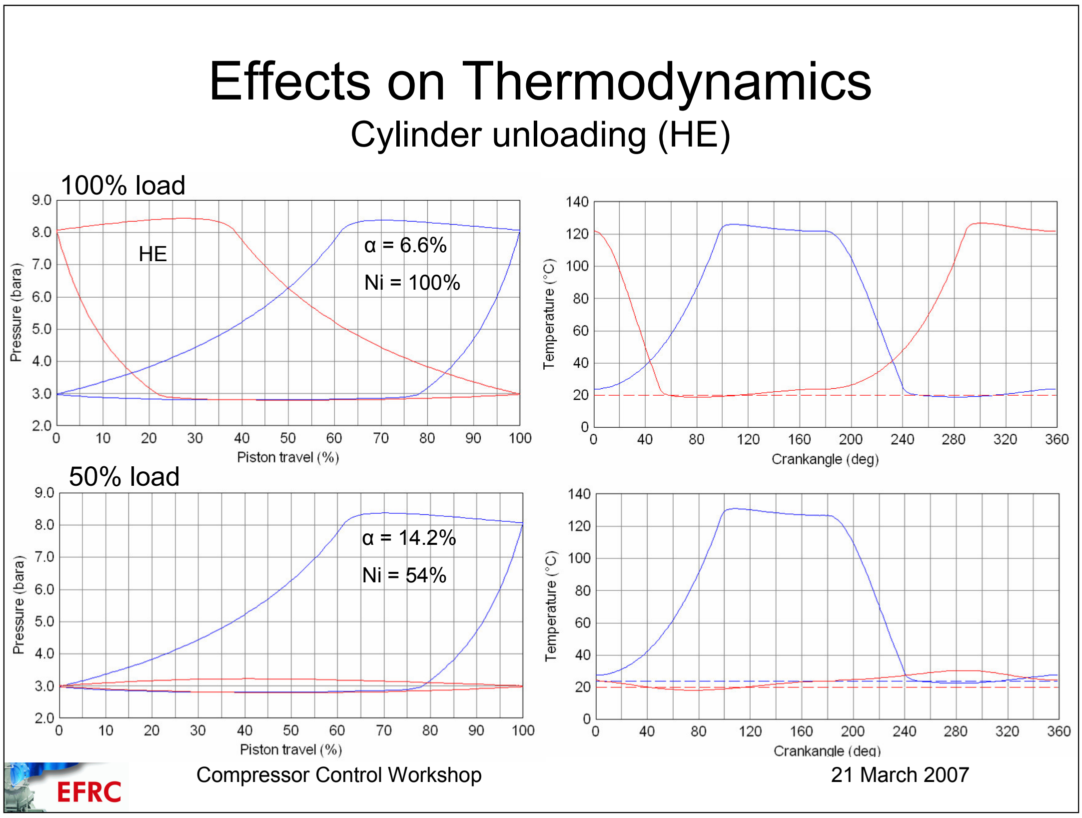


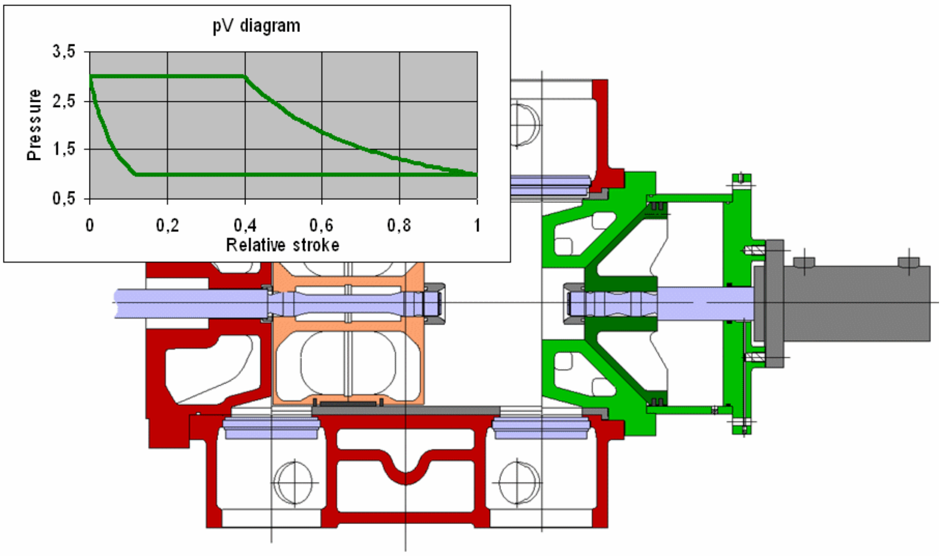
Above pV- and temperature diagrams for full load (100%) and part load show the thermodynamic effects of cylinder unloading.

