Experiment Instructions

ET 420 Ice Stores in Refrigeration

Experiment Instructions

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.

Table of Contents

1 Introduction

Ice stores are used in refrigeration in order to cover an increased additional refrigeration demand (peak load).

The device Ice Stores in Refrigeration Technology ET 420 consists of a completely functional model of the vapour-compression refrigeration process.

The clear layout of the components facilitates a clear understanding of the construction of a refrigeration plant. All components are commonly used in refrigeration engineering. They will thus be recognisable in the field and enable training to be made as similar as possible to practice, an important issue.

Apart from specific training on refrigeration plants, the basics of heat pumps can also be demonstrated with ease.

Since the refrigeration plant demonstrates the application of a thermodynamic cyclic process, the demonstration system can also used to good effect to illustrate theoretical thermodynamic relation-ships.

Apart from the basic explanation of how a refrigeration plant/heat pump functions, quantitative measurements can also be performed, for example the output coefficient can be determined experimentally.

Since the demonstration system only requires an electrical mains supply, it can be used in various locations such as training and seminar rooms, and lecture theatres.

Learning Objectives / Experiments

- Design and operation of an energy-efficient refrigeration system
- Function and operation of an ice store
  * charge
  * discharge
- Energy flow balance
- Energy transport via different media
- Compression refrigeration cycle in the log p-h diagram
- Function and operation of a wet cooling tower
- Function and operation of a dry cooling tower

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
⚠ DANGER	Indicates a situation which, if not avoided, **will** result in **death or serious injury**.
⚠ WARNING	Indicates a situation which, if not avoided, **may** result in **death or serious injury**.
⚠ CAUTION	Indicates a situation which, if not avoided, may result in **minor or moderately serious injury**.
NOTICE	Indicates a situation which may result in **damage to equipment**, or provides instructions on **operation of the equipment**.

Symbol	Explanation
	Electrical voltage
	Hot surfaces
	Cold
	Rotating Parts
	Notice

2.3 Safety instructions

WARNING

Electrical connections are exposed when the switch cabinet is open.

Risk of electric shock.

- Disconnect the mains plug before opening the switch cabinet.
- Work should only be performed by qualified electricians.
- Protect the switch cabinet against humidity.

⚠ WARNING

Rotating parts at fan outlet.

Risk of injury.

- Do not reach into the fan outlet.
- Only operate the fan when a tube is fitted at the fan outlet.

⚠ WARNING

Hot surfaces on the compressor and other tubes.

Risk of burning.

- Never touch during operation!

NOTICE

In no circumstances tamper with the working medium circuit (undoing unions etc.)! The system is pressurised!

The working medium (R134a refrigerant) may leak!

In the event of repairs, have the working medium correctly drained!

Do not adjust the pressostats! The are factory preset.

After draining the water/ glycol mixture, dispose of it correctly. Refill in the ratio 1.5: 1.

NOTICE

Risk of Overheating! Never operate without the intermediate stage or with the intermediate circuit empty!

If the compressor thermal cut-out trips, leave the plant to cool down.
Check the operating pressures after restarting.

NOTICE

The submersible motor pump is destroyed if operated without water.

- When operating the submersible motor pump, ensure that the water tank is filled.

2.4 Ambient Conditions for Operating and Storage Location

- Enclosed well vetilated room recommendet.
- Free of dirt and moisture.
- Level and secure base.
- Frost free.

3 Unit Description

The vapour-compression refrigeration process is currently the most important process in refrigeration and air-conditioning engineering, this process accounts for over 90 % of all installed plant.

The device ET 420 described below forms a complete refrigeration system which uses the above mentioned principle.

A key feature of the vapour-compression refrigeration process is the usage of a refrigerant which converts from the liquid state into a vapour whilst absorbing as much vaporisation heat as possible, and can then be liquefied again under pressure. A circuit with a glycol-water mixture is used to cool the condenser. A wet cooling tower and a dry cooling tower can be integrated into this circuit via an intermediate stage to draw off the heat.

An ice store is maintained via a heat exchanger using the refrigerant which has been cooled by the refrigeration process.

The cooling plant is characterised by the following features:

– Industrial components are used, there are therefore strong links to current practice

– The entire experimental set-up is mounted on wheeled trolleys

– Flow measurement of all relevant mass flows via variable area flowmeters

– Simple, rapid connection of the cooling towers to the intermediate stage using hoses with rapid action hose couplings

– The ice store can be used in various operational modes

3.1 Layout

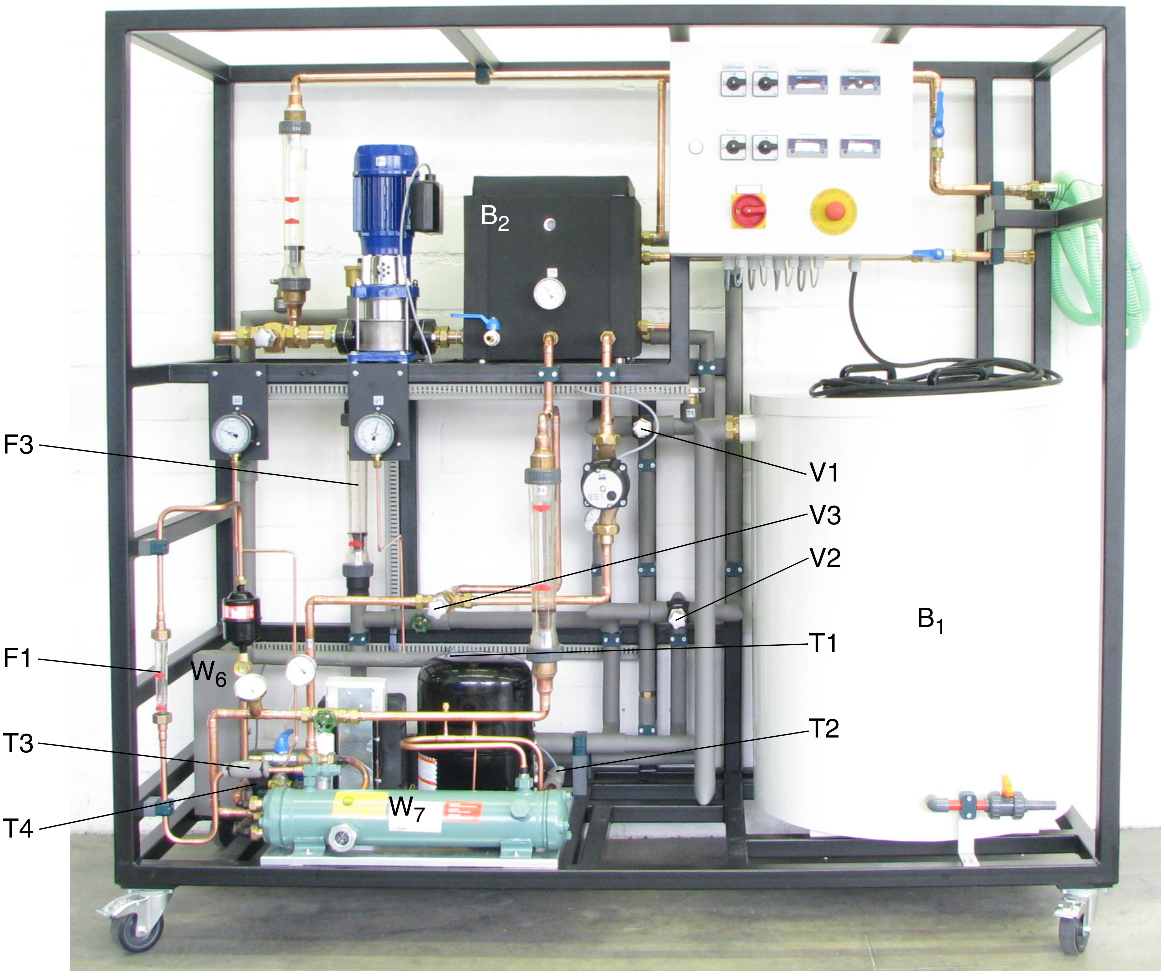


Fig. 3.1 ET 420 front view
Identification of the Measurement and Shut-Off Points in the Refrigerating Circuit with Cooling Circuit Ice Stores

