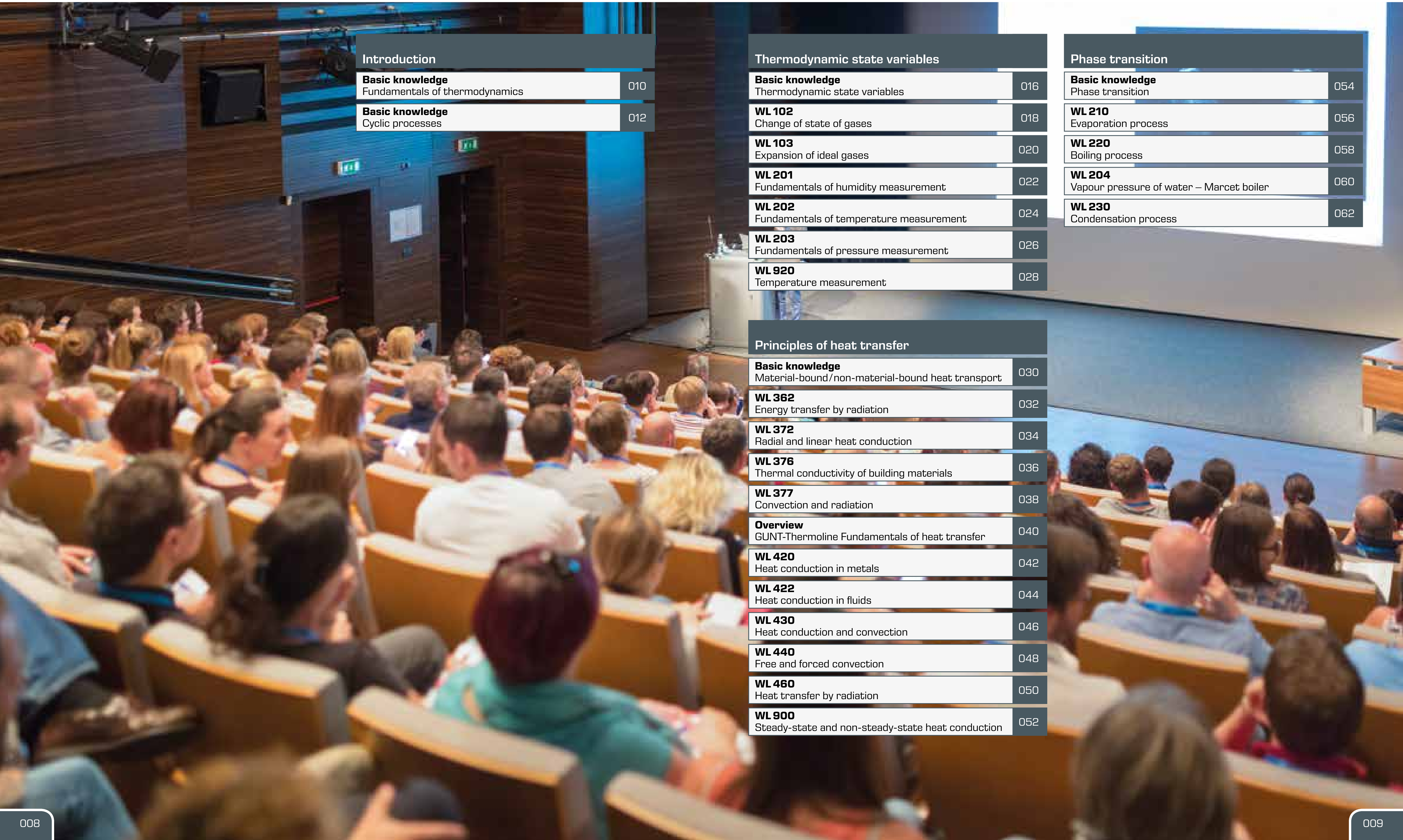
1 Fundamentals of thermodynamics



Introduction

Thermodynamic state variables

Principles of heat transfer

Phase transition

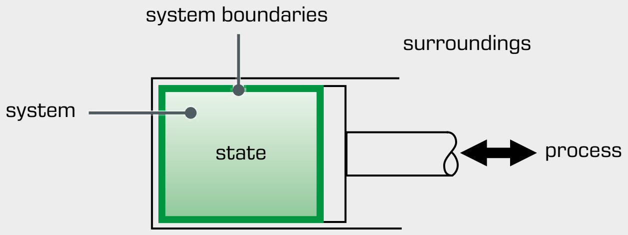
Basic knowledge

Fundamentals of thermodynamics

Thermodynamics is the general theory of energy and material transformation processes: Work is performed by redistributing energy between its different manifestations. The fundamentals of thermodynamics were developed from the study of volume, pressure, and temperature in steam engines. The following topics are selected based on the devices listed in this chapter.

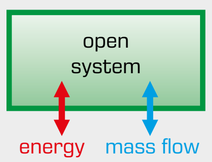
Thermodynamic systems and principles

- **system:** area of the thermodynamic examination
- **surroundings:** area outside the system
- **system boundaries:** separation of the system from its surroundings
- **process:** external impacts on the system
- **state:** collectivity of measurable properties within the system
- **state variables:** all measurable properties of the system that can be used to describe its state
- **change of state:** effect a process has on the state



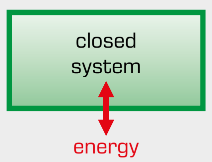
Open system

Energy or mass can be exchanged with the surroundings outside the system boundaries



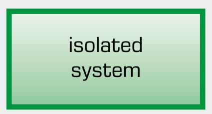
Closed system

No mass crosses the system boundary



Isolated system

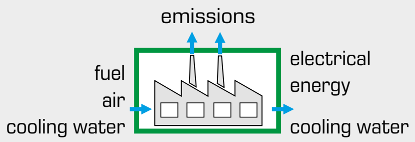
Neither mass nor energy cross the system boundaries



no exchange

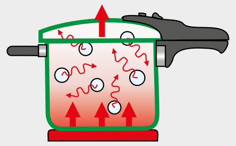
Energy transfer in the form of heat or work has the following effects in the three systems:

The energy content of the mass flow changes



Example: thermal power plant

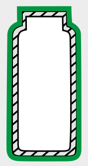
The internal system energy increases



Example: pressure cooker

The energy is constant

Thermodynamic energy conversion can take place inside the system.



Example: an ideal thermos flask

Thermodynamic laws

1st law of thermodynamics

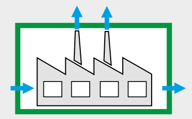
Conservation of energy in thermodynamic systems

Energy can neither be created nor destroyed, it can only be transformed.

The meaning for the three systems is illustrated in the lower left corner.

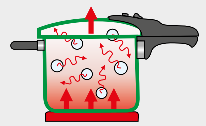
Open system

The energy content of the **mass flow** changes



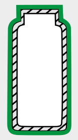
Closed system

The **internal energy** changes



Isolated system

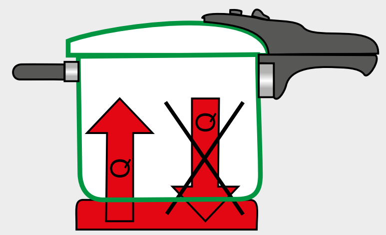
The **energy** is constant



2nd law of thermodynamics

All natural and technical processes are irreversible.

The second law places a limitation on the first law because, in reality, some energy will dissipate into the surroundings during every process. This energy can neither be used nor transformed back.



Referring to the example of the pressure cooker:

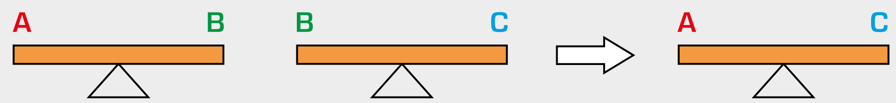
after the inside of the cooker has warmed up, the heat in the cooker cannot flow back into the heating plate.

3rd law of thermodynamics = Nernst heat theorem

The absolute zero point of 0 Kelvin is a theoretical quantity. It cannot be achieved in practice. The lowest temperature achieved to date is $2 \cdot 10^{-5}$ K.

Zeroth law of thermodynamics = law of thermal equilibrium

System A is in thermal equilibrium with system B. System B is in thermal equilibrium with system C. This means that the two systems A and C must also be in thermal equilibrium with each other.



Chronologically, the zeroth law was only formulated after the other three. Since it is fundamental to thermodynamics, it was prepended to the other three laws. This law was therefore designated as 'zeroth' to avoid having to change the names of the laws that had already been assigned.

Basic knowledge

Cyclic processes

Technology uses **cyclic thermodynamic processes** to describe the conversion of thermal energy to mechanical energy and vice versa.

During this process a medium undergoes periodically different **changes of state**, such as compression and expansion, evaporation and condensation, or heating and cooling over a period of time. In a cyclic process, the medium, after having undergone the different changes of state, goes back to its original state and can thus be reused repeatedly.

Suitable media are substances that remain in a permanent gaseous state during the cyclic process, such as air or helium, or substances that change their aggregate state during the process (phase change), like water, ammonia, fluorocarbons, or CO_2.

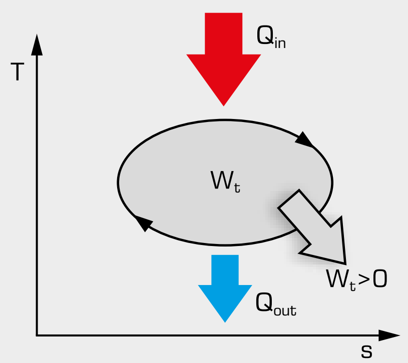
When a **phase change** occurs, more energy is converted than during simple heating or cooling. This means that phase change processes involve a higher energy density and require lower differences in temperature.

Cyclic processes can be used in driving or driven machines. Driving machines convert thermal energy to mechanical energy, such as in steam power plants. Driven machines convert the supplied mechanical energy into thermal energy, like in a compression refrigeration system.

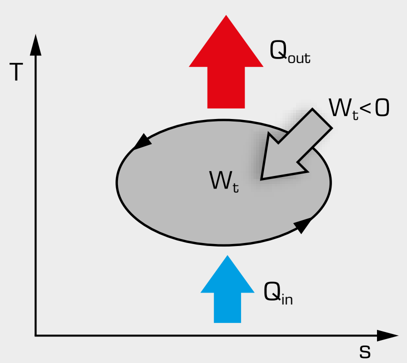
Representation of cyclic processes in state diagrams

A cyclic thermodynamic process can be illustrated clearly by what are known as state diagrams. The most commonly used state diagrams are:

- **p-v diagram:** pressure **p** against specific volume **v**, suitable for representing mechanical power. It is often used for reciprocating compressors and internal combustion engines with a purely gaseous working medium. Here, cyclic processes can be observed quite well because there is a fixed relationship between volume change and time. The enclosed area is a measure for the mechanical work performed, also known as useful work.
- **h-s diagram:** enthalpy **h** against entropy **s**, for representation of steam turbine processes. It is used for water steam and is well suited as a tool for designing steam turbines.
- **log p-h diagram:** logarithmic representation of the pressure **p** against the specific enthalpy **h**, particularly well suited for cooling processes in refrigeration engineering, as heat fluxes can be read from the diagram directly as horizontal lines. For the vertical pressure scale, a logarithmic division is used, as this is a good way to represent phase limit curves.
- **T-s diagram:** a plot of temperature **T** against entropy **s**, used for the representation of the thermodynamic conditions. The direction of the cyclic process indicates the type of system, driving or driven machine. If the cycle goes **clockwise**, the system is a driving machine, and if it goes **counter-clockwise**, it is a driven machine. In the clockwise direction, heat is absorbed at a high temperature and released at a low temperature. In the counter-clockwise direction, heat is absorbed at a low temperature and released at a high temperature. If the system is operated in the counter-clockwise direction, it is thus suitable as a heat pump or refrigeration machine. As in the p-v diagram, the enclosed area is a measure of the useful work performed.



Clockwise direction: driving machine



Counter-clockwise direction: driven machine

W_t useful work, **Q** thermal energy, **T** temperature, **s** entropy

Examples of cyclic thermodynamic processes

Type	Driving or driven machine	Working medium	Aggregate state
Steam power plant	driving	water	liquid/gaseous
Internal combustion engine	driving	air/combustion gas	gaseous
Gas turbine	driving	air/combustion gas	gaseous
Stirling engine	driving	air, helium	gaseous
ORC power plant (Organic Rankine Cycle)	driving	fluorocarbons, hydrocarbons	liquid/gaseous
Refrigeration machine	driven	fluorocarbons, hydrocarbons, ammonia, etc.	liquid/gaseous
Stirling refrigeration system	driven	air, helium	gaseous

The following section presents some technically relevant cyclic processes with their diagrams.

The Carnot process

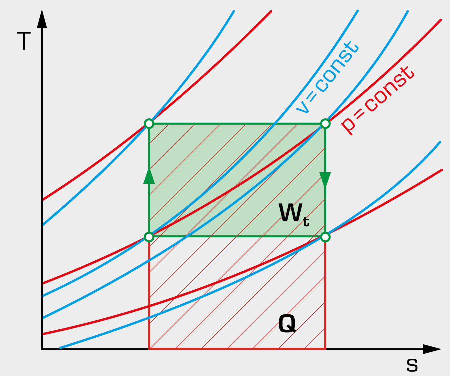
In the T-s diagram, the Carnot process forms a rectangle. The area of the rectangle is a measure of the useful work W_t. The area between the temperature zero and the maximum process temperature is a measure of the required thermal energy **Q**. This means that the following efficiency η results are derived for the Carnot process:

$$\eta = \frac{W_t}{Q} = \frac{T_{max} - T_{min}}{T_{max}}$$

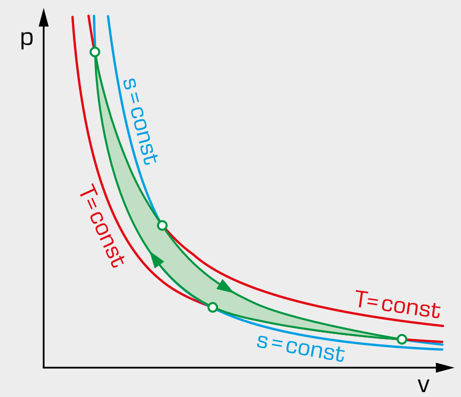
The maximum efficiency of a cyclic thermodynamic process thus only depends on the absolute maximum and minimum temperatures, T_{max} and T_{min}. This means that the Carnot process allows statements regarding the quality of any technical cyclic process. Furthermore, it is clear that every thermodynamic process requires a difference in temperatures to perform work. The efficiency of the Carnot process is the highest theoretically possible efficiency of a cyclic process.

