

# **Experiment Instructions**

CE 400      Gas Absorption





## Experiment Instructions

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**This manual must be kept by the unit.**

**Before operating the unit:**

- Read this manual.
- All participants must be instructed on handling of the unit and, where appropriate, on the necessary safety precautions.

**CE 400**

**GAS ABSORPTION**

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**CE 400**

**GAS ABSORPTION**

## 1

## Introduction

Absorption is a basic procedure in thermal process engineering. Absorption is used to separate one or more gas components from a gas flow using a solvent (detergent).

The CE 400 Gas Absorption unit provides a clear method of separating a gas mixture containing air and CO<sub>2</sub> by absorption in water.

The trainer includes three sub-processes:

- Gas mixture
- Absorption
- Desorption

In the gas mixture section, air is mixed with CO<sub>2</sub>. Mixing is carried out manually using 2 control valves and 2 rotameters.

In the absorption section, the CO<sub>2</sub> is washed out of the gas mixture in a glass absorption column using water as solvent.

In the desorption section, the CO<sub>2</sub> is separated from the water in a glass desorption column.

The key component of the trainer is the glass packed column, in which the gas mixture is brought into contact with water. During operation, samples of the gas mixture are taken at the gas inlet, in the centre of the column and at the gas outlet.

To evaluate the separation, these are analysed in terms of their CO<sub>2</sub> content using an appropriate manual gas analysis unit and the success of the absorption is thus determined. The gas sampling point in the centre of the column enables conclusions to be drawn about the characteristics of the absorption process along the column.

The trainer is supplied with the CO<sub>2</sub> gas from an external gas cylinder, which must be provided by the user. The water used for absorption can either be used in a circuit and reprocessed in the trainer or flow only once through the absorber as fresh water.

The trainer is intended for training in process engineering, process control, energy and environmental engineering.

It is suitable for performing laboratory exercises with students.

## 1.1 Learning content/Exercises

- Investigation of the absorption process when separating gas mixtures in a packed column
- Determination of pressure losses in the column
- Determination of the flooding point
- Representation of the absorption process in a load diagram
- Investigation of the variables influencing the effectiveness of absorption

## 1.2 Information for the teacher

Once the system is ready to operate, around 2,0 hours is suggested for a measuring series in a stationary condition.

The system should be cooled down at the beginning of the experiment. The required flow rates for the absorbent and the air should be set with cooled cooling water. When the system is in a stationary condition, the gas concentrations in the absorption column can be measured.

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## 2 Safety

### 2.1 Intended use

The unit is to be used only for teaching purposes.

### 2.2 Structure of the safety instructions

The signal words DANGER, WARNING or CAUTION indicate the probability and potential severity of injury.

An additional symbol indicates the nature of the hazard or a required action.

Signal word	Explanation
<b>DANGER</b>	Indicates a situation which, if not avoided, <b>will</b> result in <b>death or serious injury</b> .
<b>WARNING</b>	Indicates a situation which, if not avoided, <b>may</b> result in <b>death or serious injury</b> .
<b>CAUTION</b>	Indicates a situation which, if not avoided, may result in <b>minor or moderately serious injury</b> .
<b>NOTICE</b>	Indicates a situation which may result in <b>damage to equipment</b> , or provides instructions on <b>operation of the equipment</b> .

Symbol	Explanation
	Electrical voltage
	Hazard (general)
	Hot surfaces
	Cold
	Notice
	Wear ear protection

## 2.3 Safety instructions



### ⚠ WARNING

**Reaching into the open control cabinet can result in electric shocks.**

- Disconnect from the mains supply before opening.
- Work should only be performed by qualified electricians.
- Protect the control cabinet against moisture.

**⚠ DANGER****Risk of suffocation at high CO<sub>2</sub> concentrations.**

CO<sub>2</sub> displaces oxygen, which is essential for life, and results in fatigue in weak concentrations. The MWC (Maximum Workplace Concentration) value is 0,5%. Headaches and dizziness occur at 5%. High concentrations (8%) lead to death by suffocation in 30 to 60 minutes.

- Do not inhale CO<sub>2</sub>.
- Operate the system in as large a space as possible
- Ensure adequate ventilation
- Ensure adequate extraction
- Ensure that a maximum concentration of 0,5% is maintained

**⚠ DANGER****Risk of suffocation at high CO<sub>2</sub> concentrations.**

CO<sub>2</sub> is heavier than air and collects at floor level or in hollows. In hollows or low-lying spaces with no ventilation, dangerous gas concentrations can form, which can result in death by suffocation.

- In hollows or low-lying spaces, ensure appropriate air circulation.
- In hollows or low-lying spaces, the oxygen content must be monitored.

**⚠ WARNING**

**Hot surfaces on the compressor and other tubes.**

Risk of burning.

- Never touch during operation!

**⚠ WARNING**

**Operation of the system generates noise.**

- Wear suitable hearing protection when working near the equipment for long periods during operation.

**NOTICE**

**There is risk of destruction of the column.**

The column can burst at high pressures.

- Maximum column pressure: 1 bar may not be exceeded.

**NOTICE**

When commissioning the cooling unit, check that the water pump is actually conveying water and there is no air in the pump. With no water flow, there is a risk that the heat exchanger after the expansion valve freezing.

- Bleed the pump if necessary.
- Check the water flow at the water inlet or outlet in tank W2/ W3 with the hand.



---

**NOTICE**

Frost damage is possible when the unit is stored.

- Only store the unit in a frost-free location.
  - During longer periods without use, drain using the drain valve.
  - If the unit will not be used for a long period, drain the water.
- 



---

**NOTICE**

Never fill the column completely with water, as the column may overflow and fluid may escape from the trainer.

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**CE 400**

**GAS ABSORPTION**

### 3 Unit description

#### 3.1 Process diagram

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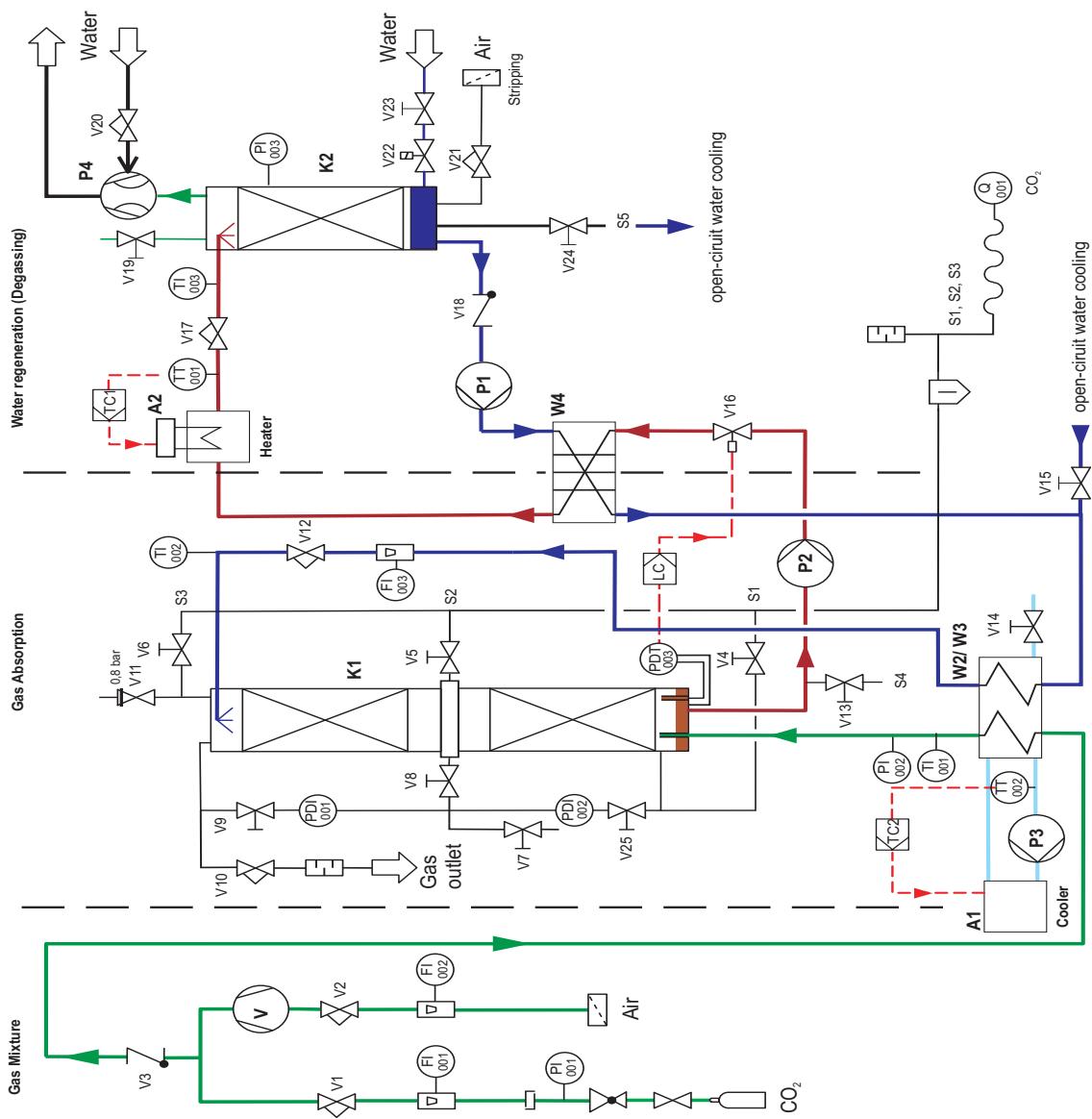


Fig. 3.1 Process diagram for CE 400 system

**CE 400**
**GAS ABSORPTION**

A1	Cooling unit
A2	Heater before desorber inlet
K1	Absorption column (Absorber)
K2	Regeneration column (Desorber)
P1	Circulation pump for delivery to the absorption column
P2	Circulation pump for delivery to the regeneration column
P3	Circulation pump in cooling circuit
P4	Vacuum water jet pump
V	Compressor for air
W2/ W3	Heat exchanger
W4	Heat exchanger (recuperator)
V1	CO <sub>2</sub> control valve
V2	Air control valve
V3	Non-return valve
V4	Ball valve for gas sampling at base of column
V5	Ball valve for gas sampling at centre of column
V6	Ball valve for gas sampling at head of column
V7	Ball valve
V8	Ball valve for releasing the pressure measuring point in the centre of the column
V9	Ball valve for releasing the pressure measuring point at the head of the column
V10	Control valve for adjusting the column pressure
V11	Safety valve on absorption column
V12	Control valve for adjusting the water flow rate
V13	Ball valve for liquid sampling from absorption column
V14	Ball valve for draining the water cooling circuit
V15	Ball valve for sampling regenerated absorbent
V16	Solenoid control valve for regulating the level in the absorption column K1
V17	Control valve for absorbent before regeneration column K2
V18	Non-return valve
V19	Ball valve for equalising the vacuum in column K2 after the experiment
V20	Control valve for adjusting the water quantity for the vacuum water jet pump
V21	Control valve for adjusting the quantity of stripping air
V22	Solenoid valve for filling the columns (K1 & K2) with water
V23	Ball valve for manually blocking the water supply connection
V24	Ball valve for draining the regeneration column
V25	Ball valve for releasing the pressure measuring point at the base of the column