Fig. 3.2 Top view of one part of the refrigeration set

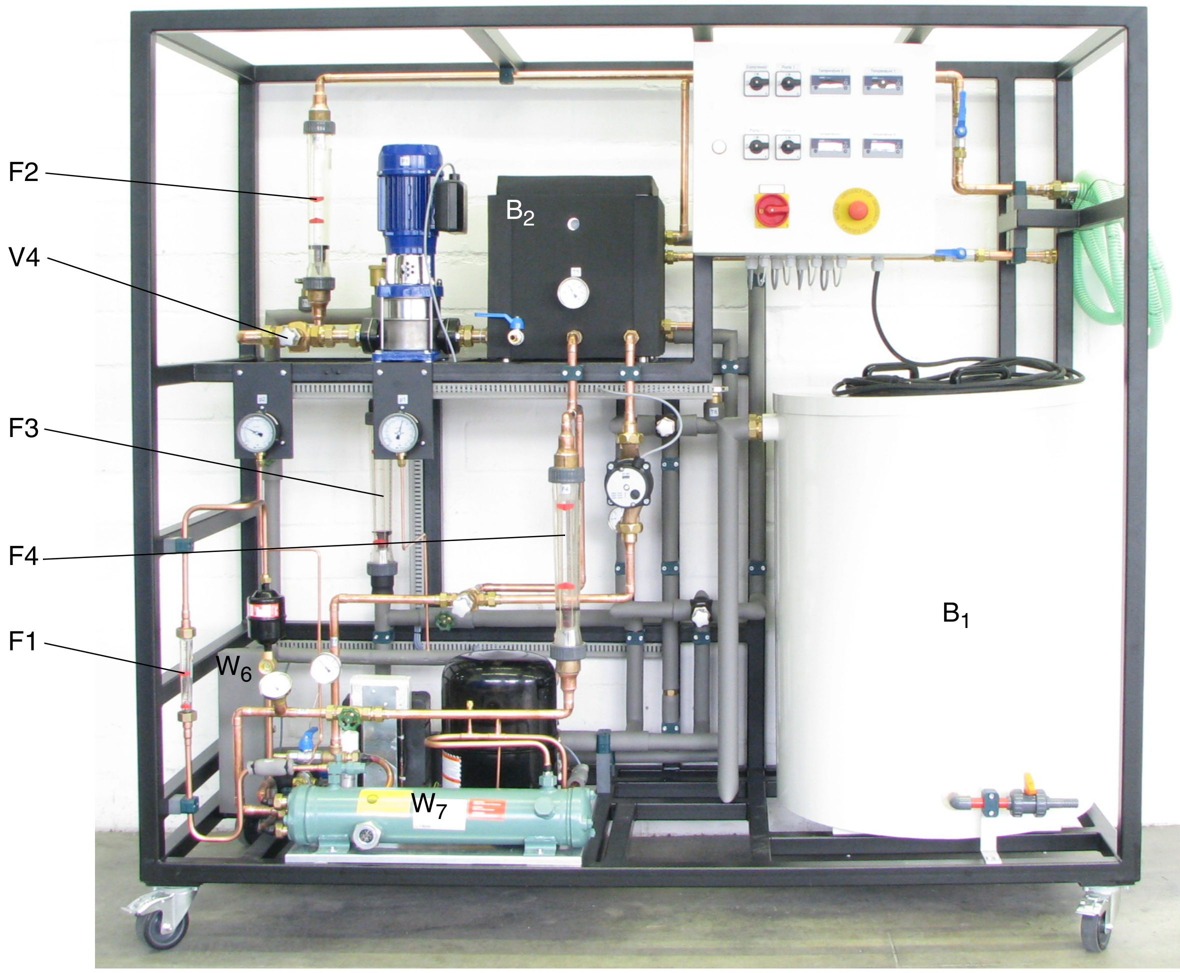


Fig. 3.3 Identification of the Measurement and Shut-Off Points in the Intermediate Stage Cooling Circuit

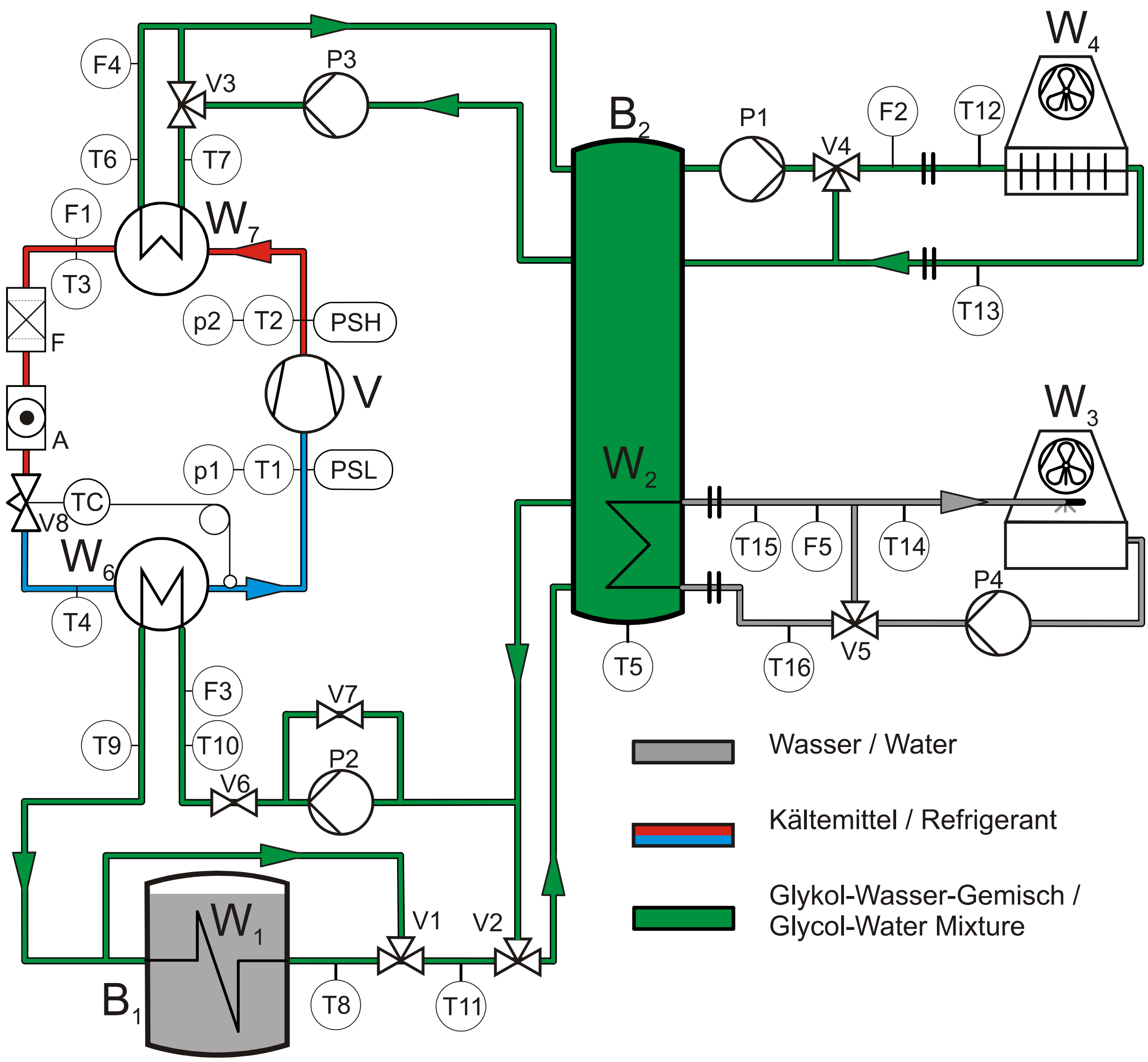


Fig. 3.4 Process Schematic of ET 420

In order to be able to easily describe the measurement and shut-off points in a uniform manner in the text, the following abbreviations are used :

V1...V5	Shut-Off and Control Valves
P1...P4	Pumps
p1...p2	Pressure Measurement Points
T1...T16	Tempertature Measurement Points
F1...F5	Flow Measurement Points

3.2 Function of the Cooling Plant

3.2.1 Cyclic Process

The basis for the operation of a refrigeration plant is a thermodynamic cyclic process.

In a thermodynamic cyclic process a process medium, referred to as the working medium, passes through a set sequence of changes in state. Since the changes in state are repeated, that is the working medium always returns to its initial state, the process is referred to as a cyclic process.

Changes in state refer to heating, cooling, compression or expansion. The state variables of the working medium such as pressure, specific volume or temperature change when the state changes. Gasses or liquids that can be easily vaporised can be used as working mediums. Pure liquids cannot be used in a cyclic process because they are incompressible and can thus not be compressed.

By careful sequencing of various changes in state, thermal and mechanical energy can be exchanged via the working medium.

- **Compression** means the absorption of mechanical energy **(compressor)**
- **Expansion** in this case means a change of phase of the refrigerant from liquid to gas and the related increase in volume**.**
- **Heating** means the absorption of thermal energy (Evaporator)

- **Cooling** means the discharge of thermal energy **(Condenser)**

These changes in state do not have to occur in stages that are clearly separated from each other. For example heat is often discharged during compression.

The changes in the state variables are interlinked. In general, compression results in

- an increase in temperature
- an increase in pressure
- a reduction in volume

The energetic values of a refrigeration system are calculated on the basis of the log p-h diagram for the refrigerant used.

3.2.2 Refrigeration Plant Cyclic Process

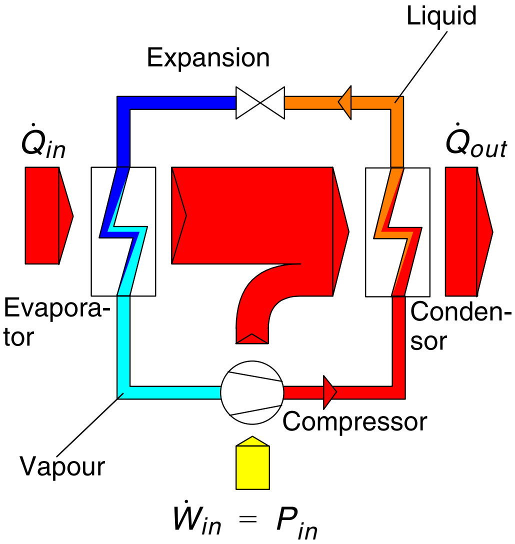


Fig. 3.5 Refrigeration Plant Cyclic Process

Whilst in the case of a steam plant the conversion of thermal energy into mechanical energy is of primary concern, in a refrigeration plant the heat transport effect is used. Mechanical energy is used to pump, so to speak, heat from a low temperature region to a higher temperature region.

The mechanical energy is not lost but is discharged into the higher temperature region in the form of thermal energy.

- A compressor compresses the vaporised working medium, during this process mechanical energy $\dot{W}_{in}$ is absorbed.