The changes of state that are necessary for the Carnot process, like isothermal and isentropic compression and/or expansion, are difficult to realise technically. Despite its high efficiency, this process is therefore of theoretical interest only.

The p-v diagram on the right shows another crucial disadvantage of the Carnot process. Despite large differences in pressure and volume, the surface area of the diagram, and thus the mechanical work performed, is very small. When the Carnot process is applied, this translates to a large and heavy machine with a small output.



Carnot process in T-s diagram



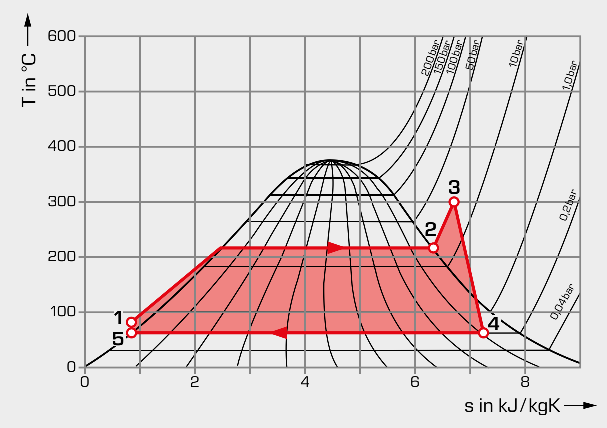
Carnot process in p-v diagram

W_t useful work, **Q** thermal energy, **T** temperature, **p** pressure, **v** specific volume, **s** entropy

Basic knowledge

Cyclic processes

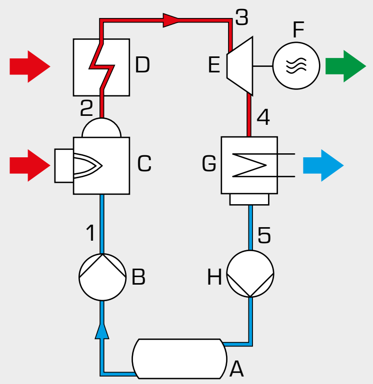
Steam power plant



T-s diagram of a steam power plant

The above T-s diagram represents the Rankine cycle of a steam power plant. The working medium is water or water steam.

1 – 2 the water is **isobarically** heated and evaporated in a steam boiler at a pressure of 22 bar
2 – 3 **isobaric** superheating of the steam to 300°C
3 – 4 **polytropic** expansion of the steam in the steam turbine to a pressure of 0,2 bar; mechanical energy is released in the process
Point 4 wet steam area: the wet steam content is now only 90 %
4 – 5 condensation of the steam
5 – 1 increase of the pressure to boiler pressure via the condensate and feed water pump, the cyclic process is complete

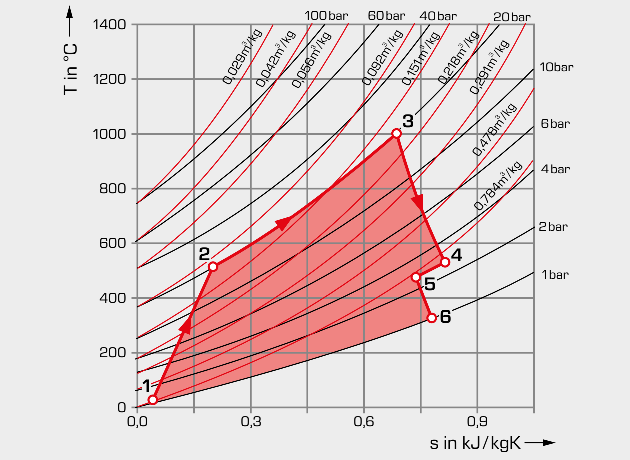


Process schematic for a steam power plant

A feed water tank, **B** feed water pump, **C** steam boiler, **D** superheater, **E** steam turbine, **F** generator, **G** condenser, **H** condensate pump;

thermal energy, low temperature,
thermal energy, high temperature,
mechanical/electrical energy

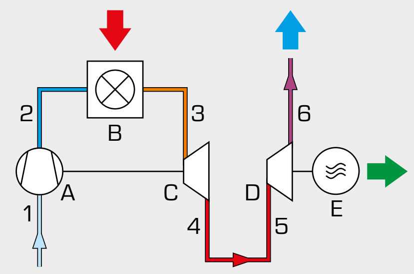
Gas turbine power plant



T-s diagram of a gas turbine power plant

The T-s diagram represents a gas turbine process with two-stage expansion in a double shaft system.

1 – 2 **polytropic** compression of air to a pressure of 20 bar; the air has a temperature of 500°C at the outlet of the compressor
2 – 3 **isobaric** heating of air to the inlet temperature of 1000°C of the high-pressure turbine via injection and combustion of fuel
3 – 4 **polytropic** expansion in the high-pressure turbine that drives the compressor
Point 5 in the transition to the power turbine the gas **isobarically** cools down slightly
5 – 6 second expansion in the power turbine: the exhaust gas exhausts and is not returned to the process again, which is why the process is known as an open gas turbine process; the process heat is released into the surroundings

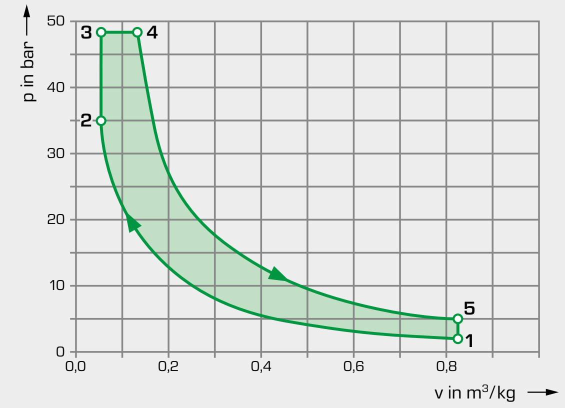


Process schematic for a gas turbine power plant

A compressor, **B** combustion chamber, **C** high-pressure turbine, **D** power turbine, **E** generator;

thermal energy, low temperature,
thermal energy, high temperature,
exhaust gas, mechanical / electrical energy

Internal combustion engine



p-v diagram of an internal combustion engine

The p-v diagram shows the Seiliger process of an internal combustion engine. In the case of the internal combustion engine, all changes of state take place in the same space: the cylinder. The changes of state occur one after the other.

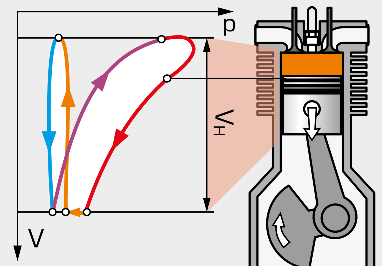
1 – 2 **polytropic** gas compression
Point 2 ignition with subsequent fuel combustion

idealised division of the combustion process into:
2 – 3 **isochoric** proportion of the combustion process
3 – 4 **isobaric** proportion of the combustion process

4 – 5 polytropic **(isentropic)** expansion, in this phase the usefull work results
5 – 1 **isochoric** decompression and exchange of working medium

In the case of a 2-stroke engine this takes place without an additional stroke, in a 4-stroke engine the exhaust and intake stroke follows. The Seiliger process, similar to the gas turbine process, is an open cyclic process.

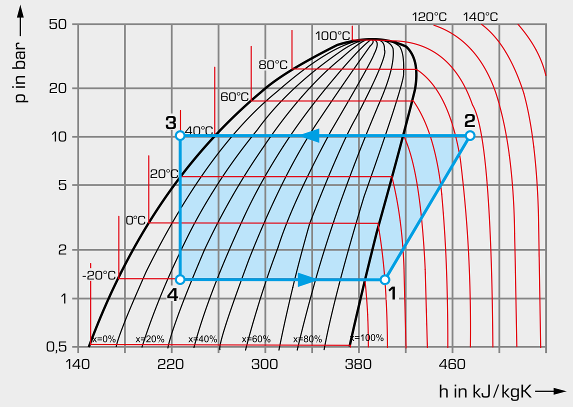
The Seiliger process is a comparative or ideal process that is based on the assumption of a perfect engine. The indicator diagram represents the actual work process.



Indicator diagram of a 4-stroke engine

p pressure, **V** volume, $\mathbf{V_H}$ displaced volume;
intake, compression, power, exhaust

Refrigeration plant

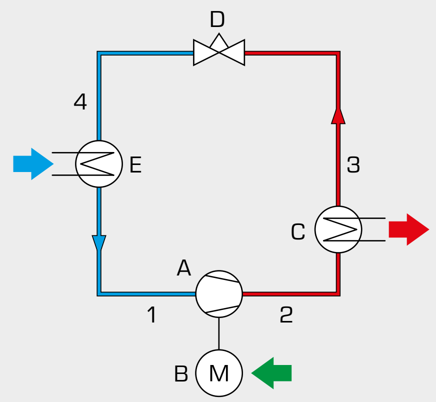


log p-h diagram of a refrigeration plant

This log p-h diagram displays a refrigeration cycle. Working medium is the fluorohydrocarbon refrigerant R134a.

1 – 2 **polytropic** compression
2 – 3 **isobaric** cooling and condensation with heat dissipation
3 – 4 **isenthalpic** expansion to evaporation pressure
4 – 1 **isobaric** evaporation with heat absorption

After being superheated to a certain degree the refrigerant vapour is once again sucked in and compressed by the compressor at point 1. The cyclic process ends.



Process schematic of a refrigeration plant

A compressor, **B** drive motor, **C** condenser, **D** expansion valve, **E** evaporator;

thermal energy, low temperature,
thermal energy, high temperature,
mechanical / electrical energy

Basic knowledge

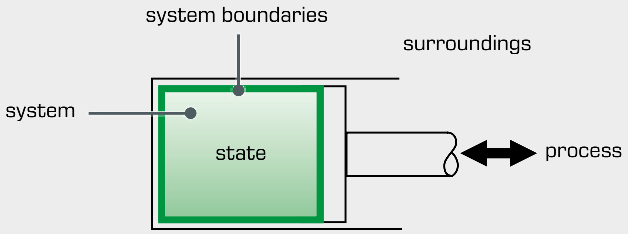
Thermodynamic state variables

Thermodynamic systems and principles

State variables are the measurable properties of a system. To describe the state of a system at least two independent state variables must be given.

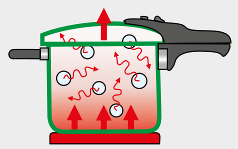
State variables are e.g.:

- pressure (**p**)
- temperature (**T**)
- volume (**V**)
- amount of substance (**n**)



The state functions can be derived from the state variables:

- **internal energy (U):** the thermal energy of a static, closed system. When external energy is added, processes result in a change of the internal energy.
  $\Delta U = Q + W$
  - **Q:** thermal energy added to the system,
  - **W:** mechanical work done on the system that results in an addition of heat
- **enthalpy (H):** defined as the sum of internal energy plus work **$p \times V$**
  $H = U + p \times V$
- **entropy (S)**: provides information on the order in a system and the associated arrangement options of particles in that system
  The change in entropy **dS** is known as **reduced heat**.
  $dS = \delta Q_{rev}/T$
  - **δQ_{rev}**: reversible heat change
  - **T:** absolute temperature



An increase in the internal energy of the system using a pressure cooker as an example.

Steam engine

When the steam engine was developed more than 200 years ago, physicists wondered why only a few percent of the thermal energy was converted into mechanical energy. Rudolf Clausius introduced the term entropy to explain why the efficiency of thermal engines is limited to a few percent. Thermal engines convert a temperature difference into mechanical work. Thermal engines include steam engines, steam turbines or internal combustion engines.

V6 engine of a racing car

Disassembled steam turbine rotor

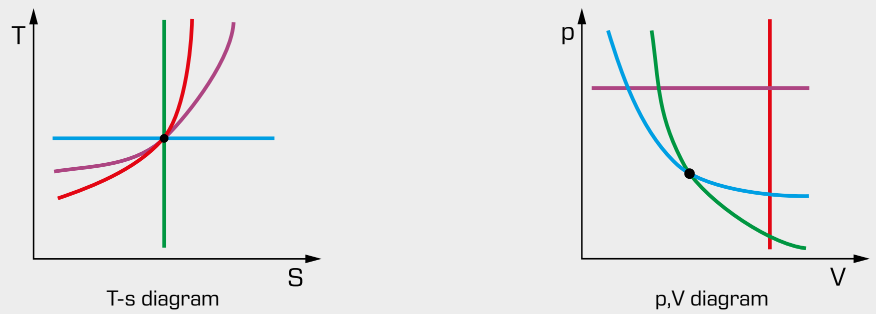
Change of state of gases

In physics, an idealised model of a real gas was introduced to make it easier to explain the behaviour of gases. This model is a highly simplified representation of the real states and is known as an "ideal gas". Many thermodynamic processes in gases in particular can be explained and described mathematically with the help of this model.

