

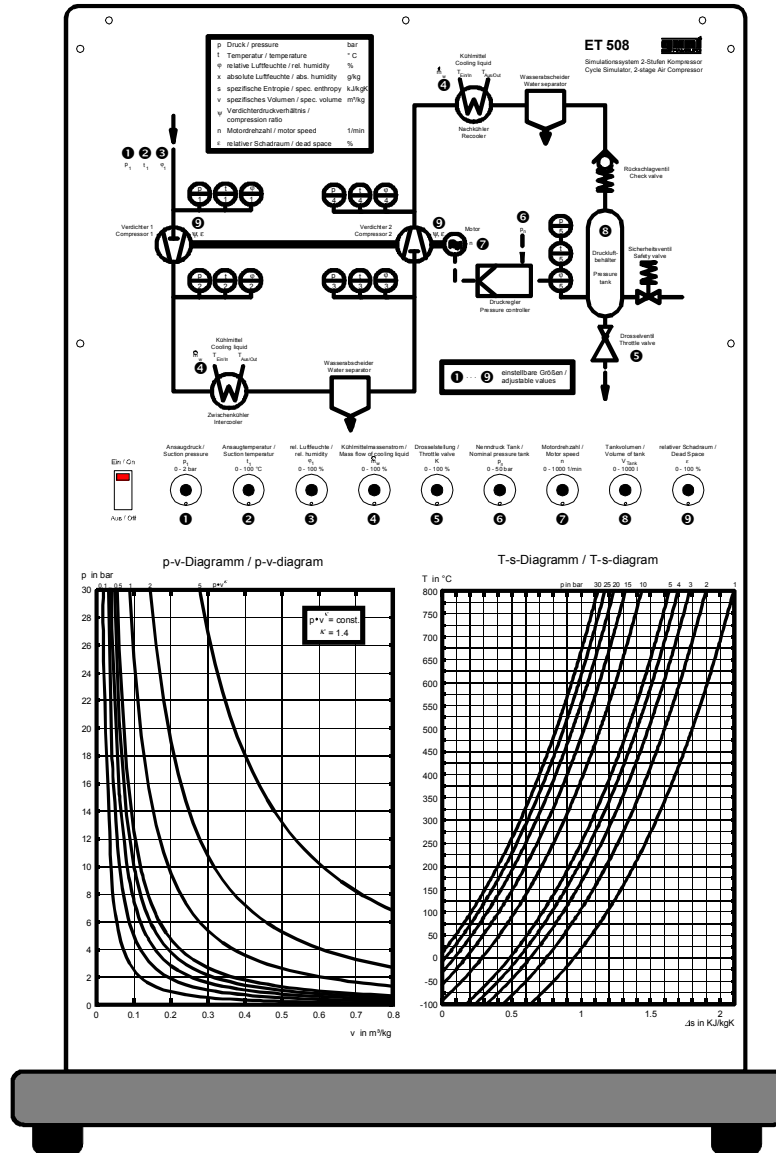
## **Experiment Instructions**

ET 508      Simulation of a  
Two-Stage Air  
Compressor

# ET 508 Cycle Simulator 2-stage Air Compressor



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## Instructions Manual

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## 1 Introduction

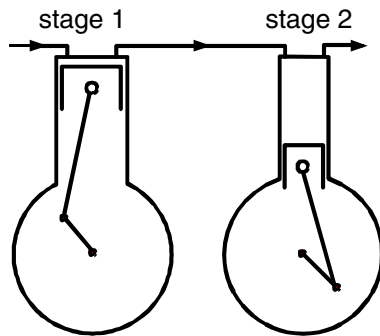


Fig. 1.1

The **Cycle Simulator, 2-stage air compressor ET 508** simulates a 2-stage air compressor system with intermediate and after-cooler, tank with bleeder valve and simple 2-point control. The special feature of this unit is the fact that most variables that affect the process, such as geometry (displacement volume, clearance, tank volume, etc.) as well as the thermodynamic state variables (intake condition of air, entropy content) can be set externally, and the influence on the process can be made immediately visible.

The unit consists of an operational and demonstration unit, a PC card and software. **Nine different variables** can be set on the control panel using the potentiometer. Two specially prepared T-s and p-V diagrams can be described using water-soluble pens to illustrate the cyclic process. The unit is therefore well-suited for demonstration purposes.

The set values are transferred to software via the PC card, which provides extensive presentation opportunities.

A p-V diagram as well as a T-s diagram can be tracked online on the screen, and all thermodynamic variables during the process are displayed. Status changes caused by the potentiometer immediately influence the cyclic process and can be observed.

In contrast to an actual unit, this system can be operated up to its theoretical limit. This makes it possible to show the significance of the re-expansion.

Online assistance in the software, as well as prepared worksheets included in the Annex of this introduction complete the unit.

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The simulation system is intended for advanced students in the area of thermodynamics.

The following **subjects** can be discussed using this unit:

- Basic understanding of a compression process
- Special features of a multistage compressor
- Thermodynamic state variables
- Illustration of a compression process on a
  - p-V diagram
  - T-s diagram
- Calculation of condensation loss in the intermediate or after-cooler
- Fundamentals of a 2-point pressure control with hysteresis

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## 2 Description

### 2.1 Construction of unit

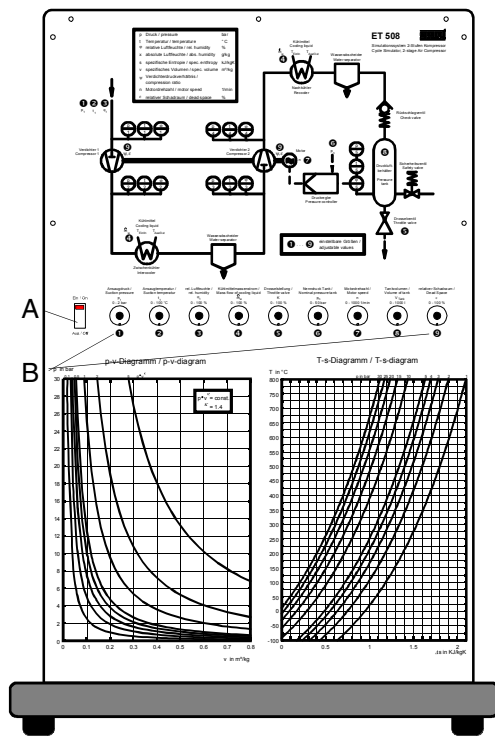


Fig. 2.1 Control and demonstration panel

The main switch (A) is located on the operating panel as well as several helical potentiometers (B), which are used to set the following variables:

Intake condition of air:

- 1 - **Intake pressure** (unit always functions with absolute pressures), 0-2 bar
- 2 - **Intake temperature** in °C, 0-100°C
- 3 - **Relative air humidity**, 0-100%
- 4 - **Coolant mass flow** to cool the intermediate and after-cooler, 0-100% (max. 100 kg/h), cooling agent (water), temperature 15°C
- 5 - **Throttle opening** at the tank outlet, 0-100 %
- 6 - **Nominal pressure** of the tank for pressure control (set value), 0-50 bar
- 7 - **Speed** of compressor drive, 0-1000 1/min
- 8 - **Tank volume**, 0-1000 l
- 9 - **Relative dead space** (dead space) of both compressors, 0-100 %

The values set by the potentiometers are transferred to a measured data recording card and evaluated in the software (included).