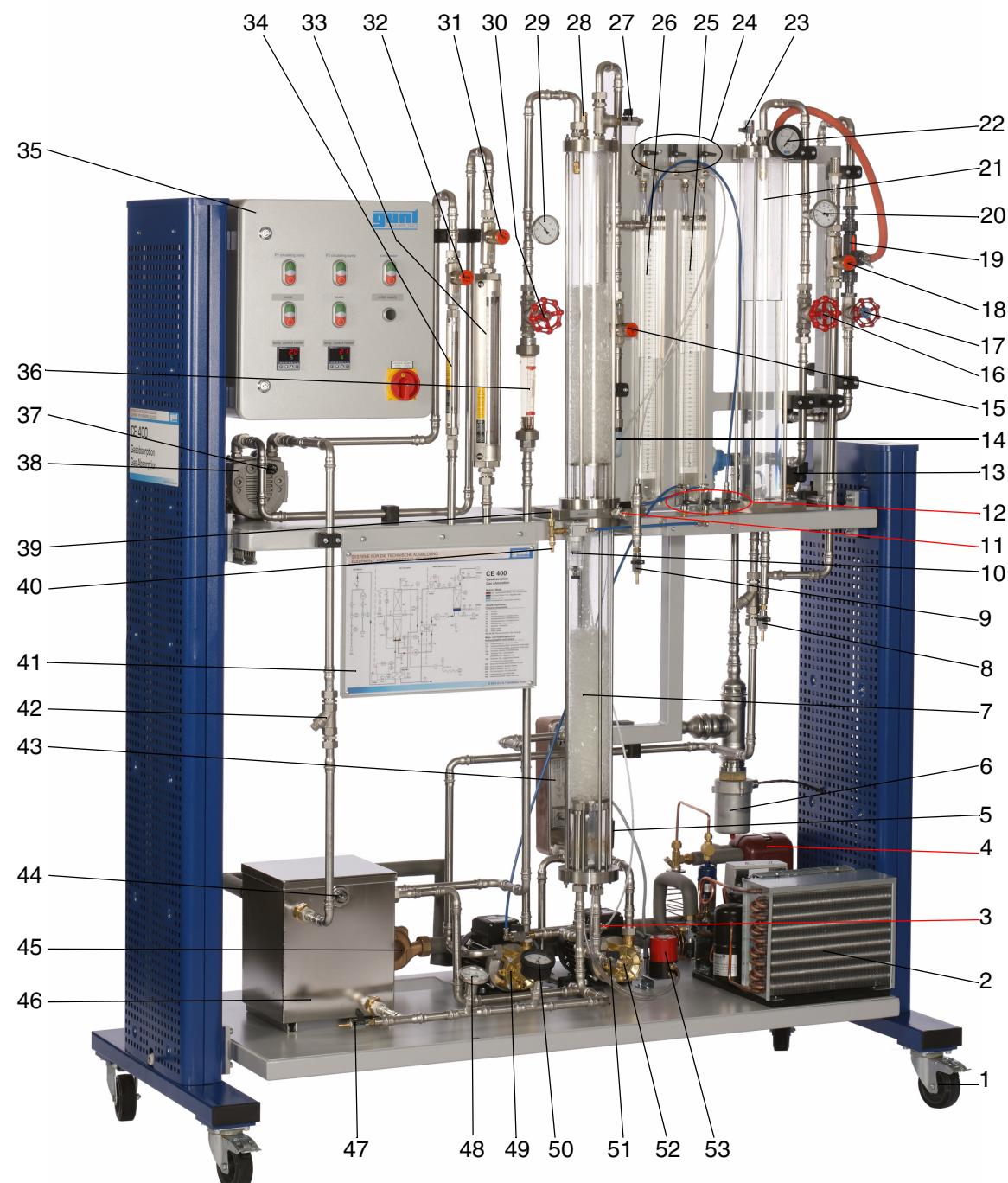


Fig. 3.2 CE 400 front view

CE 400

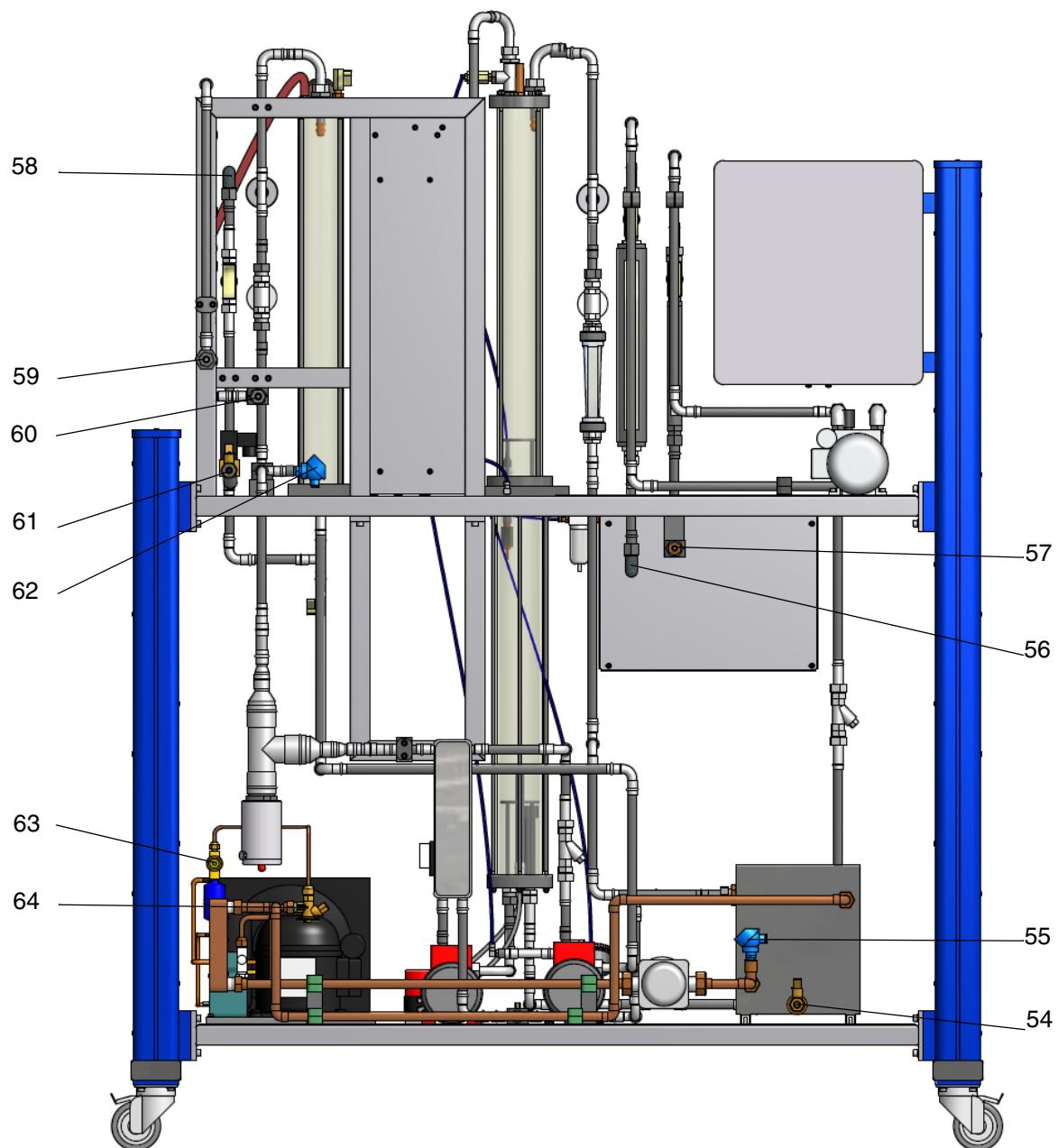
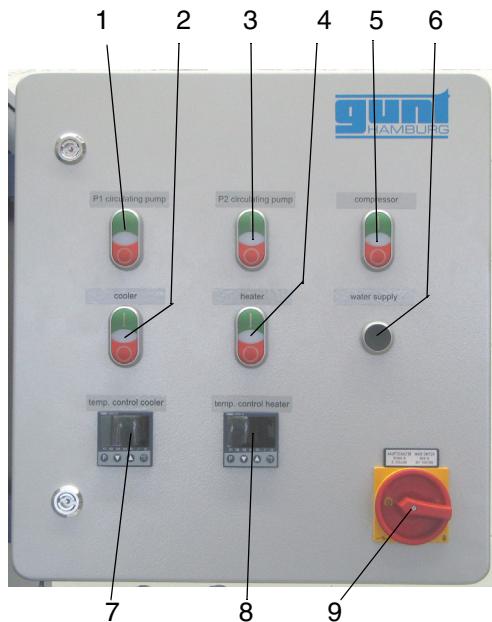
**GAS ABSORPTION**

Fig. 3.3 CE 400 rear view

1	Roller with brake	33	Flow meter FI002 (air)
2	Cooling unit	34	Flow meter FI001 (CO <sub>2</sub> )
3	Ball valve V25	35	Control cabinet with controls
4	Heat exchanger	36	Flow meter FI003 (water)
5	Solenoid control valve V16	37	Pressure limiter on compressor
6	Heater A2	38	Compressor for air V1
7	Absorption column K1	39	Gas sampling point
8	Ball valve V24	40	Gas sample bypass to outlet
9	Ball valve V7	41	Process diagram
10	Water separator	42	Non-return valve V3
11	Ball valve V8	43	Heat exchanger W4
12	Valves V4, V5, V6	44	Cooling water level inspection glass
13	Solenoid valve V22	45	Cooling water pump P3
14	Air silencer	46	Heat exchanger W2/ W3
15	Control valve V10 (gas mixture outlet)	47	Ball valve V15
16	Control valve V17 (water)	48	Thermometer TI001
17	Control valve V20 (vacuum pump)	49	Circulation pump P1
18	Control valve V21 (stripping air)	50	Manometer PI002
19	Vacuum water jet pump P4	51	Ball valve V13
20	Thermometer TI003	52	Circulation pump P2
21	Regeneration column K2	53	Differential pressure transducer PDT003
22	Manometer PI003	54	Ball valve V14
23	Ball valve V19	55	Cooling water temperature transducer TT002
24	Ball valves for bleeding the U tubes	56	Air intake filter
25	U-tube manometer for lower column K1	57	Gas connection for CO <sub>2</sub>
26	U-tube manometer for upper column K1	58	Air intake filter for stripping air
27	Ball valve V9	59	Water outlet from vacuum pump P4
28	Safety valve V11	60	Water inlet to vacuum pump P4
29	Thermometer TI002	61	Water supply connection
30	Control valve V12 (water)	62	Temperature transducer TT004 (heater)
31	Control valve V2 (air)	63	Inspection glass with moisture indicator
32	Control valve V1 (CO <sub>2</sub> )	64	Expansion valve for cooling unit

### 3.3 Controls / switch cabinet

All electrical equipment on the trainer is operated from the switch cabinet.



1	P1 Absorber feed pump
2	Cooler and P3
3	P2 Desorber feed pump
4	Heater
5	Compressor V
6	Fresh water inlet
7	Cooler temperature controller
8	Heater temperature controller
9	Master switch

Fig. 3.4 CE 400 switch cabinet

### 3.4 Gas mixture



Fig. 3.5 Gas mixture

This auxiliary process provides the gas mixture (untreated gas) for the absorption experiment.

This involves mixing standard commercial CO<sub>2</sub> gas with ambient air (carrier gas) and feeding the mixture to the column. The mixture ratio of the two components is adjusted by the user with the control valves V1 and V2.

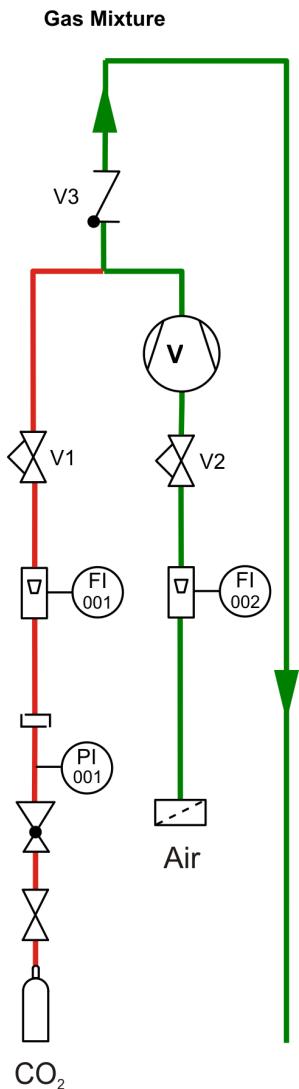


Fig. 3.6 Gas mixture process diagram

**NOTICE**

The supply of CO<sub>2</sub> gas comes from a compressed gas cylinder, which must be provided by the user. A full cylinder with at least 10 kg filling weight is recommended. This enables the absorption experiment to be carried out for around 2,5 h. A check valve for the gas supply is also required, as well as a suitable control unit for setting the constant gas pressure. If the gas pressure fluctuates, the gas concentration to be measured also fluctuates.

Required CO<sub>2</sub> gas: ~ 2...6 ltr/min

The air is conveyed into the pipe system through the compressor V. The intake air flow can be adjusted using the control valve V2 and read on the flow meter FI 002.

In Fig. 3.6, the CO<sub>2</sub> flow rate is set parallel to the air. The quantity can be adjusted using the control valve V2 and read on the flow meter FI 001.

The gas flows are then merged and fed to the column as a mixture. The non-return valve V3 prevents absorption liquid from the base of the column from getting into the auxiliary gas circuit if the gas pressure fails.

**NOTICE**

The internal pressure limiter in the compressor should be adjusted so that no air is blown off. The maximum outlet pressure without the compressor blowing off air is 1 bar relative. At values above 1 bar, the gas concentration can no longer be calculated from the flow rates.

## 3.5

## Gas absorption



Fig. 3.7 CE 400 absorption column K1

The main component of the trainer is the large vertical column. This is where the gas absorption occurs. This is done by introducing a gas mixture containing CO<sub>2</sub> and air at the base. The absorption liquid is pumped into the column at the head, flows towards the gas mixture and absorbs CO<sub>2</sub>.

The column K1 consists of two transparent cylinders of equal length, separated from one another by a central flange. This contains a sieve base that enables both sections of the column to be filled with packing separately. The type and quantity of the column packing can vary.

This purpose of this design is to bring about possible differences in the absorption process over the length of the column and to enable these to be identified.

The central flange thus allows a gas sample to be taken using valve V5 at S2 for gas analysis. A sample of the gas fed in can be taken at the base of the column using valve V4 at S1, and a sample of the outlet gas from the head of the column using valve V6 at S3.

The central flange also makes it possible to measure and compare the pressure differences PDI 001 over K1 (top) and PDI 002 over K1 (bottom), which occur as the gas mixture flows through. This enables relationships between pressure difference and absorption effect to be derived. Two U-tube manometers filled with liquid are used as indicators.

The gas mixture for the experiment is fed in from below at the base of the absorption column through a spray nozzle. It rises up through the lower section of the column K1, the central flange and the upper section of the column K1 and flows towards the absorption liquid. At the head of the column, it escapes into the open air through the control valve (for the pressure) V10 and a silencer. The gas mixture thus passes through the column only once and is not recirculated. V10 restricts the outlet of gas from the column. This enables both the flow volume of gas through the column to be adjusted and the gas pressure in the column to be influenced.

For easier operation of the absorption process, the column can be operated with the gas mixture at a slight excess pressure.

The safety valve V11 limits this to an acceptable amount (see technical data). The pressure in the column is indicated on the manometer PI002.



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**NOTICE**

The compressor has an internal pressure limiter and can generate a maximum of 1 bar relative pressure.

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The absorption liquid is conveyed in a circuit between the absorption column K1 and the regeneration column K2. The absorption liquid is fed in at the head of each column from above through a nozzle.

In the absorption column, the absorption liquid trickles over the column packing. Gravity causes it to flow downwards through the two sections of the column towards the gas and it is fed out of the

column using pump P2 and back into the regeneration column K2 through the heat exchanger W4. The absorbent can be heated using a heater to provide better desorption. To ensure that the entire gas mixture flows upwards through the absorption column, a liquid level (around 8 cm) is regulated at the base of the absorption column. The liquid level is regulated by actuation of the solenoid control valve V16 depending on the level. The level is recorded by making a differential pressure measurement PDT003 for the liquid pressure.



#### NOTICE

For correct measurement of the liquid pressure and functioning of the regulation, it is important that there are no air bubbles in the PVC supply lines to the pressure transducer.

### 3.6 Cooling unit for absorption

To enable the absorber to be operated at different temperatures, the system has a cooling unit. The cooling unit consists of a refrigeration system, which uses a water circuit to cool down both the gas mixture and the absorption liquid before they enter the absorber. The cooling circuit is limited to a minimum of 4°C. For experiments, we recommend turning on the cooling circuit around 1/2 hour in advance as the lower temperature can be reached more quickly with no heat load.



Fig. 3.8 CE 400 regeneration column  
K2

### 3.7 Water regeneration / gas desorption

This process involves regenerating the absorption liquid for the experiment.

Water is used as the absorption liquid for absorbing the CO<sub>2</sub> from the gas mixture in the absorption column K1.

This is conveyed by the pump P1 from the base of the regeneration column K2 through a heat exchanger W4 for heat recovery and a heat exchanger W2/W3 to the head of the absorption column. The water flow pumped can be adjusted using the control valve V12 and read on the flow meter F003.

After passing through the absorption column, the water – now enriched with CO<sub>2</sub> – is discharged at the base of the column and is conveyed by the pump P2 through the heat exchanger W4 and the heater A2 to the head of the regeneration column. The level control in the absorption column ensures that the liquid level in the column is kept constant (approx. 8 cm). In addition, the control valve V17 can also be used to influence the back pressure after the solenoid control valve V16.



---

**NOTICE**

A slight back pressure improves the control behaviour of the solenoid control valve and reduces noise emissions.

After absorption, the water is loaded with CO<sub>2</sub>. For it to be continue being used for absorption, the CO<sub>2</sub> must be removed. To degasify it, it is conveyed into the regeneration column K2 using the pump P2. In the regeneration column, the water is once again sprayed in at the head of the column and collects at the base.

To improve regeneration, the absorbent is sprayed and a vacuum is also generated in the column using a vacuum water jet pump P4.

The vacuum water jet pump requires a connection to an external water mains to operate. The control valve V20 restricts the flow of the water supply through P4 and thus regulates the vacuum at PI003 in the column K2.

In addition, adding fresh air using the valve V21 – known as “stripping” – further improves the regeneration process.

When the water is regenerated, the water – now low in CO<sub>2</sub> - can be conveyed back into the absorption column K1 by P1. This flow rate at FI003 can be controlled using the valve V12. Adjusting V20 and V21 enables the vacuum in the column K2 to be adjusted.

### 3.8 Other components and functional tests in the system

#### 3.8.1 Testing the function of pump P3 in the cooling circuit

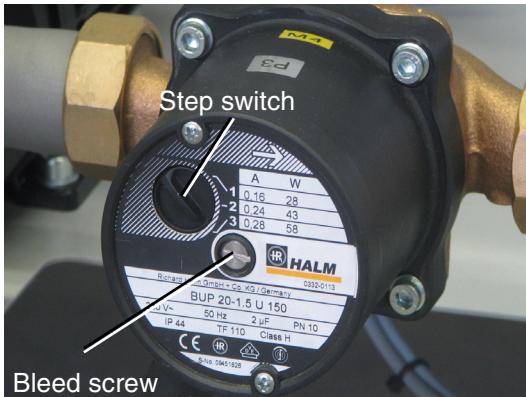


Fig. 3.9 Pump P3 with 3 step switch and bleed screw

- Turn on the pump or the cooler at the switch cabinet. The selected step 2 or 3 can be checked on the pump.
- Check the water flow rate in the tank W2/W3 with the fingers at the water inlet or outlet. If you cannot feel any water flow, bleed the pump. This test should always be performed after refilling or longer periods without use.

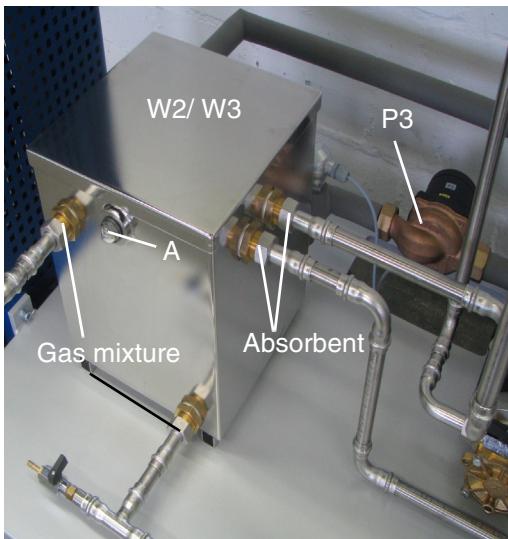


Fig. 3.10 Water tank for heat exchanger W2/W3 with level display (A)

### 3.8.2 Air compressor V1, blow off pressure and column pressure



Fig. 3.11 Compressor with pressure limiter feature

- The compressor should be adjusted with the pressure limiter so that no air is blown off by the compressor. This is the only way to ensure that the air intake quantity will actually be conveyed into the column. The maximum value that can be set on the compressor is 1 bar relative.



Fig. 3.12 Control valve V10 and gas outlet from column K1

- The control valve V10 and the manometer PI002 can be used to set the pressure in the column K1 at around 0 bar relative. At pressures close to 1 bar relative, the intake side flow rate displayed for air is no longer correct as the compressor blows off internally above a bar relative. However, the pressure should be adjusted so that the gas mixture reaches S1, S2 and S3 for sampling.

### 3.8.3 CO<sub>2</sub> supply

- With the CO<sub>2</sub> supply, it is important that the pressure is kept constant as fluctuations have a direct effect on the concentration of the gas mixture. A two-stage pressure reducer with a low output pressure is recommended for reducing the pressure and controlling the CO<sub>2</sub> supply provided by the operator.
- The measured flow rate values and the associated pressures can be used to calculate the theoretical gas concentration to be expected, which can then be compared with the measured gas concentration. The relevant measuring tolerances must be taken into account.