When unloading the HE side of a cylinder by valve unloading the process gas on that side of the cylinder will be sucked into the cylinder and returns via the suction valves that are opened. These additional valve losses result in an slightly increased suction temperature on the active side and consequently an increase in the discharge temperature. The total valve losses will increase since the valve losses on the unloaded side are still present and will be added to the total valve losses. Consequently the power will be slightly higher than the 50%.

Care should be taken when unloading both sides of the cylinder. When unloading a cylinder the valve- and friction losses still exist. Where normally the heat generated by these losses are removed by the process gas this heat will accumulate in the amount of gas that goes from one to the other end of the cylinder and back in a reciprocating manner following piston movement. So heating up the gas and prolonged unloaded operation can cause severe overheating.

Effects on Thermodynamics

Volumetric control (clearance pocket)



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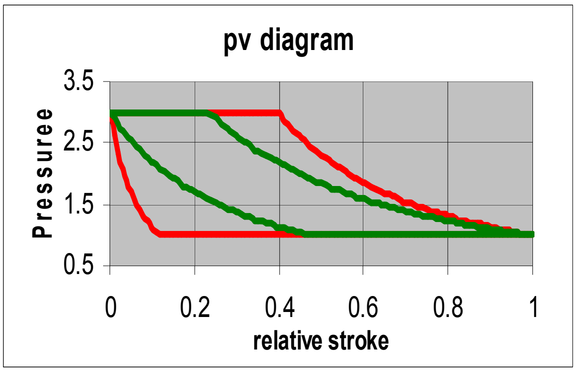
By the use of clearance pockets, the cylinder capacity can be lowered by increasing the clearance volume and thus lowering the volumetric efficiency. As indicated earlier the clearance pocket can be a fixed volume or variable volume. An example of a hydraulically operated variable clearance pocket is indicated above showing the movement of the clearance pocket piston and the effect on the pV diagram.

Effects on Thermodynamics

Volumetric control (clearance pocket)