- Heat $\dot{Q}_{out}$ is removed from the working medium in the condenser, the working medium condenses.
- The liquid working medium pressure is reduced in an expansion valve, during this process the medium cools.
- The working medium evaporates in an evaporator whilst absorbing heat $\dot{Q}_{in}$.

The medium is again fed to the compressor and the circuit is complete.

3.3 Components

3.3.1 Refrigeration Unit

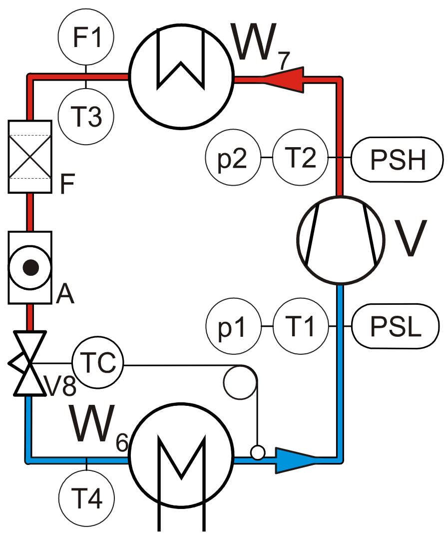


Fig. 3.6 Process Schematic of the Refrigeration Unit

The refrigeration unit uses R134a refrigerant in a closed circuit. The following schematic diagram shows the circuit and the components of the unit. The components marked are named as follows:

V	Compressor
p1/ p2	Manometer
PSH/ PSL	Pressostat (pressure switch)
W7	Condenser
F	Filter/ dryer
A	Sight glas
V8	Expansion valve
W6	Evaporator

3.3.2 Compressor

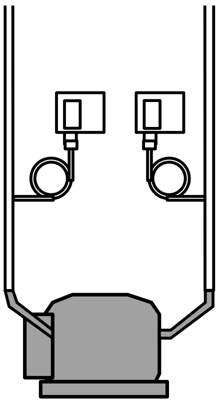


Fig. 3.7 Compressor with Pressostats

An electrically driven piston compressor is used to compress the vaporised working medium.

This is a fully hermetically sealed unit. The electrical motor and compressor are housed in a gas tight welded enclosure.

The motor is cooled by the working medium. This is useful for the necessary suction side gas superheating. The compressor does not require any maintenance.

3.3.3 Condenser

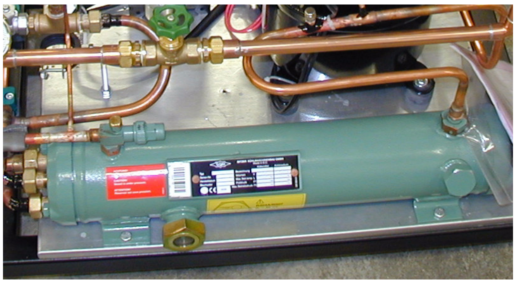


Fig. 3.8 Pipe cluster heat exchanger

The compressed, and in the process heated, vaporised working medium is cooled and condensed in a pipe cluster heat exchanger.

3.3.4 Expansion Valve

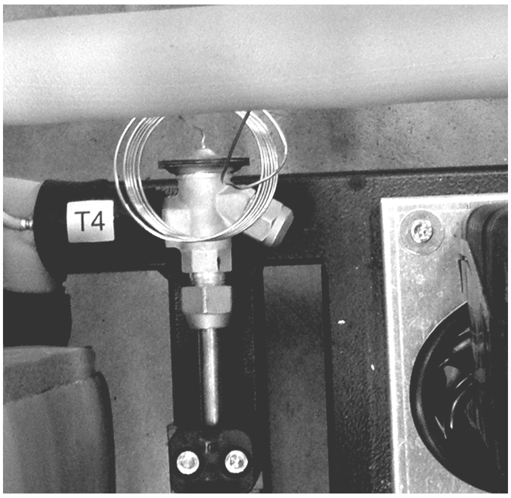


Fig. 3.9 Expansion Valve

The working medium pressure is reduced again in the expansion valve. During this process part of the working medium vaporises and the temperature drops considerably.

A thermostatic expansion valve is used. This measures the outlet temperature from the evaporator via a temperature sensor and controls the flow such that the working medium leaves the evaporator slightly superheated.

This measure prevents working medium that is not vaporised from entering the compressor and causing damage.

3.3.5 Evaporator

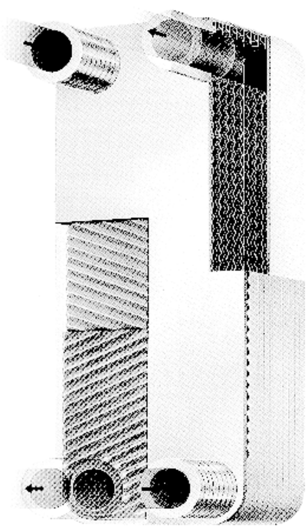


Fig. 3.10 Counterflow Plate Heat Exchanger

This is a plate heat exchanger made from corrosion resistant steel that is also resistant to acids, the heat exchanger consists of 20 shaped plates. Every second plate is soldered at 180° offset. This results in the soldering forming two separate flow channels. The two media involved in the exchange of heat flow through these channels in opposite directions.

3.3.6 Rotameter

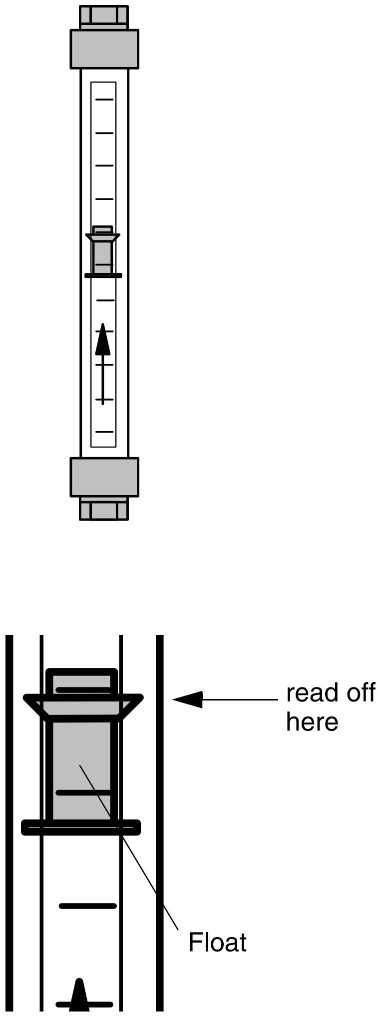


Fig. 3.11 Rotameter

Rotameters with the following features are used to measure the various flows:

– Precision glass measurement tube

– Replaceable corrosion resistant steel float

– Precision class 1.5

The flow is read off at the upper edge of the conical shoulder.

Air bubbles or particles of dirt can affect the precision of the measurement.

In order to wash these away, run the test setup at maximum flow by fully opening all the necessary valves for a short time.

3.3.7 Ice Store

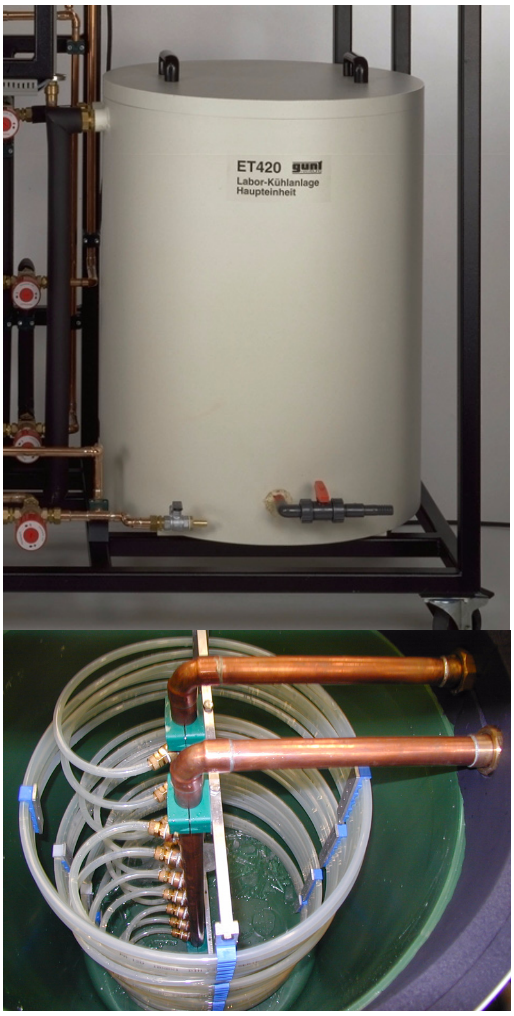


Fig. 3.12 Insulated ice storage (top)
Interior view of ice storage (below)

Ice stores are used nowadays as buffers, either to maintain a certain temperature for a given period of time following a possible failure of the refrigeration plant, or to reduce the peak loading on the refrigeration plant through the storage of cooling energy. Additional advantages can be gained by charging the store during low tariff periods.

When charging the ice store the cooling energy to freeze the water is fed to the storage medium, in this case water, via a coiled pipe through which the glycol/ water mixture flows. This is in contrast to direct vaporisation method (in this case the refrigerant flows directly through the coiled pipe, that is the vaporisation occurs directly).

During discharging the transfer of heat occurs directly from the ice to the water/glycol mixture flowing through the coiled pipe.

During the freezing process the water crystallises first on the surface of the pipe.

Due to the poor heat conduction of ice, performance drops with increasing ice thickness. This results in a certain degree of self-regulation against complete freezing.