### 3.8.4 Level control

- Level control is based on a differential pressure measurement at the base of the column. The differential pressure between the liquid pressure in the Pitot tube (1) and the pressure at the base of the column is measured and fed to an electronic controller in the switch cabinet. This then actuates the solenoid control valve (4 or Fig. 3.2, position 5). If the controller is working correctly, a water level of 5 to 8 cm (Fig. 3.34) is established over the base of the column. For correct function is it necessary to deaerate the pressure-measuring tubes with the screws opposite the connectors and keep the tubes free of air bubbles.

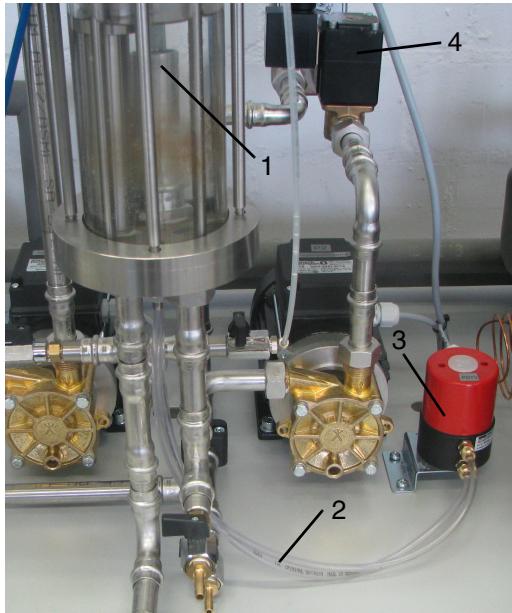


Fig. 3.13 Base of column with Pitot tube, pressure measuring hoses, differential pressure meter and solenoid control valve

1 – Pitot tube

2 – Pressure measuring hoses

3 – Differential pressure meter PDT003

4 – Solenoid control valve

### 3.8.5 Dial manometer



Fig. 3.14 Dial manometer (class 1,6)

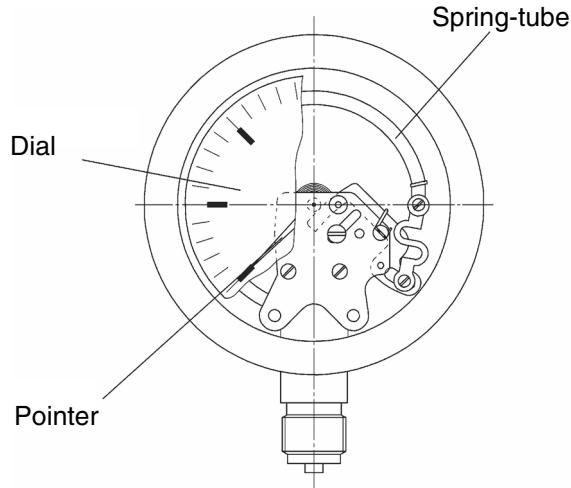


Fig. 3.15 Bourdon gauge construction

The dial manometers used have a Bourdon gauge construction.

Spring-tubes are tubes bent in a circle with an oval cross-section. The pressure to be measured acts on the inside of the tube, which causes the oval cross-section to become approximately circular, as the pressure tries to change the cross-section of the tube to a circle. The curvature of the spring-tube results in cyclic stresses, which bend the spring. The end of the spring that is not under stress moves. A mechanism converts this movement into rotation, which then moves the pointer and indicates the measured pressure value on the scale. The accuracy is specified on the dial, e.g. with class 1,6.

Class 1,6 means that a maximum error of  $\pm 1,6\%$  of the full scale value is permitted.

### 3.8.6 Vacuum water jet pump

The vacuum pump is a water jet pump. A water jet pump is a pump with no moving mechanical parts.

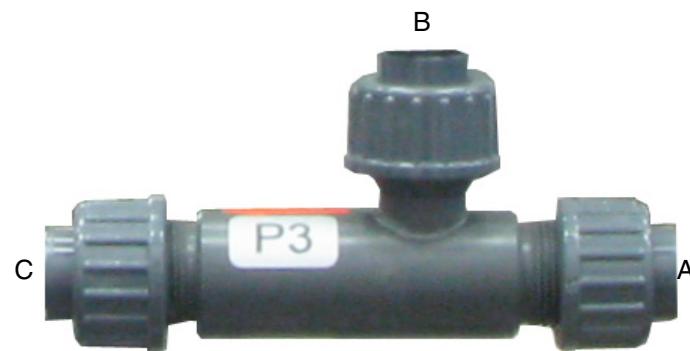
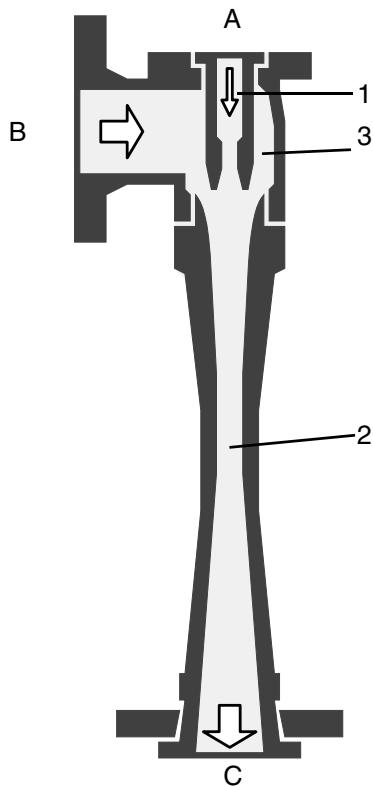


Fig. 3.17 Vacuum water jet pump

1	Propellant nozzle
2	Diffusor
3	Head
A	Water inlet
B	Air inlet
C	Water/air mixture outlet

The basic principle is based on a liquid jet (in this case water) emerging at high speed from a propellant nozzle (1), which in this application picks up gas (air in this case) from its surroundings (3) and accelerates it.

The result of this process is a mixture of the propellant (water) and the substance carried or taken in (air), the speed of which is reduced again in a diffusor (2) by increasing the pressure.

The effect of the air taken in generates a vacuum.

Fig. 3.16 Principle of a water jet pump

### 3.8.7 Rotameter

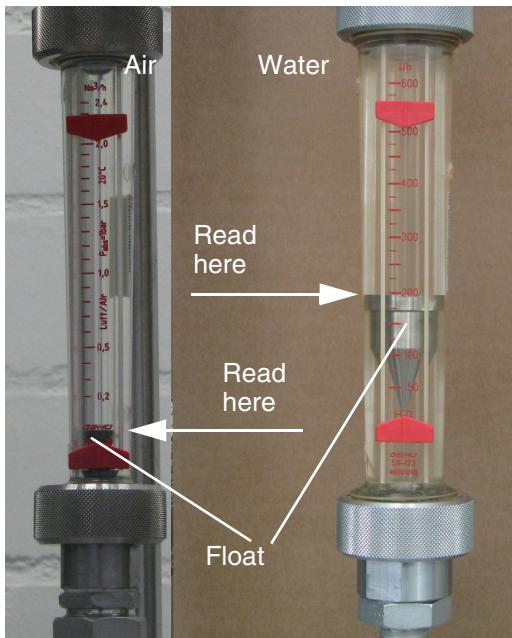


Fig. 3.18 Rotameter

Rotameters are used to measure the flow rates of the gas, air and water.

These flow meters have an upright tube, continuously extended upwards, in which a specially shaped float can move freely upwards and downwards.

The medium flows through the tube from bottom to top. As it does so, it raises the float until a ring gap is formed between the wall of the tube and the float, which means that the forces acting on the body are in equilibrium.

Each height of the float corresponds to a certain flow rate, which can then be read on a scale.

The flow rate can be read at the upper edge of the tapered lip of the float.

Air bubbles or dirt particles on the float can influence the measuring accuracy. To wash them away, the maximum flow rate is briefly generated.

### 3.8.8 Differential pressure measurement with U-tube manometer



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Measurement for system operation without pressure

- Close the 3 ball valves over the U-tubes
- Open the ball valve V8
- Open the ball valves V9 and V25
- Carry out the measurements
- At the end of the measurement, close the ball valves V8, V9 and V25 to prevent water getting in when changing the operating points.

#### NOTICE

If water gets into the measuring line for the U-tubes, this leads to incorrect measurements. To prevent this, the ball valves V8, V9 and V25 should only be opened when the liquid level in the column is steady.

Fig. 3.19 U-tube manometer with ball valves

### 3.8.9 Cooling unit



Fig. 3.20 Cooling unit A1

The cooling unit A1 is used to reduce the temperature of the substances in the absorption column K1, to positively influence the temperature-dependent process. The cooling unit is made up of a refrigeration set with compressor, condenser, pressostat, collector and expansion valve. The expansion valve sprays the refrigerant directly into the plate heat exchanger for evaporation. A temperature transducer TT002 before the heat exchanger W2/W3 and an electronic temperature controller prevent the temperature falling below 5°C. A pressostat monitors the pressures in the refrigeration system and shuts down the refrigeration system if required.

### 3.8.10 Heater



Fig. 3.21 Heater A2, arrow points to button

The heater A2 can be used to increase the temperature of the loaded absorption fluid before the regeneration column K2 to improve degasification.

The heater contains a temperature limiter, which shuts down the heater in case of overheating. Once the temperature limiter has tripped, it has to be reset. To do this, remove the cap nut under the heater and then press the exposed button.

### 3.8.11 Heat exchanger (recuperator)

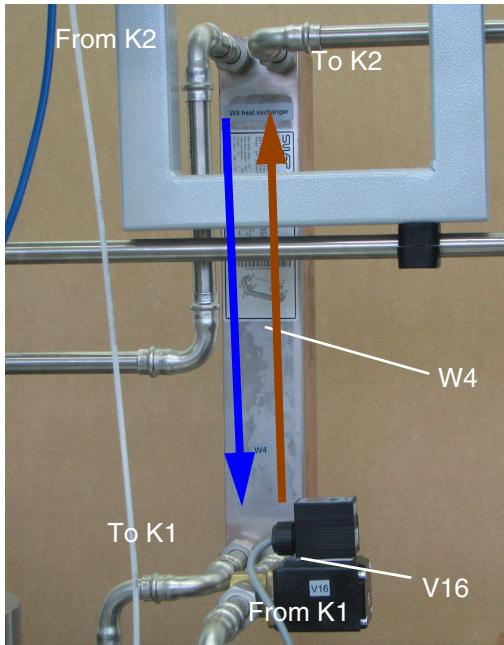


Fig. 3.22 Heat exchanger W4 (recuperator)  
Blue => To absorber K1  
Brown => To desorber K2

The heat exchanger W4 has the task of re-exchanging the amount of heat added by the heater A2 before the regeneration column after regeneration in K2 (recuperator), so that the heat remains in the regeneration process in K2 and is not transferred to the absorption process K1. The heat exchanger W4 is a plate heat exchanger operated in counter flow mode.



Fig. 3.23 Controller

On the controllers, the current actual value (red) of the controlled variable is shown in the upper section of the display. The setpoint (green) appears below. The arrow keys can be used to change the setpoint.

### 3.8.13 Connections for fresh water operation

In order to operate the system with fresh water as an alternative to circuit mode, there are two connections with large hose nozzles on the system.



Fig. 3.24 Fresh water supply at V15

Fresh water supply: At V15

Fresh water outlet: At V24

The flow rate is adjusted using the valve V12 and the flow meter FI 003.

The pump P2 should be turned on. Only P1 is not required and can be left turned off.



Fig. 3.25 Water outlet at V24

### 3.9 Sampling and CO<sub>2</sub> analysis

#### 3.9.1 Gas sampling



Fig. 3.26 Ball valves for sampling, S1, S2 and S3

Samples of the gas mixture from the column K1 can be taken at three different points while the process is underway:

Bottom S1: Gas sampling point at the column gas inlet

Centre S2: Gas sampling point in the centre between the upper and lower sections of the column K1

Top S3: Gas sampling point at the column gas outlet



Fig. 3.27 Gas sampling point with water separator

For the measurements, it is necessary for the gas samples to be completely dry so that no water is carried to the measuring instrument with the gas. A water separator is used to achieve this.

Open the valve for the selected gas sampling point and allow the gas mixture to escape. Wait until it has displaced the ambient air from the water separator and the connection hoses (around 15 - 20 seconds).

Then carry out the CO<sub>2</sub> measurements at the sampling point after the water separator using the analysis unit.



#### NOTICE

Water can collect in the water separator during experiments. You should therefore check the separator before every experiment. If necessary, excess water can be drained off by slightly unscrewing the drain plug on the underside.

### 3.9.2 CO<sub>2</sub> analysis



Fig. 3.28 CO<sub>2</sub> meter only with plastic-filter

To determine the CO<sub>2</sub> content of gas samples, the CE 400 trainer includes a manual gas analysis unit.

For details of the use, application, operation and calibration of this analysis unit, refer to the manual provided by the manufacturer.

In particular, the safety guidelines must be observed.

Note that gas samples should be taken with the shortest possible hose to the flowing gas, as the pump has a delivery volume of around 10 ml per measurement. In addition, the flow must completely pass through the column and the hoses before performing a new measurement with changed parameters. Slightly restricting the valve V10 ensures that enough measuring gas reaches the gas sampling point (Q 001) and emerges at the end of the nozzle.

We have removed the needle and the needle protection mechanism for measurement and connected the measuring instrument to the 4 mm PVC hose at the gas flow escaping upwards, Fig. 3.29, with the plastic filter for each measurement.



Fig. 3.29 Measurement with CO<sub>2</sub> meter

**⚠ CAUTION**

The analysis unit contains a sharp hollow measuring needle.

This can cause injury.

- Handle with care.
- Use the unit without the sharp measuring needle but with a filter.

**NOTICE**

The analysis unit is highly sensitive and must always be protected against moisture.

Water or other liquids may never be allowed to pass through the hollow measuring needle into the unit. This will damage the analysis unit.

- Always use the water separator for measurements.

**NOTICE**

The hollow measuring needle in the analysis unit is sensitive. Handle the analysis unit with care during measurements to prevent damage to the hollow measuring needle.

### 3.9.3 Absorbent samples

There are two sampling points on the trainer for taking samples of the absorption liquid.

S4: Sampling point after absorption (with valve V13),

Column K1 outlet

S5: Sampling point after regeneration (with valve V24 only at atmospheric pressure in K2, with valve V15 during operation of the system)

Column K2 outlet



---

**NOTICE**

Analysis of this liquid is not the topic of one of the experiments on the CE 400. However, the sampling points can be used at the user's own discretion.

---

### 3.10 Commissioning

#### 3.10.1 Setting up the trainer

Set up the trainer on a solid and level surface and block the rollers. The front and rear must be freely accessible for the connections on the trainer.

The space must be adequately ventilated to ensure effective dissipation of the escaping CO<sub>2</sub> gas.



#### ⚠ DANGER

#### Risk of suffocation at high CO<sub>2</sub> concentrations.

CO<sub>2</sub> displaces oxygen, which is essential for life, and results in fatigue in weak concentrations. The MWC (Maximum Workplace Concentration) value is 0,5%. Headaches and dizziness occur at 5%. High concentrations (8%) lead to death by suffocation in 30 to 60 minutes.

- Do not inhale CO<sub>2</sub>.
- Operate the system in as large a space as possible
- Ensure adequate ventilation
- Ensure adequate extraction
- Ensure that a maximum concentration of 0,5% is maintained

**⚠ DANGER****Risk of suffocation at high CO<sub>2</sub> concentrations.**

CO<sub>2</sub> is heavier than air and collects at floor level or in hollows. In hollows or low-lying spaces with no ventilation, dangerous gas concentrations can form, which can result in death by suffocation.

- In hollows or low-lying spaces, ensure appropriate air circulation.
- In hollows or low-lying spaces, the oxygen content must be monitored.

### 3.10.2 Connections and filling

- Electrical connection

Connecting the system to the power supply



Fig. 3.30 Cooling water tank W2/ W3

- Refrigeration circuit filling
  - Close the valve V14.
  - Fill up the tank W2/W3 with water as far as the inspection glass (1)

- Set up the fresh water connection.

Connection for filling up the absorbent

- Close valve V23
- Connect the fresh water connection (2) or (Fig. 3.3, position 61) to the water supply

- Vacuum water jet pump connection

- Close valve V20

- Connect the water supply at the inlet (3) or (Fig. 3.3, position 60) to the vacuum water jet pump.

- Connect the drain hose at the outlet (4) or (Fig. 3.3, position 59) from the vacuum water jet pump.

- Filling the system with absorbent

- Close the following valves: V13, V24, V15, V8, V25, V6, V5, V4, V21, V20

- Open the following valves: V10, V19, V23, V17, V12



Fig. 3.31 Water connections

- Press the “Fresh water” button (Fig. 3.4, position 6) to start the flow of water into the column K2. Half fill the column K2 with water.
- Wait for a short time until the water has spread throughout the pipe system.
- If necessary, top up with a little more water so that the column K2 remains around 1/3 full of water.