Equation of state for ideal gases:
$p \times V = m \times R_s \times T$
- **m**: mass
- **R_s**: spec. gas constant of the corresponding gas

Changes of state of an ideal gas

Change of state	isochoric	isobaric	isothermal	isentropic
Condition	V = constant	p = constant	T = constant	S = constant
Result	dV = 0	dp = 0	dT = 0	dS = 0
Law	p/T = constant	V/T = constant	p×V = constant	$p \times V^{\kappa}$ = constant κ = isentropic exponent



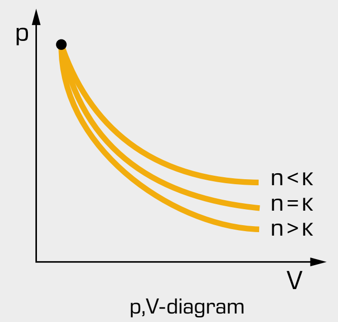
Changes of state can be clearly illustrated in diagrams

Changes of state under real conditions

Change of state	polytropic
Condition	technical process under real conditions
Result	heat exchange with the environment
Law	$p \times V^n$ = constant n = polytropic exponent

The changes of state listed above are special cases of polytropic change of state, in which part of the heat is exchanged with the environment.

- isochoric $n \rightarrow \infty$
- isobaric $n = 0$
- isothermal $n = 1$
- isentropic $n = \kappa$



Polytropic changes of state with different heat exchange:
n<κ heat dissipation
n>κ heat absorption

WL 102
Change of state of gases

Description

- **isothermal and isochoric change of state of air**
- **GUNT software for acquisition, processing and display of measured data**

Gas laws belong to the fundamentals of thermodynamics and are dealt with in every training course on thermodynamics.

The WL 102 experimental unit enables two changes of state to be studied experimentally: isothermal change of state, also known as the Boyle-Mariotte law, and isochoric change of state, which occurs at constant volume. Transparent tanks enable the change of state to be observed. Air is used as the test gas.

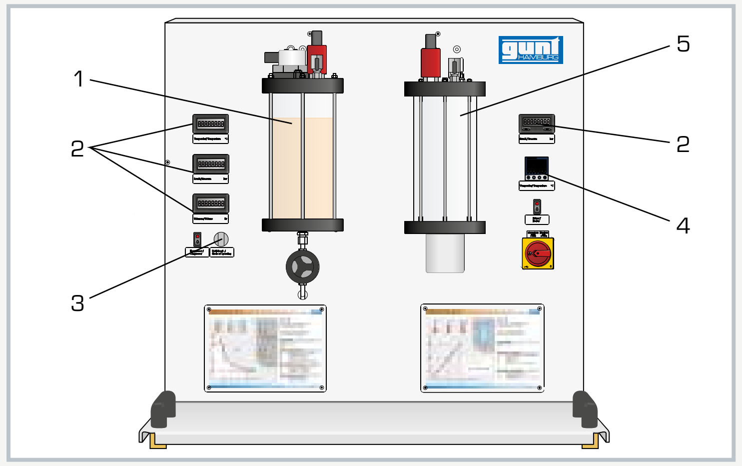
In the first tank, positioned on the left, the hermetically enclosed air volume is reduced or increased using a compressor and hydraulic oil. This results in an isothermal change of state. The compressor can also operate as a vacuum pump. If the changes occur slowly, the change of state takes place at an almost constant temperature.

In the second tank, positioned on the right, the temperature of the test gas is increased by a controlled electric heater and the resulting pressure rise is measured. The volume of the enclosed gas remains constant. Temperatures, pressures and volumes are measured electronically, digitally displayed and transferred to a PC for processing.

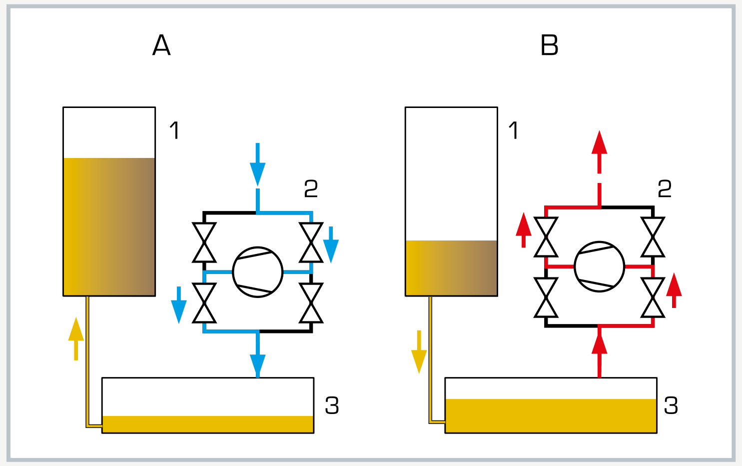
Learning objectives/experiments

- demonstrating the laws of state changes in gases experimentally
- isothermal change of state, Boyle-Mariotte law
- isochoric change of state, Gay-Lussac's 2nd law

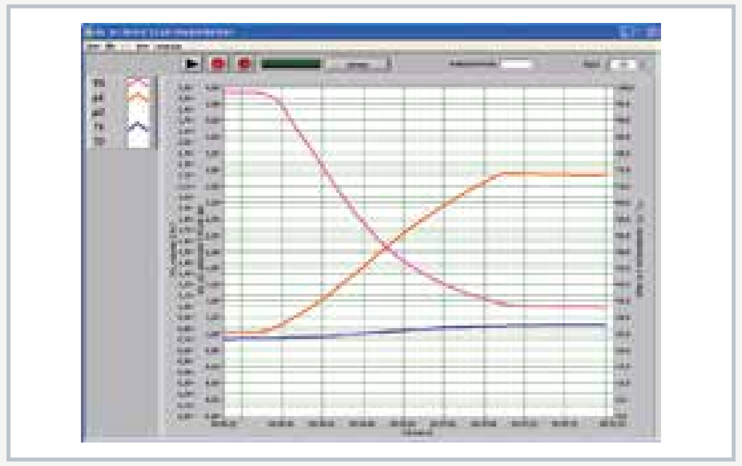
WL 102
Change of state of gases



1 tank 1 for isothermic change of state, 2 digital displays, 3 5/2-way valve for switching between compression and expansion, 4 heating controller, 5 tank 2 for isochoric change of state



Representation of the change of volume
1 oil-filled tank for isothermic change of state, 2 valve arrangement with compressor, 3 storage tank; A compression (blue), B expansion (red)



Software screenshot: charts for isothermic compression

Specification

[1] experimental investigation of gas laws
[2] transparent measuring tank 1 for investigation of isothermic change of state
[3] hydraulic oil filling for changing volume of test gas
[4] built-in compressor generates necessary pressure differences to move the oil volume
[5] compressor can also be used as vacuum pump
[6] 5/2-way valve for switching between compression and expansion
[7] transparent measuring tank 2 for investigation of isochoric change of state
[8] electrical heater with temperature control in tank 2
[9] sensors and digital displays for temperatures, pressures and volumes
[10] GUNT software for data acquisition via USB under Windows 7, 8.1, 10

Technical data

Compressor / vacuum pump
- power output: 60W
- pressure at inlet: 213mbar
- pressure at outlet: 2bar

Temperature controller: PID, 300W, limited to 80°C

Measuring ranges
- temperature:
  - tank 1: 0...80°C
  - tank 2: 0...80°C
- pressure:
  - tank 1: 0...4bar abs.
  - tank 2: 0...2bar abs.
- volume:
  - tank 1: 0...3L

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase; 120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 900x550x900mm
Weight: approx. 50kg

Required for operation

PC with Windows recommended

Scope of delivery

1 experimental unit
1 GUNT software CD + USB cable
1 set of instructional material

WL 103
Expansion of ideal gases

Learning objectives/experiments

- determination of the adiabatic exponent according to Clément-Desormes
- adiabatic change of state of air
- isochoric change of state of air

Description

- **operation with negative pressure and positive pressure**
- **precise pressure measurement**
- **experiments according to Clément-Desormes**

Gas laws belong to the fundamentals of thermodynamics and are dealt with in every training course on thermodynamics.

The experimental unit WL 103 enables the user to examine the expansion of ideal gases. The focus is on the experimental determination of the adiabatic exponent of air using the Clément-Desormes method.

The main components of the experimental unit are two interconnected cylindrical tanks. Positive pressure can be applied to one tank, negative pressure can be applied to the other tank.

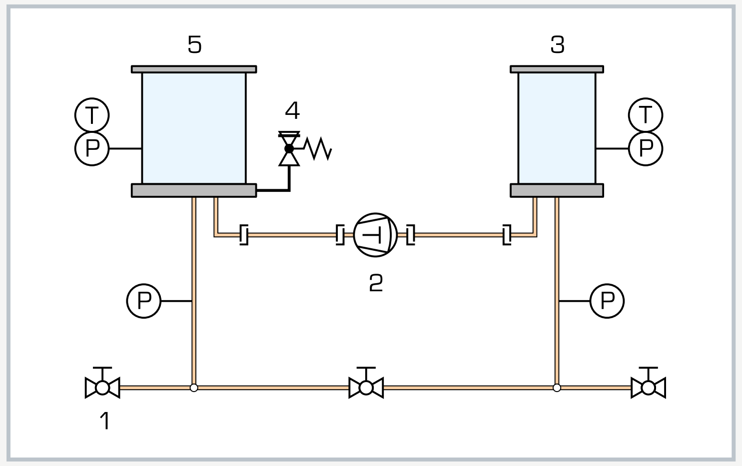
To generate the positive pressure and the negative pressure in the tanks, the tanks are connected to each other via a compressor. The pressure equalisation can either take place with the environment or with the other tank through a bypass. Due to the high velocity of the pressure compensation the change of state is quasi adiabatic. Ball valves are used for pressure equalisation.

Precise pressure measurement technology is integrated in the tanks to enable the determination of the adiabatic exponent using the Clément-Desormes method. The measured temperatures and pressures are recorded, transmitted to the software and displayed.

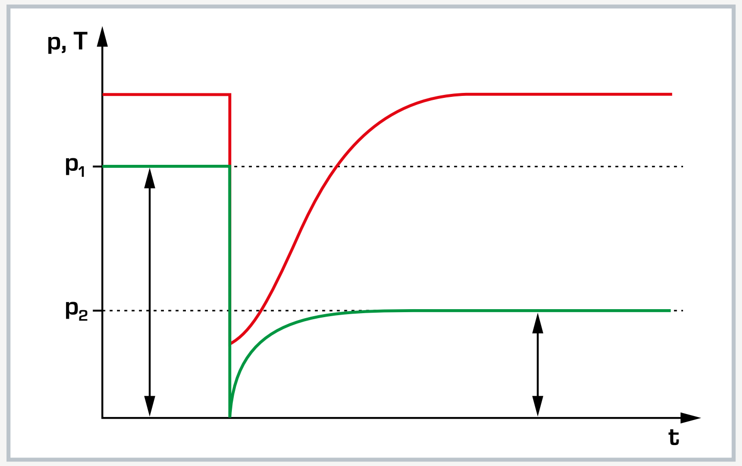
The GUNT software of WL 103 offers all the advantages of software-supported experimental procedure and analysis.

WL 103
Expansion of ideal gases

1 positive pressure tank, 2 safety valve, 3 ball valve, 4 manometer, 5 compressor, 6 negative pressure tank



1 ball valve, 2 compressor, 3 negative pressure tank, 4 safety valve, 5 positive pressure tank; P pressure, T temperature



Schematic diagram of a typical experiment according to Clément-Desormes;
p pressure, T temperature, t time, red: temperature, green: pressure

Specification

[1] behaviour of ideal gases
[2] precise measurement of pressures and temperatures
[3] transparent components
[4] experiment according to Clément-Desormes
[5] determination of the adiabatic exponent of air
[6] GUNT software with control functions and data acquisition via USB under Windows 7, 8.1, 10

Technical data

Positive pressure tank
- volume: 20,5L
- diameter: 0,25m
- max. operating pressure: 0,9bar

Negative pressure tank
- volume: 11L
- diameter: 0,18m
- min. operating pressure: -0,6bar

Measuring ranges
- temperature: 0...150°C
- pressure: 0...1,6bar (abs)

230V, 50Hz, 1 phase
LxWxH: approx. 670x590x680mm
Weight: approx. 36kg

Required for operation

PC with Windows

Scope of delivery

1 experimental unit
1 GUNT software CD + USB cable
1 set of instructional material

WL 201
Fundamentals of humidity measurement

Description

- **different measuring methods for measuring humidity**
- **climatic chamber with adjustable humidity and transparent door**

The measurement of air humidity plays an important role in many branches of industry, e.g. during drying or in the air conditioning of buildings and vehicles. There are different measuring methods to determine humidity.

The trainer WL 201 enables the measurement of air humidity with four different instruments which can be directly compared to each other: two different hygrometers, a capacitive hygrometer and a psychrometer.

Psychrometers operate based on the principle of evaporation cooling and compare the ambient temperature with the wet bulb temperature to determine the humidity. Hygrometers utilise the property of specific fibres, e.g. hair, to expand with increasing air humidity. In the capacitive sensor the dielectricity constant of a layer and with it its capacity changes due to the water molecules absorbed.

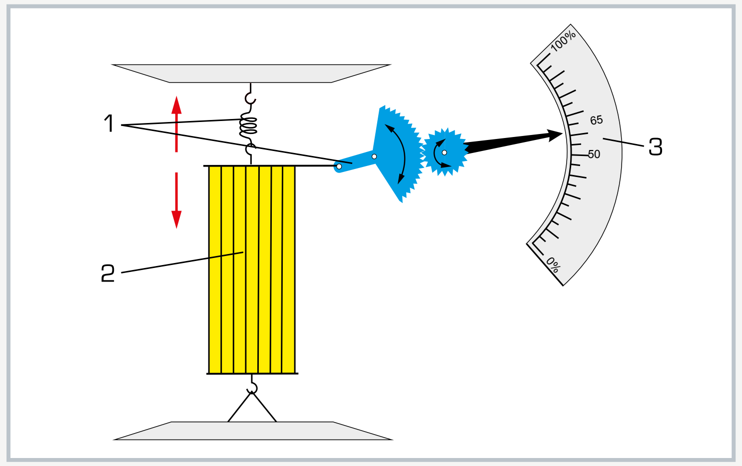
The core element of the trainer is a climatic chamber with transparent door. This chamber can be humidified and dehumidified and contains the four instruments. A Peltier cooling element is used for dehumidification. An ultrasonic atomiser is used for humidification. To circulate the air and ensure good mixing a fan is used.