Clearance pocket

$$\eta_v = 1 - CV(\varepsilon - 1)$$

$CV\% = \frac{Vc + Va}{Vs}$

Vc = CV in cylinder

Vs = piston displacement

Va = additional CV in pocket

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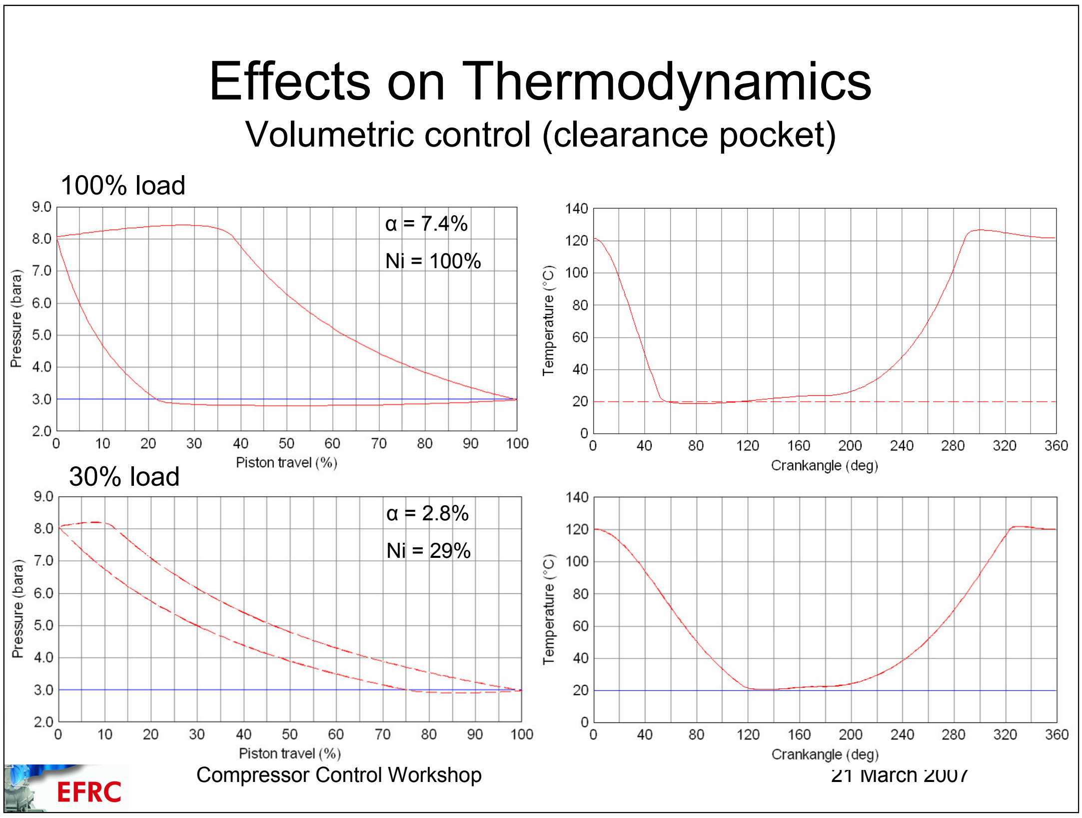
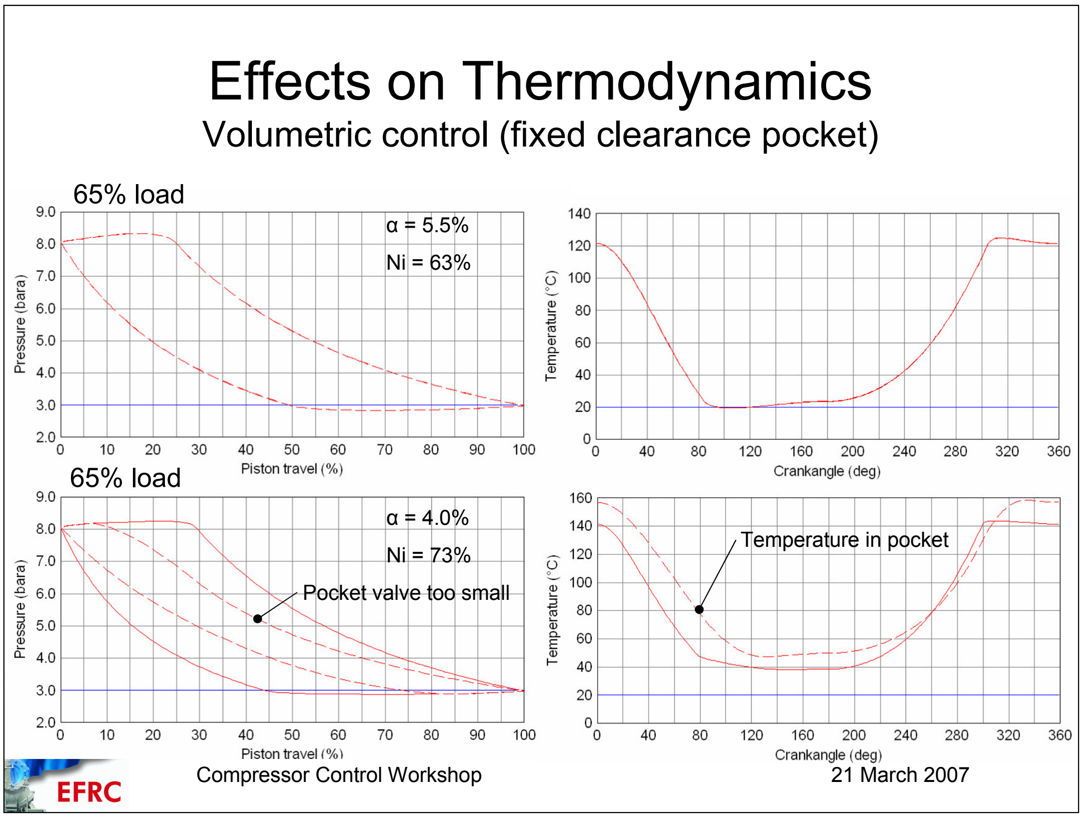
The above diagram shows the effect of a additional clearance volume. The volumetric efficiency, ηv, was defined as the inhaled volume divided by the swept (or displacement) volume per cycle and by increasing the clearance volume this volumetric efficiency will decrease.