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## 2.2 PC measured data recording

### 2.2.1 Installing the measured data recording card

The measured data recording card must be inserted in a PC before the system is put into operation:

- Switch off PC and remove the mains plug
- Open PC housing (Important! Observe warranty terms)
- Find available ISA slot on the motherboard (ensure that the address 0320 HEX in the computer has not been assigned.)
- Insert card carefully and secure in place. Do not touch electronic components in the computer - risk of electrical discharge and destruction of components.
- Shut PC housing, connect unit and measured data recording card with ribbon cable.

### 2.2.2 Installing the software

Operating system: Windows 95

- Switch on PC and start Windows
- Place first installation diskette in the drive
- Start button: execute file: execute a:\install.exe
- The software will then be installed on the PC by user. An entry ("G.U.N.T.") will be generated in the start menu for starting the software.



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## 2.2.3 Menu structure

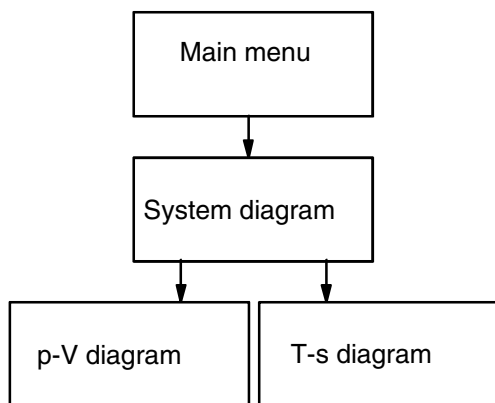


Fig. 2.2 Menu structure

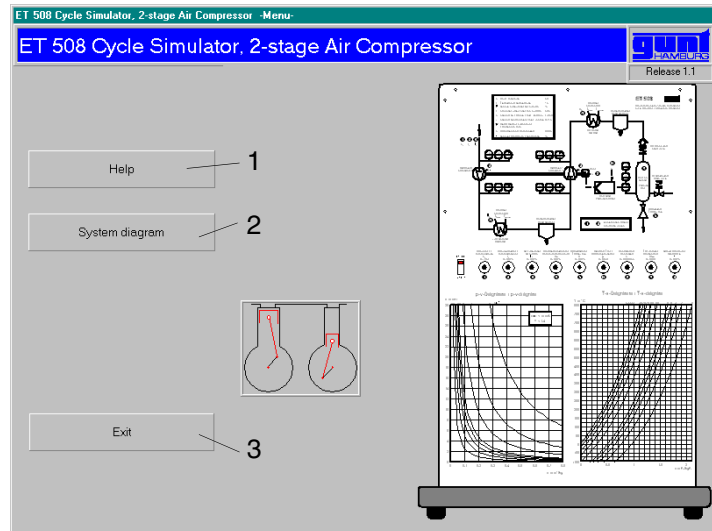


Fig. 2.3 Main menu

## 2.2.4 Main menu

(Abb. 2.3) The online assistance (1) and the central system diagram (2) can be called up from this point, and the software can be shut down (3).

## 2.2.5 System diagram

(Fig. on following page)

This is the central mask of the software. The air way (red) in the compression process is shown along the **first compression stage** (with intermediate cooling and condensation), the **second compression stage** (with after-cooling and condensation), a non-return valve, storage tank and a throttle as outlet valve.

The motor is started using the main switch (1).

The current tank pressure can be read at the measuring instrument (2).

A tank pressure control device with 2-point controller (3) affects the motor speed.

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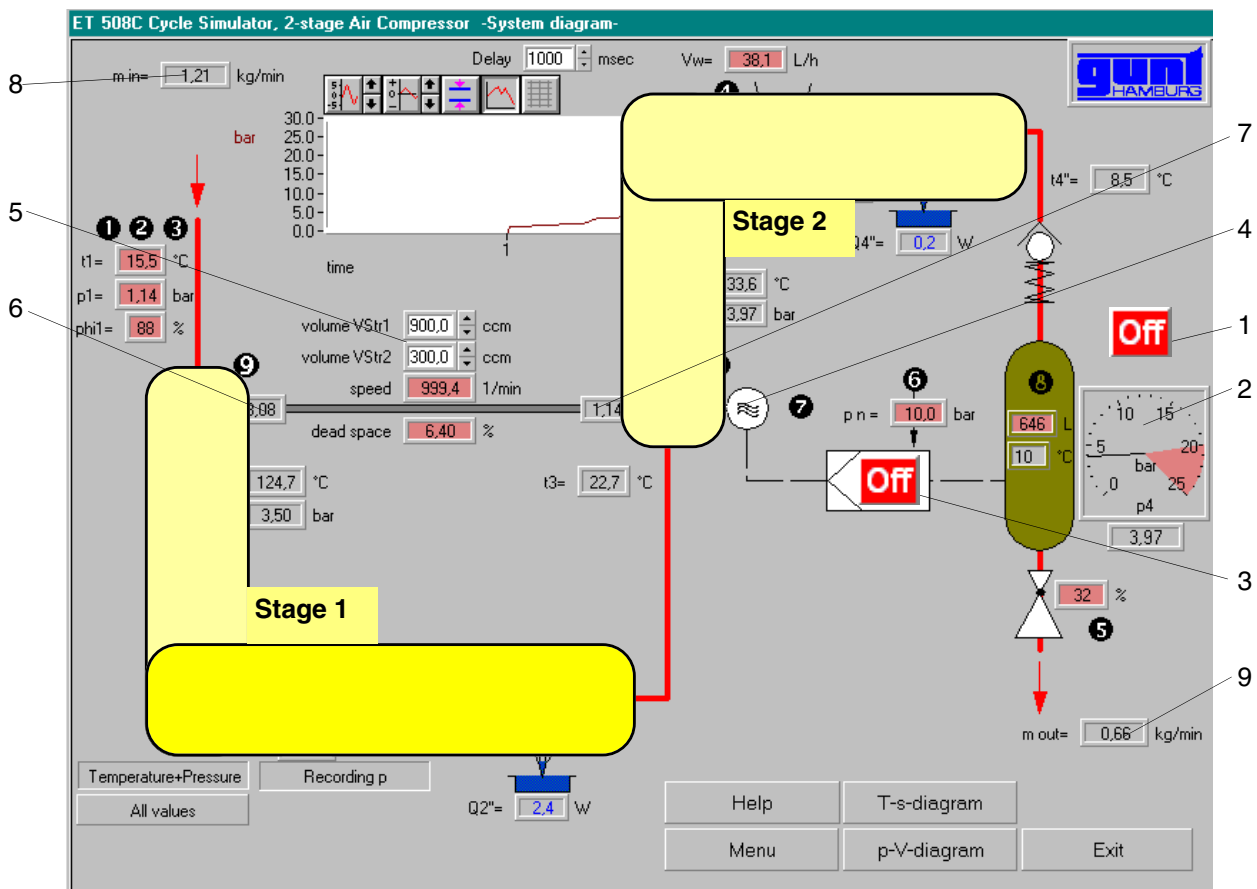


Fig. 2.4 System diagram

The motor (4) drives both stages at the same speed. The piston displacements can be set separately (5). The stage pressure ratios for Stage 1 (6) and Stage 2 (7) result from the calculations.