Learning objectives/experiments

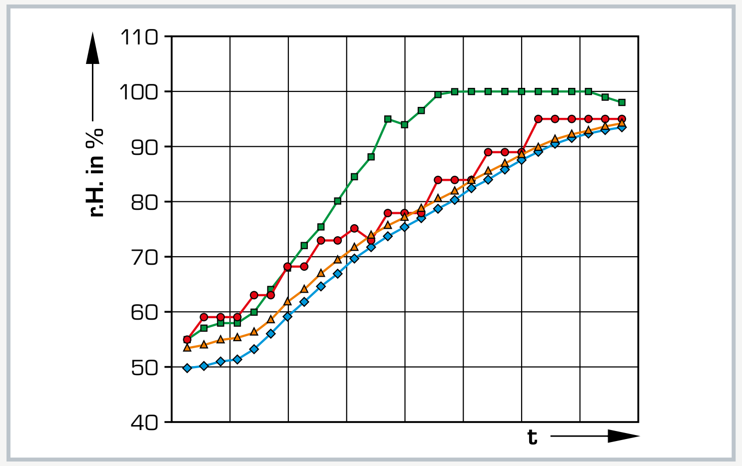
- measuring methods for air humidity measurement
  - psychrometric humidity measurement
  - hygrometric humidity measurement
  - capacitive humidity measurement
- characteristic variables to describe air humidity
- changes of the state of humid air in the h-x diagram
- determination of the relative air humidity with
  - psychrometer
  - hair hygrometer
  - hygrometer with synthetic fibre
  - capacitive humidity sensor
- design and operation of the instruments
- comparison of the instruments

WL 201
Fundamentals of humidity measurement

1 capacitive humidity sensor, 2 displays and controls, 3 humidifier, 4 psychrometer, 5 hair hygrometer, 6 dehumidifier, 7 hygrometer with synthetic fibre and combined temperature sensor



Principle of the hair hygrometer: 1 mechanism to measure the humidity-dependent change in length of the hair bundle, 2 hair bundle, 3 humidity scale



Relative humidity (r. h.) over time (t) with rising content of humidity; blue: capacitive sensor, orange: hygrometer with synthetic fibre, red: psychrometer, green: hair hygrometer

Specification

[1] different measuring methods for measuring humidity
[2] climatic chamber with adjustable humidity and transparent door
[3] humidification via ultrasonic atomiser
[4] dehumidification via Peltier cooling element
[5] fan for air recirculation
[6] 2 mechanical instruments: psychrometer, hair hygrometer
[7] 2 electronic instruments: capacitive sensor, hygrometer with synthetic fibre and combined temperature sensor

Technical data

Humidifier
- ultrasonic atomiser
- power consumption: 21,6W
- low water cut-off

Dehumidifier
- Peltier element
  - cooling capacity: 56,6W (50°C ambient temperature)
  - cooling surface: 1600mm²

Hair hygrometer with deflective needle
- measuring range: 0...100% r. h.

Hygrometer with synthetic fibre
- output voltage: 0...10V
- measuring ranges: 0...100% r. h. / -30...80°C

Capacitive sensor with digital display
- output voltage: 0...10V
- measuring range: 1...100% r. h.

Psychrometer with thermometer
- measuring range: -10...60°C, graduation: 0,5°C

230V, 50Hz, 1 phase
120V, 60Hz, 1 phase; 230V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 1400x800x1630mm
Weight: approx. 110kg

Scope of delivery

1 trainer
1 psychrometer
2 hygrometers
1 set of instructional material

WL 202

Fundamentals of temperature measurement

Description

- **experimental introduction to temperature measurement: methods, areas of application, characteristics**
- **clearly laid out unit primarily for laboratory experiments, also suitable for demonstration purposes**

Recording temperature is one of the basic tasks in metrology. Electric temperature sensors are the most widely used in automation applications but conventional thermometer types are still widely applied in many areas. The WL 202 experimental setup covers the full range of temperature measurement methods. As well as non-electrical measuring methods, such as gas- and liquid-filled thermometers and bimetallic thermometers, all typical electric measuring methods are covered in the experiments. The electrically measured temperatures are displayed directly on programmable digital displays. A temperature-proportionate output voltage signal (0...10V) is accessible from lab jacks, enabling temperature characteristics to be recorded with, for example, a plotter.

For measuring the relative air humidity a psychrometer with two thermometers is available, one of the thermometers measures the dry bulb. The wet bulb thermometer is covered in a wet cotton cloth and measures the evaporative cooling. The temperature difference allows the relative air humidity to be determined.

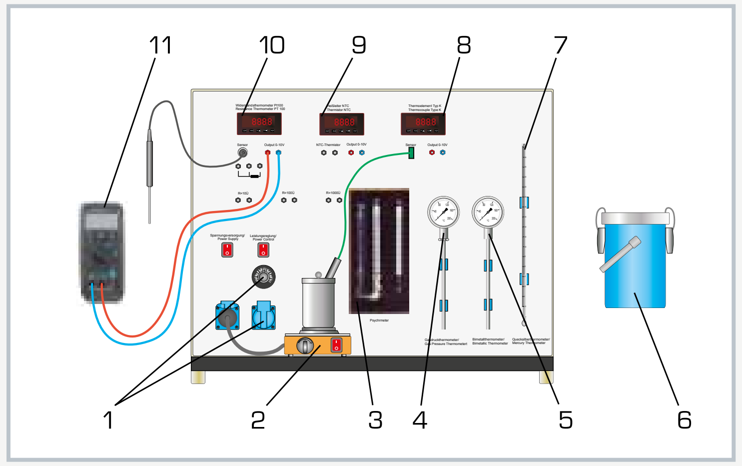
A digital multimeter with precision resistors is used to calibrate the electrical measuring devices. Various heat sources or storage units (immersion heater, vacuum flask and laboratory heater) permit relevant temperature ranges to be achieved for the sensors being tested. A tool box houses the sensors, cables, temperature measuring strips and immersion heater.

Learning objectives/experiments

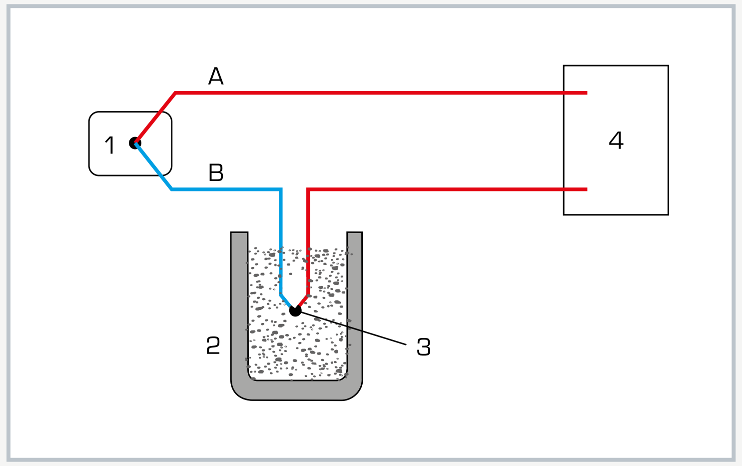
- learning the fundamentals of temperature measurement by experimentation
- familiarisation with the various methods, their areas of application and special features
  - non-electrical methods: gas- and liquid-filled thermometers, bimetallic thermometers and temperature measuring strips
  - electric methods: thermocouple, resistance temperature detector Pt100, thermistor (NTC)
- determining air humidity with a psychrometer
- calibrating electric temperature sensors

WL 202

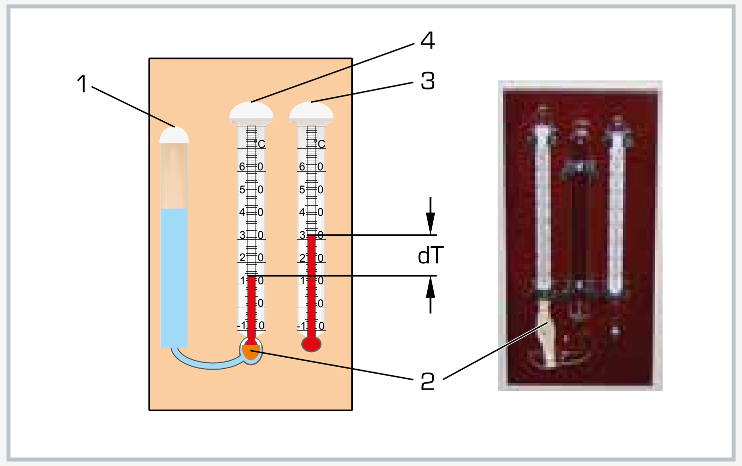
Fundamentals of temperature measurement



1 power-regulated socket, 2 laboratory heater for water and sand, 3 psychrometer to determine air humidity, 4 gas pressure thermometer, 5 bimetal thermometer, 6 vacuum flask, 7 mercury thermometer, 8 digital display, thermocouple type K, 9 digital display, thermistor (NTC), 10 digital display, Pt100, 11 multimeter



Temperature measurement with a thermocouple type K: A) nickel chrome, B) nickel; 1 measuring point, 2 tank at constant temperature, 3 reference point, 4 voltmeter



Psychrometer: 1 water tank, 2 wet cotton cloth for covering the wet bulb thermometer, 3 dry bulb thermometer, 4 wet bulb thermometer; dT temperature difference

Specification

[1] experiments in the fundamentals of temperature measurement with 7 typical measuring devices
[2] various heat sources or storage units: laboratory heater, immersion heater, vacuum flask
[3] calibration units: precision resistors and digital multimeter
[4] liquid, bimetallic and gas pressure thermometers
[5] temperature sensors: Pt100, thermocouple type K, thermistor (NTC)
[6] various temperature measuring strips
[7] psychrometer for humidity measurement
[8] tool box for sensors, cables, measuring strips and immersion heater

Technical data

Immersion heater
- power output: 300W
- adjustment of power feed via power-regulated socket

Laboratory heater with thermostat
- power output: 450W
- max. temperature: 425°C

Vacuum flask: 1L

Measuring ranges
- resistance temperature detector Pt100: 0...100°C
- thermocouple type K: 0...1000°C
- thermistor (NTC): 20...55°C
- liquid thermometer: -10...250°C
- bimetallic, gas pressure thermometer: 0...200°C
- temperature measuring strips: 29...290°C

Precision resistors: 10 Ω, 100 Ω, 1000 Ω
Psychrometer:
- 2x temperature: 0...60°C
- rel. humidity: 3...96%

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase; 120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 800x450x650mm
Weight: approx. 45kg

Scope of delivery

1 experimental unit
1 tool box
1 set of cables
1 laboratory heater
1 immersion heater
1 vacuum flask
1 digital multimeter
1 set of instructional material

WL 203
Fundamentals of pressure measurement

Description

- **comparison of different pressure measurement methods**
- **measuring positive and negative pressure**
- **calibration device with Bourdon tube pressure gauge for calibrating mechanical manometers**

Measuring pressure is important in the engineering industry, e.g. in plant, turbomachine and aircraft construction and in process engineering. Other fundamental factors such as flow rate or flow velocity can also be determined based on a pressure measurement.

The WL 203 experimental unit enables the user to measure the pressure with two different measuring methods: directly by measuring the length of a liquid column (U-tube manometer, inclined tube manometer) and indirectly by measuring the change of shape of a Bourdon tube (Bourdon tube pressure gauge).

In a U-tube manometer, the pressure causes the liquid column to move. The pressure difference is read directly from a scale and is the measure for the applied pressure. In inclined tube manometers, one leg points diagonally up. A small height difference therefore changes the length of the liquid column significantly.

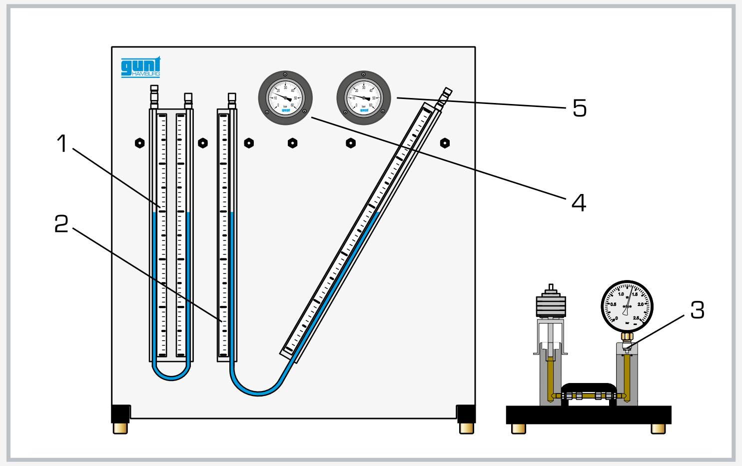
The principle of the Bourdon tube pressure gauge is based on the change in cross-section of the bent Bourdon tube under pressure. The change in cross-section leads to an expansion of the Bourdon tube diameter. A Bourdon tube pressure gauge is therefore an indirectly acting pressure gauge where the pressure differential is indicated via a transmission gearing and a pointer.