Above pV- and temperature diagrams for full load (100%) and part load show the thermodynamic effects of volumetric control using a variable clearance pocket. Only the HE side is shown.

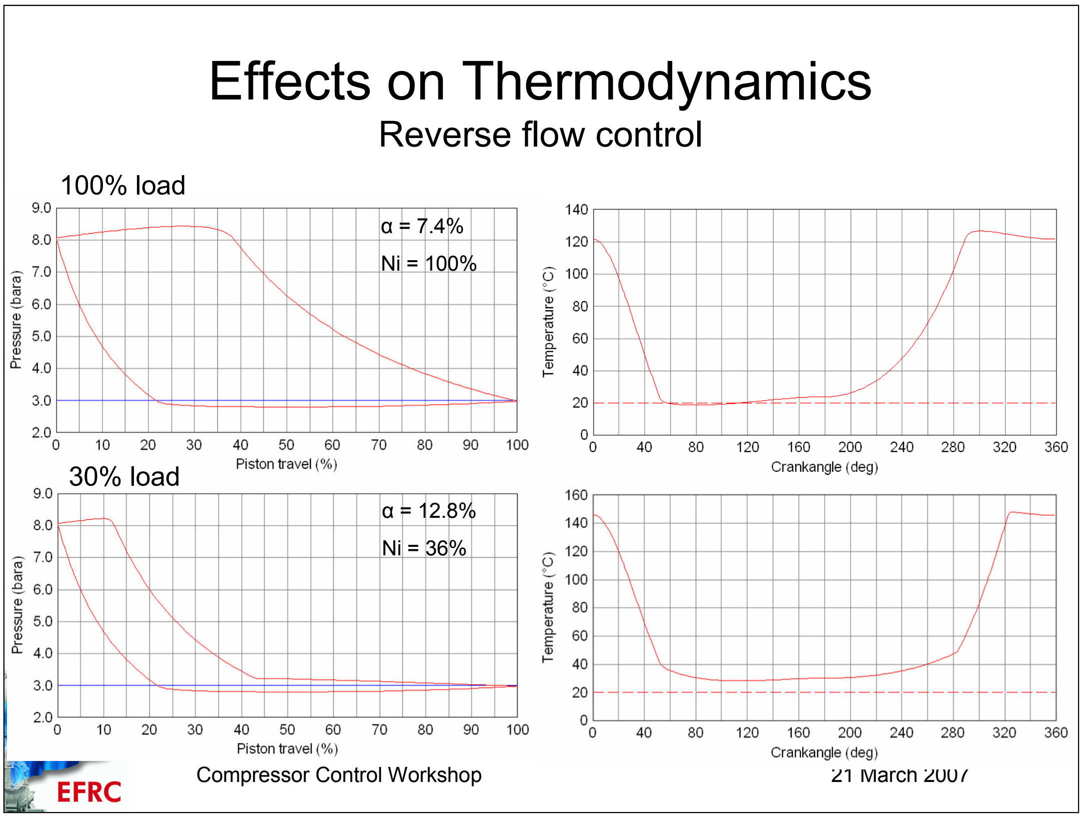
When activating the clearance pocket the capacity is reduced and the work of the compressed gas in the clearance volume will be recovered during expansion. With a variable clearance pocket the gas does not pass through a valve when entering the additional clearance volume so no additional valve losses are encountered. The suction and discharge valve losses are also reduced so the total indicated power amounts to 29%.