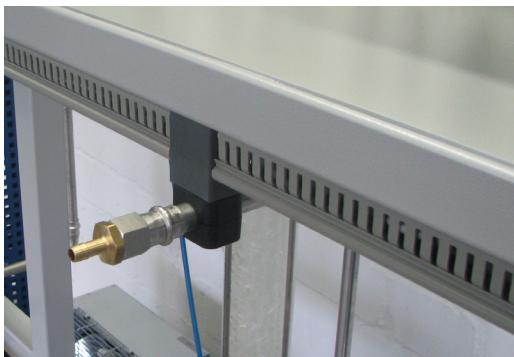


Fig. 3.32 CO<sub>2</sub> connection on rear of unit

- CO<sub>2</sub> supply

Connect the CO<sub>2</sub> supply. In most cases, this is a steel CO<sub>2</sub> cylinder with a pressure reducer. With the pressure reducer, it is important to note that the quality of the gas mixture depends on the fluctuation of the CO<sub>2</sub> pressure. The CO<sub>2</sub> gas should be fed using a hose at Fig. 3.3, position 57.

- U-tube manometer

#### Filling the U-tubes



Fig. 3.33 U-tube manometer with 3 bleed ball valves

- Close the ball valves V9, V8 and V25
- Open the 3 ball valves, Fig. 3.2 or Fig. 3.33, position 24.
- Add water up to the zero line using a spray bottle in the outer vent holes.
- Detach the scales and realign.
- Close the 3 ball valves Fig. 3.33 above the U-tube manometers.

### 3.11 Operating the system

When operating the trainer, the absorption process and the regeneration process run at the same time in a circuit.

#### 3.11.1 Starting up the system

- Connect the power supply
- Connect the water supply
- Connect the CO<sub>2</sub> gas supply. The set outlet pressure on the cylinder pressure reducer should be around 0,8bar relative
- Turn on the trainer using the master switch.
- Turn on the ready-to-use cooler. The cooler should be turned on first so that the cooling water can be cooled down. At initial commissioning, the cooling water flow should be checked.
- Add water to the system as the absorbent (see Chapter 3.10.2).
- Turn on pumps P1 and P2. Water is sprayed into the absorption column. Set the water flow rate to around 200ltr/h using valve V12.
- If necessary, top up the fresh water with the push button (Fig. 3.4 , position 6).
- Turn off pumps P1 and P2 again.
- Purge the flexible hoses to the differential pressure transducer of air bubbles so that the level control functions.
- Turn on pumps P1 and P2 again.

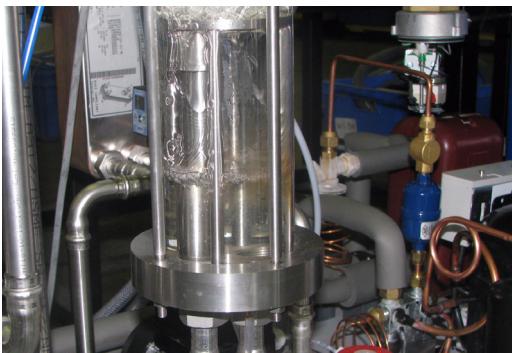


Fig. 3.34 Liquid level at base of K1



Fig. 3.35 "Stripping" in desorber



Fig. 3.36 Spray cone in desorber

- Observe the liquid level control. The liquid level must settle to around 5-10 cm above the base of the column.
- Open the valve V10
- Turn on the compressor and adjust the air flow rate to around 5ltr/min.
- Set the vacuum in the regeneration column K2. To do this, close the valve V19, open the control valve V20 and set the vacuum to around 0,5bar relative vacuum. If the pressure falls below this, slightly open the control valve V21 and let "stripping" air into the regeneration column from below.
- The noise level can be reduced by increasing the back pressure for the solenoid control valve V16. To do this, close the control valve V17 until the spray cone in the regeneration column is reduced to a minimum.
- During experiments with heater operation, the heater can now be turned on using the switch (Fig. 3.4, position 8). The current temperature value is displayed on the temperature controller in the switch cabinet. The setpoint can be adjusted up and down on the controller by pressing the arrow keys.
- Finally, the CO<sub>2</sub> air flow is added to the mixture. This is done by setting the CO<sub>2</sub> gas volumetric flow rate to 5ltr/min with the control valve V1, with the secondary pressure on the cylinder pressure reducer already set.

### 3.11.2 Turning off the system

- Shut down the CO<sub>2</sub> gas volumetric flow
- Turn off the heater
- Turn off the cooler.
- Disconnect the vacuum water jet pump and simultaneously open the valve V19 to equalise the pressure.
- Turn off the compressor
- Turn off both pumps P1 and P2.

## 4

**Fundamental principles**

The basic principles set out in the following make no claim to completeness. For further theoretical explanations, refer to the specialist literature.

Absorption refers to the incorporation and solution of gases and vapours in liquids.

Absorption enables gas and vapour mixtures to be partially separated. For partial separation of a gas component out of a mixture by selective absorption using a liquid solvent (scrubbing agent, absorbent), depending on the type of solution process or the type of gas/solvent absorption system, we differentiate between a physical solution (physical gas scrubbing, physisorption) or a loose chemical bond (chemical gas scrubbing, chemisorption) of the gas component and the solvent.

In physical absorption the scrubbing agent is a pure liquid and the bond between the gas and liquid is the result of inter-molecular interactions (e.g. van der Waal's forces).

In chemical absorption, a substance is often dissolved in the scrubbing agent, which forms a chemical bond with the gas component to be absorbed.

The solvent loaded with gas that is obtained in absorption is frequently regenerated in a reverse process to absorption so that it can be used again for absorption. This process is referred to as desorption.

In the absorber, the determine becomes loaded with gas. In the downstream desorber, the dissolved gas is expelled from the scrubbing agent.

The regenerated scrubbing agent is cooled and fed back into the circuit to the absorber.

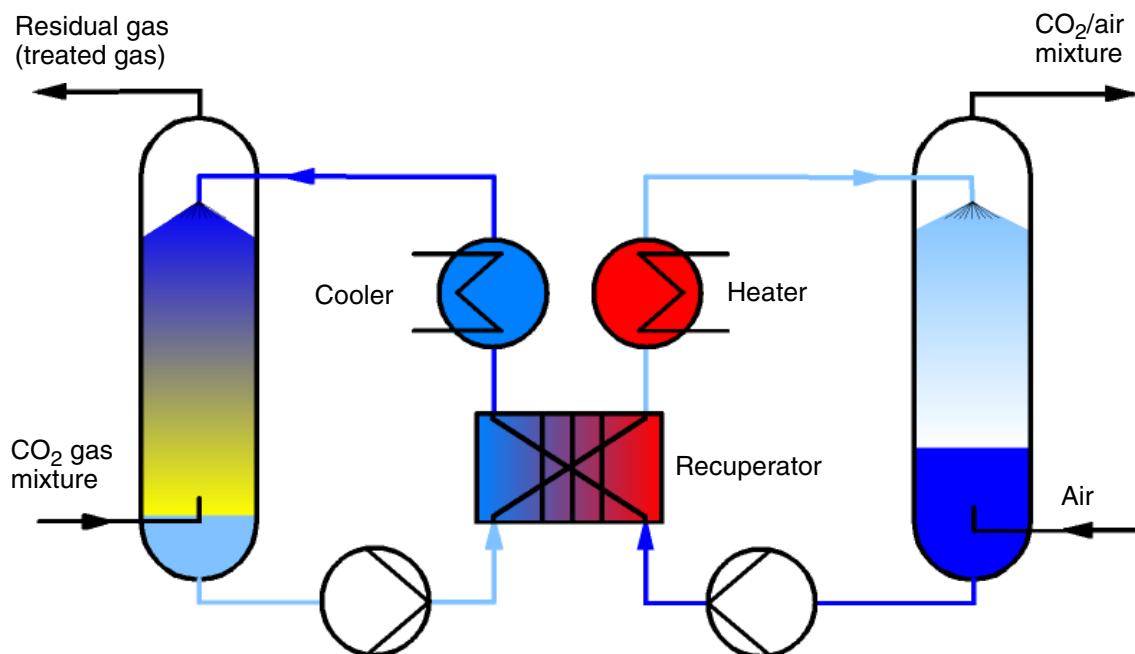


Fig. 4.1 Simplified diagram of an absorption/desorption process

## 4.1 Fundamentals of thermodynamics

When the absorbed gas and the scrubbing agent from physical absorption form an ideal mixture, Raoult's Law applies for the dissolved gas.

$$p_i = x_i \cdot p_{0,i}(T) \quad (4.1)$$

If the solution does not demonstrate ideal behaviour due to different interactions between the molecules, e.g. because of weak chemical bonding, the variation from the ideal behaviour is represented by the activity coefficients  $\gamma_i$ .

$$p_i = \gamma_i \cdot x_i \cdot p_{0,i}(T) \quad (4.2)$$

If we assume ideal behaviour in the gas phase:

$$p_i = y_i \cdot p \quad (4.3)$$

Consequently:

$$y_i = \frac{\gamma_i \cdot p_{0,i}(T)}{p} \cdot x_i \quad (4.4)$$

The activity coefficient  $\gamma_i$  depends on the temperature and the concentration of the dissolved substance.

Absorption processes often occur at operating temperatures that are higher than the critical temperature of the gas component. The gas component is then dissolved as a gas and does not condense during the absorption process. The liquid states no longer exists with absorption conditions, the saturated vapour pressure  $p_{0,i}(T)$  cannot be specified and the phase equilibrium cannot be described using the extended Raoult's Law (4.4).

However, to obtain a method of describing the solubility of the gas, we refer to the ideally diluted solution, in which the gas component is dissolved in a large surplus of solvent.

The gas solubility of the gas component  $i$  in the solvent is then given by Henry's Law for ideal diluted solutions.

$$p_i = H_{i,px} \cdot x_i \quad \text{where } \vartheta = \text{const.} \quad (4.5)$$

$$y_i = \frac{H_{i,px}}{p} \cdot x_i \quad (4.6)$$

#### 4.1.1 Henry constant

The Henry constant  $H_i$  - often referred to as the Henry coefficient – is named after William Henry and is a measure of the gas absorption capacity of a water phase / solution. The volatile substance is in solution equilibrium with the liquid phase.

As several versions of Henry's Law exist, it is essential that the Henry constant used always corresponds to the formula being used.

Selected versions of Henry's Law with constants (gas in water at 298 K)				
Equation	$H_{i,cp} = \frac{c_{aq}}{p_{gas}}$	$H_{i,pc} = \frac{p_{gas}}{c_{aq}}$	$H_{i,px} = \frac{p_{gas}}{x_{aq}}$	$H_{i,cc} = \frac{c_{aq}}{c_{gas}}$
Units	$\frac{\text{mol}_{\text{gas}}}{\text{litr} \cdot \text{atm}}$	$\frac{\text{litr} \cdot \text{atm}}{\text{mol}_{\text{gas}}}$	$\frac{\text{atm} \cdot \text{mol}_{\text{aq}}}{\text{mol}_{\text{gas}}}$	1
CO <sub>2</sub>	$3,4 \cdot 10^{-2}$	29,41	$0,163 \cdot 10^4$	0,8317

#### 4.1.2 Temperature dependency of the Henry constant

The Henry constant is not constant when there are temperature changes, which is why it is sometimes referred to as the Henry coefficient. There are several methods of setting out this dependency using formulae, one possibility is:

$$H_{i,cp} = H_{i,cp,T_{25}} \cdot e^{(C \cdot \left(\frac{1}{T} - \frac{1}{T_{25}}\right))} \quad (4.7)$$

where

$T_{25}$ : 298 K (standard temperature)

$C$ : 2400 K (constant for CO<sub>2</sub>)

#### 4.1.3 Conversion of Henry constant $H_{i,cp}$ into $H_{i,p_x}$

Starting from the equation with Henry constant taking account of temperature

$$H_{i,cp} = \frac{c_{aq}}{p_{gas}} \quad (4.8)$$

Replacing molar concentration  $c_{aq}$

$$c_{aq} = \frac{n_{CO_2}}{V_{aq}} \quad (4.9)$$

$$p_{gas} = \frac{n_{CO_2}}{V_{aq}} \cdot \frac{1}{H_{i,cp}} \text{ (rearranged)} \quad (4.10)$$

Replacing water volume  $V_{aq}$

$$V_{aq} = \frac{m_{aq}}{\rho_{aq}} \quad (4.11)$$

gives

$$p_{gas} = \frac{n_{CO_2}}{\frac{m_{aq}}{\rho_{aq}}} \cdot \frac{1}{H_{i,cp}} \quad (4.12)$$

Replacing water mass  $m_{aq}$

$$m_{aq} = M_{aq} \cdot n_{aq} \quad (4.13)$$

$$p_{gas} = \frac{n_{CO_2}}{M_{aq} \cdot n_{aq}} \cdot \frac{1}{H_{i,cp}} \cdot \rho_{aq} \quad (4.14)$$

rearranged

$$p_{gas} = \frac{n_{CO_2}}{1} \cdot \frac{\rho_{aq}}{M_{aq} \cdot n_{aq}} \cdot \frac{1}{H_{i,cp}} \quad (4.15)$$

Inserting loading  $X_{CO_2}$

$$X_{CO_2} = \frac{n_{CO_2}}{n_{aq}} \quad (4.16)$$

$$p_{gas} = X_{CO_2} \cdot \frac{\rho_{aq}}{M_{aq} \cdot H_{i,cp}} \quad (4.17)$$

rearranged

$$H_{i,px} = \frac{p_{gas}}{X_{CO_2}} = \frac{\rho_{aq}}{M_{aq} \cdot H_{i,cp}} \quad (4.18)$$

For this special case:

$$x \approx X \quad (4.19)$$

Because

$$X = \frac{n_{CO_2}}{n_{aq}} = \frac{0,034 \frac{\text{mol}_{CO_2}}{\text{litr}}}{55,5 \frac{\text{mol}_{aq}}{\text{litr}}} = 0,00061 \quad (4.20)$$

and

$$x = \frac{X}{1+X} = \frac{0,00061}{1+0,00061} = 0,00061 \quad (4.21)$$

we can also state:

$$H_{i,px} = \frac{p_{gas}}{X_{CO_2}} = \frac{\rho_{aq}}{M_{aq} \cdot H_{i,cp}} \quad (4.22)$$

#### 4.1.4 Representation in diagrams

The following diagrams are used to represent the phase equilibrium for absorption graphically:

##### Composition diagram $y_i(x_i)$

The composition diagram represents the linear physical property of the substances as a straight line using the equilibrium line.

where

$y_i$  = Molar fraction of gas

The equation for the equilibrium line is:

$$y_i = \frac{H_{i,px}}{p} \cdot x_i \quad (4.23)$$

##### Load diagram $Y_i(X_i)$

The load diagram represents the equilibrium line as a curve. The advantage of this is that the line of balance can be represented as a straight line.

The following definitions apply:

$$Y_i = \frac{\dot{N}_i}{\dot{N}_G} = \frac{\text{Molar flow of gas component to be absorbed } i}{\text{Molar flow of inert residual gas mixture (air)}} \quad (4.24)$$

$$X_i = \frac{\dot{N}_i}{\dot{N}_L} = \frac{\text{Molar flow of gas component to be absorbed } i}{\text{Molar flow of pure solvent (water)}} \quad (4.25)$$

Or, more briefly:

$Y_i$ : Loading in the gaseous phase, gas loading

$X_i$ : Loading in the liquid phase, liquid loading

To convert the molar fractions into the molar loads:

$$X_i = \frac{x_i}{1-x_i} \text{ and} \quad (4.26)$$

$$Y_i = \frac{y_i}{1-y_i} \quad (4.27)$$

To convert the molar loads into the molar fractions:

$$x_i = \frac{X_i}{1+X_i} \text{ and} \quad (4.28)$$

$$y_i = \frac{Y_i}{1+Y_i} \quad (4.29)$$

#### 4.1.5 Equilibrium line in the load diagram

Inserting Formula (4.28) and Formula (4.29) into Formula (4.23) gives us the equation for the equilibrium line according to Henry's Law in the load diagram.

$$Y_i = \frac{\frac{H_{i,px}}{p} \cdot X_i}{1 + \left(1 - \frac{H_{i,px}}{p}\right) \cdot X_i} \quad \text{or} \quad (4.30)$$

$$X_i = \frac{Y_i \cdot \frac{p}{H_{i,px}}}{1 + \left(1 - \frac{p}{H_{i,px}}\right) \cdot Y_i} \quad (4.31)$$

The temperature pressure dependency of the absorption equilibrium follows from Formula (4.4) and Formula (4.5).