In experiments, pressures in the millibar range are generated with a plastic syringe and displayed on the manometers. The experimental unit is equipped with two Bourdon tube pressure gauges for measuring positive and negative pressure. The U-tube manometer, inclined tube manometer and Bourdon tube pressure gauges at the experimental unit can be combined using tubes. A calibration device enables calibration of an additional Bourdon tube pressure gauge using a weight-loaded piston manometer.

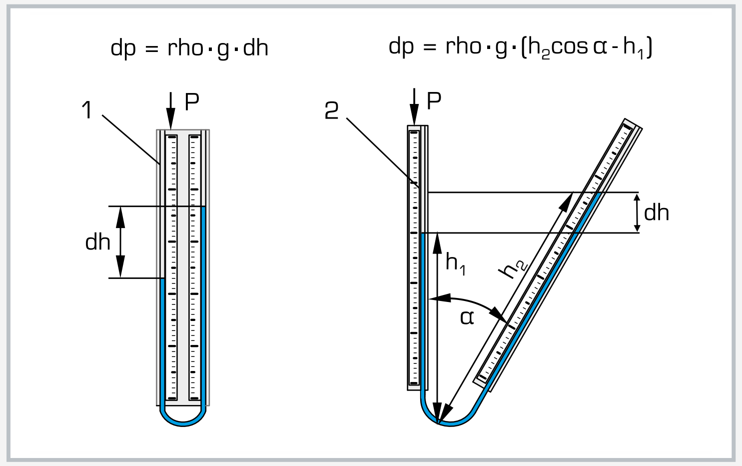
Learning objectives/experiments

- familiarisation with 2 different measuring methods:
  - direct method with U-tube manometer and inclined tube manometer
  - indirect method with Bourdon tube pressure gauge
- principle of a Bourdon tube pressure gauge
- calibrating mechanical manometers

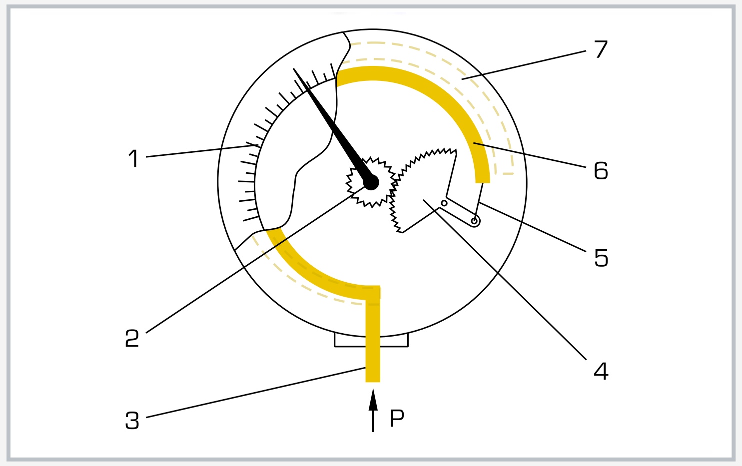
WL 203
Fundamentals of pressure measurement



1 U-tube manometer, 2 inclined tube manometer, 3 calibration device with Bourdon tube pressure gauge, 4 Bourdon tube pressure gauge for positive pressure, 5 Bourdon tube pressure gauge for negative pressure



Principle of operation of liquid column manometers
1 U-tube manometer, 2 inclined tube manometer; dp pressure difference, dh height difference, rho density of measuring fluid, g acceleration of gravity



Principle of operation of a Bourdon tube pressure gauge
1 scale, 2 pointer, 3 Bourdon tube fixed in place, 4 gearing, 5 tie rod, 6 Bourdon tube without pressure, 7 Bourdon tube expanded under pressure

Specification

[1] basic experiments for measuring pressure with three different measuring instruments
[2] U-tube and inclined tube manometer
[3] one Bourdon tube pressure gauge each for positive and negative pressure
[4] plastic syringe generates test pressures in the millibar range
[5] calibration device with Bourdon tube pressure gauge for calibrating mechanical manometers

Technical data

Inclined tube manometer
- angle: 30°

Measuring ranges
- pressure:
  - 0...±60mbar (Bourdon tube pressure gauge)
  - 0...500mmWC (U-tube manometer)
  - 0...500mmWC (inclined tube manometer)

LxWxH: 750x610x810mm
LxWxH: 410x410x410mm (calibration device)
Total weight: approx. 40kg

Scope of delivery

1 experimental unit
1 calibration device
1 set of weights
1 oil, 500mL
1 ink, 30mL
1 funnel
1 syringe
1 set of hoses
1 set of instructional material

WL 920
Temperature measurement

Learning objectives/experiments

- familiarisation with different temperature measurement methods:
  - non-electrical methods: liquid thermometers, bimetal thermometers
  - electronic methods: thermocouple, Pt100 resistance thermometer, NTC thermistor
- determination of air humidity with a psychrometer
- familiarisation with the function of the individual temperature measuring instruments
- response behaviour of the sensors
- steady and transient behaviour

Description

- **comparison of different temperature measurement methods**
- **investigation of transient temperature behaviour and defined temperature jumps**

Different physical processes are used to measure temperatures. Temperatures can be read off directly on a scale, e.g. by the expansion of a measuring medium.

In industry, temperatures are often measured electronically. The advantage of electronic measurement is that further processing or transmission of signals to remote locations (controllers, external displays) is easier.

The WL 920 trainer can be used to carry out and compare different temperature measurement procedures.

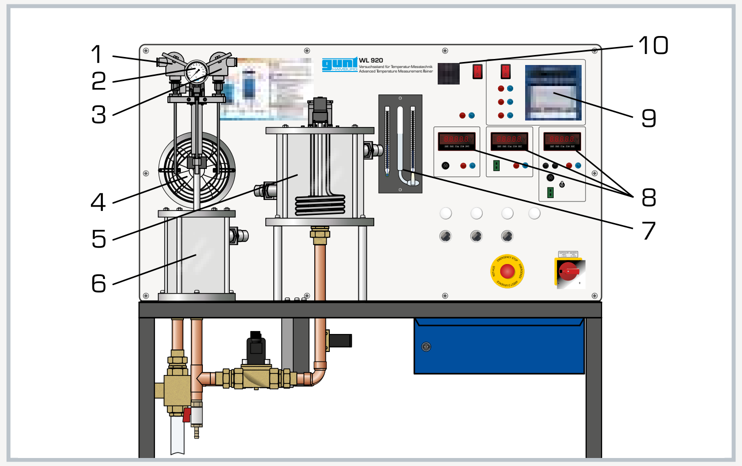
The trainer includes liquid thermometers, bimetal thermometers, as well as a thermocouple,a Pt100 resistance thermometer and an NTC thermistor, each with different protective sleeves, for electronic temperature measurement. A psychrometer with two liquid thermometers is used to measure the relative air humidity.

To compare the different measuring methods, the temperature sensors being studied are attached to a height-adjustable device above the experimental tank. A fan ensures almost constant ambient conditions. A second tank with electronically controlled heater supplies water temperatures up to approx. 80°C.

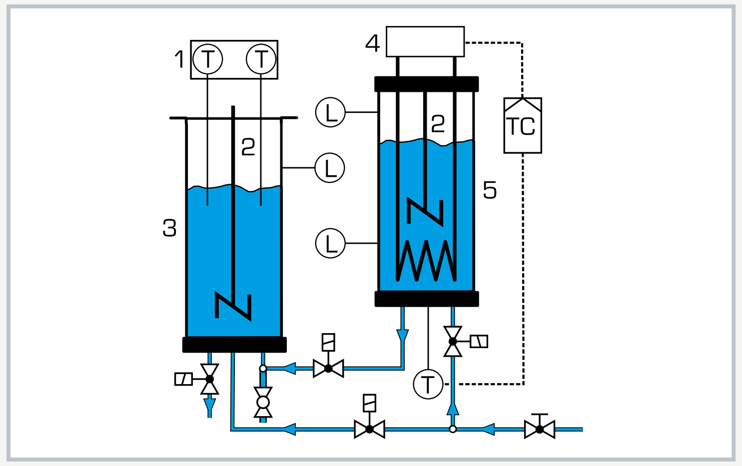
The heated water at a specified temperature is fed into the experimental tank. By lowering the height-adjustable device, the temperature sensors are immersed in the water and the temperature measurement begins.

The measured values can be read as analogue or digital values. A 3-channel line recorder can record the measured values of the electronic temperature sensors continuously over time and thus also document the different time response. Defined temperature jumps and steady and transient temperature behaviour can be studied.

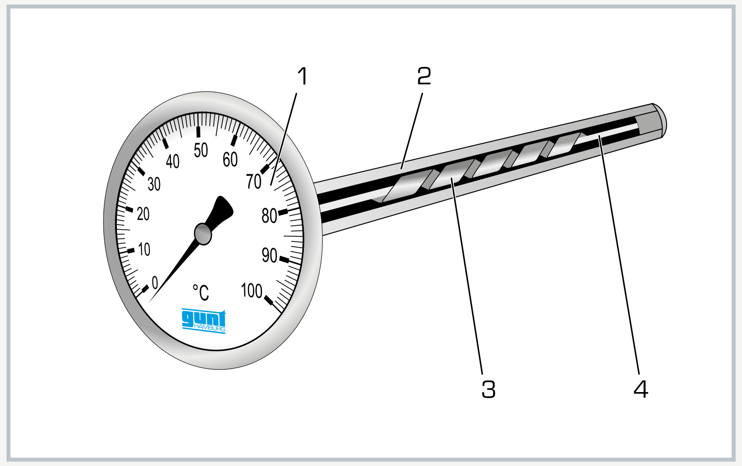
WL 920
Temperature measurement



1 Pt100 resistance thermometer, 2 bimetal thermometers, 3 thermocouple, 4 fan, 5 heating tank, 6 experimental tank, 7 psychrometer, 8 digital displays, 9 3-channel line recorder



1 temperature sensor being studied, 2 stirring machine, 3 experimental tank, 4 heater, 5 heating tank; T temperature, L level, TC temperature controller, blue: water



Design of the bimetal thermometer
1 scale housing, 2 protective tube, 3 bimetallic strips, 4 fixed bearing

Specification

[1] steady and transient temperature measurement with typical measurement instruments
[2] temperature sensors: liquid thermometer, bimetal thermometer, Pt100, thermistor (NTC), type K thermocouple
[3] psychrometer for determining the relative air humidity
[4] defined temperature jumps up to 80°C
[5] experimental tank and heating tank with temperature control, water-filled
[6] both tanks equipped with stirring machine
[7] fan generates constant air temperature above the experimental tank
[8] 3-channel line recorder for recording the measured values

Technical data

Heater
- output: 2kW at 230V, 1,5kW at 120V
- tank capacity: 4L

Temperature controller
- PID

Line recorder
- 3 channels
- serial interface

Temperature sensors
- liquid thermometer with organic liquid
- bimetal thermometer
- psychrometer
- thermocouple type K
- thermistor (NTC)
- Pt100

Measuring ranges
- temperature: 0...100°C
- rel. humidity: 3...96%

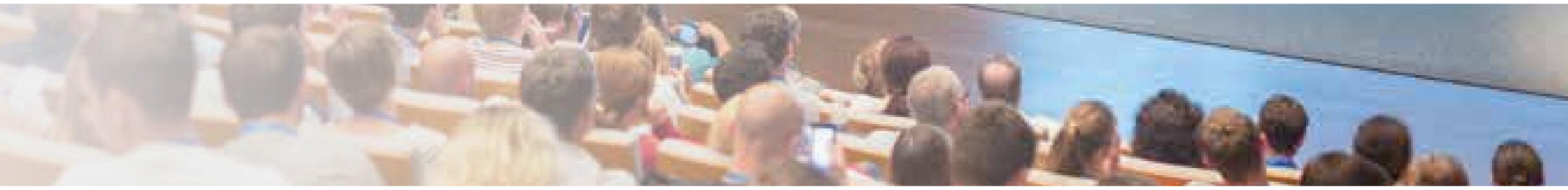
230V, 50Hz, 1 phase
230V, 60Hz, 1 phase; 120V, 60Hz, 1 phase
LxWxH: 1200x700x1550mm
Weight: approx. 185kg

Required for operation

water connection, drain

Scope of delivery

1 trainer
1 set of accessories
1 set of instructional material



Basic knowledge

Material-bound/non-material-bound heat transport

Material-bound heat transport

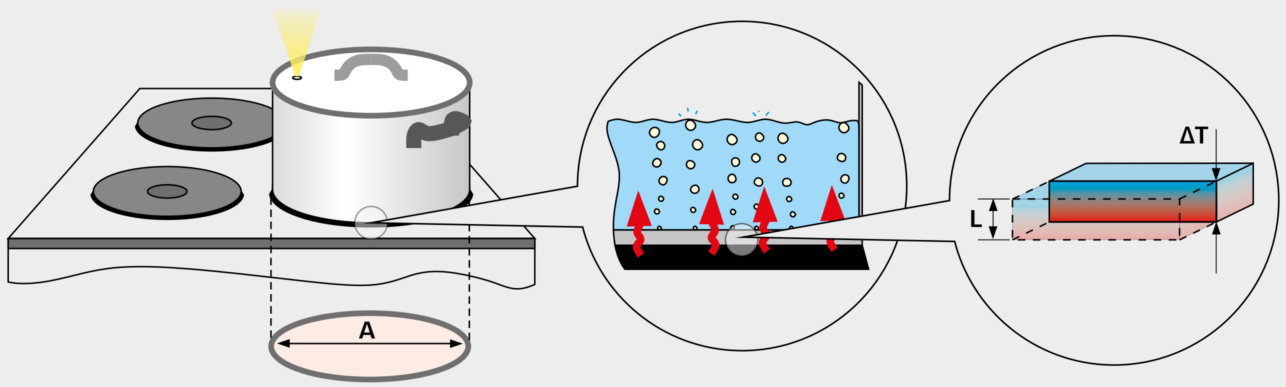
by conduction and convection

Conduction

In the case of thermal conduction, heat transport takes place through direct interaction between the molecules (e.g. molecule collisions) within a solid or a fluid at rest. A prerequisite for this is that there is a temperature difference within the substance or that substances of different temperatures come into direct contact with each other. All aggregate states allow this transfer mechanism.