In general there are two types of fixed clearance pockets, manually operated or pneumatically operated. With the pneumatically operated clearance pocket a valve, identical to a normal compressor valve, is opened to increase the clearance volume.

Attention has to be paid to the sizing of this pocket valve. If this valve is too small the compression and expansion of the gas inside the pocket will be delayed compared to the gas inside the cylinder. An example of this is given in above pV- and temperature diagrams which show the thermodynamic effects. With a pocket valve that is too small the following effects can be determined:

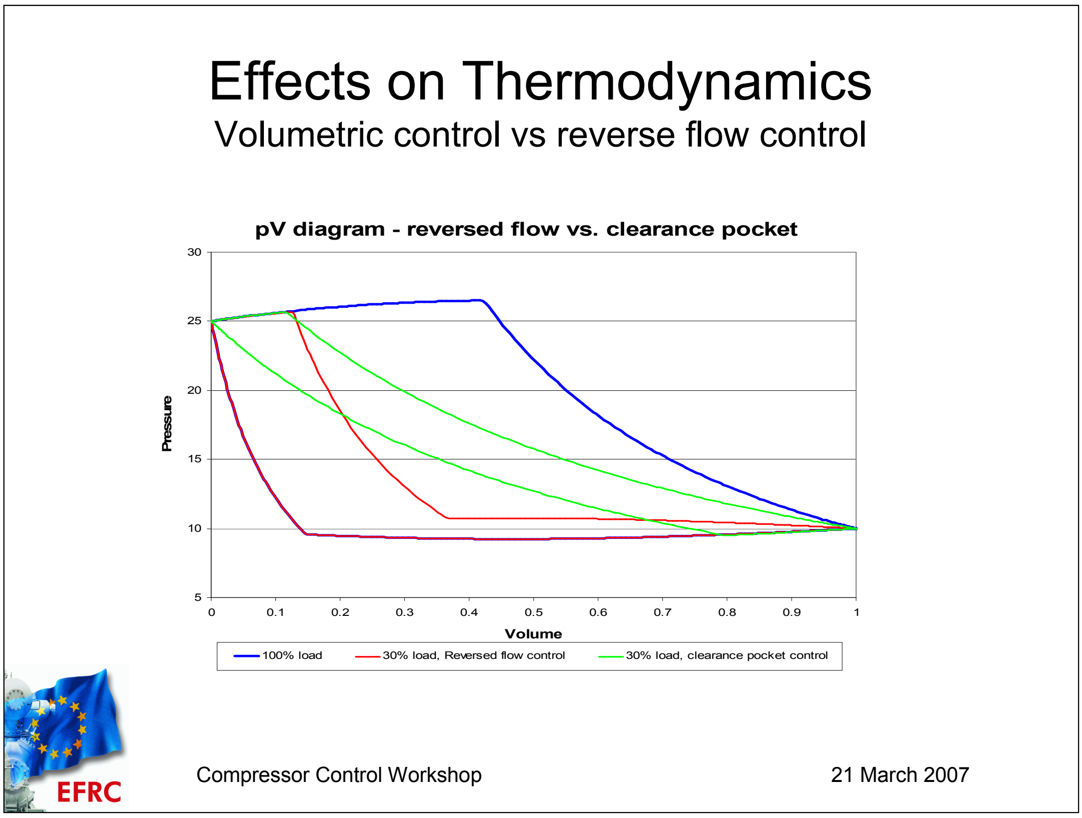
- deviation in capacity;
- increased power;
- increased discharge temperature;
- pocket temperature that might be exceeding the discharge temperature.



Above pV- and temperature diagrams for full load (100%) and part load show the thermodynamic effects of reverse flow control.

In reverse flow control the closing time of the suction valve is delayed. As part of the gas returns in the suction line and passes the suction valves 2 times, the valve losses and the suction temperature increase. Since the total valve losses increase also the indicated power will increase. The increased suction temperature results in a increased discharge temperature.