The quantity of added or discharged air is shown at (8) or (9), respectively.

## 2.2.5.1 Function of buttons

- **Help** - Call up online assistance
- **Menu** - Return to main menu
- **T-s diagram** - Display of a temperature-entropy diagram
- **p-V diagram** - Display of a diagram - pressure plotted against volume
- **Exit** - Ending the program

# ET 508 Cycle Simulator 2-stage Air Compressor

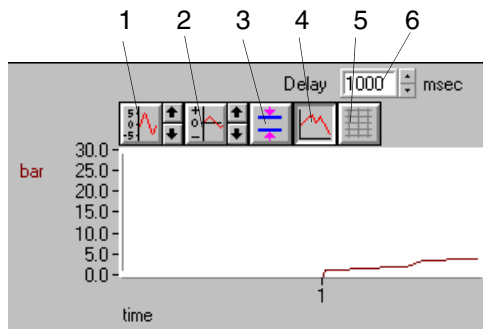


Fig. 2.5 Record tank pressure

Pressing the button "**Recording p**" permits the recording of the tank pressure  $p_5$  with respect to time. A diagram is shown with the following functions:

- 1 - Scaling the y-axis
- 2 - Offset for y-axis
- 3 - Show auxiliary lines
- 4 - Connect measured points
- 5 - Show grid
- 6 - Set advance feed

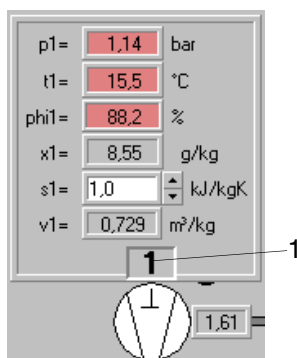


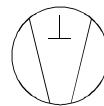
Fig. 2.6 Pull-down menu at measuring point 1 in Mode 2

It is possible to switch between two types of display: "Temperature + pressure" (Mode 1) or "All values" (Mode 2).

Temperatures and pressures are shown at the measuring points in Mode 1; all values can be shown in Mode 2. The values will appear by clicking on the desired measuring point (Fig. 2.6, 1). The pull-down menu is closed by clicking on the measuring point again.

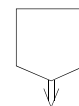
## 2.2.5.2 Symbols and methods of representation

Compressor

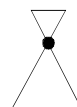


Intermediate cooler / After-cooler

Water separator



Throttle valve



Drive motor for compressor



Measuring variables always have an index which indicates the measuring point:

Numerals with black circles indicate the variables which can be changed with the potentiometers. These variables will be shown on the screen with a red background.

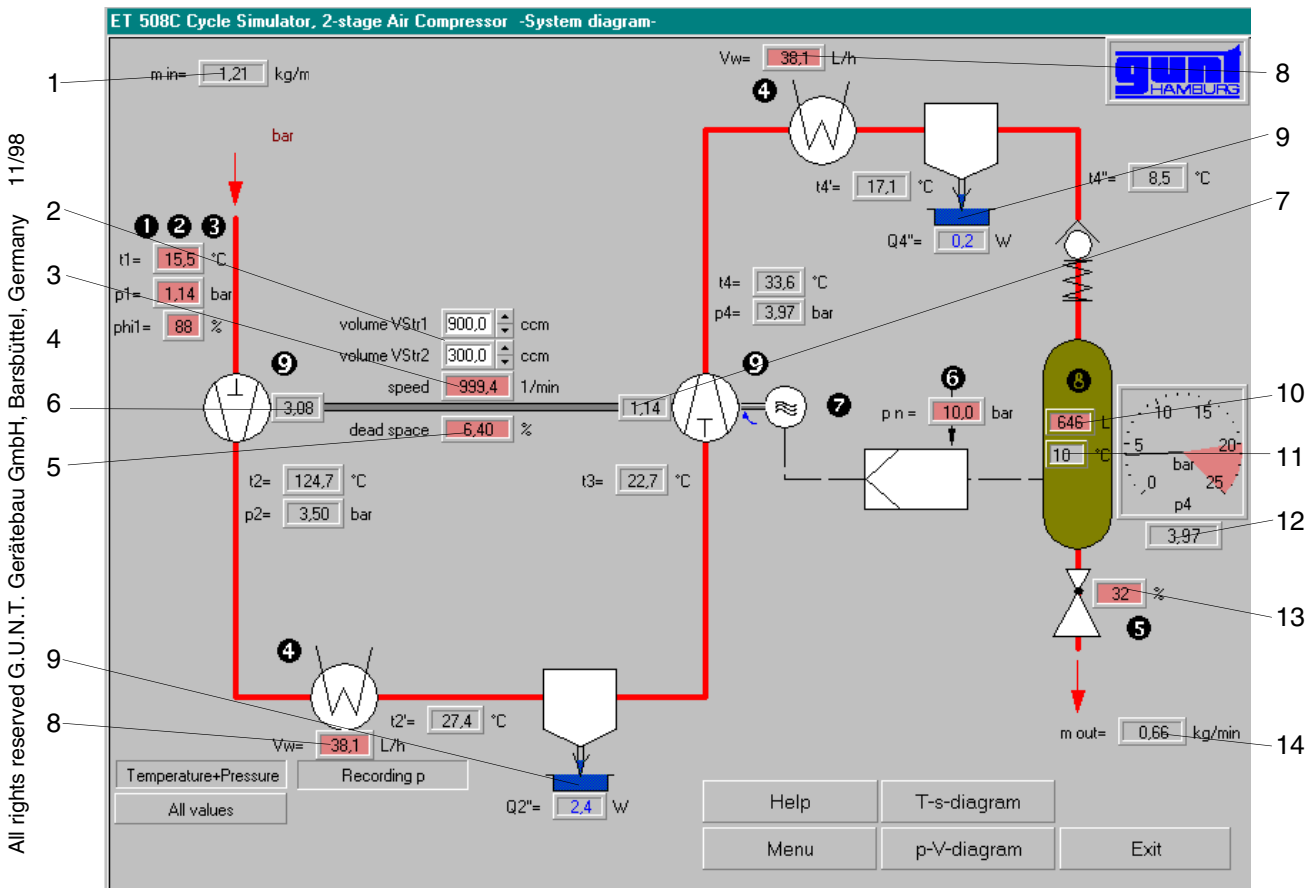


Fig. 2.7 Displayed variables

### 2.2.5.3 Displayed variables

1 - Added mass flow  $\dot{m}_{in}$

#### Compressor data:

2 - Piston displacement - Stage 1,  $V_{Hub1}$

3 - Piston displacement - Stage 2,  $V_{Hub2}$

4 - Speed of motor  $n$

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5 - Relative dead space (dead space volume) of both stages  $\varepsilon$

6 - Pressure ratio - Stage 1  $\psi_1$

7 - Pressure ratio - Stage 2  $\psi_2$

8 - Coolant flow rate  $\dot{V}_w$ , same for both stages

9 - Only visible when condensation is present in the water separator  $\dot{Q}$

### **Tank condition**

10 - Tank volume  $V$

11 - Air temperature in tank  $T_5$

12 - Tank pressure  $p_5$

13 - Throttle setting based on max. opening

14 - Discharged mass flow  $\dot{m}_{out}$

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## 2.2.5.4 2-point control

The system permits the automatic control of the tank pressure. For this purpose a set value is set at the potentiometer 6 (nominal pressure - tank). A hysteresis of 2 bar is effective for the switching on and off point.