The amount of heat transported depends on:

- the thermal conductivity **λ** of the material,
- the heat conducting length **L**,
- the heat transferring area **A**,
- the dwell time **t** and
- the temperature difference **ΔT** between the beginning and end of the thermal conductor



The hot stove transfers the heat to the water through the bottom of the saucepan with the cross-sectional area **A**.

The red arrows indicate the direction of the heat flux.

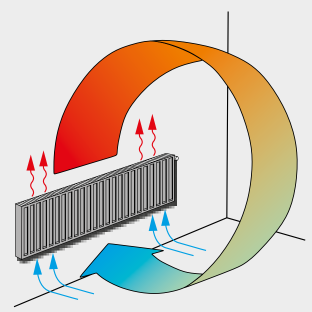
The heat is transferred from the hot to the cold material along the heat-conducting length **L** due to the interaction of the molecules via the temperature difference **ΔT**.

Convection

Heat transport takes place in flowing liquids or gases by means of material movement, i.e. material transport. Where **forced convection** occurs, the flow is forced by external forces. Examples: a pump in a warm water heater, fans in a power pack or PC.

If the flow is caused by differences in density due to different temperatures within the fluid this is called **free or natural convection.** Examples: water movement when heated in a pot, by a foehn wind, the gulf stream, or a vent in a chimney.

Cold air is sucked in by the fan, cools the internal components and flows out again as heated air.



The air molecules warmed by the heater rise due to differences in density.

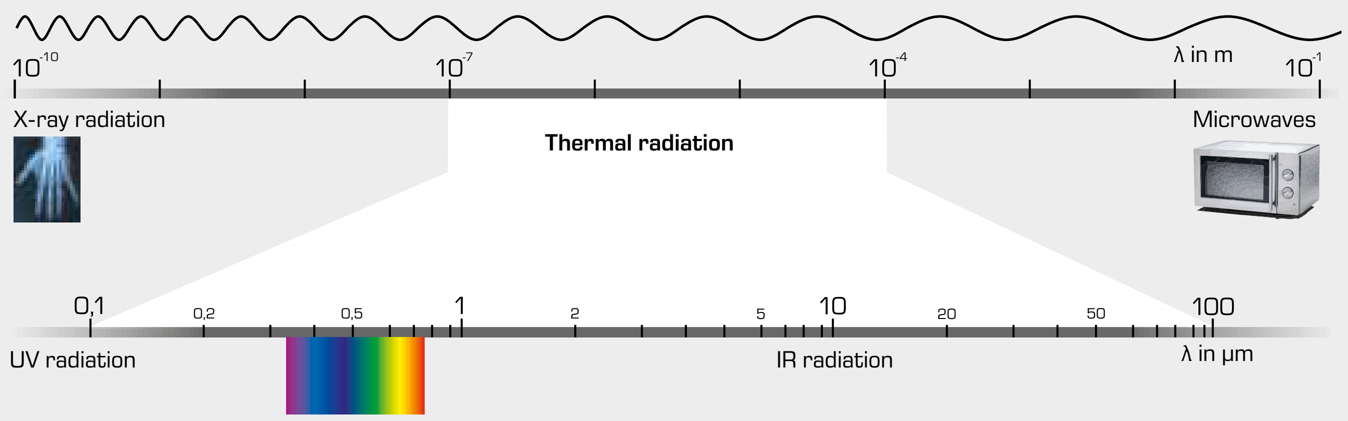
Non-material-bound heat transport

by thermal radiation

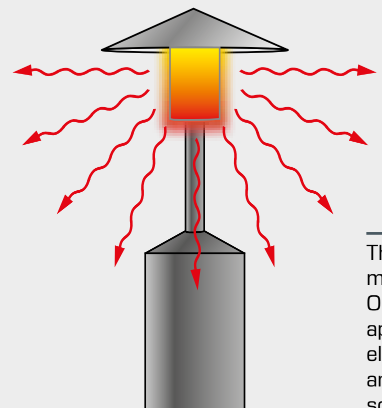
Radiation

Energy transport through electromagnetic oscillation in a specific wavelength range. Any body with a temperature above zero Kelvin emits radiation known as thermal radiation.

Thermal radiation includes UV radiation, light radiation and infrared radiation. Light radiation covers the wavelength range visible to the human eye.



Using a thermal imaging camera, it is possible to make thermal radiation visible: the thermal camera converts long-wave infrared radiation into visible radiation.



The best example of thermal radiation is the sun.
One example of a technical application is a patio heater: electromagnetic oscillations are emitted by the heat source as thermal radiation in all directions.
The portion of the thermal radiation directed upwards is reflected by the canopy.

Material characteristics

Heat transfer coefficient α: a measure of how much heat is transferred from a solid to a fluid or vice versa (convection)

Thermal conductivity λ: a measure of how well heat is transferred into a solid (conduction)

Overall heat transfer coefficient k: describes the overall heat transfer between fluids separated by solids (convection and conduction)

Reflectance, absorbance and transmittance: a measure of the proportion of thermal radiation reflected, absorbed or transmitted to a body (radiation)

WL 362
Energy transfer by radiation

Description

- **investigation of thermal and light radiation**
- **influence of distance and angle of incidence**
- **broad range of experiments**

Thermal radiation is a non-material-bound energy transport by means of electromagnetic oscillations in a certain wavelength range. Any body with a temperature above zero Kelvin emits radiation known as thermal radiation. Thermal radiation includes UV radiation, light radiation and infrared radiation. Light radiation covers the wavelength range visible to the human eye.

The WL 362 experimental unit contains two radiation sources: a heat radiator and a light emitter. Thermal radiation is detected by means of a thermopile. Light radiation is recorded by means of a luxmeter with photodiode. Various optical elements such as apertures, absorption plates or colour filters can be set up between the emitter and the detector. All components are mounted on an optical bench. The distance between the optical elements can be read from a scale along the optical bench.

Luxmeter, thermopile and light emitter can be rotated to study how the angle of incidence affects the radiation intensity. The angles are read off the angular scale.

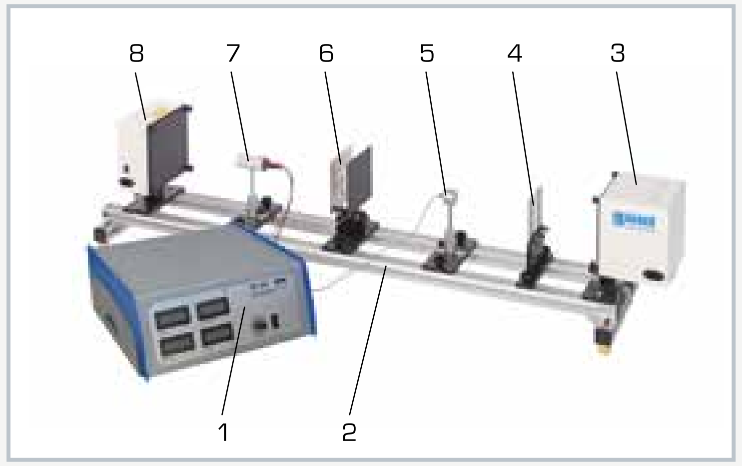
The optical elements are used to investigate the reflection, absorption and transmission of different materials at different wavelengths and temperatures. The radiant power of both emitters can be adjusted. The aim of the experiments is to check optical laws: e.g. Kirchhoff's law of radiation, the Stefan-Boltzmann law, Lambert's distance and direction law.

The measured values are displayed digitally on the measuring amplifier. The measured values are transmitted directly to a PC via USB where they can be analysed using the software included.

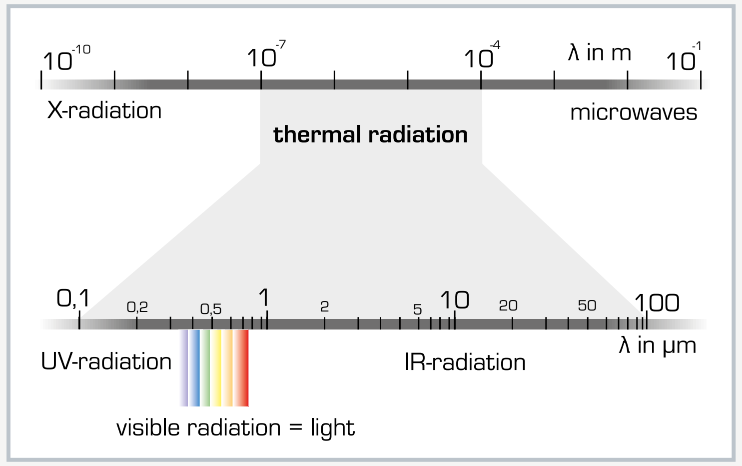
Learning objectives/experiments

- Lambert's direction law
- Lambert's distance law
- Stefan-Boltzmann law
- Kirchhoff's laws
  - radiation absorption
  - radiation reflection
  - radiation emission

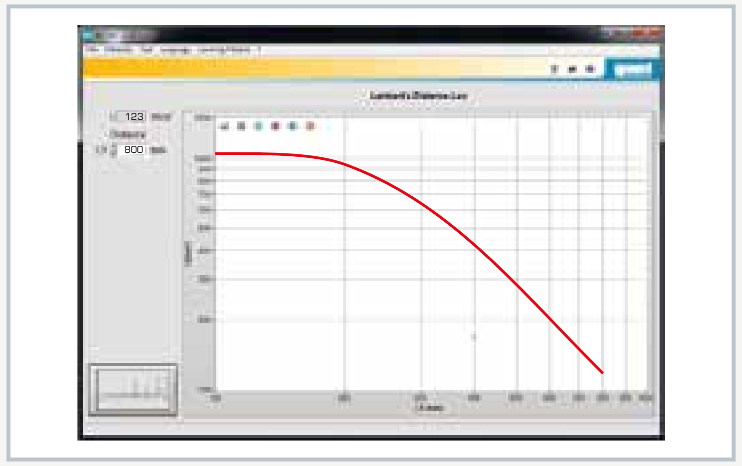
WL 362
Energy transfer by radiation



1 measuring amplifier, 2 optical bench with scale for reading the distances, 3 pivoting light source, 4 holder for slit diaphragm or optional colour filter (red, green, infrared), 5 luxmeter, 6 absorption plates and reflection plate each with temperature measuring point, 7 thermopile, 8 thermal radiator



Spectrum of thermal radiation
top scale wavelength λ in m, bottom scale wavelength λ in µm



Software screenshot: investigations on the distance to the radiation source

Specification

[1] thermal radiator and thermopile for the investigation of thermal radiation
[2] light source and luxmeter for the investigation of illuminance
[3] absorption plate and reflection plate with thermocouples for the investigation of Kirchhoff's laws
[4] adjustable radiant power of thermal radiator and light source
[5] 3 colour filters with holder (red, green, infrared), slit diaphragm
[6] luxmeter for measuring illuminance
[7] thermocouple for measuring the temperature
[8] thermopile for measuring radiant power
[9] GUNT software for data acquisition via USB under Windows 7, 8.1, 10

Technical data

Thermal radiator
- material: $AlMg_3$, black anodized
- output: 400W at 230V, 340W at 120V
- max. achievable temperature: 300°C
- radiant area, LxW: 200x200mm

Light source
- halogen lamp
  - output: 42W
  - luminous flux: 630lm
  - colour temperature: 2900K
- range of rotation on both sides: 0... 90°
- optional illuminated surface
  - diffusing lens, LxW: 193x193mm or
  - orifice plate, Ø 25mm

Optical elements to insert
- slit diaphragm
- 3 colour filters: red, green, infrared
- absorption plate and reflection plate with thermocouple type K, matt black lacquered

Measuring ranges
- illuminance: 0...1000 lux
- temperature: 2x 0...200°C
- radiant power: 0...1000W/m^2

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase; 120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 1460x310x390mm
LxWxH: 420x400x170mm (measuring amplifier)
Weight: approx. 27kg

Required for operation

PC with Windows recommended

Scope of delivery

1 experimental unit
1 set of accessories
1 GUNT software CD + USB cable
1 set of instructional material

WL 372
Radial and linear heat conduction

Description

- **investigation of heat conduction in solid bodies**
- **linear and radial heat conduction**
- **GUNT software for displaying temperature profiles**

Heat conduction is one of the three basic forms of heat transfer. Kinetic energy is transferred between neighbouring atoms or molecules. The heat transport is material-bound. This type of heat transfer is an irreversible process and transports heat from the higher energy level, i.e. higher absolute temperature, to the lower level with lower temperature. If the heat transport is maintained permanently by means of the supply of heat, this is called steady heat conduction. The most common application of heat conduction in engineering is in heat exchangers.

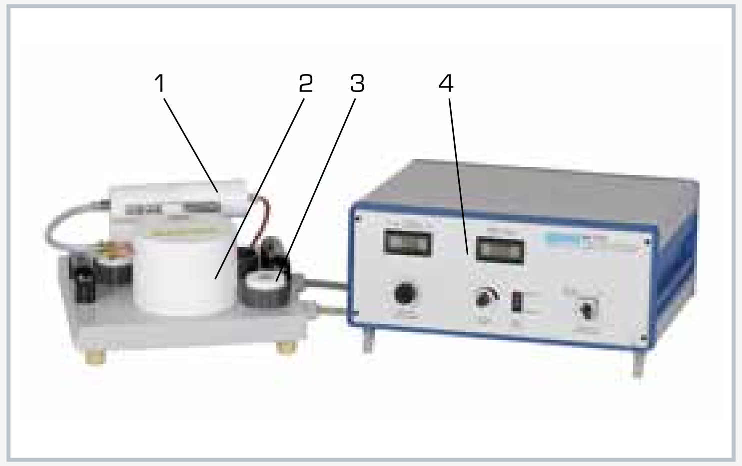
The WL 372 experimental unit can be used to determine basic laws and characteristic variables of heat conduction in solid bodies by way of experiment. The experimental unit comprises a linear and a radial experimental setup, each equipped with a heating and cooling element. Different measurement objects with different heat transfer properties can be installed in the experimental setup for linear heat conduction. The experimental unit includes with a display and control unit.