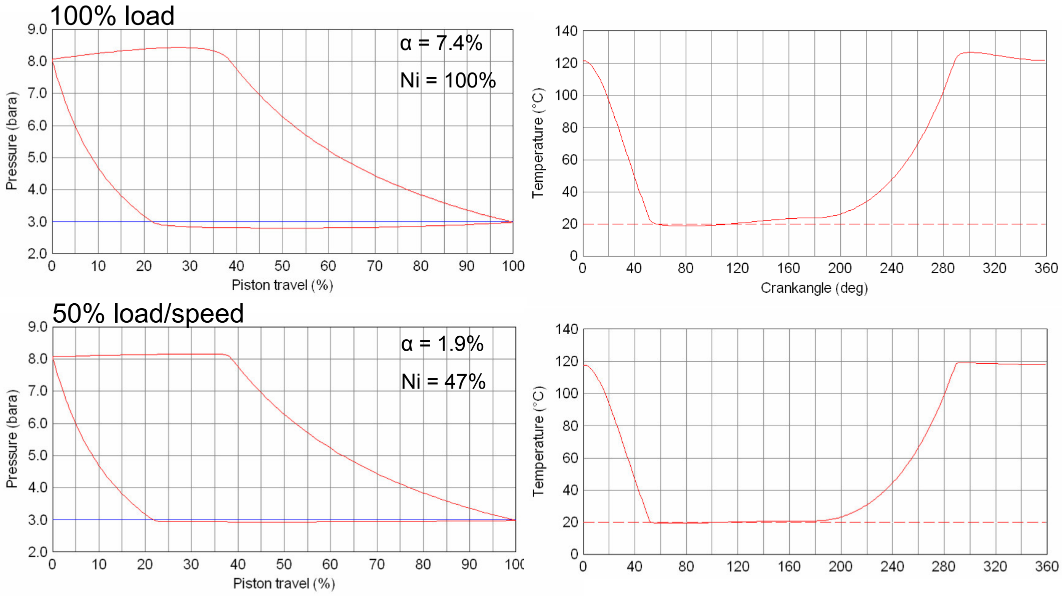
The lower the capacity the higher the increase in suction temperature.



Above pV- diagrams for full load and part load using reverse flow control and clearance pocket control show the differences between the two capacity control options.

Effects on Thermodynamics

Speed control



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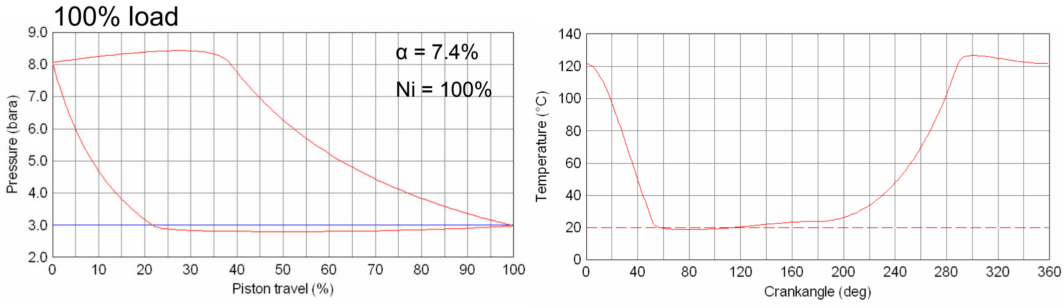
Above pV- and temperature diagrams for full load (100%) and part load show the thermodynamic effects of speed control.

When reducing the speed of a compressor the capacity will be reduced by the same amount (linear dependant). The gas velocities through the valves will be reduced and consequently the valve losses and the related indicated power decrease. As a consequence of the reduced valve losses the discharge temperature will also decrease.