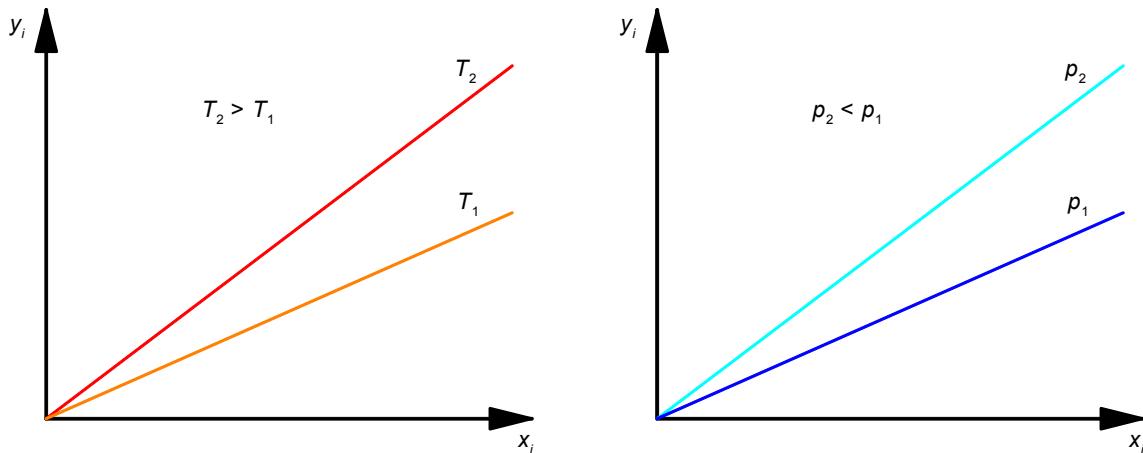


Fig. 4.2 Temperature and pressure dependency of absorption in the composition diagram

The solubility of a gas in the scrubbing agent increases as the temperature falls and the pressure increases.

#### 4.1.6 Line of balance in the load diagram

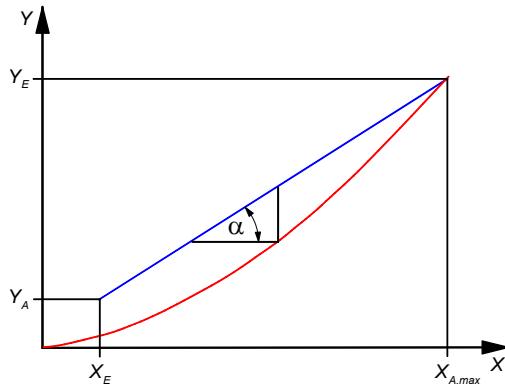


Fig. 4.3 Gradient of balance lines in the load diagram

From the quantity balance around the head of the head of the column

$$0 = \dot{L} \cdot X_E + \dot{G} \cdot Y - \dot{L} \cdot X - \dot{G} \cdot Y_A \quad (4.32)$$

and the assumption that the gas is in phase equilibrium with the liquid at every height in the column, rearranging gives the line of balance. (See figure on next page)

$$Y = \frac{\dot{L}}{\dot{G}} \cdot X - \frac{\dot{L}}{\dot{G}} \cdot X_E + Y_A \quad (4.33)$$

Assuming that the liquid loading at the inlet is  $X_E = 0$  the line of balance equation can be simplified to

$$Y = \frac{\dot{L}}{\dot{G}} \cdot X + Y_A \quad \text{Equation for counter current} \quad (4.34)$$

Rearranging gives us the equation for calculating the liquid loading depending on the change in gas loading.

$$X_A = \Delta Y \cdot \frac{\dot{G}}{\dot{L}} \quad (4.35)$$

For the constant molar flows  $\dot{L}$  and  $\dot{G}$  the line of balance is always a straight line in the load diagram. Its gradient is

$$\tan \alpha = \frac{\dot{L}}{\dot{G}} = \frac{\Delta y}{\Delta x} \quad (4.36)$$

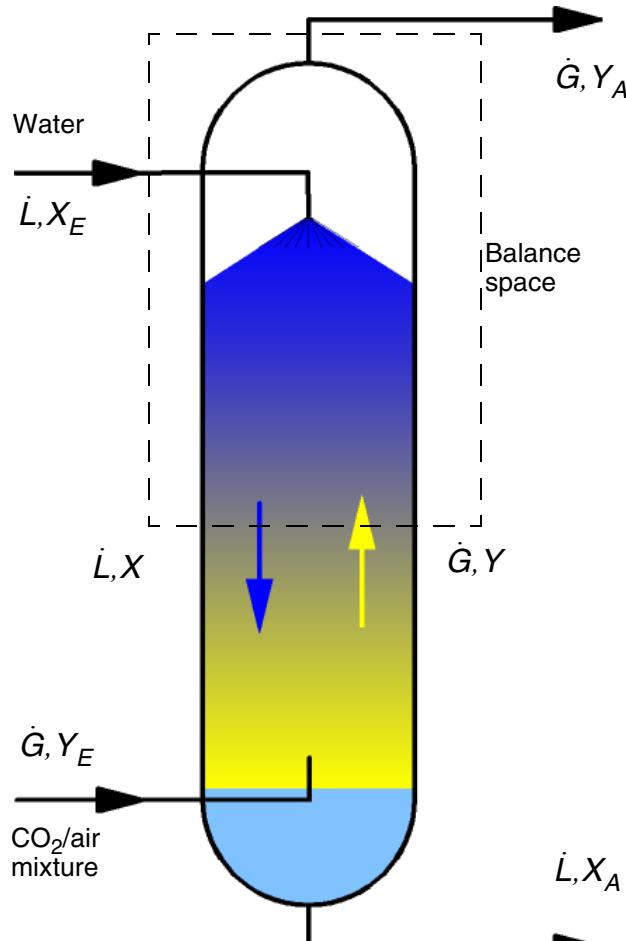


Fig. 4.4 Absorption column K1 operated with water and  $\text{CO}_2/\text{air}$  mixture

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As with the absorption column, a balance can be established for the desorption column. As before, a straight line is obtained as the line of balance, with a slope determined by the ratio of the carrier flows.

For desorption, the line of balance is below the equilibrium line. Fig. 4.5 shows the entire process schematically as a circuit in the load diagram. The direction arrows relate to the water circuit. Only one equilibrium line is plotted in this diagram.

If absorption and desorption take place under different conditions (pressure, temperature), different equilibrium lines need to be taken into account.

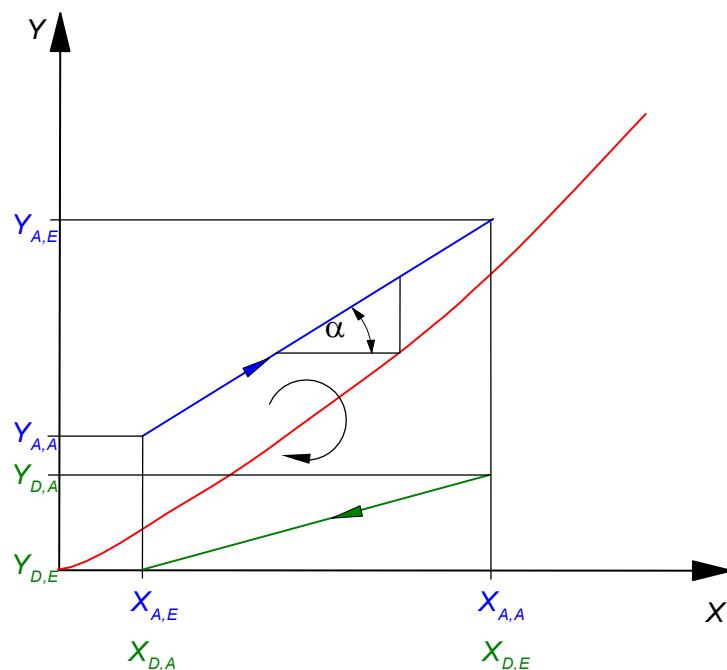


Fig. 4.5 Load diagram showing line of balance for absorption (blue) and line of balance for desorption (green) in a cyclic process with a common equilibrium line (red).

## 5

**Experiments**

The selection of experiments makes no claims of completeness but is intended to be used as a stimulus for your own experiments.

The results shown are intended as a guide only. Depending on the construction of the individual components, experimental skills and environmental conditions, deviations may occur in the experiments. Nevertheless, the laws can be clearly demonstrated.

For experiments to determine the composition of the gas samples, the manual gas analysis unit must be prepared as described in the instructions.

**5.1 Determination of pressure losses in the column K1****5.1.1 Purpose of the experiment**

Measurement of pressure losses in the column K1

**5.1.2 Preparation**

Set up the trainer, see Chapter 3.10.1

Set up all connections and fill the system, see Chapter 3.10.2

### 5.1.3 Performing the experiment

- Start up the system, see Chapter 3.11.1
- Set the operating point
- Turn on the cooling unit

To cool the system down more quickly, the cooler should be turned on around 1/2h beforehand.

- Heater turned off
- Set the flow rates

Water volumetric flow rate: 300ltr/h

Air volumetric flow rate: 5ltr/min

Vacuum in K2: 0,5bar rel.

Finally, set the CO<sub>2</sub> gas volumetric flow rate.

CO<sub>2</sub> gas volumetric flow rate: 1,2ltr/min

(As an alternative, 6.2 ltr/min of air has been set as the total gas flow.)

---

#### NOTICE

The CO<sub>2</sub> supply is not needed for the differential pressure measurement because the bulk of the gas flow is generated by the compressor.

---

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#### NOTICE

During the experiment, there may not be any liquid in the connecting hoses to the U-tubes. Otherwise, this causes incorrect measurements.

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### 5.1.4 Measurement / results of experiment

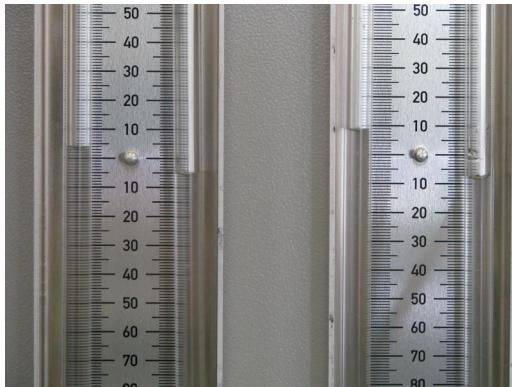


Fig. 5.1 Example reading  
Left: 9 mmH<sub>2</sub>O  
Right: 16 mmH<sub>2</sub>O

With the system in stationary mode, the differential pressures are measured using the U-tube manometer.

- Open the ball valve V8
- Open the ball valves V9 and V25
- Read off the measured values
- At the end of the measurement, close the ball valves V8, V9 and V25 to prevent water getting in when changing the operating points.

	PD1	PD2
	mmH <sub>2</sub> O	mmH <sub>2</sub> O
<b>Measurement 1</b>		
<b>300ltr/h water, 0,35 m<sup>3</sup>/h air</b>	9	16
<b>Measurement 2</b>		
<b>300 ltr/h water, 2,4 m<sup>3</sup>/h air (max)</b>	40	64

Tab. 5.1 Readings at 300 ltr/h water / 6.2 ltr/min air and at 300 ltr/h water / 2.4 m<sup>3</sup>/h air

## 5.2 Representation of the absorption process in a load diagram

### 5.2.1 Purpose of the experiment

Determination of the gas concentrations before and after the absorption column K1 in the circuit operation mode. Determination of the loads in the gas and water flow. Representation of the values in a load diagram with equilibrium line and line of balance.

### 5.2.2 Preparation

Set up the trainer, see Chapter 3.10.1

Set up all connections and fill the system, see Chapter 3.10.2

### 5.2.3 Performing the experiment

- Start up the system, see Chapter 3.11.1
- Set the operating point
- Turn on the cooling unit

To cool the system down more quickly, the cooler should be turned on around 1/2h beforehand.

- Heater: Off
- Set the flow rates

Water flow rate 300ltr/h

Air volumetric flow rate: 5ltr/min ( $0,3m^3/h$ )

Vacuum in K2: -0,2 bar rel.

Finally, set the CO<sub>2</sub> gas volumetric flow rate.

CO<sub>2</sub> gas volumetric flow rate: 1,2ltr/min  
at a pressure of +0,8bar abs.

#### 5.2.4 Experiment results

In stationary operation, the following measured values are obtained:

Ambient conditions: 20,3°C, 1,013bar

Air: 5ltr/min (at 20,3°C and 1,013bar)

CO<sub>2</sub>: 1,2ltr/min (at 20,3°C and 1,013bar)

Water: 300ltr/h (at 12°C)

Measurement of CO<sub>2</sub> concentration at

Column inlet (S1): 29,6Vol%

Column outlet (S3): 22,7Vol%

Before the first measurement, you should ensure that a gas cycle took place in the column. The measured values (S1) and (S3) are mean values recorded over a period of 30 minutes at 5 minute intervals.

	Series of measurements No.1 - Values in Vol%							Mean values
	1	2	3	4	5	6	7	$\bar{X}$
Measuring point	Time							
	10:50	10:55	11:00	11:05	11:10	11:15	11:20	
S1	30,2	30,1	30,0	29,6	29,6	29,4	28,2	29,6
S2	22,1	21	25,2	18	19	22,5	13	26,6
S3	11,7	10,6	13,9	8,7	11,1	14,1	11	22,7

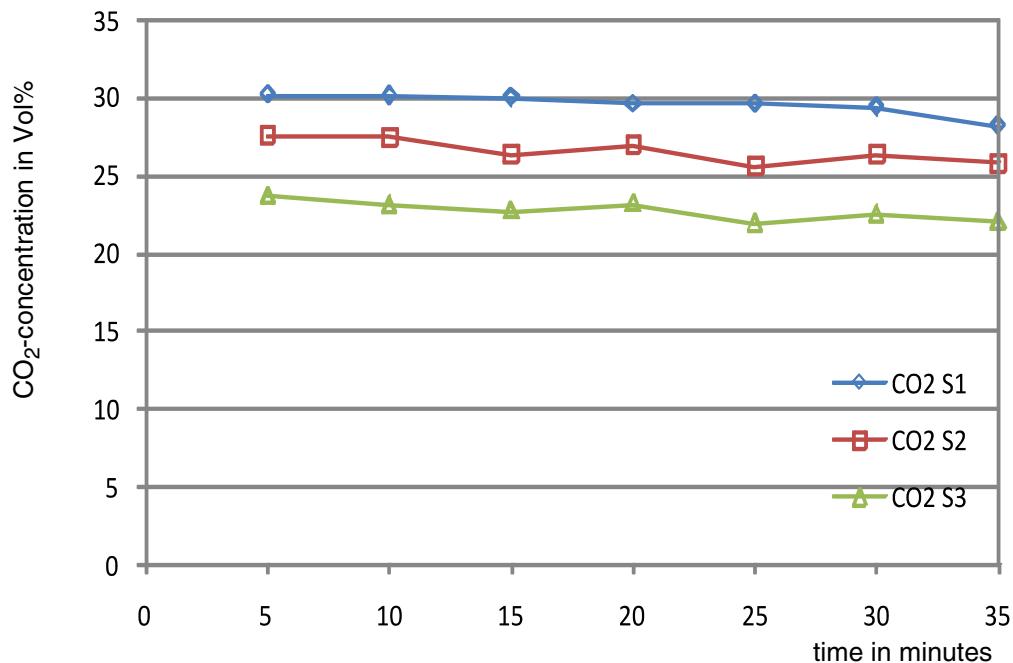


Fig. 5.2 CO<sub>2</sub> concentration over time. At time 0 the gas flow was connected in stationary mode

Below, the loading of the air volumetric flow rate is calculated using the CO<sub>2</sub> gas concentrations at the absorption column inlet and outlet.