Sensors record the temperatures at all relevant points. The measured values are read from digital displays and can be transmitted simultaneously via USB directly to a PC, where they can be analysed using the software included.

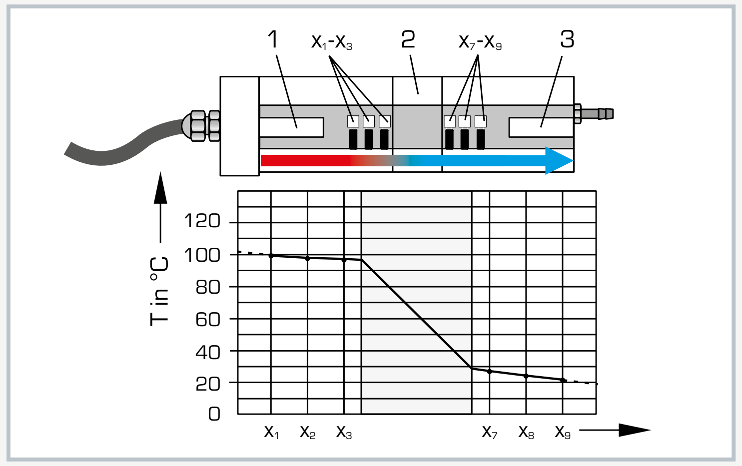
Learning objectives/experiments

- linear heat conduction (plane wall)
  - determination of temperature profiles for different materials
  - determination of the temperature profile in case of a disturbance
  - determination of the thermal conductivity λ
- radial heat conduction
  - determination of the temperature profile
  - determination of the thermal conductivity λ

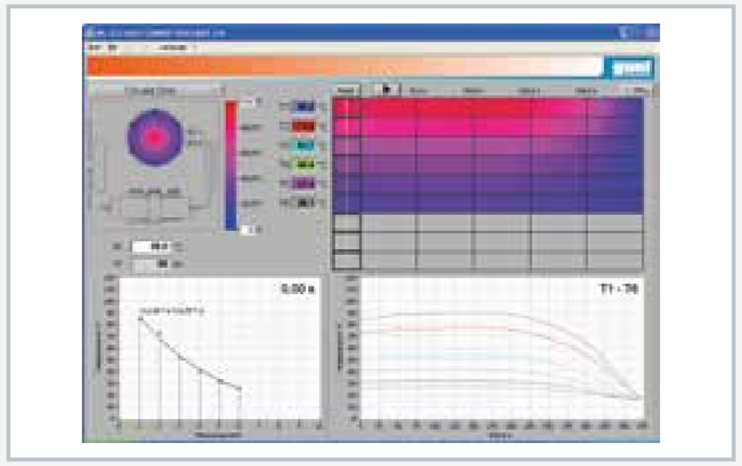
WL 372
Radial and linear heat conduction



1 display and control unit, 2 measurement object, 3 experimental setup for radial heat conduction, 4 experimental setup for linear heat conduction



Experimental setup for linear heat conduction with graphic representation of the temperature profile: 1 heater, 2 measurement object, 3 cooling element; x_1-x_3 and x_7-x_9: measuring points



Software screenshot: temperature profile for radial heat conduction

Specification

[1] investigation of heat conduction in solid bodies
[2] experimental setup consisting of experimental unit and display and control unit
[3] linear heat conduction: 3 measurement objects, heating and cooling element, 9 temperature measuring points
[4] radial heat conduction: brass disc with heating and cooling element, 6 temperature measuring points
[5] cooling by means of tap water
[6] electrical heating element
[7] representation of the temperature profiles with GUNT software
[8] GUNT software for data acquisition via USB under Windows 7, 8.1, 10

Technical data

Linear heat conduction
- 3 measurement objects, insulated
- 1x DxL: 25x30mm, steel
- 1x DxL: 15x30mm, brass
- 1x DxL: 25x30mm, brass
- heater: 140W

Radial heat conduction
- disc DxL: 110x4mm
- heater in the centre of the disc: 125W
- cooling coil on the outer edge of the disc

Measuring ranges
- temperature: 0...100°C
- power: 0...200W

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase
120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 400x360x210mm (experimental unit)
LxWxH: 470x380x210mm (display and control unit)
Weight: approx. 22kg

Required for operation

water connection, drain
PC with Windows recommended

Scope of delivery

1 experimental unit
1 display and control unit
1 set of measuring objects
1 set of hoses
1 GUNT software CD + USB cable
1 set of instructional material

WL 376
Thermal conductivity of building materials

Learning objectives/experiments

- determine the thermal conductivity λ of different materials
- determine the thermal resistance
- thermal conductivity λ for several samples connected in series (up to a thickness of 50mm)

Description

- **heat conduction in non-metallic building materials**
- **material thicknesses or combinations up to a thickness of 50mm can be used**

Thermal insulation in building planning is a sub-area of construction physics; it uses appropriate measures such as component design to enable a comfortable room climate all year round while at the same time consuming little energy. This is achieved by using building materials with high thermal resistance and low transmission by heat radiation.

The WL 376 device is used to investigate various non-metallic building materials with regard to their thermal conductivity in accordance with DIN 52612. The scope of delivery includes samples made of different materials: insulating panels made of Armaflex, chipboard, PMMA (acrylic glass), styrofoam, Polystyrene-PS, Polyoxymethylene-POM, cork and plaster. The samples all have the same dimensions and are placed between a heated plate and a water-cooled plate. A clamping device ensures reproducible contact pressure and heat contact.

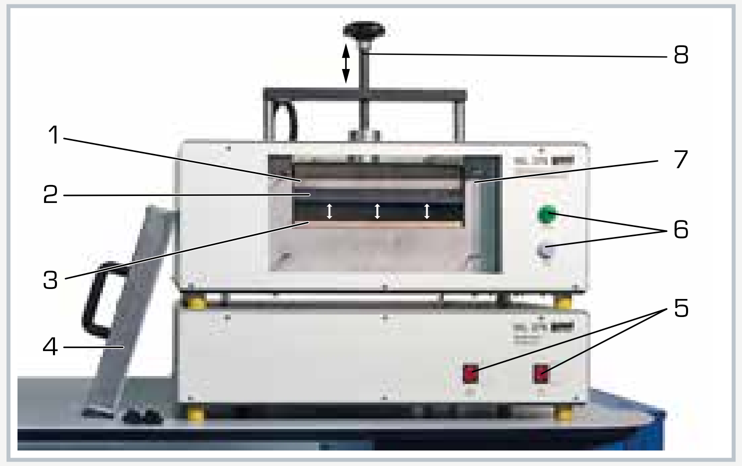
The hot plate is heated by an electric heating mat. In the cold plate, the temperature is achieved by water cooling. Sensors measure the temperatures at the cooling water inlet and outlet and in the centre of both plates.

The temperatures for the hot plate above the sample and for the cold plate underneath the sample are set using the software provided. A temperature control system ensures constant temperatures.

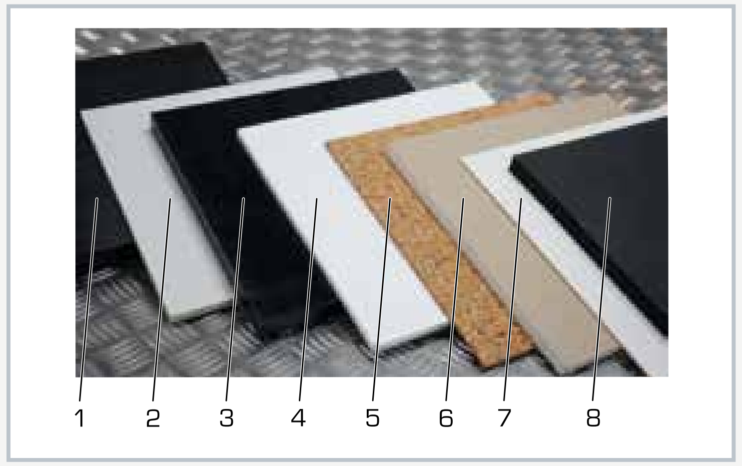
The heat flux between the hot plate and the cold plate passes through the sample and is measured by a special heat flux sensor. The entire housing, including the cover, is thermally insulated to ensure constant ambient conditions.

The measured values are transmitted directly to a PC via USB where they can be analysed using the software included.

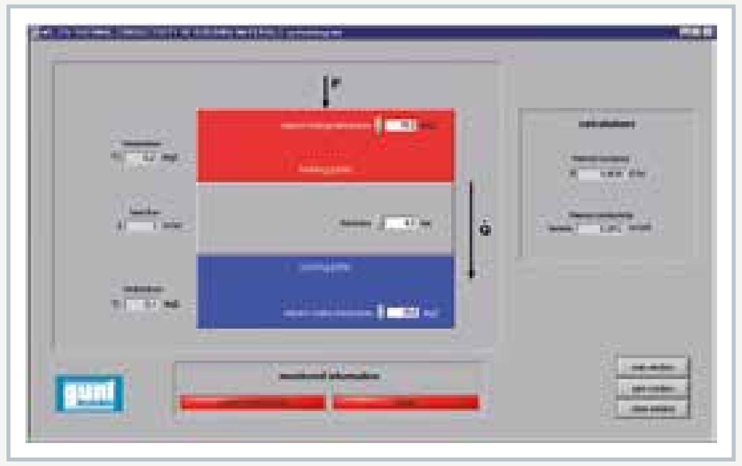
WL 376
Thermal conductivity of building materials



1 hot plate insulation, 2 hot plate, 3 sample, in this case chipboard (cold plate not visible), 4 cover for insulating housing, 5 main switch and heater switch, 6 indicator lights, 7 insulating housing, 8 contact spindle



Insulating materials included in the scope of delivery:
1 Armaflex, 2 PMMA (polymethyl methacrylate), 3 POM (polyoxymethylene), 4 styrofoam, 5 cork, 6 plaster, 7 chipboard, 8 PS (polystyrene)



Software screenshot: system diagram

Specification

[1] determine the thermal conductivity λ in building materials
[2] thermal conductivity λ and thermal resistance measurement according to DIN 52612
[3] reproducible contact pressure via clamping device
[4] 8 samples to be inserted between hot and cold plate
[5] hot plate with heating mat
[6] cold plate with water cooling and heat flux sensor
[7] software controller for temperature adjustment of cold and hot plate
[8] 3 temperature sensors for cooling water: at the inlet, outlet and centre of the plate
[9] 2 temperature sensors for the surface temperature of the hot and cold plate
[10] GUNT software for data acquisition via USB under Windows 7, 8.1, 10

Technical data

Electric heating mat
- output: 500W
- max. temperature: 80°C

Samples
- LxW: 300x300mm
- thickness: up to max. 50mm
- material: Armaflex, chipboard, PMMA, styrofoam, PS, POM, cork, plaster

Measuring ranges
- temperature: 3x 0...100°C, 2x 0...200°C
- heat flux density: 0...1533W/m^2

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase; 120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 710x440x550mm
LxWxH: 710x440x200mm (control unit)
Total weight: approx. 90kg

Required for operation

water connection, drain
PC with Windows

Scope of delivery

1 experimental unit
1 set of accessories
1 GUNT software CD + USB cable
1 set of instructional material

WL 377
Convection and radiation

Description

- **heat transport between heating element and vessel wall by convection and radiation**
- **GUNT software for data acquisition**

Under real conditions, the heat transport between two objects is normally substance-bound, i.e. convection and/or heat conduction, and not substance-bound, i.e. radiation, at the same time. Determining the individual heat quantities of one type of transfer is difficult.

The WL 377 trainer enables users to match the individual heat quantities to the corresponding type of transfer. The core element is a heated metal cylinder located at the centre of the pressure vessel. The surface temperature of the heated metal cylinder is regulated. Temperature sensors measure the surface temperature of the metal cylinder and the wall temperature of the pressure vessel. In addition to the heating power of the metal cylinder, it is possible to study the heat transport from the metal cylinder to the wall of the pressure vessel.

The pressure vessel can be put under vacuum or positive gauge pressure. In the vacuum, heat is transported primarily by radiation. If the vessel is filled with gas and is under positive gauge pressure, heat is also transferred by convection. It is possible to compare the heat transfer in different gases. In addition to air, nitrogen, helium, carbon dioxide or other gases are also suitable.

Heat transport by conduction is largely suppressed by adequately suspending the metal cylinder.

A rotary vane pump generates negative pressures down to approx. 0,02mbar. Positive gauge pressures up to approx. 1bar can be realised with compressed air. Two pressure sensors with suitable measuring ranges are available for the pressure measurement: a Pirani sensor measures the negative pressure while a piezo-resistive sensor measures the positive pressure.

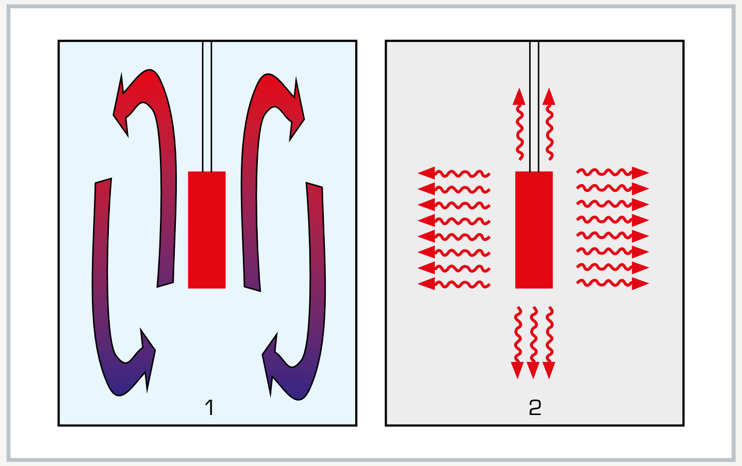
The measured values can be read on digital displays. At the same time, the measured values can also be transmitted directly to a PC via USB, where they can be analysed with the GUNT software.