Water is used as the storage medium, as water has the highest heat of fusion (also enthalpy of fusion c = 333,5 kJ/ kg) under the potential process conditions. Using water, you can store 333,5 kJ of energy per kg of water during phase transition (liquid/solid).

Using water, you can store 80 times more energy during phase transition (liquid/solid) than when only using a liquid at the same volume and a difference of 1°C. (Spec. heat capacity c = 4,187 kJ/ kg K).

3.3.8 Further Components

The following additional devices are needed for the safe operation of the cooling plant

- Two pressostats (pressure switches) monitor the pressure on the suction and delivery sides of the compressor.
- Using two manometers on the suction and delivery sides, the pressure levels and therefore the temperatures in the condenser (condensation temperature) and evaporator (evaporation temperature) can be monitored in the wet vapour zone.
- A filter/ dryer unit is fitted after the condenser. This unit filters moisture and any particles of dirt from the working medium.
- A sight glass with moisture indicator is incorporated to allow checks to be made.

3.4 Operating States of the Plant

3.4.1 Charging the Plant and Commissioning

Position the demonstration system on an even surface.

NOTICE

It is to be ensured that the refrigeration unit is left to stand for at least 2 hours after transportation in order that the refrigerant can settle. Only start the plant after it has been left to stand.
If this instruction is not complied with, there is a risk of liquid causing damage the compressor.

– Secure against rolling away by applying the brakes.

– Connect the VT, RT, VN and RN connectors to the correspondingly marked connectors on the dry and wet cooling towers using the hoses with rapid action hose couplings which are supplied.

– Fill the intermediate stage with a 40 percent water/glycol mixture, use 27 litres of water and 18 litres of propylene glycol.

– This quantity is also sufficient to fill the dry cooling tower at the same time.

– Make an external water connection to the hose fitting on the wet cooling tower and fill with approx. 60 l of water. When the maximum water level is reached the water inlet is shut-off by a magnetic valve.

– Check that the emergency stop switch is released and that the main switch is off.

– Connect up to the electrical supply.

– Main switch on.

- Circulation pumps P1...P3 on.
- Alternately operate the dry and wet cooling towers (the motor circuit-breakers are on the individual units).
- Leave the cooling towers and plant running until there are no more air bubbles in the system (watch the Rotameter F1...F4).
- Compressor on.

NOTICE

It is to be ensured that the refrigeration unit is left to stand for at least 2 hours after transportation in order that the refrigerant can settle. Only start the plant after it has been left to stand.
If this instruction is not complied with, there is a risk of liquid causing damage the compressor.

- Check the suction side and delivery side pressures (p1),(p2).
  ($p_{suction\ side}$ = 0,3 bar,
  $p_{delivery\ side}$ = 6,0...9,0 bar)

The demonstration apparatus is now operational.

3.4.2 Operation

During operation of the refrigeration unit it is to be ensured that no vapour bubbles rise through the rotameter F1. This will always occur if the refrigerant temperature T3 is higher than the vapour temperature of the R 134a refrigerant.

Since the vapour temperature is dependant on the pressure present, the pressure must be continually monitored on the combined pressure and temperature measurement instrument (p2).

The secondary of the clustered pipe condenser, described later in detail, is operated with the water/ glycol mixture. If the temperature of the mixture increases, for example due to continuous operation without an external cooling tower being switched on, then the temperature of the refrigerant can also not be held constant and will increase. The result is that the refrigerant cannot be cooled down enough and the vapour bubbles will start to form. With increasing pressure, the vapour temperature also increases.

3.4.3 Operational Modes

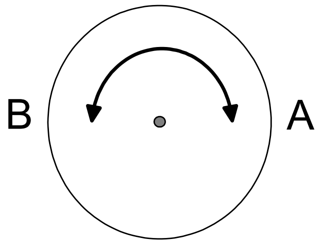


Fig. 3.13 Three-way valve handwheel (V1...V4)

In order to ensure that the ice store is used in a meaningful way, different operating modes must be used at different times.

The three operational modes are explained in the following and the positions of the individual three way valves (V1...V4) given in tabular form, so that the respective circuit on the device ET 420 can be set up easily and correctly. Valve position B means left stop, valve position A means right stop.

The calculations of Chapter 4.1.4 - Chapter 4.1.8 can be performed for every operational condition. A detail discussion is not given here.

3.4.3.1 Charge Mode

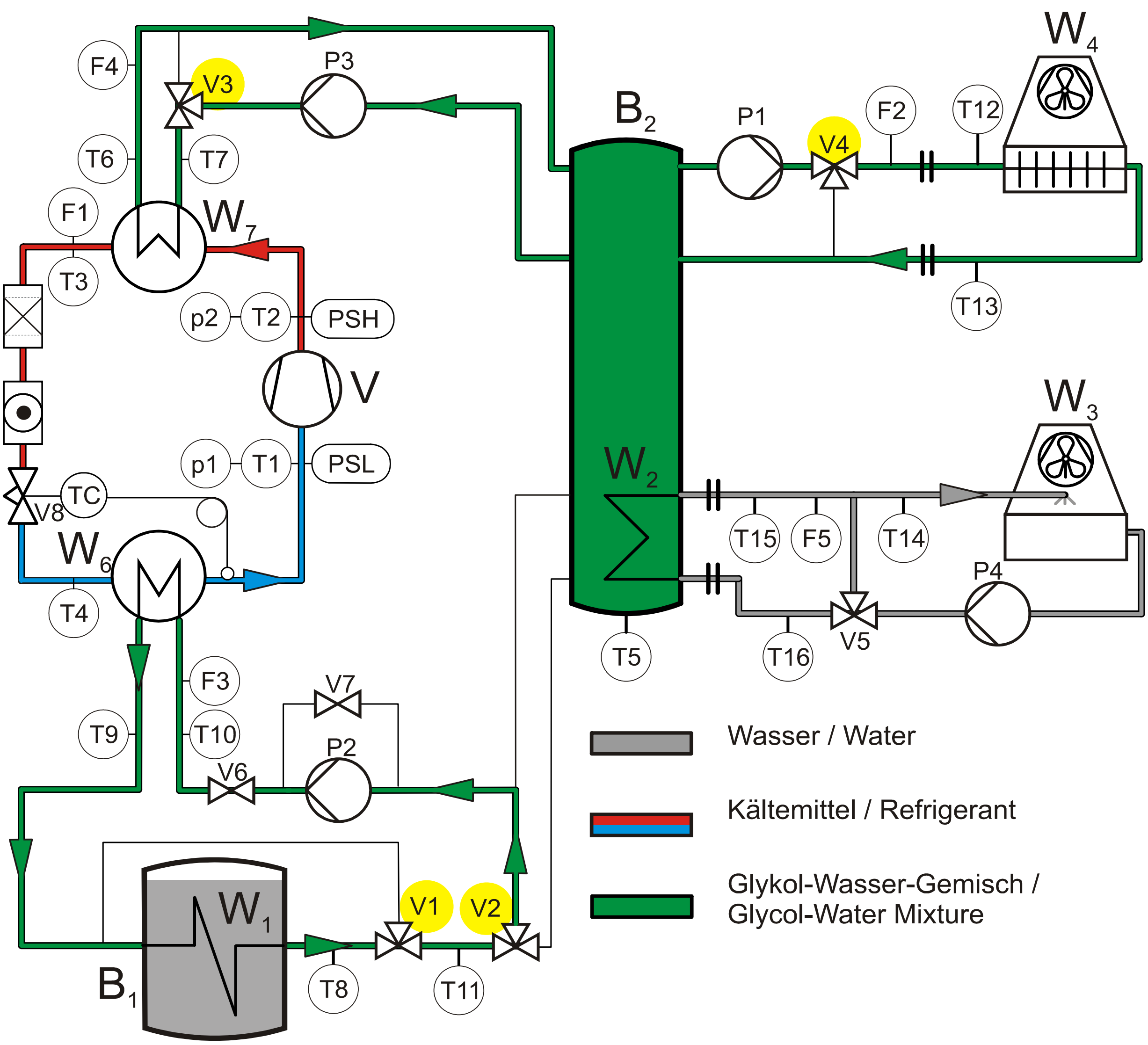


Fig. 3.14 Charge Mode (operation at night)

Valve	V1	V2	V3	V4
Position	A	B	A	A/B

Tab. 3.1 Valve-Positions - Charge Mode

In charge mode the glycol/water mixture cools the water in the ice store until it freezes. This operational mode is always used if either no or little cooling capacity is required, or during period of cheap electricity tariffs, principally at night. In practice when the temperature T8 at the output of the ice store falls below -3°C, charge mode is normally ended since there is, from this point, insufficient temperature spread (should be approx. 3°C) between the feed and return temperatures.

In order to achieve rapid charging, it is recommended to switch on both external cooling towers in this operational mode, since otherwise the temperature of the glycol/water mixture in the intermediate stage will increase and thus reduce the cooling capacity of the refrigeration unit.