**Calculation of air volumetric flow rate under normal conditions (standard condition 0°C, 1,013bar)**

According to the thermal state equation for ideal gases

$$\frac{p_0 \cdot V_0}{T_0} = \frac{p_1 \cdot V_1}{T_1} = R_m \text{ where } R_m = M \cdot R \quad (5.1)$$

we can see that:

$$\dot{V}_{air, St. Cond.} = \dot{V}_{air, Exp.} \cdot \left( \frac{p_{Exp.} \cdot T_{St. Cond.}}{p_{St. Cond.} \cdot T_{Exp.}} \right)$$

$$\dot{V}_{air, St. Cond.} = 5 \frac{\text{ltr}}{\text{min}} \cdot \left( \frac{1,013 \text{ bar} \cdot 273 \text{ K}}{1,013 \text{ bar} \cdot 293,3 \text{ K}} \right)$$

$$\dot{V}_{air, St. Cond.} = 4,65 \frac{\text{ltr}}{\text{min}}$$

### Calculation of molar flow

$$\dot{N}_{air} = \frac{\dot{V}_{air, St. Cond.}}{V_m} \quad (5.2)$$

where

$$V_m = \text{Molar volume} = 22,4 \frac{\text{ltr}}{\text{mol}}$$

$$\dot{N}_{air} = \frac{4,65 \frac{\text{ltr}}{\text{min}}}{22,4 \frac{\text{ltr}}{\text{mol}}}$$

$$\dot{N}_{air} = 0,208 \frac{\text{mol}}{\text{min}}$$

### Calculation of water molar flow

$$\dot{N}_{aq} = \frac{\dot{V}_{aq} \cdot \rho_{aq}}{M_{aq}} \quad (5.3)$$

where

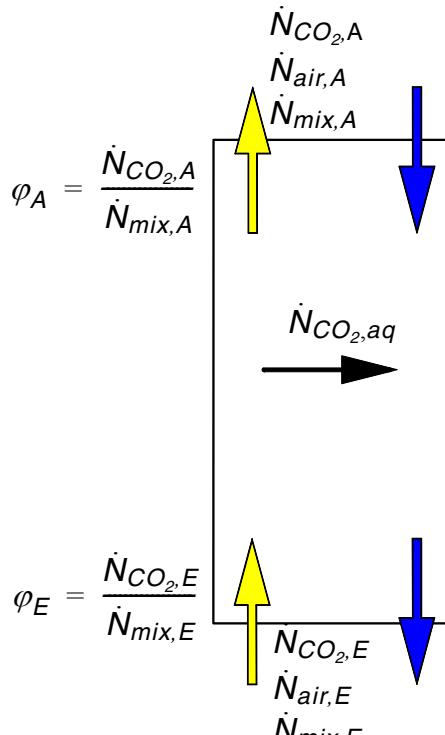
$$\rho_{aq} = 999,869 \frac{\text{g}}{\text{ltr}} \text{ at } 0^\circ\text{C}$$

$$\dot{N}_{aq} = \frac{300 \frac{\text{ltr}}{\text{h}} \cdot 999,869 \frac{\text{g}}{\text{ltr}}}{18,02 \frac{\text{g}}{\text{mol}}}$$

$$\dot{N}_{aq} = 277,43 \frac{\text{mol}}{\text{min}}$$

### 5.2.4.1 Determination of loading

The gas loading at the inlet is defined as



$$Y_E = \frac{\dot{N}_{CO_2,E}}{\dot{N}_{air}} \quad (5.4)$$

The gas loading at the outlet is defined as

$$Y_A = \frac{\dot{N}_{CO_2,A}}{\dot{N}_{air}} \quad (5.5)$$

Here,  $\dot{N}_{air}$  is the carrier gas flow (5 ltr/min), measured directly using FI002.

In order to determine the 3 molar flows  $\dot{N}_{CO_2,E}$ ,  $\dot{N}_{CO_2,A}$  and  $\dot{N}_{CO_2,aq}$  at least 3 equations are necessary.

$$\varphi_E = \frac{\dot{N}_{CO_2,E}}{\dot{N}_{mix,E}} \text{ where } \varphi: \text{Concentration in Vol\%} \quad (5.6)$$

$$\dot{N}_{CO_2,aq} = \dot{N}_{CO_2,E} - \dot{N}_{CO_2,A} \quad (5.7)$$

$$\dot{N}_{mix,E} = \dot{N}_{air} + \dot{N}_{CO_2,E} \quad (5.8)$$

with  $\dot{N}_{air} = \dot{N}_{air,E} = \dot{N}_{air,A}$

Inserting Formula (5.8) into Formula (5.6) and then rearranging gives the expression for the CO<sub>2</sub> molar flow at the column inlet:

$$\dot{N}_{CO_2,E} = \frac{\frac{\varphi_E}{100 \text{ Vol\%}}}{1 - \frac{\varphi_E}{100 \text{ Vol\%}}} \cdot \dot{N}_{air} \quad (5.9)$$

Fig. 5.3 Molar flows in absorber

The CO<sub>2</sub> molar flow at the column outlet is obtained in the same way:

$$\dot{N}_{CO_2,A} = \frac{\frac{\varphi_A}{100 \text{ Vol\%}}}{1 - \frac{\varphi_A}{100 \text{ Vol\%}}} \cdot \dot{N}_{air} \quad (5.10)$$

For the experiment, this means:

CO<sub>2</sub> molar flow at inlet

$$\dot{N}_{CO_2,E} = \frac{\frac{29,6 \text{ Vol\%}}{100 \text{ Vol\%}}}{1 - \frac{29,6 \text{ Vol\%}}{100 \text{ Vol\%}}} \cdot 0,208 \frac{\text{mol}}{\text{min}} = 0,0875 \frac{\text{mol}}{\text{min}}$$

CO<sub>2</sub> loading at inlet

$$Y_E = \frac{0,0875 \frac{\text{mol}}{\text{min}}}{0,208 \frac{\text{mol}}{\text{min}}} = 0,420$$

CO<sub>2</sub> molar flow at outlet

$$\dot{N}_{CO_2,A} = \frac{\frac{22,7 \text{ Vol\%}}{100 \text{ Vol\%}}}{1 - \frac{22,7 \text{ Vol\%}}{100 \text{ Vol\%}}} \cdot 0,208 \frac{\text{mol}}{\text{min}} = 0,0611 \frac{\text{mol}}{\text{min}}$$

CO<sub>2</sub> loading at outlet

$$Y_A = \frac{0,0611 \frac{\text{mol}}{\text{min}}}{0,208 \frac{\text{mol}}{\text{min}}} = 0,293$$

The CO<sub>2</sub> loading difference in the gas flow between the inlet and the outlet

$$\Delta Y = Y_E - Y_A \quad (5.11)$$

$$\Delta Y = 0,127$$

The above loading difference  $\Delta Y$  in the gas flow must have exited the column with the water flow.

In order to be able to plot the position of the line of balance in the load diagram, the following general conditions must be met (see Fig. 5.4):

- The upper limit for the end point of the straight line is  $Y_E$ .
- The lower limit for the end point of the straight line is  $Y_A$ .
- The right-hand limit for the possible straight line end point  $X_A$  is given by the intersection of the horizontal through  $Y_E$  and the equilibrium line.
- The left-hand limit for the possible straight line end point  $X_E$  is given by the intersection of the horizontal through  $Y_A$  and the load  $X=0$ .
- The slope of the line is given by:

$$\tan \alpha = \frac{\dot{L}}{\dot{G}} = \frac{\Delta Y}{\Delta X}$$

In order to be able to plot the slope of the line, the associated  $\Delta X$  is calculated for the  $\Delta Y$ .

$$\Delta X = \Delta Y \cdot \frac{\dot{G}}{\dot{L}} = 0,127 \cdot \frac{0,208 \cdot \frac{\text{mol}}{\text{min}}}{277,43 \cdot \frac{\text{mol}}{\text{min}}} = 0,00009522 \quad (5.12)$$

with  $\dot{G} = \dot{N}_{air}$  and  $\dot{L} = \dot{N}_{aq}$

Complying with these conditions results in the area plotted in Fig. 5.4 for the possible positions of the lines of balance.

Assuming that the water is almost totally free of load when it enters the column, Formula (5.12) states that the loading of the water at the outlet is:

$$X_A = 0,00009522$$

Thus, with the above assumption the 2 end points of the line of balance for this experiment are:

$$P1(X_A / Y_E) \text{ and } P2(X_E / Y_A)$$

$$P1(0,00009522 / 0,420) \text{ and } P2(0 / 0,293)$$

If the inlet load of the water is greater than 0 and the assumption  $X_E = 0$  does not apply, the line of balance will move to the right parallel to the X-axis in the load diagram (Fig. 5.4).

The slope gives a change in the water loading of  $\Delta X = 0,00009522$ .

### 5.2.4.2 Determination of the equilibrium line for CO<sub>2</sub> and water at 12°C

Henry constant at 298K (see Chapter 4.1.1)

$$H_{i, cp, T_0} = 3,4 \cdot 10^{-2} \frac{\text{mol}_{\text{CO}_2}}{\text{litr} \cdot \text{atm}}$$

Henry constant at 12°C (see Chapter 4.1.2)

$$H_{i, cp} = H_{i, cp, T_0} \cdot e^{(c \cdot (\frac{1}{T} - \frac{1}{T_0}))}$$

$$H_{i, cp, T_{12}} = 3,4 \cdot 10^{-2} \frac{\text{mol}_{\text{CO}_2}}{\text{litr atm}} \cdot e^{(2400 \text{ K} \cdot (\frac{1}{288 \text{ K}} - \frac{1}{298 \text{ K}}))}$$

$$H_{i, cp, T_{12}} = 0,04497 \frac{\text{mol}_{\text{CO}_2}}{\text{litr} \cdot \text{atm}}$$

Conversion of Henry constant (see Chapter 4.1.3)

$$H_{i, px} = \frac{\rho_{\text{gas}}}{x} = \frac{\rho_{\text{aq}}}{M_{\text{aq}} \cdot H_{i, cp}} \text{ where } \rho_{\text{aq}} \text{ at } 12^\circ\text{C}$$

$$H_{i, px, T_{12}} = \frac{0,999499 \frac{\text{kg}}{\text{litr}}}{0,018 \frac{\text{kg}}{\text{mol}_{\text{aq}}} \cdot 0,04497 \frac{\text{mol}_{\text{CO}_2}}{\text{litr} \cdot \text{atm}}}$$

$$H_{i, px, T_{12}} = 1235 \frac{\text{atm} \cdot \text{mol}_{\text{aq}}}{\text{mol}_{\text{CO}_2}}$$

Equilibrium line  $X_i = f(Y_i)$  with temperature corrected Henry constant (section 4.1.5)

$$X_i(Y_i) = \frac{Y_i \cdot \frac{p}{H_{i, px}}}{1 + \left(1 - \frac{p}{H_{i, px}}\right) \cdot Y_i}$$

### 5.2.4.3 Representation of results in load diagram

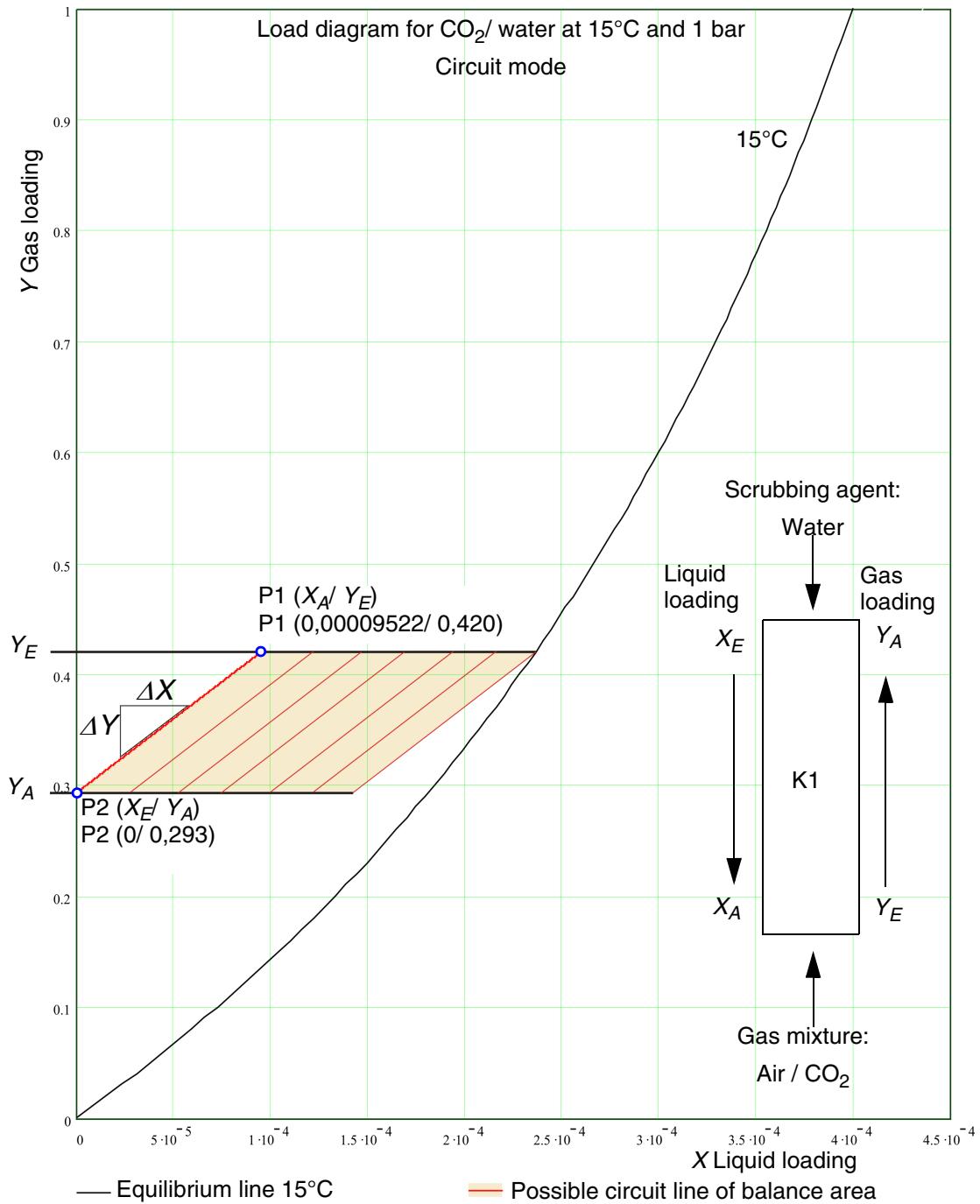


Fig. 5.4 Load diagram for  $\text{CO}_2$  / water with the equilibrium line and the possible area in which the circuit line of balance can be located.

In order to obtain a better estimate of the quality of the absorption column and the position of the line of balance without additional specialist measuring equipment for recording the water loading, a measurement was carried out with fresh water using the same carrier flows. As fresh water does not contain any significant proportion of  $\text{CO}_2$ , the inlet loading of fresh water is known to be  $X_E=0$ . This means that the fresh water line of balance can simply be plotted in the load diagram with the known slope (Formula (4.36)).

The fresh water was fed in at V15 and discharged after absorption at V24. Of the two pumps, only P2 was turned on (see Chapter 3.8.13).

If we look at the two lines of balance for circuit and fresh water mode in Fig. 5.5, we can see the following:

- With the same carrier flows, lines of balance have the same slope.
- The line of balance for the fresh water experiment is significantly longer than the line of balance for the circuit experiment with the same carrier flows. This finding suggests that the desorber in circuit mode cannot reach the liquid loading at the fresh water inlet ( $X_E$ ).
- The assumption for circuit mode - that the water loading at the inlet is zero ( $X_E=0$ ) - is not plausible.

- The circuit line of balance will probably lie to the right of the fresh water line of balance (yellow). To determine the exact position of the line of balance in the load diagram, we would need to establish the liquid loading at the inlet or outlet of the absorber using additional measuring equipment.

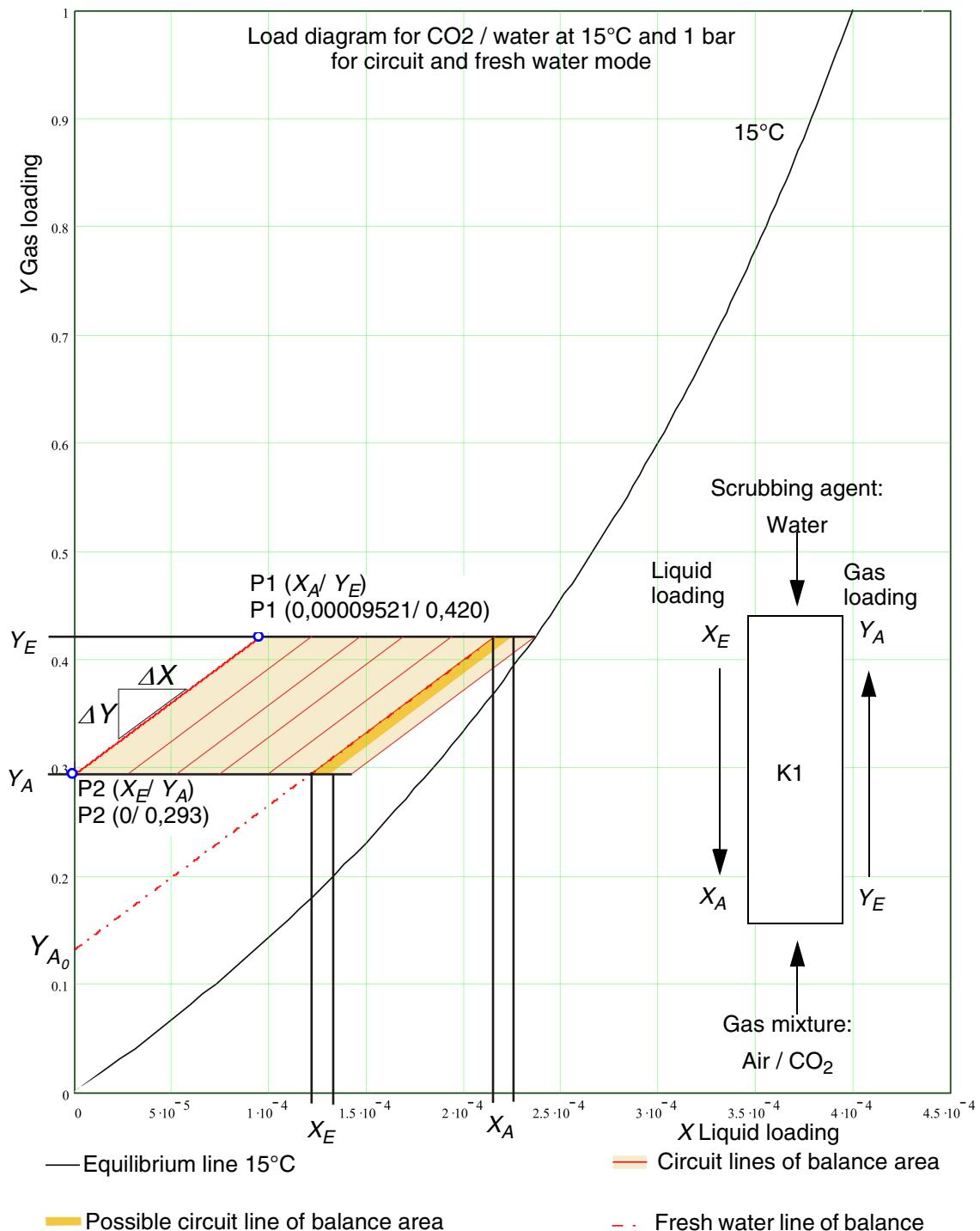


Fig. 5.5 Load diagram for CO<sub>2</sub> / water with the equilibrium line and the possible area in which the circuit line of balance and the fresh water line of balance can be located.