Example: Nominal pressure set at 10 bar. When the tank pressure reaches 12 bar, the motor will switch off (speed 0); when the pressure falls to 8 bar, the motor will re-start.

## 2.2.6 p-V diagram

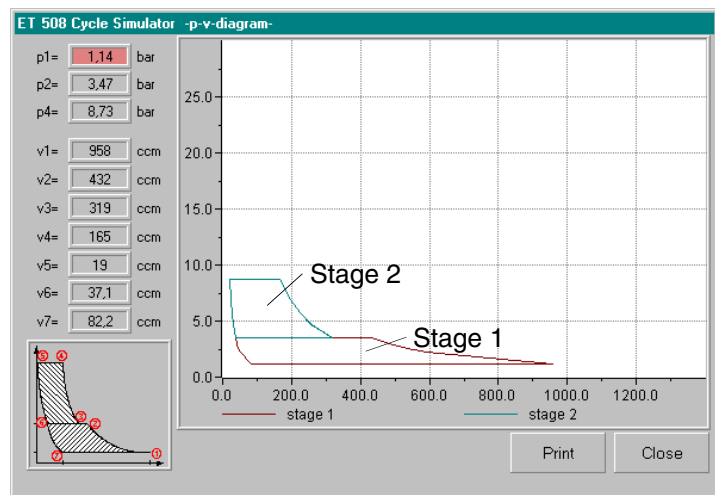


Fig. 2.8 Screen with p-V diagram

The pressures or volumes of Stage 1 and Stage 2 are shown. The indices of these values correspond to the numbers in the illustration.

**"Print"** button prints the screen on a linked system printer; pressing **"Close"** will close the p-V diagram and returns to the system diagram.

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## 2.2.7 T-s diagram

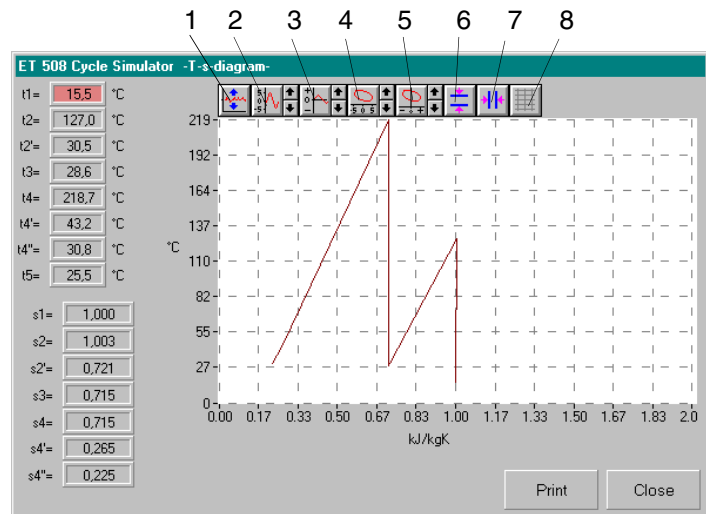


Fig. 2.9 Screen with T-s diagram

In this diagram the temperature  $T$  is plotted against the entropy  $s$  of the various measuring points. The user has the following opportunities for setting the diagram:

- 1 - Automatic scaling of x- and y-axes
- 2 - Scaling of y-axis
- 3 - Offset y-axis
- 4 - Scaling of x-axis
- 5 - Offset x-axis
- 6,7 - Show horizontal and vertical auxiliary lines
- 8 - Show grid

The buttons "**Print**" and "**Exit**" correspond to those in the p-V diagram.

### 3 Fundamentals and experiments

#### 3.1 Comparison of one-stage/multistage compression

If the pressure ratio is increased during **single-stage compression**, the counter-pressure and the temperature of the air will increase. The higher pressure increases the linkage forces and the loss of volume via the re-expansion (see 3.4). The higher temperature warms the cylinder walls. The pressure ratio is limited by the temperature at which the lubricant-gas mixture can ignite. For this reason there are safety guidelines, according to which the temperature in the pressure joints cannot exceed 200°C. This results in a maximum pressure ratio of  $\psi = 8..10$ .

When **multistage compression** takes place in several consecutive areas, it is possible to cool the air between stages. This causes a decrease in volumetric losses, linkage forces and drive power, while increasing the service life. Higher discharge pressures can be obtained, though stage pressure ratios of  $\psi = 4$  are common for a two-stage system. As shown below, the division into two stages results in the simplification of work.

#### 3.2 Stage pressure ratio

A two-stage compression  $p_1 \rightarrow p_2$  or  $p_3 \rightarrow p_4$  results in the stage pressure ratios at

$$\psi_1 = \frac{p_2}{p_1} \text{ (Stage 1)} \quad (3.1)$$

$$\psi_2 = \frac{p_4}{p_3} \text{ (Stage 2)} \quad (3.2)$$



### 3.3 Clearance

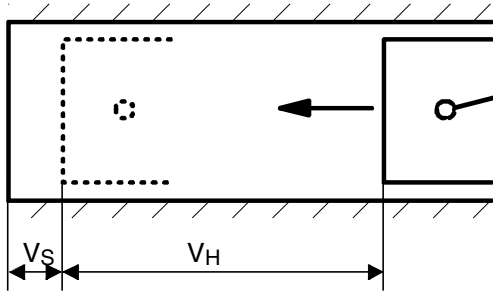


Fig. 3.1 dead space  $\varepsilon$

If the pressure ratios are increased, the counter-pressure and the temperature of the medium increase. Since each piston compressor has a specific dead space volume (dead space)  $V_S$ , the volume of which cannot be compressed, this results in a **re-expansion** of this volume during the return stroke of the piston.