3.4.3.2 Discharge Mode

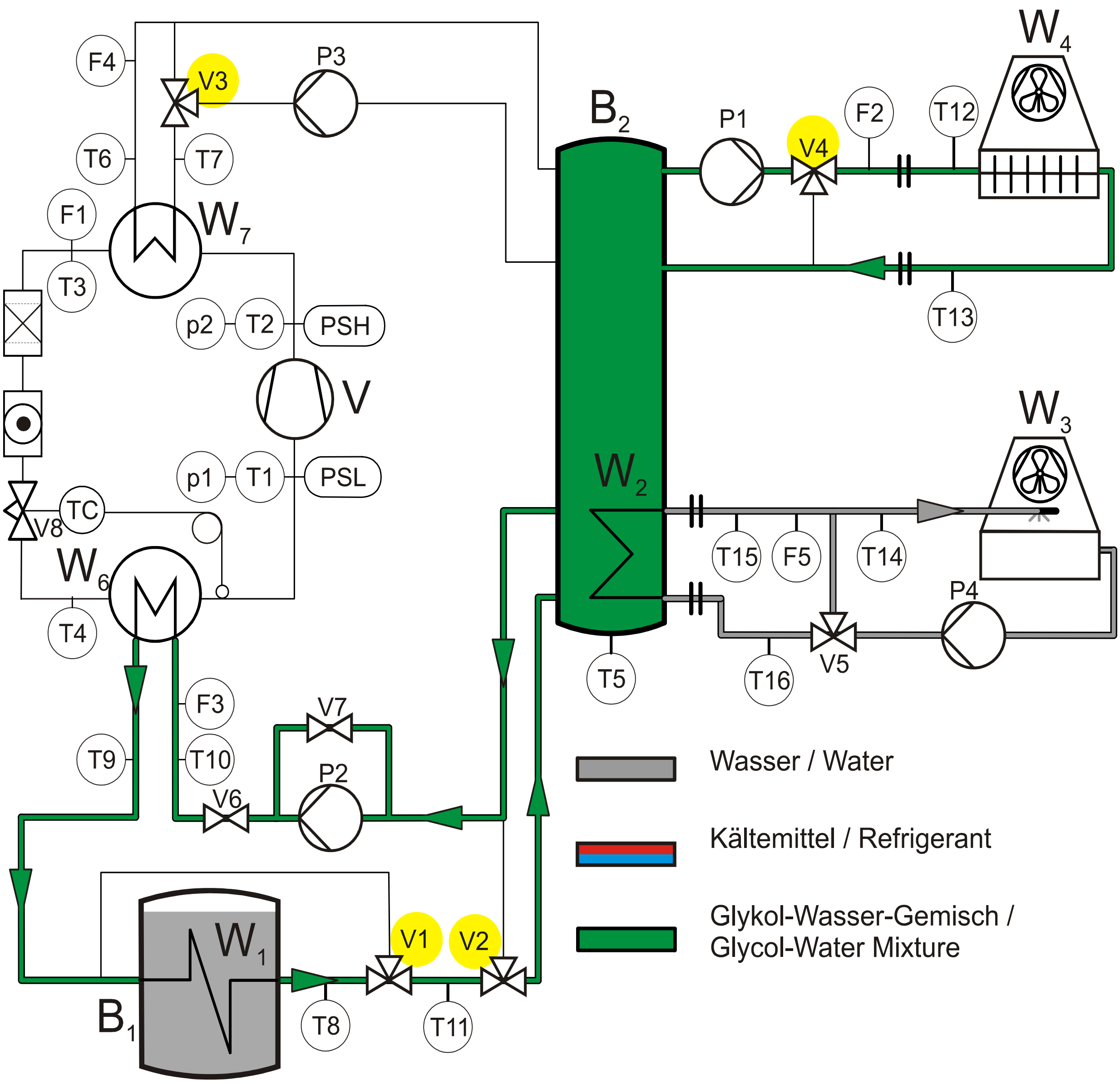


Fig. 3.15 Discharge Mode (Operation during the day)

Valve	V1	V2	V3	V4
Position	A/B	A	A	A/B

Tab. 3.2 Valve-Positions - Discharge Mode

The compressor of the refrigeration-plant is switched off. At high loads the outlet temperature of the evaporator increases as a result of an increase in temperature of the glycol/ water mixture in the intermediate stage such that satisfactory cooling can no longer be guaranteed. The glycol/ water mixture now flows via the bypass through the charged ice store and is cooled again.

If the ice store is fully charged, then the cooling unit can be switched off for a period of time that can be calculated in advance (see Chapter 4.1.8 and Chapter 4.1.9).

This operational mode is used during the day for ecological reasons to save electricity through switching off the refrigeration plant.

3.4.3.3 Bypass Mode

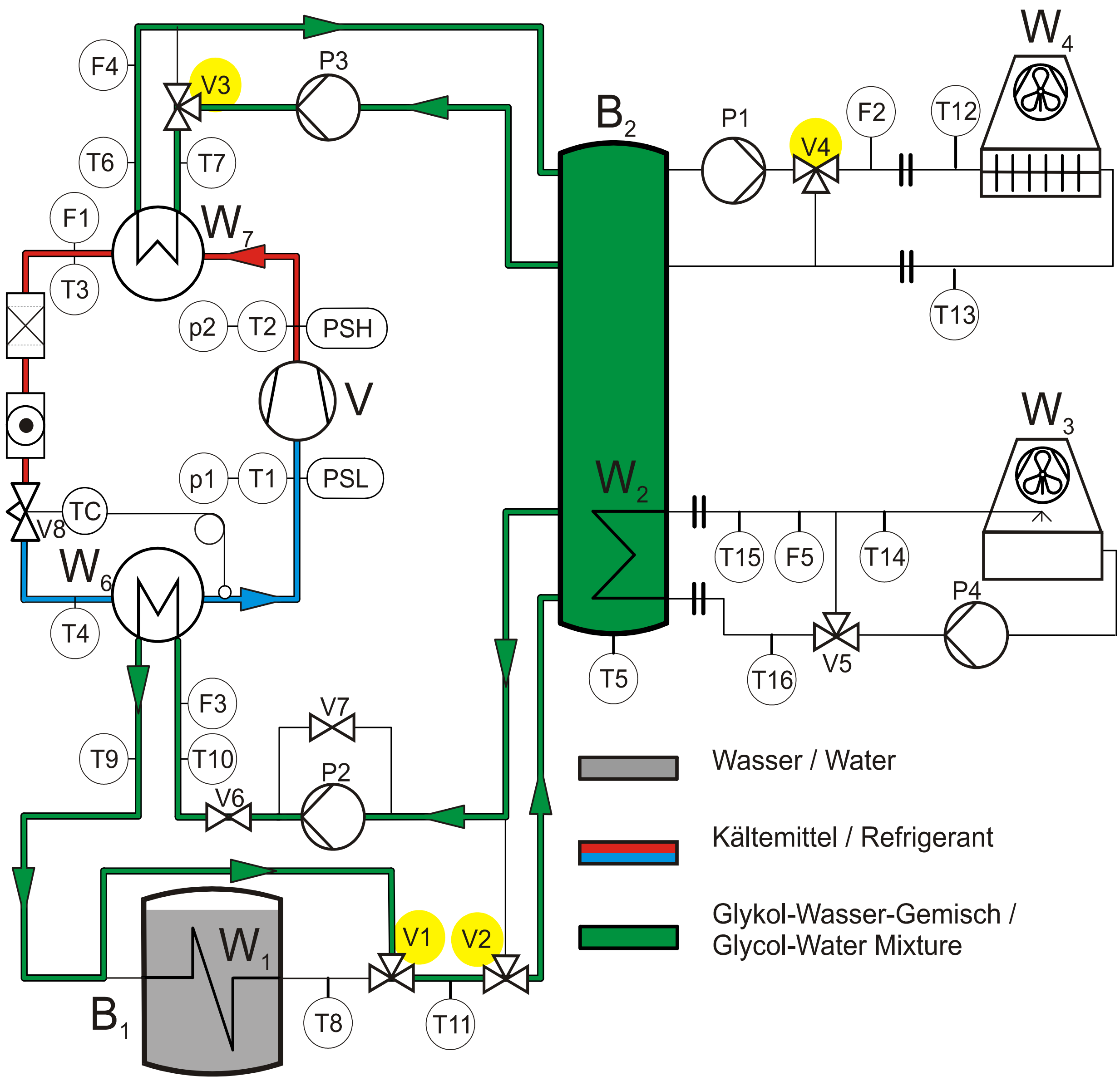


Fig. 3.16 Bypass Mode

Valve	V1	V2	V3	V4
Position	B	A	A	A/B

Tab. 3.3 Valve-Positions - Bypass Mode

The ice store is bypassed, that is the store is neither charged or discharged.

At lower loads the cooling capacity of the evaporator is sufficient to provide the necessary cooling.

At higher loads bypass operation is not sufficient on its own because temperature T5 on the intermediate stage increases. In order to guarantee continuous operation at least one cooling tower must be switched in.

4 Experiments

4.1 Basics

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

4.1.1 Vapour-Compression Refrigeration Process in pressure - entahalpy - chart

The changes of state in a vapour-compression refrigeration process can be usefully depicted in a pressure - enthalpy - chart.

In a pressure-enthalpy-chart pressure p is plotted against enthalpy h.

Enthalpy refers to the total energy content of a gas or vapour. It is comprised of the internal energy U, a measure of the thermal energy content of a material and the displacement work $p \cdot V$.

$$H = U + p \cdot V$$

Values per unit mass also yield specific values in this case

$$h = u + p \cdot v$$

with the internal energy $u = u_0 + c_v (T - T_o)$.

u_o and T_o are, in principle, freely selectable reference points because, in general, only differences are considered.

There are special pressure-enthalpy-charts for the different working mediums in which the liquid phase, wet vapour and dry saturated vapour zones are plotted. Wet vapour means that the working medium is present as a mixture of liquid and vapour. The temperature corresponds exactly to the boiling point. In the dry saturated vapour zone the working medium is present purely as vapour.