#### 5.2.4.4 Investigating the factors influencing loading - More measured results with changed parameters and corresponding fresh water measurements

The following table lists the measured results. Measurements were carried out in circuit mode with different gas concentrations, different material flows and different temperatures. For each measurement, only one parameter was changed each time (see yellow markings).

Experiment no.:	1	2	3	4
<b>Mode</b>	Circuit	Circuit	Circuit	Circuit
<b>Changed parameter</b>	-	$\dot{V}_{CO_2}$	$\dot{V}_{aq}$	Temperature
<b>Temperature Absorber in °C</b>	15	15	15	29
<b>Temperature Desorber in °C</b>	ca. 20	ca. 20	ca. 20	49
<b>Pressure Desorber in bar rel.</b>	0,2	0,2	0,2	0,2
<b>Pressure CO<sub>2</sub> in bar rel</b>	0,8	0,8	0,8	0,8
$\dot{V}_{CO_2}$ in ltr/min	1,2	0,4	1,2	1,2
$\dot{V}_{air}$ in ltr/min	5	5	5	5
$\dot{V}_{aq}$ in ltr/h	300	300	200	300
$\varphi_E$ in Vol%	29,6	15,5	29,4	29,8
$\varphi_A$ in Vol%	22,7	10,8	21,8	22,9
<b>Loading YE</b>	0,420	0,18343	0,41643	0,42409
<b>Loading YA</b>	0,293	0,12107	0,27844	0,29752
<b>Loading XA</b>	0,00009521	0,00004665	0,000155	0,00009468

Tab. 5.2 Experiment data - Circuit mode

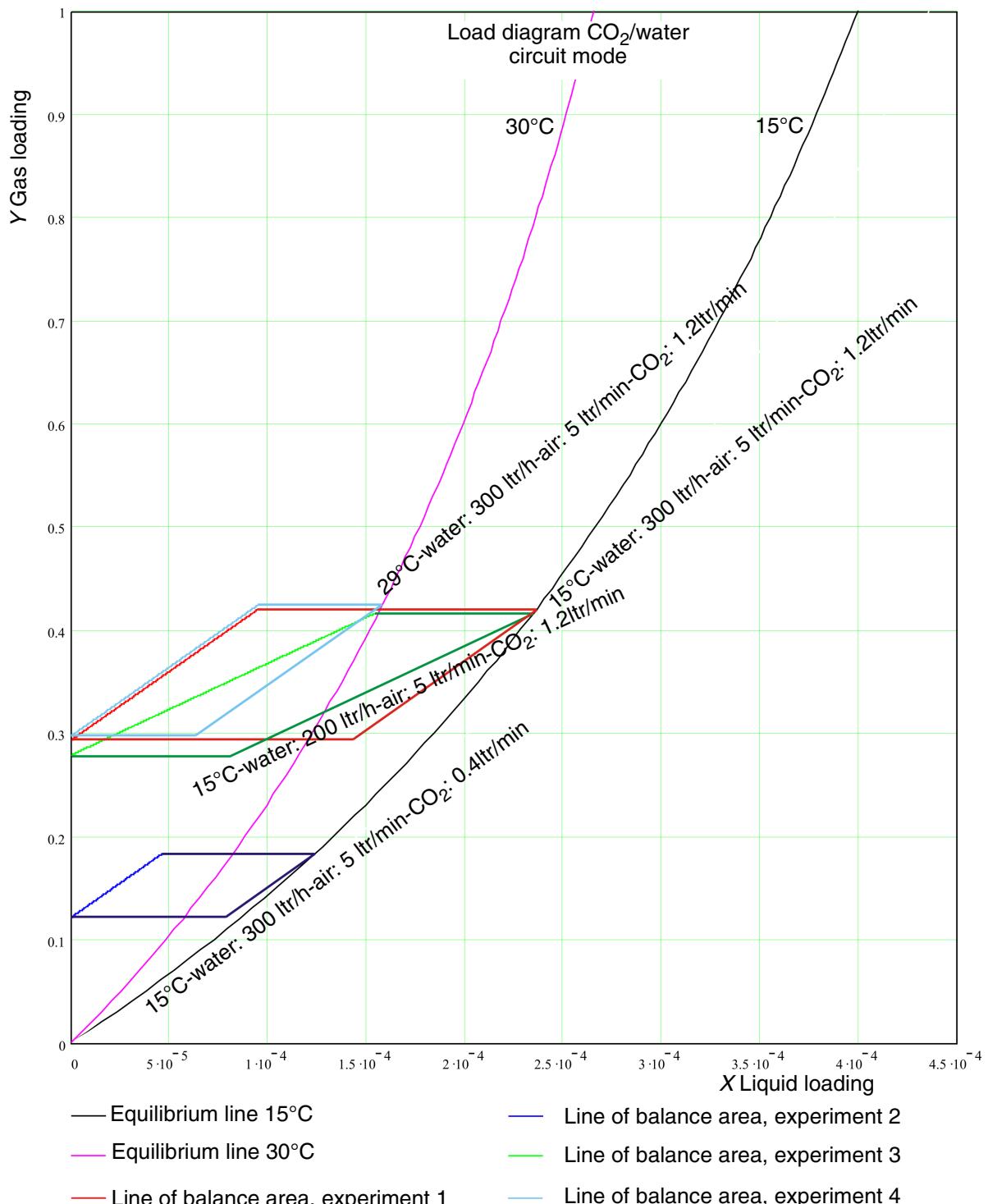


Fig. 5.6 Load diagram for  $\text{CO}_2/\text{water}$  in circuit mode with the areas for the circuit lines of balance and the equilibrium lines.

The following table lists the measured results as before, except that this time the absorber was operated with fresh water.

For fresh water mode, see Chapter 3.8.13.

Measurements were carried out with different gas concentrations and different material flows. For each measurement, only one parameter was changed each time (see yellow markings).

	5	6	7
Mode	Fresh water mode	Fresh water mode	Fresh water mode
Changed parameter	-	$\dot{V}_{CO_2}$	$\dot{V}_{aq}$
Temperature Absorber in °C	15	15	15
Temperature Desorber in °C	-	-	-
Pressure Desorber in bar rel.	-	-	-
Pressure CO <sub>2</sub> in bar rel	0,8	0,8	0,8
$\dot{V}_{CO_2}$ in ltr/min	1,2	0,4	1,2
$\dot{V}_{air}$ in ltr/min	5	5	5
$\dot{V}_{aq}$ in ltr/h	300	300	200
$\varphi_E$ in Vol%	29,1	13,7	29,5
$\varphi_A$ in Vol%	11,6	5,4	18,9
Loading YE	0,40944	0,15821	0,40190
Loading YA	0,13122	0,05753	0,23244
Loading XA	0,000208	0,00007531	0,000209

Tab. 5.3

Experiment data - Fresh water mode

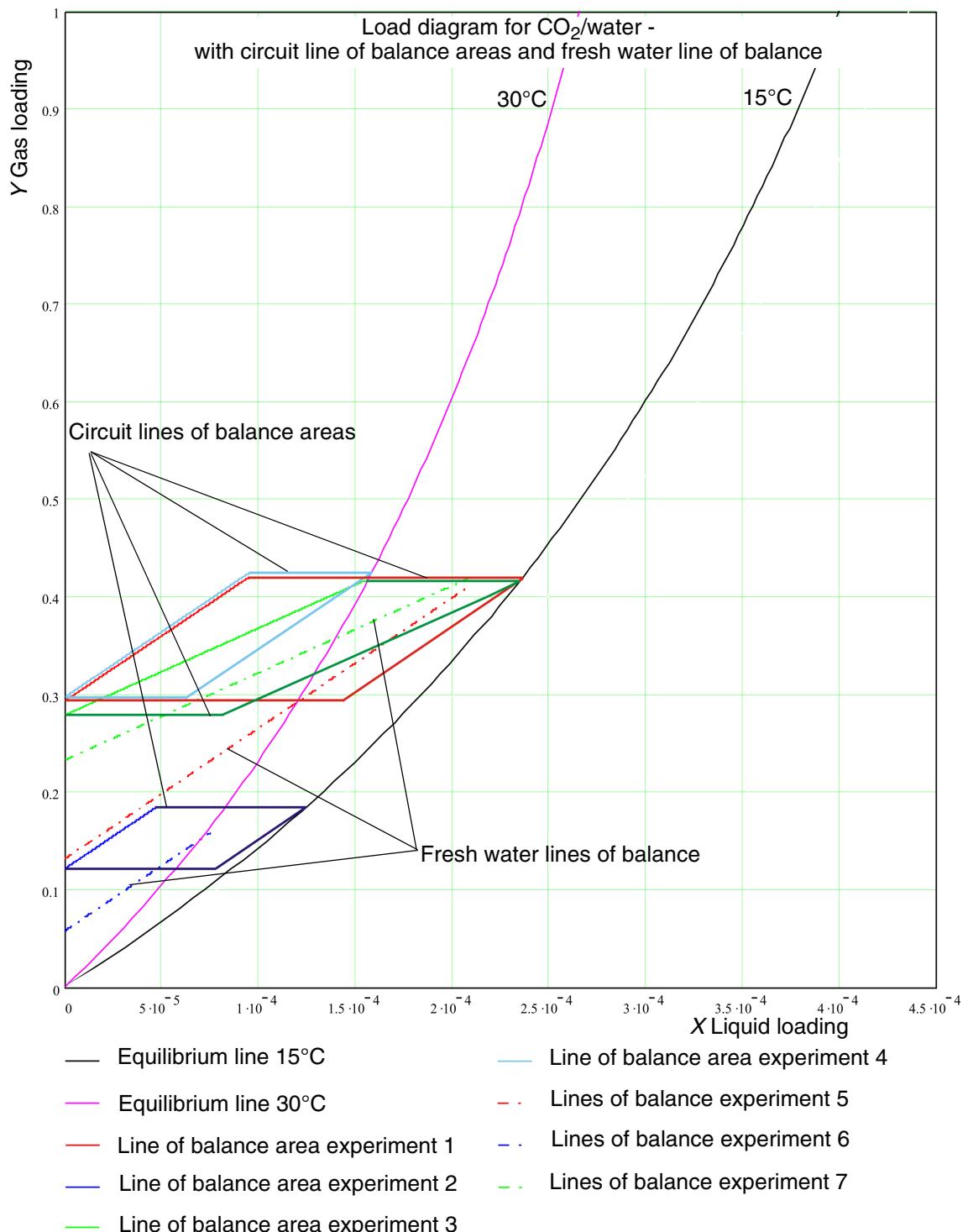


Fig. 5.7 Load diagram for CO<sub>2</sub>/water with equilibrium lines, areas for circuit lines of balance and associated fresh water lines of balance

**6 Appendix****6.1 Technical data****Dimensions**

Length x Width x Height	1750 x 790 x 2300 mm
Weight	approx. 295 kg

**Connections**

Power supply:	230 V/ 50 Hz
Rated power consumption:	3,4 kW
Optional alternatives, see rating plate	

**CO<sub>2</sub> gas cylinder with pressure reducer**

Inlet pressure (approx. 20°):	60 bar
Outlet pressure regulated, constant where possible	
Outlet pressure adjustment range:	1 to 2 bar abs.
Gas consumption for experiments:	5,4 ltr/min

**Column dimensions**

Material	Duran glass
External diameter	90 mm
Internal diameter	80 mm
Length of K1	750 mm
Filling level in K1	400 mm
Length of K2	750 mm
Packing:	Raschig rings $D = 10$ mm, $L = 10$ mm

**Compressor**

Manufacturer:	Becker
Model:	DT 4.8
Voltage:	230 V 50/ 60 Hz
Power output:	0,35/ 0,42 kW
Speed:	2800/ 3300 rpm
Maximum delivery volume:	8,0/ 9,5 m <sup>3</sup> /h
Maximum pressure:	1,0 bar rel.
Maximum delivery volume at 1 bar rel.	6,5/ 7,5 m <sup>3</sup> /h

**Pump P1 and P2**

Manufacturer:	Speck
Model:	NPY-2051
Voltage:	230 V 50/ 60 Hz
Power output:	0,25 kW
Maximum head:	47 m
Maximum flow rate:	17,5 ltr/min

**Pump P3**

Manufacturer:	Halm
Model:	BUP 20-1.5 U 150
Voltage:	230 V 50 Hz
Power output:	28/ 43/ 58 W
Maximum head:	1,4 m
Maximum flow rate:	1,8 m <sup>3</sup> /h

**Controller**

Manufacturer:	Jumo
Model:	Cetron 16

**Vacuum water jet pump P4**

Manufacturer:

Stübbe

Model:

SP 820 (DN 10)

Nozzle aperture:

2 mm

Minimum air intake quantity:

200 ltr/h air with 250 ltr/h propulsion water or  
2 bar propulsion water pressure

Maximum air intake quantity:

750 ltr/h air with 375 ltr/h propulsion water or  
6 bar propulsion water pressure**Safety valve for K1**

Tripping value:

0,8 bar rel.

**Rotameter FI001 (CO<sub>2</sub>)**

Measuring range:

0,4...5,4 ltr/min

Precision class:

1,6

Pressure:

1,013 bar abs.

Temperature:

20,0 °C

**Rotameter FI002 (air)**

Measuring range:

0,2...2,4 m<sup>3</sup>/h

Pressure:

1,013 bar abs.