The relative dead space  $\varepsilon$  is based on the piston displacement  $V_H$  and is calculated as

$$\varepsilon = \frac{V_S}{V_H} \quad (3.3)$$

### 3.4 Re-expansion

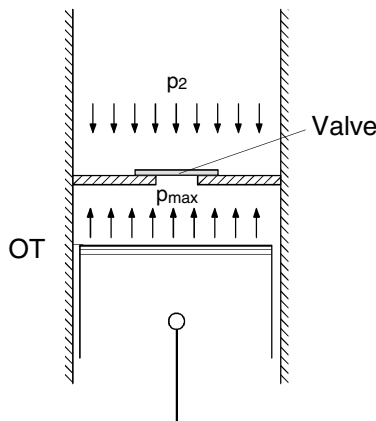


Fig. 3.2 Volume flow=0 at  $p_{max} < p_2$

The re-expansion is calculated with the stage pressure ratio  $\psi$  and the polytropic exponents  $\kappa$  (as follows)

$$\mu = 1 - \varepsilon(\psi^{\frac{1}{\kappa}} - 1) \quad (3.4)$$

A considerable reduction of the actual mass flow is the result of the re-expansion, which then allows the entire conveyed volume to fall to zero. The volumetric loss is

$$\Delta V_{loss} = V_S \cdot (\psi^{\frac{1}{\kappa}} - 1) \quad (3.5)$$

### 3.5 Conveyed mass flow

If the losses due to leakage are disregarded, the **theoretical intake flow**  $\dot{V}_{theo}$  with a piston-type pump with a displacement volume  $V_H$

$$\dot{V}_{theo} = V_H \cdot n \quad (3.6)$$

where  $n$  is the pump speed.

The actual intake flow results in

$$\dot{V}_{\text{tats}} = \mu \cdot \dot{V}_{\text{theo}} \quad (3.7)$$

From this it is possible to determine the **actual mass flow**  $\dot{m}$ :

$$\dot{m} = \mu \cdot \dot{V}_{\text{tats}} \cdot \rho_{\text{air}} \quad (3.8)$$

The law of Gay-Lussac states that

$$pv = RT \quad (3.9)$$

at  $v = \frac{1}{\rho_{\text{air}}}$  is the result for intake state 1

$$\dot{m} = \frac{\mu \cdot \dot{V}_{\text{tats}} \cdot p_1}{R_d \cdot T_1 \cdot (0.622+x)} \quad (3.10)$$

The additional term (0.622+x) is necessary because air is conveyed at the absolute humidity x, whose gas constant R depends on the moisture content. The mole mass ratio of steam to air is 0.622.

### 3.6 p-V diagram

The compression process is generally illustrated in a diagram, where pressure is plotted against the volume of conveyed air. This type of **p-V diagram** is shown in (Fig. 3.3) for single-stage compression.

The re-expansion 3-4 of the residual gases in the clearance space and the intake 4-1 of the fresh medium take place during the forward stroke; compression 1-2 and expulsion 2-3 take place during the return stroke.

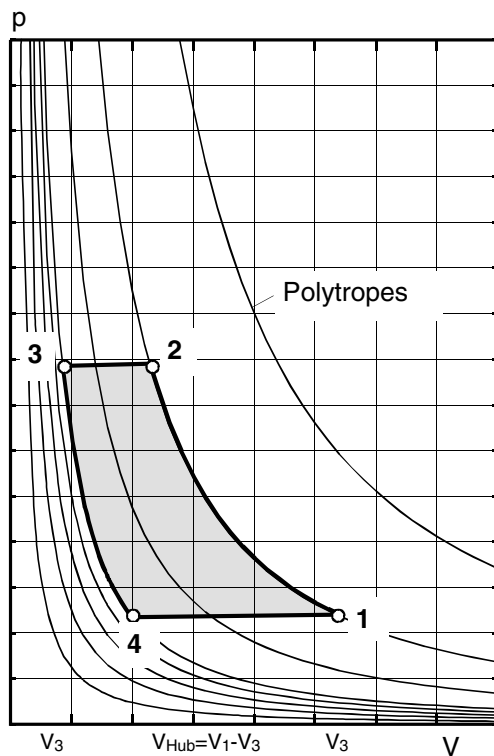


Fig. 3.3 p-V diagram

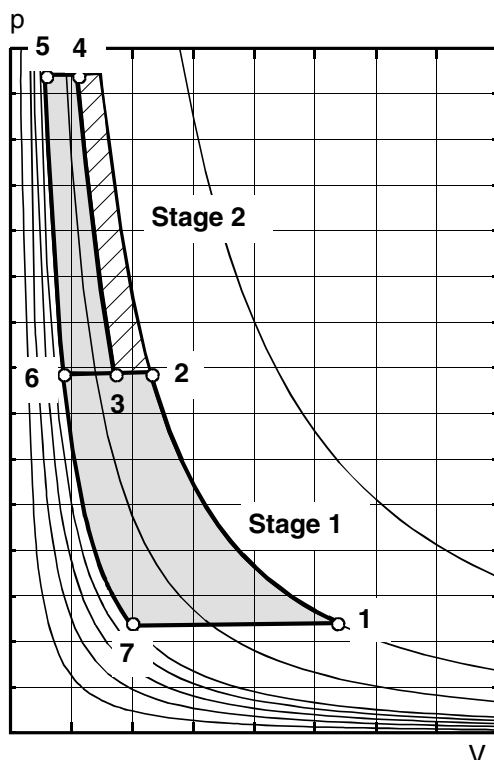


Fig. 3.4 p-V diagram: two-stage compression

Compression and expansion approximate so-called polytropes. These are lines in which the following applies:

$$p \cdot V^\kappa = \text{const.} \quad (3.11)$$

$\kappa$  is the polytropic exponent. It is set here for compression and re-expansion at a value of 1.4.

The p-V diagram can also show the **work** required for compression. It is the result of

$$W = \int_{V_2}^{V_1} p \, dV \quad (3.12)$$

This shows that the work required for compression is equal to the enclosed area in the p-V diagram.

The relationships in two-stage compression with intermediate cooling is shown in (Fig. 3.4).

Isobaric intermediate cooling 2-3 takes place following compression 1-2 in Stage 1 (pressure losses are disregarded). Stage 2 compressed up to state 4. Polytropic re-expansion 5-6-7 also occurs.

The following results from the law of Gay-Lussac for the stage pressure following Stage 1 (measuring point 3):

$$p_3 = p_1 \cdot \frac{V_1}{V_3} \cdot \frac{T_3}{T_1} \quad (3.13)$$

$V_1$  is the intake volume, or the piston displacement  $V_{Hub1}$ . The second-stage piston creates a vacuum while the first stage is compressing.  $V_3$  is the compressed volume, e.g. piston displacement of the second stage  $V_{Hub2}$ .

(Fig. 3.4) clearly shows the labour savings of two-stage compression over one-stage compression (shaded area).

### 3.7 Re-cooling and condensation

Ambient air always has a certain water content, known as **absolute humidity  $x$** , which is based on 1 kg of dry air.

Air with a certain temperature and pressure has a maximum moisture content. The relative humidity  $\phi$  in this state is 100%. If the air is cooled further, water will condense under the release of heat.

According to definition, compression and re-cooling both take place without condensation; water condenses only at the water separator.