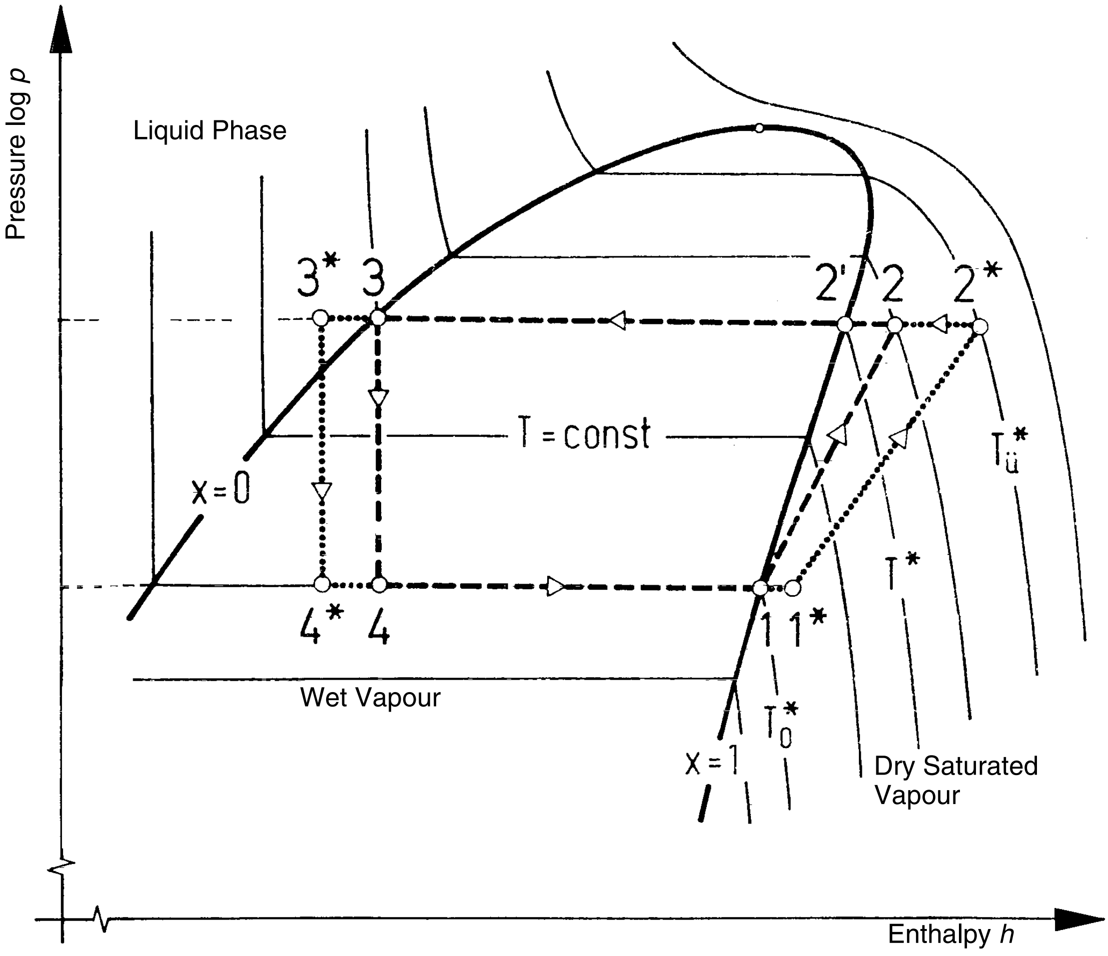


Fig. 4.1 *pressure*-enthalpy chart of a Working Medium

4.1.2 Ideal Cyclic Process

The changes of state in the refrigeration plant cyclic process are now to be plotted on the pressure - enthalpy chart.

1-2 : Isentropic compression to the final compression temperature of the working medium, no discharge of heat

2-2‘: Isobaric cooling to the condensation temperature, discharge of the superheating enthalpy $h_{2,2'}$

2‘-3: Isobaric condensation, discharge of the condensation enthalpy $h_{2',3}$

3 -4: Pressure reduction in the wet vapour zone, no discharge of enthalpy, cooling and partial vaporisation

4 -1: Isobaric vaporisation, absorption of the vaporisation enthalpy $h_{4,1}$

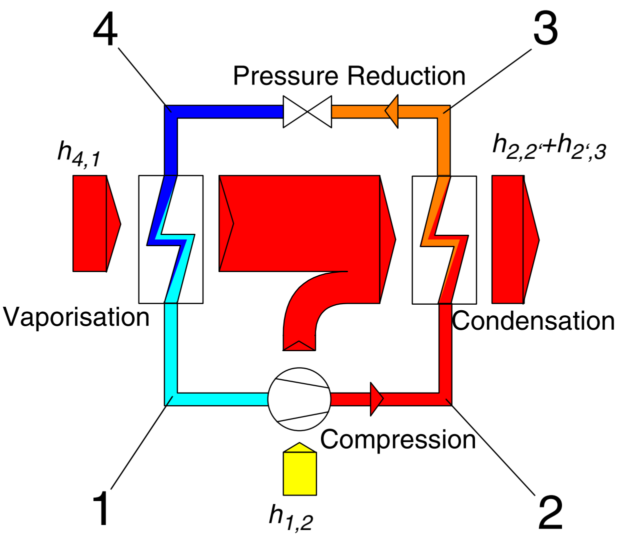


Fig. 4.2 Vapour-Compression Refrigeration Process

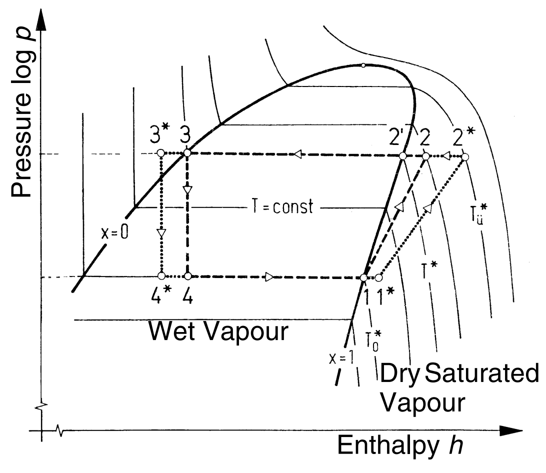


Fig. 4.3 Vapour-Compression Refrigeration Process on the pressure - enthalpyh-chart

4.1.3 Actual Cyclic Process

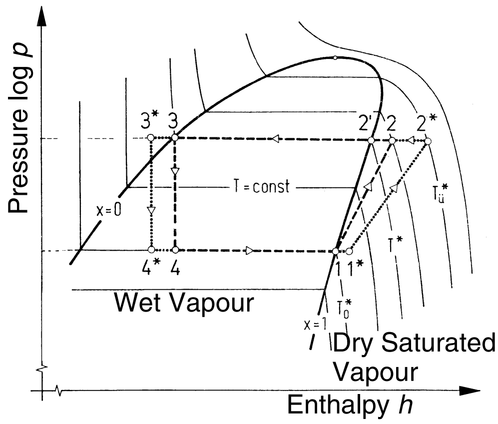


Fig. 4.4 Vapour-Compression Refrigeration Process on the pressure - enthalpy - chart

The main difference in the case of an actual cyclic process is that compression is not isentropic, but runs along the line 1*-2* due to internal friction in the working medium vapour and heat losses in the compressor. Thus more work is required at the compressor to achieve the same final pressure.

Furthermore, superheating 1-1* of the working medium is necessary prior to compression in order to ensure that no liquid droplets enter the compressor (risk of damage to the compressor).

Liquid subcooling 3-3* can be used to reduce the vapour content on entry into the evaporator. By this means more evaporation heat 4*-1 can be absorbed.

4.1.4 Refrigeration Unit, Cooling capacity

In the following sections, the power rating of the refrigeration set is determined. In addition some further characteristic variables for cooling plants will be calculated. These experiments will be performed in charge mode.

In order to calculate the cooling capacity, the refrigerant mass flow must first be determined. To do this the volume flow $\dot{V}_K$ is read during operation.

The refrigerant mass flow is the product of the two values.

$$\dot{m}_K = \dot{V}_K \cdot \rho_K$$

Taking account of the volume flow set during operation, the following refrigerant mass flow is found:

$$\dot{m}_K = \dot{V}_K \cdot \rho_K = 29\frac{\text{L}}{\text{h}} \cdot 1,162\frac{\text{kg}}{\text{L}} = 32,65\frac{\text{kg}}{\text{h}}$$

The value ρ_K= 1,126 kg/L stems from the manufacturer’s information for the rotometer for the R134a refrigerant at 20°C in liquid state. The rotometer is calibrated at this value.