Temperature:

20,0 °C

**Rotameter FI003 (water)**

Measuring range:

50...600 ltr/h

Temperature:

20 °C

**Manometer PI002**

Type:	Bourdon gauge
Measuring range:	0...2,5 bar rel.
Accuracy:	Class 1,6

**Manometer PI003**

Type:	Bourdon gauge
Measuring range:	-1,0...+0,6 bar rel.
Accuracy:	Class 1,6

**U-tube manometer**

Measuring range:	250...0...250 mmH <sub>2</sub> O
------------------	----------------------------------

**Thermometer TI001, TI002 and TI003**

Type	Bimetallic
Measuring range:	0...60/ 80 °C
Accuracy:	Class 1,0

**Temperature transducer TT002 and TT004**

Type	Pt100
Measuring range:	-50...400 °C
Accuracy:	Class B

**CO<sub>2</sub> measuring instrument**

Manufacturer:	Witt-Gasetechnik
Model:	Oxybaby M+O <sub>2</sub> /CO <sub>2</sub>
Measuring range:	0...100 Vol% CO <sub>2</sub>
Accuracy:	±2% FS at 20°C (±2% CO <sub>2</sub> )

## 6.2 Tables and diagrams

### 6.2.1 CO<sub>2</sub>/ water composition diagram for different temperatures

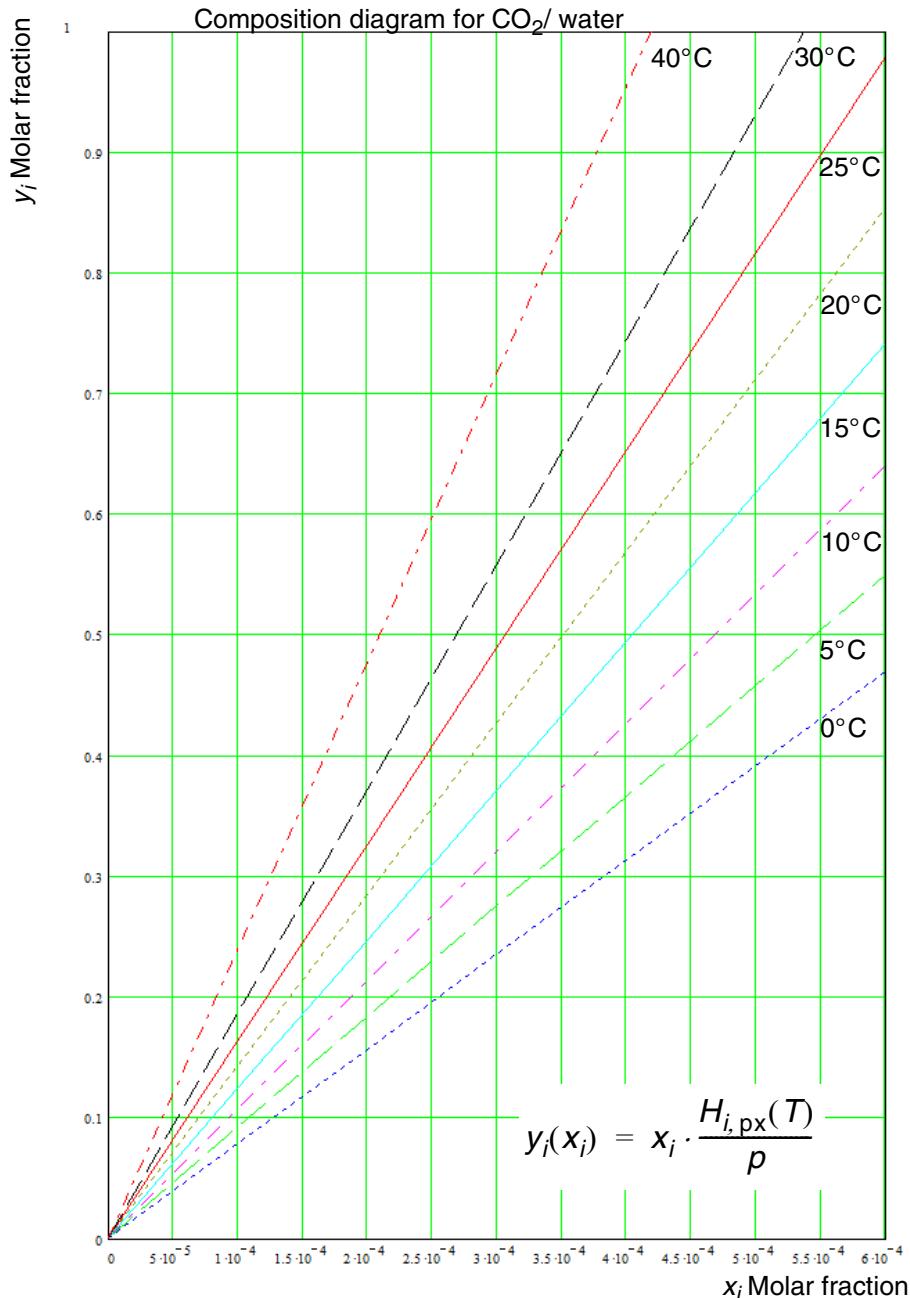


Fig. 6.1 Composition diagram for different temperatures

### 6.2.2 CO<sub>2</sub>/ water composition diagram for different temperatures

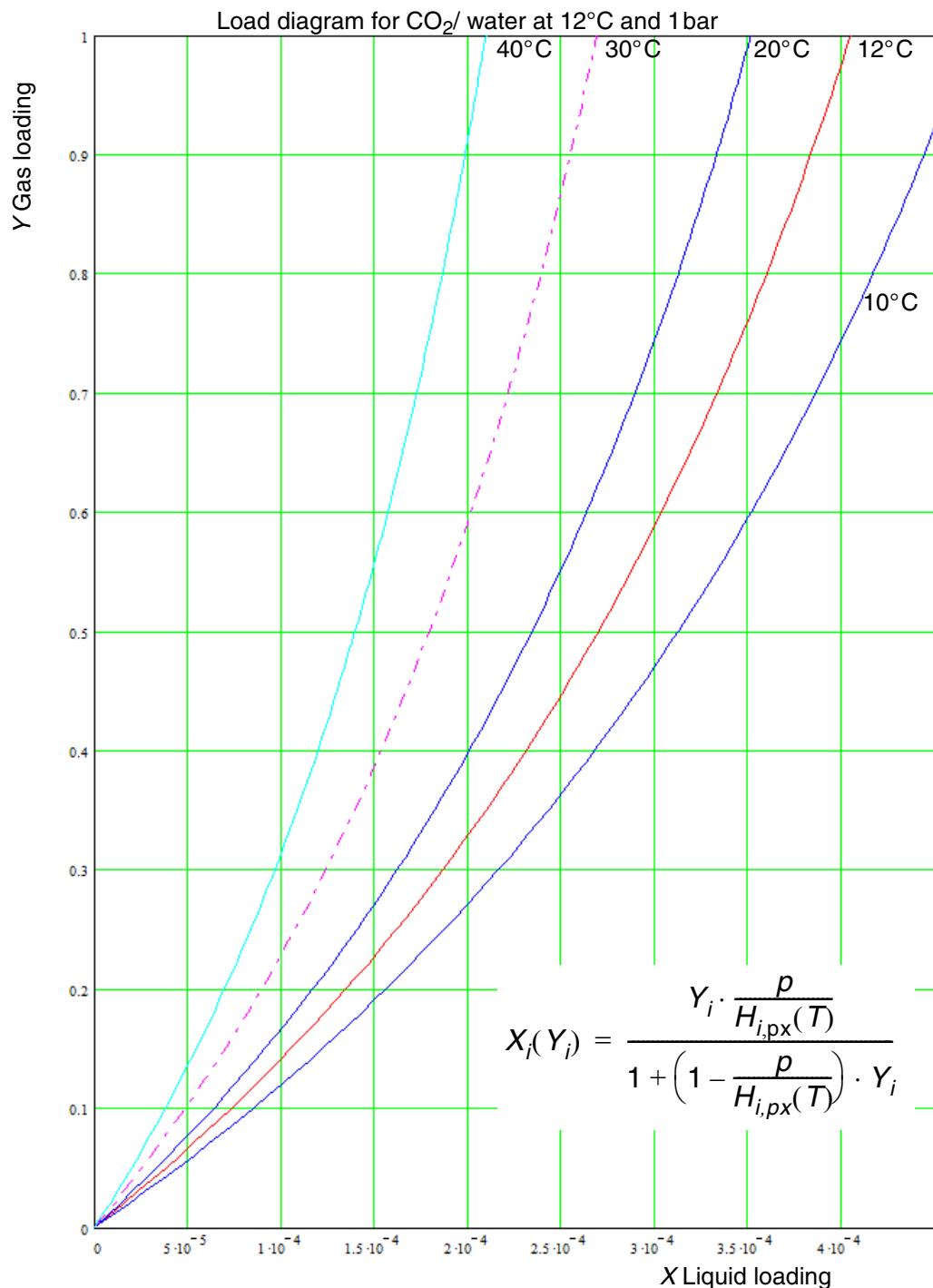


Fig. 6.2 CO<sub>2</sub>/ water load diagram for different temperatures

### 6.3 Conversion table air rotameter

Volume flow air	
m <sup>3</sup> /h	ltr/min
<b>2,4</b>	<b>40</b>
2,3	38,3
2,2	36,7
2,1	35
<b>2,0</b>	<b>33,3</b>
1,9	31,7
1,8	30
1,7	28,3
1,6	26,7
<b>1,5</b>	<b>25</b>
1,4	23,3
1,3	21,7
1,2	20
1,1	18,3
<b>1,0</b>	<b>16,7</b>
0,9	15
0,8	13,3
0,7	11,7
0,6	10
<b>0,5</b>	<b>8,3</b>
0,4	6,7
0,3	5
0,2	3,3

### 6.3.1 Specific volume of CO<sub>2</sub>

T in °C	p in bar								
	1	2	3	4	5	6	7	8	9
-30	455	225	149	110	87,2	71,8	60,8	52,6	46,2
-20	474	235	155	115	91,4	75,4	64,0	55,4	48,7
-15	484	240	159	118	93,5	77,2	65,6	56,8	50,0
-10	494	245	162	120	95,6	79,0	67,1	58,2	51,3
-5	503	250	165	123	97,6	80,7	68,6	59,6	52,5
0	513	255	169	125	100	82,4	70,1	60,9	53,7
5	522	259	172	128	102	84,2	71,6	62,2	54,9
10	532	264	175	131	104	85,9	73,1	63,6	56,1
15	541	269	178	133	106	87,6	74,6	64,9	57,3
20	551	274	182	135	108	89,3	76,1	66,2	58,5
25	561	279	185	138	110	91,0	77,6	67,5	59,7
30	570	284	188	140	112	92,7	79,0	68,8	60,8
35	580	289	191	143	114	94,4	80,5	70,1	62,0
40	589	293	195	145	116	96,0	82,0	71,4	63,2
45	599	298	198	148	118	97,7	83,4	72,7	64,3
50	608	303	201	150	120	99,4	84,8	73,9	65,4

Tab. 6.1 Specific volume of CO<sub>2</sub> in m<sup>3</sup>/kg

## 6.4 List of abbreviations

Abbreviation	Meaning
G	Gas / gaseous, in this case carrier gas
L	Liquid, in this case carrier liquid
TG	Carrier gas, inert component of gas mixture, residual gas mixture (all components except for component i)
TL	Carrier liquid, solvent, scrubbing agent (only the carrier liquid itself, unloaded, without component i)
Exp.	Experiment
St. Cond.	Standard Conditions
ltr	Litre, unit of volume 1 ltr = 1 dm <sup>3</sup>
atm	Atmospheric pressure, 1 atm = 1,013bar (here 1 atm $\approx$ 1 bar)
mmH <sub>2</sub> O	Millimetres of water column 1 mmH <sub>2</sub> O $\approx$ 9,8067 Pa

## 6.5 List of chemical names

Chemical formula	Name
CO <sub>2</sub>	Carbon dioxide
H <sub>2</sub> O	Water

## 6.6 List of key symbols and units used

Symbols	Explanation, definition	Unit
$\alpha$	Angle of lines of balance	Degrees of angle
$\tan \alpha$	Gradient of lines of balance	
$\gamma_i$	Activity coefficient of component i	
$\varphi_E$	CO <sub>2</sub> gas concentration at inlet	Vol%
$\varphi_A$	CO <sub>2</sub> gas concentration at outlet	Vol%
$\rho_{aq}$	Density of water	kg/m <sup>3</sup> ;
$C$	Constant for calculating temperature dependency of Henry constant	K
$c_{aq}$	Molar concentration in water, molar quantity / volume of water	mol/ltr
$c_1:$	Molar concentration in gas molar quantity / volume of gas	mol/ltr
$\dot{G}$	Gas carrier flow	mol <sub>gas</sub> /min
$H_{i,pc}$	Henry constant of substance i for px equation	$\frac{\text{atm} \cdot \text{mol}_{\text{aq}}}{\text{mol}_{\text{gas}}}$
$H_{i,cp}$	Henry constant of substance i for cp equation	$\frac{\text{mol}_{\text{gas}}}{\text{litr} \cdot \text{atm}}$
$H_{i,cc}$	Henry constant of substance i for cc equation	$\frac{\text{litr} \cdot \text{atm}}{\text{mol}_{\text{gas}}}$
$\dot{L}$	Liquid carrier flow	mol <sub>aq</sub> /min
$m$	Mass	kg
$m_{aq}$	Mass of water	kg
$\dot{m}$	Mass flow rate	kg/s; g/min
$M_{aq}$	Molar mass of water: 18	g/mol

Symbols	Explanation, definition	Unit
$n_i$	Molar quantity of component i	mol <sub>i</sub>
$n_{aq}$	Molar quantity of water	mol <sub>aq</sub>
$n_{CO_2}$	Molar quantity of CO <sub>2</sub>	mol <sub>CO<sub>2</sub></sub>
$\dot{N}_{air}$	Molar flow of air	mol <sub>air</sub> /min
$\dot{N}_{CO_2,E}$	Molar flow of CO <sub>2</sub> at column inlet	mol <sub>CO<sub>2</sub></sub> /min
$\dot{N}_{CO_2,A}$	Molar flow of CO <sub>2</sub> at column outlet	mol <sub>CO<sub>2</sub></sub> /min
$\dot{N}_{mix,A}$	Molar flow of mixture at outlet	mol/min
$\dot{N}_{mix,E}$	Molar flow of mixture at inlet	mol/min
$\dot{N}_i$	Molar flow of component i	mol <sub>i</sub> /min
$\dot{N}_G$	Molar flow of carrier gas (air)	mol <sub>air</sub> /min
$\dot{N}_L$	Molar flow of carrier liquid (water)	mol <sub>aq</sub> /min
$p$	Pressure	bar
$p_i$	Partial pressure of component i	bar
$p_{O,i}(T)$	Saturated vapour pressure	bar
$PD1$	Differential pressure in upper half of column	mmH <sub>2</sub> O
$PD2$	Differential pressure in lower half of column	mmH <sub>2</sub> O
$R$	Special gas constant	J/(kg K)
$R_m$	Universal gas constant	J/(Kmol K)
$T_0$	Temperature at 0°C in Kelvin: 273 K	K
$T_{25}$	Temperature at 25°C in Kelvin: 298 K	K
$T_N$	Temperature at standard conditions 0°C in Kelvin: 273 K	K
$T_1$	Temperature in point 1 in Kelvin	K
$\vartheta$	Temperature	°C
$V_{aq}$	Water volume	
$V$	Volume	m <sup>3</sup>
$\dot{V}$	Flow rate	m <sup>3</sup> /s; ltr/min
$x_{aq}$	Molar fraction of water	mol <sub>i</sub> /(mol <sub>i</sub> +mol <sub>aq</sub> )
$x_i$	Liquid molar fraction of component i	mol <sub>i</sub> /(mol <sub>i</sub> +mol <sub>aq</sub> )

<b>Symbols</b>	<b>Explanation, definition</b>	<b>Unit</b>
$X_i$	Liquid loading with component i	$\text{mol}_i/\text{mol}_{\text{aq}}$
$y_i$	Gas molar fraction of component i	$\text{mol}_i/(\text{mol}_i + \text{mol}_{\text{gas}})$
$Y_i$	Gas loading with component i	$\text{mol}_i/\text{mol}_{\text{gas}}$

<b>Index</b>	<b>Explanation</b>
<i>air</i>	Air
<i>mix</i>	Mixture
<i>aq</i>	Aqua / water
<i>CO<sub>2</sub></i>	Carbon dioxide
<i>gas</i>	Gas
<i>i</i>	Component i
<i>L</i>	Liquid
<i>G</i>	Gas
<i>St. Cond.</i>	Standard Conditions
<i>Exp.</i>	Experiment

Molar fraction  $x_i$ : 
$$x_i = \frac{n_i}{n_{TL} + n_i}$$

Molar fraction  $y_i$ : 
$$y_i = \frac{n_i}{n_{TG} + n_i}$$

Gas loading  $Y_i$ : 
$$Y_i = \frac{n_i}{n_{TG}}$$

Liquid loading  $X_i$ : 
$$X_i = \frac{n_i}{n_{TL}}$$

## 6.7 List of symbols for process schematic

Symbol	Name
	Pump, general
	Propellant vacuum pump
	Compressor
	Tank, general
	Tank, general
	Heating or cooling
	Plate heat exchanger
	Fitting, general
	Fitting, manually operated
	Fitting with magnetic actuation
	Fitting with continuous adjustment characteristics
	Ventilator fitting
	Non-return fitting
	Valve, general
	Safety valve
	Dirt trap

Symbol	Name
	Silencer
	Coupling
	Pressure reducer
	Rotameter
	Flow line
	Function line
	Measuring point with local display
	Measuring point with remote evaluation
	Substance inlet / outlet
	Controller
	Hose line

## 6.8 List of code letters in process schematics

Code letter	Name
<b>Equipment and machines</b>	
A	Plant component or machine, unless assigned to one of the groups below
B	Tank, bunker, silo, vessel
K	Column
P	Pump
V	Compressor, vacuum pump, fan
W	Heat exchanger
<b>Fittings</b>	
V	Valve, general
<b>Pipes</b>	
S	Hose

Tab. 6.2 Code letters for equipment, machines, fittings and pipes

Code letter	Measured variable or other input variable, actuator		Processing <b>As following letter (sequence I, R, C)</b>
	<b>As first letter</b>	<b>As supplementary letter</b>	
C			Automatic control
F	Flow rate, throughput	Ratio	
I			Display
P	Pressure		
T	Temperature		Transmitter

Tab. 6.3 Code letters for measuring points

## 6.9 References

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