The released condensation heat, e.g. downstream of the intermediate cooler, is:

$$\dot{Q} = (T_3 - T_2) \cdot (c_{pL} + x_2 \cdot c_{pD}) \quad (3.14)$$

$c_{pL}$  specific thermal capacity of dry air  
(=1.004kJ/kgK)

$c_{pD}$  specific thermal capacity of saturated steam  
(=1,858 kJ/kgK)

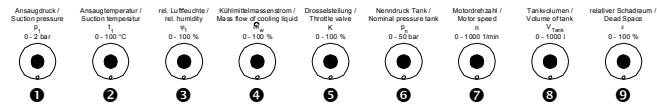
### 3.8 System performance

To obtain an overview of the effect of the parameters on the performance of the unit (such as displacement volume, speed, intake state of the air) the unit should first be started with commonly used values of a two-stage compressor:

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- Switch on the unit and start the software
- Set the following parameters:



- 1 Intake pressure 1.13 bar
  - 2 Intake temperature 20°C
  - 3 Relative air humidity 30%
  - 4 Coolant mass flow 0 L/h
  - 5 Throttle position 0% (throttle is shut)
  - 6 Nominal pressure in tank 50 bar
  - 7 Motor speed 1000 1/min
  - 8 Tank volume 600 L
  - 9 Relative dead space 5%
- Pressure control device off (software)

- Start the mask "System diagram"
- Switching on the compressor (Fig. 3.5)

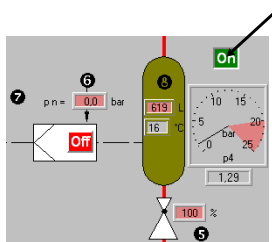


Fig. 3.5

Stage 1 begins to build up pressure slowly. Because no intermediate cooling takes place, no water is condensed.

Reduce the tank volume (Poti 8) and observe the pressure increase: the pressure build-up occurs more quickly because the counter-pressure from the tank increases more rapidly.

Reset the tank volume to a value around 600 l.

Stage 2 becomes involved in the pressure build-up only when the intermediate pressure has been reached according to Eq. 3.13.

Open the throttle (Poti 5) to approximately 30%. The pressure will decrease since air is escaping from the tank.

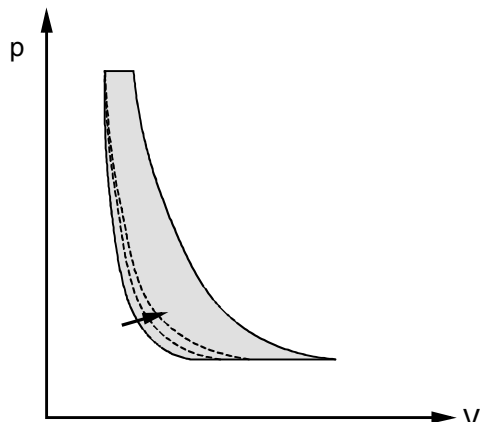


Fig. 3.6 Increasing dead space

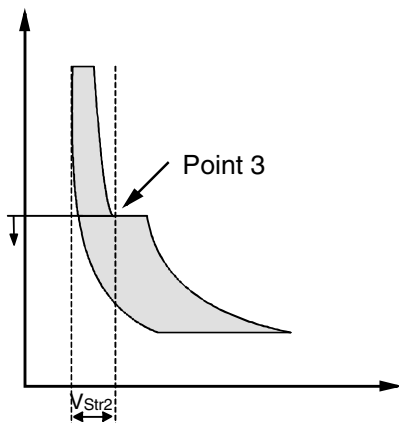


Fig. 3.7 Intermediate cooling

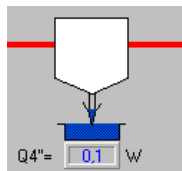


Fig. 3.8

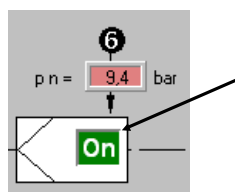


Fig. 3.9

Shut the throttle again.

Open the p-V diagram by clicking on the button.

Increase the relative dead space  $\varepsilon$  (Poti 9) and observe the effects in the p-V diagram. The volumetric loss during re-expansion will increase and the curve will shift to the right (Fig. 3.6).

Reset the relative dead space to the original value.

When the second stage is conveying, cool the compressed air by setting a coolant mass flow of approximately 10% (Poti 4). The stage pressure decreases, causing Point 3 in the diagram to move downwards on the isentrope (Fig. 3.7).

Shut the p-V diagram.

Increase the relative air humidity of the inlet air to  $\varphi=100\%$ . Condensation is discharged after the intermediate or after-cooler, which releases the thermal output  $\dot{Q}$ .

Reduce the air humidity to the original value.

In order to show the effect of the pressure control device, set the nominal pressure in the tank to the current tank pressure (Poti 6). Switch on the pressure control device.

As soon as the tank pressure has increased to 2 bar, the compressors will be switched off and the pressure will no longer increase. If the pressure should fall, e.g. by opening the throttle to a value to less than 2 bar below the nominal pressure, the compressors will be switched on again. The pres-

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sure control device therefore has a **hysteresis of +/-2 bar**.

Switch off the pressure control and shut the throttle.

## 3.9 Limiting values

The maximum obtainable pressure is limited in "real" compression units by a safety valve. The simulation system ET 508, however, can be operated up to the theoretical limit. This makes the relationships in the p-V diagram even more clear.

### 3.9.1 With intermediate cooling

the pressure in the tank should be about 5 bar.

Set the following values:

- Shut throttle
- Coolant mass flow 20 l/h
- Rel. dead space 40%

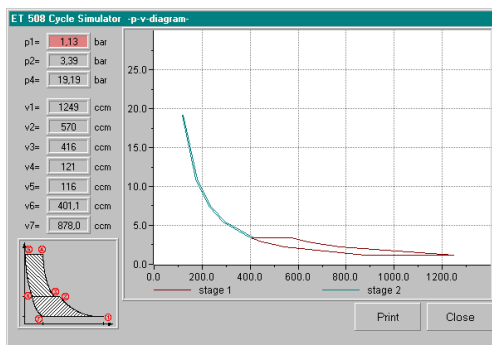
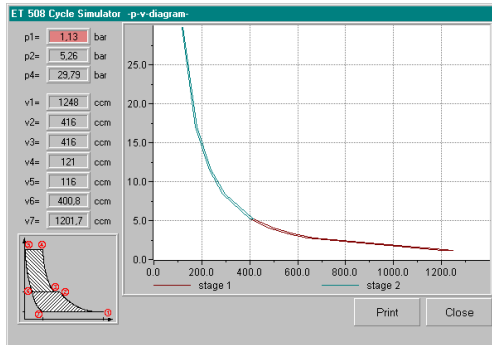


Fig. 3.10 Max. pressure with intermediate cooling

After a few minutes (tank pressure is approximately 20 bar) the p-V diagram will show that the re-expansion of the second level is so large that nothing is being conveyed; no air is taken in as the piston returns.

Stage 1 is still compressing; this increases the intrinsic energy of the air.

### 3.9.2 Without intermediate cooling



- Switch off the cooling system ( $\dot{m}_W=0$  L/h).

The re-expansion of both stages increases greatly; the go-and-return paths in the p-V diagram coincide and the compression falls to zero.

**Note:** This situation will not occur in actual practice. The extremely high temperatures will have already caused damage to the components.