Once the measured values (temperatures and pressures) from the refrigerant circuit are plotted on the lg pressure - enthalpy - chart , the following enthalpy values are found for the corner points.

h_1* = 403 kJ/kg

h_2* = 450 kJ/kg

$h_{3/4}$ = 235 kJ/kg

The difference in the enthalpy between the evaporator input and the state after the evaporator is defined as the specific cooling capacity q_0 .

$$q_0 = h_1 - h_{3/4}$$

$$q_0 = 403\frac{\text{kJ}}{\text{kg}} - 235\frac{\text{kJ}}{\text{kg}} = 168\frac{\text{kJ}}{\text{kg}}$$

The cooling capacity $\dot{Q}_0$ is then the product of the refrigerant mass flow and the specific cooling capacity.

$$\dot{Q}_0 = \dot{m}_K \cdot q_0$$

$$\dot{Q}_0 = 32,65\frac{\text{kJ}}{\text{h}} \cdot \frac{\text{h}}{3600\text{s}} \cdot 168\frac{\text{kJ}}{\text{kg}}$$

$$\dot{Q}_0 = 1,52\text{kW}$$

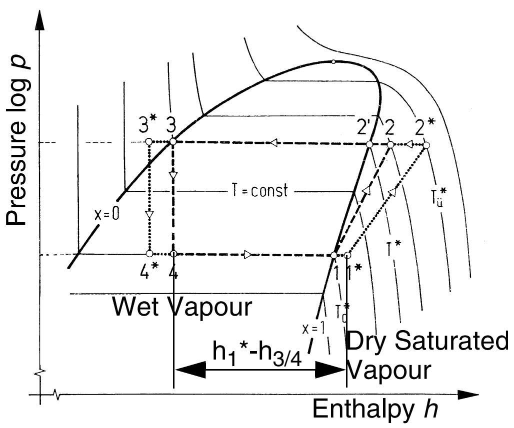


Fig. 4.5 Enthalpiedifferenz h_1*-$h_{3/4}$ im p,h-Diagramm

4.1.5 Coefficient of performance (COP)

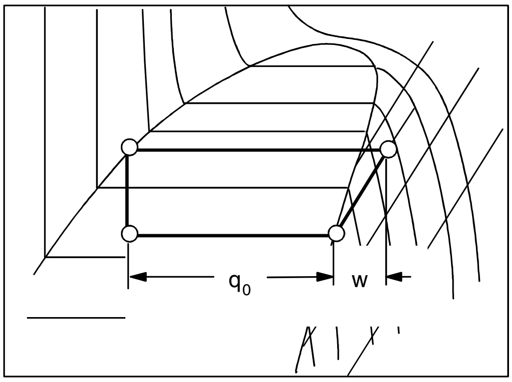


Fig. 4.6 Coefficient of performance on the pressure-enthapy-chart

The coefficient of performance ε is one of the key characteristic variables of a cooling plant. It provides information on how many kJ of cooling (heating) can be achieved per kJ of compressor work. It is calculated by the division of the cooling capacity by the compressor work or with the corresponding specific sizes.

$$\varepsilon = \frac{\text{Kältegewinn kWh}}{\text{Arbeitsaufwand kWh}}$$

$$\varepsilon = \frac{\dot{Q}_0}{W}$$

$$\varepsilon = \frac{q_0}{w}$$

The specific compressor work w defines which type of coefficient of performance is determined. A differentiation is made principally between:

$$\varepsilon_{theo} = \frac{q_0}{w_{theo}}$$, theoretical coefficient of performance

$$\varepsilon_{act} = \frac{q_0}{w_i}$$, actual coefficient of performance

The actual compressor work w_i can be calculated directly from the measured values and is determined from the difference between h_2* and h_1*.

$$w_i = h_2{}^* - h_1{}^*$$

$$w_i = 450\frac{\text{kJ}}{\text{kg}} - 403\frac{\text{kJ}}{\text{kg}} = 47\frac{\text{kJ}}{\text{kg}}$$

This yields an actual output coefficient of:

$$\varepsilon_{act} = \frac{168\frac{\text{kJ}}{\text{kg}}}{47\frac{\text{kJ}}{\text{kg}}} = 3{,}57$$

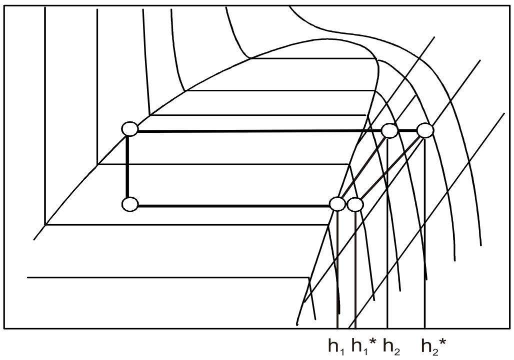


Fig. 4.7 Lossy Compression on pressure - enthalpy - chart

The theoretical compressor work w_{theo} can be determined by drawing using the pressure - enthalpy - chart . The theoretical compressor work is characterised by isentropic (loss free) compression. If the isentrope is plotted from point 1* to the $p_{2/3}$ pressure line, point 2 is at the intersection of these two lines. For the refrigeration unit of the device, this point yields an enthalpy of:

$$h_2 = 430\frac{kJ}{kg}$$

The work of the loss free compression process is defined by the difference between the enthalpies h_1 and h_2.

$$w_{theo} = h_2 - h_1$$

If the measured values are now input into this formula, the theoretical compressor work is determined as:

$$w_{theo} = 405\frac{kJ}{kg} - 370\frac{kJ}{kg} = 35\frac{kJ}{kg}$$

This yields a theoretical coefficient of performance:

$$\varepsilon_{theo} = \frac{168\frac{kJ}{kg}}{35\frac{kJ}{kg}} = 4{,}8$$

Apart from the coefficients of performance calculated here there is also the effective coefficient of performance ε_e. This is formed from the product of the actual coefficient of performance and the mechanical efficiency η_m of the compressor.

$$\varepsilon_e = \varepsilon_{act} \cdot \eta_m$$

The mechanical efficiency of the reciprocating piston compressor used is 0,8, yielding the following effective coefficient of performance.

$$\varepsilon_e = 3{,}57 \cdot 0{,}8 = 2{,}85$$

If you include all losses and efficiencies, you come to a definition in which the coefficient of performance of the specified heating power is stated in relation to the drive power that is electrically expended.

$$\varepsilon = \frac{\dot{Q}_0}{P_{el}}$$

4.1.6 Compressor output

A differentiation is made between several forms of compressor output P:

Theoretical Compressor Output:

$$P_{theo} = \dot{m}_K \cdot w_{theo}$$

Internal Compressor Output:

$$P_i = \dot{m}_K \cdot w_i$$

Compressor Drive Power or Coupled Output:

$$P_K = \frac{P_i}{\eta_m}$$

If the previously measured and calculated values are input into these formulae, then the following results are obtained:

$$P_{theo} = 0{,}009069 \frac{\text{kg}}{\text{s}} \cdot 60 \frac{\text{kJ}}{\text{kg}} = 0{,}54 \text{ kW}$$

$$P_\text{i} = 0{,}009069 \frac{\text{kg}}{\text{s}} \cdot 47 \frac{\text{kJ}}{\text{kg}} = 0{,}43 \text{ kW}$$

$$P_K = \frac{0{,}54 \text{ kW}}{0{,}8} = 0{,}675 \text{ kW}$$

4.1.7 Further Characteristic Variables

Apart from the characteristic variables addressed above, there are other characterising parameters which are used in refrigeration engineering to evaluate and classify cooling plants.

The performance factor η_g of the compressor is such a characteristic variable. This is calculated according to the following formula:

$$\eta_g = \frac{w_{theo}}{w_i}$$

This yields a performance factor for the reciprocating piston compressor of the device of:

$$\eta_g = \frac{h_2 - h_1}{h_2{*} - h_1{*}} = \frac{35\frac{\text{kJ}}{\text{kg}}}{40\frac{\text{kJ}}{\text{kg}}}$$

$$\eta_g = 0{,}875$$

The compressor compression ratio Ψ is also considered a characteristic variable of a cooling plant. This ratio defines the pressure increase that occurs in the compressor. For the device this ratio is determined as follows:

$$\Psi = \frac{p_{2/3}}{p_{1/4}} = \frac{8\text{ bar (abs)}}{1{,}4\text{ bar (abs)}} = 5{,}71$$

In practice this value should not be above 7 for a single stage compressor. If this limit is exceeded then a multiple stage compressor should be used.

4.1.8 Heat output at the condenser

The heat output is calculated from the difference in the enthalpies between points 2* and 3, which is also described as the specific heat output q_K, and the refrigerant mass flow. The following formula is used to calculate the heat output:

$$\dot{Q}_K = (h_{2^*} - h_{3/4}) \cdot \dot{m}_K = q_K \cdot \dot{m}_K$$

If one now puts the measured and calculated values in this equation, the result is a heat output of:

$$\dot{Q}_K = \left(450\frac{kJ}{kg} - 235\frac{kJ}{kg}\right) \cdot 32{,}65\frac{kg}{h} = 7019{,}75\frac{kJ}{h}$$

$$\dot{Q}_K = 7019{,}75\frac{kJ}{h} \cdot \frac{1\ h}{3600\ s} = 1{,}949 kW$$

4.1.9 Capacity of the Ice Store

To melt 1 kg of ice, $c = 333{,}5$ kJ of energy at constant temperature must be supplied (exact the spezific heat of fusion $c = 333{,}5$ kJ/kg). In order to determine the storage capacity of the ice store, the volume of ice must be known.

This was established after charging for 10 hours by emptying the remaining water. Of the 150 litres added at the start, 100 litres were drained. Thus 50 litres were frozen into ice.

The storage density q is the product of the density of the $\rho = 916$ kg / m^3 and the heat of fusion *c.*

$$q = \rho \cdot c$$

$$q = 916\frac{kg}{m^3} \cdot 332{,}5\frac{kJ}{kg} = 304570\frac{kJ}{m^3}$$

This yields a capacity of the Ice Store of:

$$E_{Store} = q \cdot V_{Ice}$$

$$E_{Store} = 304570 \frac{\text{kJ}}{\text{m}^3} \cdot 0{,}05\ \text{m}^3 = 15228{,}5\ \text{kJ}$$

$$15228{,}5\ \text{kJ} = 4{,}23\ \text{kWh}$$

Thus in discharge mode 1 kW of cooling power can be drawn for approx. 4 hours, or at the cooling capacity calculated in charging mode of approx. 2 kW, cooling can be provided at full load for 2 hours following failure of the cooling unit.