Effects on Thermodynamics

Bypass control



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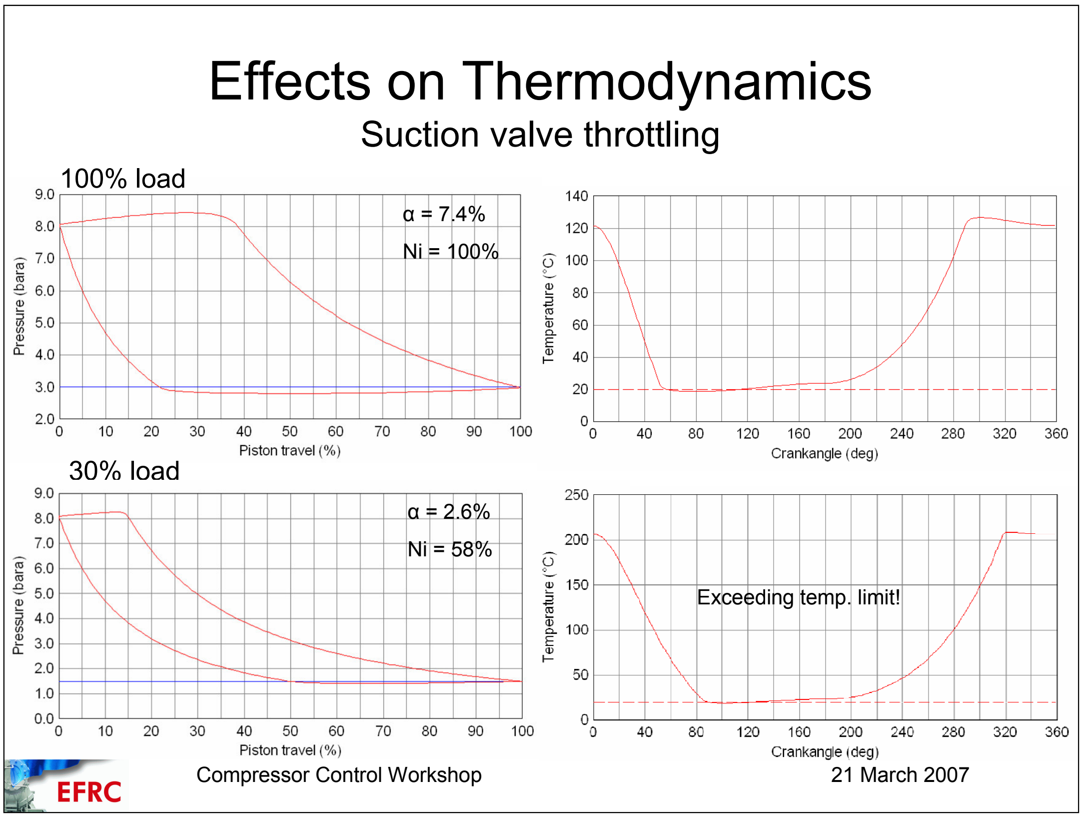
With bypass control the compressor remains to operate at full load and (part of) the compressed gas is recycled to the suction side. In this case only the full load pV- and temperature diagrams can be shown.

This method represents a loss of energy of compression equivalent to the amount of recycled gas. The discharge gas at discharge pressure and temperature will be recycled over a throttle valve and a cooler and fed back to the suction side of the compressor. Indicated work, valve losses or discharge temperature are not influenced by this capacity control method.

It should be noted that above is only valid for processes without interstage dropout. When the composition of the recycled differs from the suction gas composition, due to interstage dropout, this will off course influence the compressor performance.



Above pV- and temperature diagrams for full load (100%) and part load show the thermodynamic effects of suction valve throttling.

Suction valve throttling will decrease the suction pressure (with a constant discharge pressure). This results in an increased pressure ratio and thus a decreased volumetric efficiency. In the example case the valve losses are strongly reduced but with decreasing capacity the required power will increase. Increasing the pressure ratio will also result in an increased discharge temperature.

It is also possible that the power will increase again with a further reduction of the capacity. This depends on the pressure ratio.

Effects on Thermodynamics

Overview

Method	Temp.	Power (eff.)	Pressures
Unloading	☹	☺	☺
Reverse flow control	☹	☺	☺
Volumetric control (fixed)	☺	☺	☺
Volumetric control (variable)	☺☺	☺☺	☺
Speed control	☺☺	☺☺	☺☺
Bypass control	-	☹☹	-
Suction valve throttling	☹☹	☹☹	☹☹

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An overview of the capacity options and the effects on (discharge) temperature, effective power and pressures is given in the table above.

Notes:

- A "-" denotes that there is no effect.
- Effective power is including mechanical losses
- Losses in the drive system are not included. With speed control using an electric motor the electrical efficiency of the driver is dependent on the speed which could decrease the overall efficiency.

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