Fig. 3.11

### 3.10 T-s diagram

If the temperature is plotted against the entropy, the advantage of multistage compression can be demonstrated very dramatically.

The inlet air can have any desired entropy content  $s_1$ .

The following applies to States 1 (intake state) and 2 (directly downstream of the compression) during **isentropic compression**

$$s_2 - s_1 = (c_{pL} + x_1 c_{pD}) \ln \frac{T_2}{T_1} - (R_L + x_1 R_D) \ln \frac{p_2}{p_1} \quad (3.15)$$

**Isobar re-cooling** in the intermediate cooler has the following effect on the entropy  $s$ :

$$s_{2'} - s_2 = (c_{pL} + x_2 c_{pD}) \ln \frac{T_{2'}}{T_2} \quad (3.16)$$

For this illustration assume the entire compression process is isothermic, i.e. it will be cooled to the intake temperature after each stage.



# ET 508 Cycle Simulator

## 2-stage Air Compressor

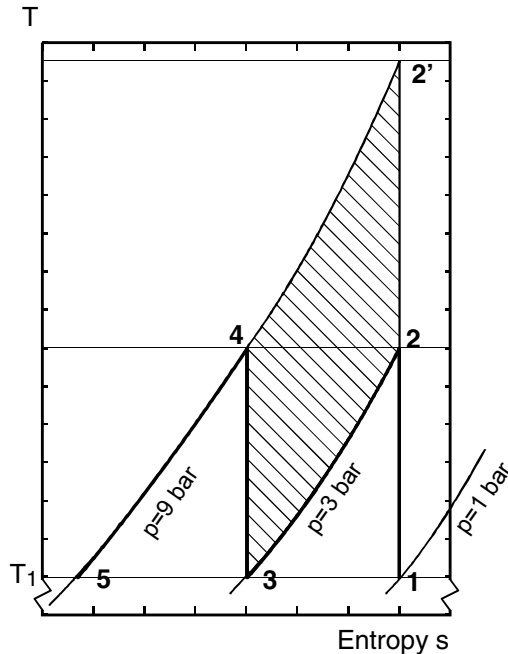


Fig. 3.12 T-s diagram for one- and two-stage compression

1 kg air at 1 bar, 20°C at 9 bar  
Labour savings (shaded)

For a simple qualitative view, let the ideal 2-stage compression be identified by the isentrope 12 or 34. The stage pressure ratio ( $\psi_1 = \psi_2 = 3$ ) should be constant and the intermediate or after-cooler should return the isobar to the intake temperature  $T_1$ . Points 1, 3 and 5 therefore are located on one isotherm.

The one-level compression 12' with after-cooling 2'5 requires a considerably greater effort to reach the same final state.

Work and thermal energy can be determined with the **T-s diagram**. The work required to compress the air mass is the surface area enclosed by the lines; the thermal energy appears as the areas below the relevant state lines.

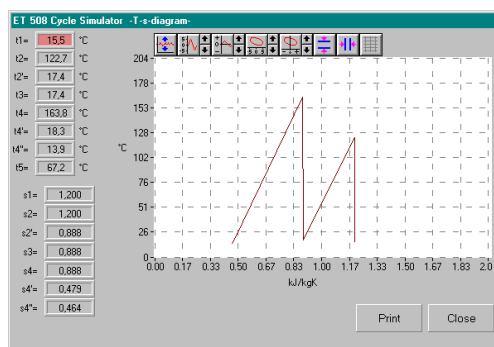


Fig. 3.13 T-s diagram

The T-s diagram is called up from the "system diagram" screen and shows this diagram, depending on the state.

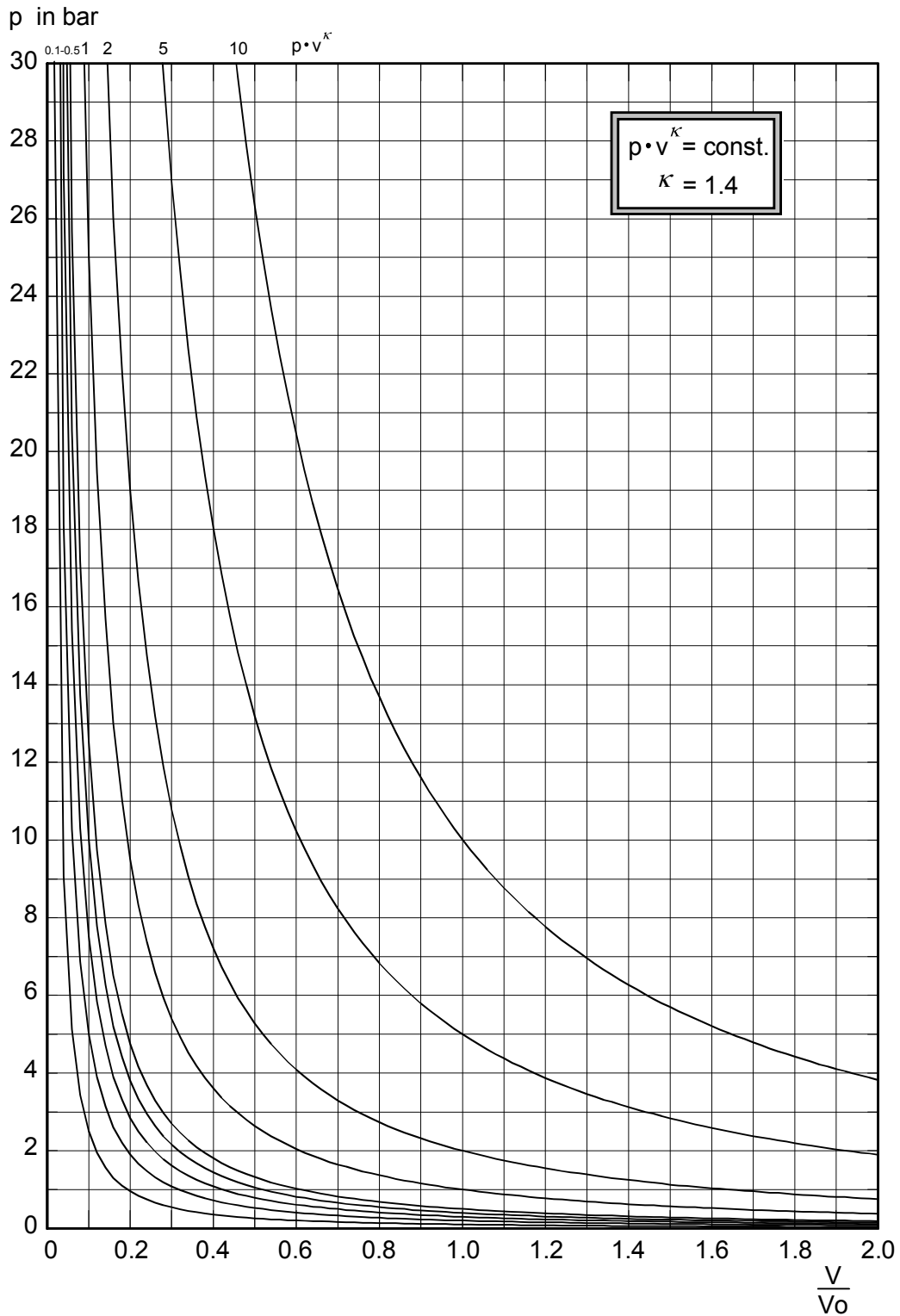
Changing the cooling Poti 4 moves Points 3 and 5 to their isobars.