4.1.10 Concluding Energy Balance

Finally an energy balance should be drawn up by equating the heat output $\dot{Q}_K$. The sum of all energy supplied must equal the sum of all energy extracted:

$$\dot{Q}_K = \dot{Q}_0 + P_i$$

$$Q_K = 1{,}52\ \text{kW} + 0{,}43\ \text{kW} = 1{,}95\ \text{kW}$$

This value agrees with the value calculated for $\dot{Q}_K$ = 1.96 kW in Chapter 4.1.8 to within 10 W.

5 Appendix

5.1 Technical Data

Basic unit:

Overall dimensions

Lenght x Depth x Heigh	1950 x 800 x 1900	mm
Weight	130	kg

Elec. supply

Voltage	230	V
Frequency	50	Hz
Phase	1	Ph
Nominal power consumption	2	kW
Alternatives optional, see Type plate		

Capacities (incl. dry cooling tower)

Water	27	L
Propylene-Glycol	18	L

Temperature measurment

Qty. 4 PTC-Semiconductor sensors with digital display, 3,5-digit		
Measurement accuracy	±2	°C
Qty. 2 Bi-metallic dial thermometer		
Measurement range	0...60	°C
Precision class	1.5	
Qty. 4 Bi-metallic dial thermometer		
Measurement range	-20...40	°C
Precision class	1.5	

Pressure measurement

Qty. 1 Spring-tube manometer	
Measurement range	-1...9 bar
Precision class	1.0
Qty. 1 Spring-tube manometer	
Measurement range	-1...24 bar
Precision class	1.0

Flow measurement

Qty. 1 Rotameter	
Glykol/ Water	
Measurement range	106...1060 L/h
Precision class	1.5
Qty. 1 Rotameter	
R134a	
Measurement range	8...102 L/h
Precision class	1.5

Components

Qty. 1 Refrigeration unit	
Refrigerant	R134a
Elec. Supply	230 V/50 Hz
Elec. power consumption	2200 W
Qty. 1 Ice store	
Contents	150 L
Qty. 1 Circulation pump	
Type: UPS 25-80	
Pump head	8 m
Pump capacity	140 L/min

Qty. 1 Circulation pump		
Type: UPS 25-40		
Pump head	4	m
Pump capacity	60	L/min
Qty. 1 High pressure rotary pump		
Type: In-V2-10		
Pump head	8,2	m
Pump capacity	36	L/min
Qty. 4 Three-way-valve		
Manually operated	DN 20	
Qty. 1 Pressostat		
Type: KP17W Kombi		
Low pressure range	-0,2...7,5	bar
High pressure range	0,7...4	bar
Difference	4	bar
Qty. 1 Expansion valve		
R134a		
Nominal rating at -15°C	1,8	kW
QTY 1 Filter dryer		
Type: DN 162	10	mm
Qty. 1 Sight glass		

Wet cooling tower

Overall dimensions:		
Length x Depth x Height	1350 x 636 x 1850	mm
Weight	70	kg
Elec. Supply	230 V/ 50 Hz	
Cooling tower		
Volume flow	1,1	m^3/h
Cooling capacity	12,8	kW
Pressure loss	0,28	bar
Water capacity	60	L
Temperature Measurement		
Qty. 3 Bi-metallic dial thermometers		
Measurement range	0...60	°C
Precision class	1.5	
Flow measurement		
Qty. 1 Rotameter		
Water		
Measurement range	395...3995	L/h
Precision class	1.5	
Components		
Qty. 1 High pressure rotary pump		
Type: In-V2-10		
Pump head	8,2	m
Pump capacity	36	L/min
Qty. 1 three way valve manually operated	DN 20	
Qty. 1 Magnetic valve		
2/2 Ways		

Dry cooling tower

Overall dimensions:	
Lenght x Depth x Height	710 x 600 x 550 mm
Weight	45 kg
Elec. Supply	230 V/ 50 Hz
Axial recooler	
Volume flow	700 L/h
Cooling capacity	3 kW
Pressure loss	0,03 bar
Air flow	1330 m^3/h
Temperature measurement	
Qty. 2 Bi-metallic dial thermometes	
Measurement range	0...60 °C
Precision class	1.5

5.2 List of abbreviations

Abbreviation	Meaning
VT	Flow Dry Cooling Tower
RT	Return Dry Cooling Tower
VN	Flow Wet Cooling Tower
RN	Return Wet Cooling Tower
R134a	Refrigerant (Company: Solvey)
COP	Coefficient Of Performance

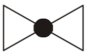
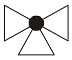
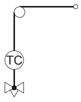
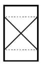
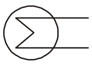
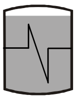
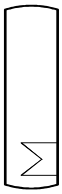
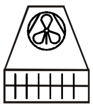
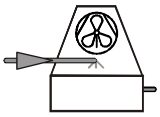
5.3 List of key symbols and units used

Symbols	Explanation, definition	Unit
c	Specific Heat of Fusion	kJ/kg
E_{Store}	Capacity of the Ice Store	kJ
H	Enthalpy	kJ
h	Specific Enthalpy	kJ/kg
$\dot{m}_K$	Refrigerant Mass Flow	kg/s
P_{theo}	Theoretic Compressor Output	kW
P_i	Internal Compressor Output	kW
P_K	Compressor Drive Power or Coupled Output	kW
p	Pressure	bar
$p_{suction}=p_1$	Pressure on the suction side of the compressor	bar
$p_{delivery}=p_2$	Pressure on the delivery side of the compressor	bar
$\dot{Q}_{out}$	Heat Output (Kondenser)	kW
$\dot{Q}_{in}$	Heat Input (Verdampfer)	kW
$\dot{Q}_0$	Cooling Capacity	kW
q	Storage Density	kJ/m^3
q_0	Specific Cooling Capacity	
t_0	Reference Temperature	°C
U	Internal Energy	kJ
u	Specific Internal Energy	kJ/kg
V	Volume	m^3
V_{Ice}	Ice Volume	m^3
$\dot{V}_K$	Refrigerant Volume Flow	kg/s
v	Specific Volume	m^3/kg
w	Specific Work	kJ/kg
$\dot{w}_{theo}$	Specific Theoretic Compressor Work	kJ/kg
$\dot{w}_i$	Specific Internal Compressor Work	kJ/kg
$\dot{W}_{in}$	Mechanical Work Input (Compressor)	kW

Symbols	Explanation, definition	Unit
ε	Coefficient of Performance COP	-
ρ	Density	kg/m^3
ρ_K	Density of Refrigerant	kg/m^3
η_m	Mechanical Efficience of the Compressor	%
η_g	Performance Faktor	%
Ψ	Compressor Compression Ratio	-

Index	Erläuterung	
a	Luft	(Englisch „air“)
actual	tatsächlich	(Englisch „actual“)
adm	zulässig	(Englisch „admissible“)
calc	berechnet	(Englisch „calculated“)
const	konstant	(Englisch „constant“)
effective	nutzbar	(Englisch „effective“)
h	oberer	(Englisch „high“)
ideal	ideal	(Englisch „ideal“)
in	eingehend	(Englisch „in“)
in	zugeführt	(Englisch „in“)
l	unterer	(Englisch „low“)
meas	gemessen	(Englisch „measured“)
out	abgehend	(Englisch „out“)
out	abgegeben	(Englisch „out“)
real	real	(Englisch „real“)
theo	theoretisch	(Englisch „theoretical“)

5.4 Liste der Symbole im Prozessschema

Symbol	Benennung
	Valve
	Three-Way-Valve
	Expansion Valve
	Filter/ Dryer
	Sight Glass
	Compressor
	Pumpe
	Heat exchanger
	Ice Store (Tank with heat exchanger)
	Intermediate Storage (Tank with heat exchanger)
	Dry Cooling Tower
	Wet Cooling Tower

5.5 List of code letters in process schematics

Code letter	Name
Equipment and machines	
A	Plant component or machine, unless assigned to one of the groups below
B	Tank, bunker, silo, vessel
F	Filter apparatus, liquid filter, gas filter, sieve apparatus, separator
P	Pump
V	Compressor, vacuum pump, fan
W	Heat exchanger
Fittings	
V	Valve, general

Tab. 5.1 Code letters for equipment, machines, fittings and pipes

Code letter	Measured variable or other input variable, actuator		Processing
	As first letter	As supplementary letter	As following letter (sequence I, R, C)
F	Flow rate, throughput	Ratio	
H	Hand-operated, manual		Upper limit (high)
I			Display
P	Pressure		
T	Temperature		Transmitter

Tab. 5.2 Kennbuchstaben für Messpunkte

5.6 Tabels and Charts

Units	mm^3	cm^3	L	m^3
1 mm^3	1	0,001	0,000001	0,000000001
1 cm^3	1.000	1	0,001	0,000001
1 L	1.000.000	1.000	1	0,001
1 m^3	1.000.000.000	1.000.000	1.000	1

Tab. 5.3 Conversiontable - Volume Units

Units	L/s	L/min	L/h	m^3/min	m^3/h
1 L/s	1	60	3600	0,06	3,6
1 L/min	0,01667	1	60	0,001	0,06
1 L/h	0,000278	0,01667	1	0,00001667	0,001
1 m^3/min	16,667	1000	0,0006	1	60
1 m^3/h	0,278	16,667	1000	0,01667	1

Tab. 5.4 Conversiontable - Volume Flow Units

Units	bar	mbar	Pa	kPa
1 bar	1	1000	100000	100
1 mbar	0,001	1	100	0,1
1 Pa	0,00001	0,01	1	0,001
1 kPa	0,01	10	1000	1

Tab. 5.5 Conversiontable - Pressure Units

6 Index

A

B

C

D

E

F

I

M

P

R

S

T