# ET 508 Cycle Simulator 2-stage Air Compressor



## 4 Annex

### 4.1 p-V diagram

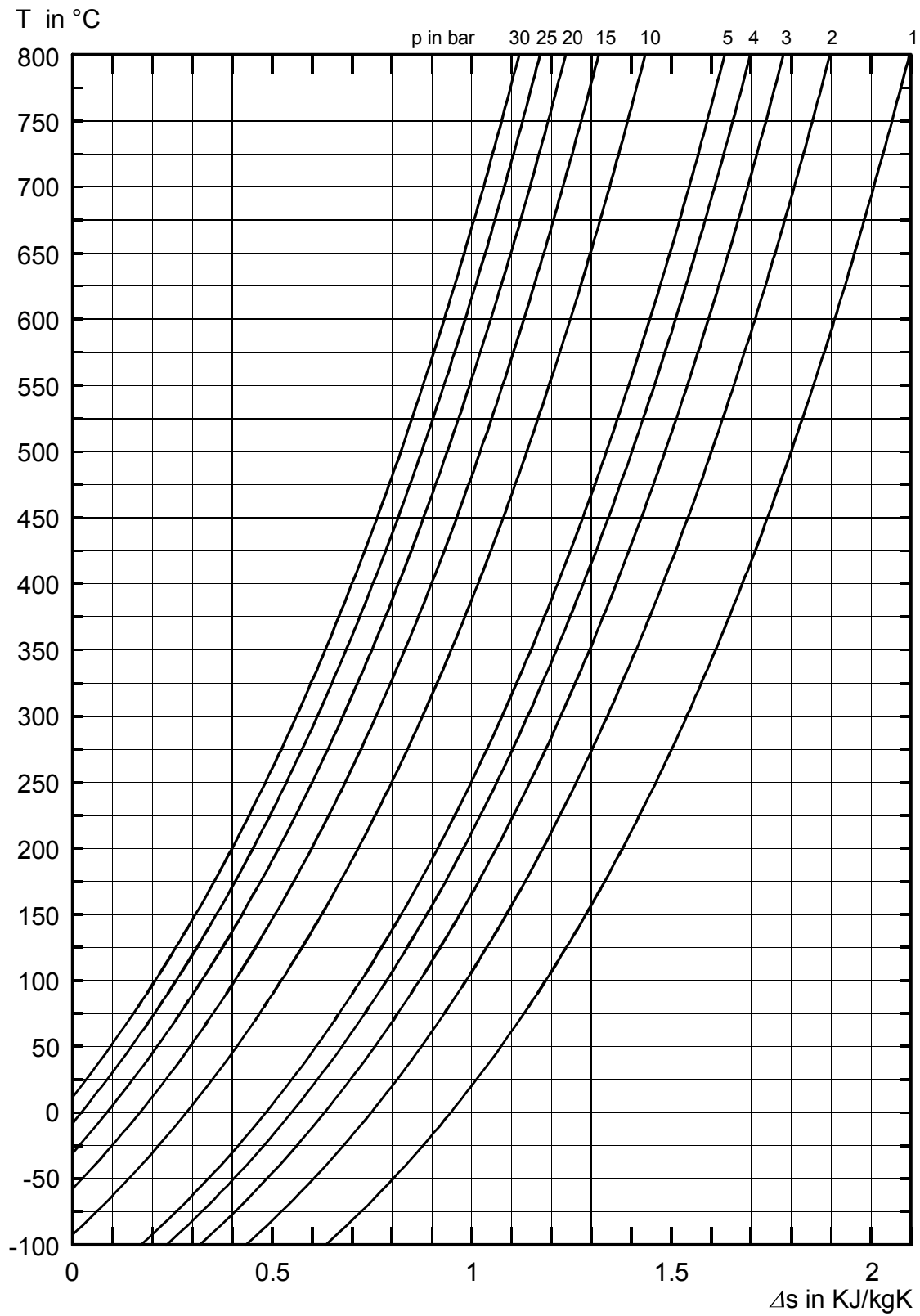


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# ET 508 Cycle Simulator 2-stage Air Compressor



## 4.2 T-s diagram



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# ET 508 Cycle Simulator

## 2-stage Air Compressor



### 4.3 Symbols and units

$c_{pL}$	Specific thermal capacity of dry air	$\text{kJ/kgK}$
$c_{pD}$	Spec. thermal capacity of steam	$\text{kJ/kgK}$
$\varepsilon$	Relative dead space	1
$\kappa$	Polytropic exponent	1
$\dot{m}$	Mass flow	$\text{kg/h}$
$\dot{m}_{in}$	Added mass flow - air	$\text{kg/min}$
$\dot{m}_{out}$	Discharged mass flow - air	$\text{kg/min}$
$\mu$	Re-expansion	1
$n$	Speed of drive motor	$1/\text{min}$
$p$	Absolute pressure	bar
$p_n$	Nominal pressure control	bar
$\varphi$	Relative air humidity	%
$\psi$	(Stage) pressure ratio	1
$Q$	Thermal energy	W
$\dot{Q}$	Heat flow	$\text{W/sec}$
$R_d$	Gas constant of steam at $20^\circ\text{C}$ , 1 bar	$\text{kJ/kgK}$
$s$	Specific entropy	$\text{kJ/kgK}$
$t$	Temperature	$^\circ\text{C}$
$T$	Temperature	K
$v$	Specific volume of air	$\text{m}^3/\text{kg}$
$V$	Volume of air	$\text{m}^3$
$V_{Str}$	Displacement volume of compressor	$\text{cm}^3$
$\dot{V}$	Volume flow	$\text{l/h}$
$V_S$	dead space volume	$\text{cm}^3$
$W$	Work of compressor	W
$x$	Absolute air humidity	$\frac{\text{g water}}{\text{kg dry air}}$

# ET 508 Cycle Simulator 2-stage Air Compressor



## 4.4 Technical Data

### Compressor:

Type: 2-stage piston compressor

Adjustable:

Piston displacement  
each 0-1000 cm<sup>3</sup>

Speed of drive 0-1000 1/min

Rel. dead space (both stages equal)  
0-100 %

(based on displacement of each piston)

### Intake condition of air (adjustable):

Pressure 0-2 bar

Temperature 0-100 °C

Rel. air humidity 0-100 %

Entropy content 0-100 kJ/kgK

Nominal pressure for pressure control  
0-50 bar

Tank volume 0-1000 L

Polytropic exponent  $\kappa=$  1.4

Coolant inlet temperature 15 °C

Max. coolant flow rate 100 l/h

### Dimensions (l x w x h)

250 x 490 x 710 mm

Weight: ca. 15 kg

# ET 508 Cycle Simulator

## 2-stage Air Compressor



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