Learning objectives/experiments

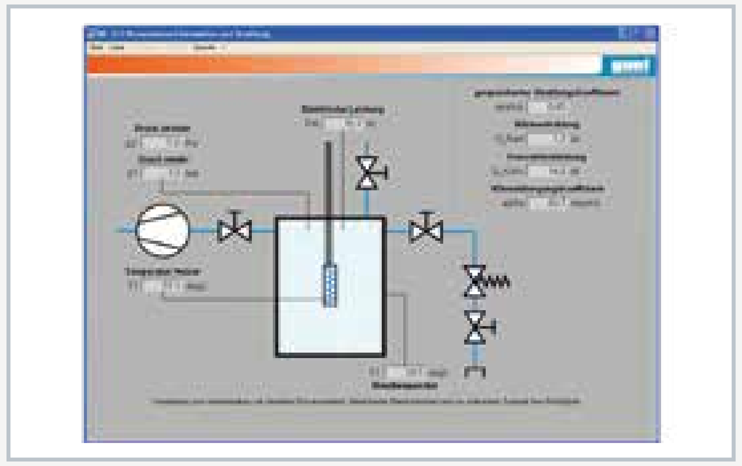
- experiments in vacuum
  - heat transfer by radiation
  - determination of the radiation coefficient
- experiments at ambient pressure or positive gauge pressure
  - heat transfer by convection and radiation
  - determination of the heat quantity transferred by convection
  - determination of the heat transfer coefficient based on measured values
  - theoretical determination of the heat transfer coefficient based on the Nusselt number
  - comparison of the heat transfer in different gases

WL 377
Convection and radiation

1 temperature controller with temperature display, 2 temperature display, 3 power display, 4 vacuum pump, 5 pressure vessel, 6 vessel's absolute pressure display, 7 vessel's relative pressure display



Heat transfer in the vessel:
1 convection (vessel filled with gas), 2 radiation (vessel filled with vacuum)



Software screenshot: process schematic

Specification

[1] heat transfer between heated metal cylinder and vessel wall by convection and radiation
[2] operation with various gases possible
[3] experiments in vacuum or at a slight positive gauge pressure
[4] electrically heated metal cylinder in the pressure vessel as experimental vessel
[5] temperature-controlled heating element
[6] vacuum generation with rotary vane pump
[7] instrumentation: 1 temperature sensor on the metal cylinder, 1 power sensor at the heating element, 1 Pirani pressure sensor, 1 piezo-resistive pressure sensor
[8] digital displays for temperature, pressure and heating power
[9] GUNT software for data acquisition via USB under Windows 7, 8.1, 10

Technical data

Heating element
- output: 20W
- radiation surface area: approx. 61cm^2

Pressure vessel
- pressure: -1...1,5bar
- volume: 11l

Pump for vacuum generation
- power consumption: 250W
- nominal suction capacity: 5m^3/h
- final pressure with gas ballast: 3*10^{-3}mbar
- final pressure without gas ballast: 3*10^{-3}mbar

Measuring ranges
- negative pressure: 0,5*10^{-3}...1000mbar
- pressure: -1...1,5bar rel.
- temperature: 0...250°C
- power: 0...23W

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase; 120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 1340x790x1500mm
Weight: approx. 160kg

Required for operation

compressed air: min. 1,5bar
PC with Windows recommended

Scope of delivery

1 trainer
1 GUNT software CD + USB cable
1 set of instructional material

GUNT-Thermoline
Fundamentals of heat transfer

Overall didactic concept for targeted teaching on the fundamentals of heat transfer.

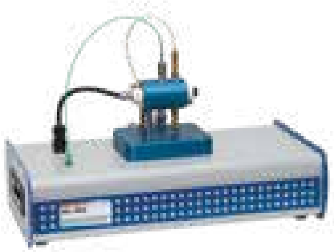
- accurate measurements
- software-controlled
- training software

WL 420
Heat conduction in metals

WL 430
Heat conduction and convection

WL 460
Heat transfer by radiation

WL 422
Heat conduction in fluids

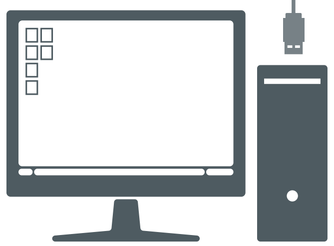


WL 440
Free and forced convection

Network capability

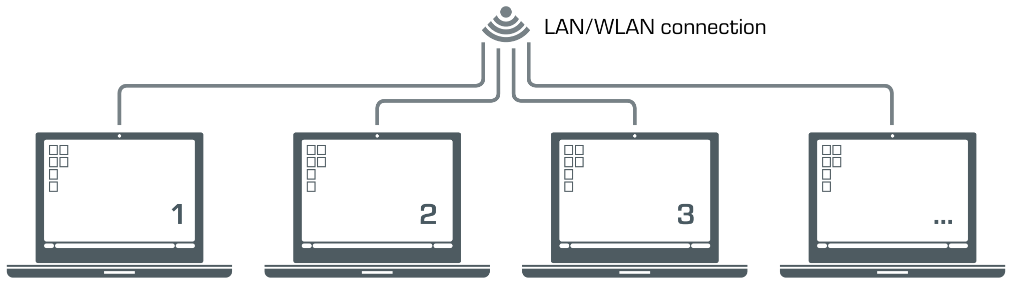
- full network access to ongoing experiments by any number of external workstations
- experiments can be independently followed and evaluated by students at all workstations when using a single training system

USB connection



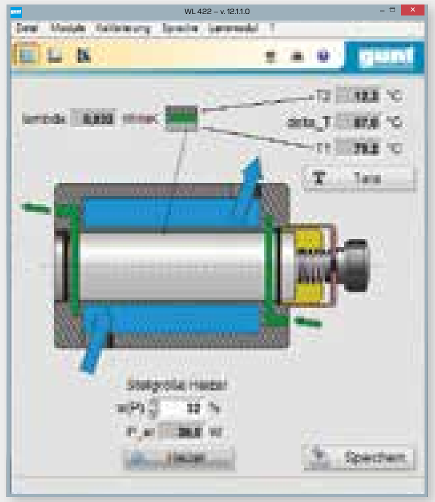
One computer for control and operation of the experimental unit

LAN/WLAN connection



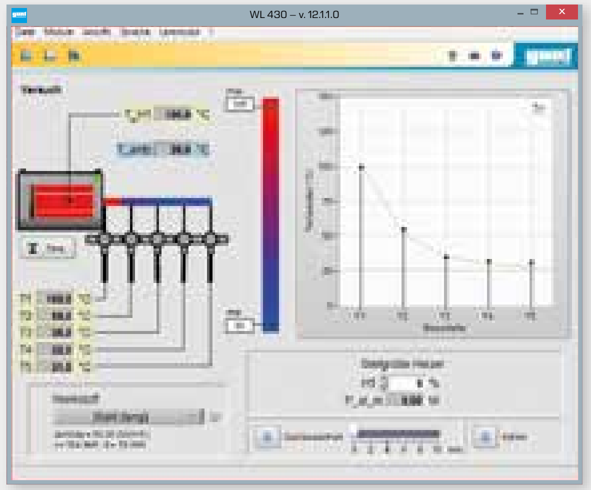
...any number of workstations with GUNT software with just a single licence

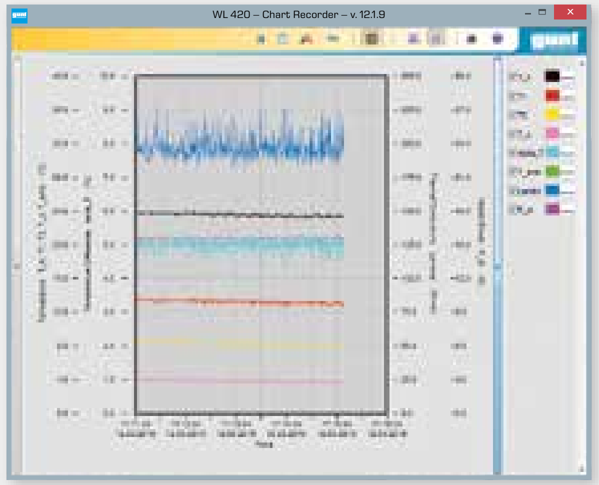
Operation and data acquisition



Operation

- simple operation of the system via the software
- adjust operating parameters via respective button icons
- check and read off measured values





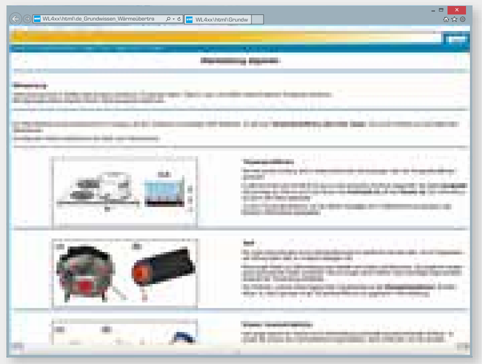
Time dependency

- representation of the measured values as a function of time
- plot and log your own characteristics
- freely selectable form of presentation of the measured values
  - measured values selection
  - resolution
  - colour
  - time intervals

Geometric temperature curve

- representations of the temperature curves make it easier to understand the respective heat transfer mechanisms

Training software



Course in the fundamentals
Educationally thought-out and media-rich learning content in the field of heat transfer

Detailed thematic courses

- the various forms of heat transfer are explained using concrete examples
- independent preparation for handling the equipment

Targeted review of the learning content

- allows learning progress to be checked discreetly and automatically
- detect weaknesses and provide targeted support

For further information, please refer also to the Thermoline-brochure.

WL 420
Heat conduction in metals

Description

- **effect of different metals on heat conduction**
- **functions of the GUNT software: educational software, data acquisition, system operation**
- **part of the GUNT-Thermoline: Fundamentals of Heat Transfer**

Heat conduction is one of the three basic forms of heat transfer. According to the second law of thermodynamics, heat is always transferred from the higher energy level to the low energy level. If the temperature of a body does not change despite continuous addition or removal of heat, this is known as steady-state heat conduction.

WL 420 offers basic experiments for targeted teaching on the topic of heat conduction through various metals. To this end, one of eleven samples is used. The upper region of the sample is heated by an electrical heater and the lower section cooled by a Peltier element. Heat conduction occurs through the respective sample from top to bottom. Two samples can be inserted into the experimental unit at the same time, in order to investigate thermal conductivity through multi-layered metals. Perfectly matched components ensure rapid heating and trouble-free measurements.

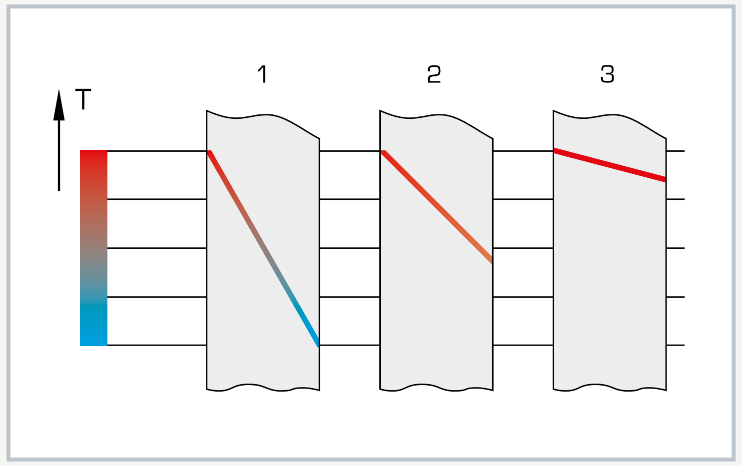
The temperature of the metal samples is taken on the top and bottom by means of thermocouples. The microprocessor-based instrumentation is well protected in the housing. The GUNT software consists of a software for system operation and for data acquisition and an educational software. With explanatory texts and illustrations the educational software significantly aids the understanding of the theoretical principles. The unit is connected to the PC via USB.

Learning objectives/experiments

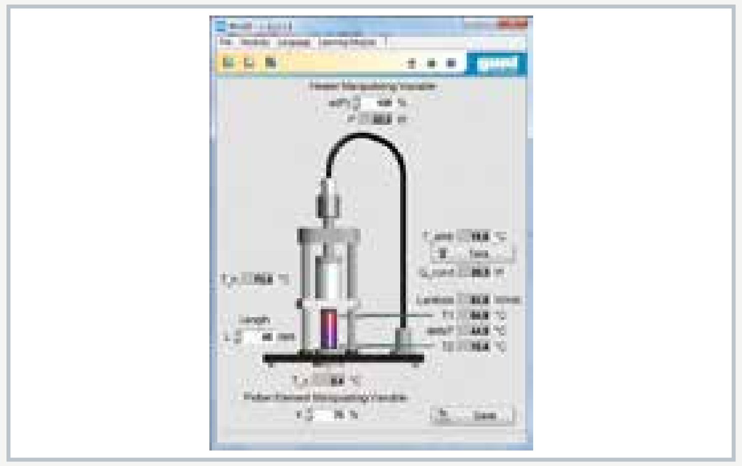
- time dependency until the steady state is reached
- calculate the thermal conductivity λ of different metals
- calculate the thermal resistance of the sample
- heat transfer with different samples connected in series
- effect of sample length on heat transfer

WL 420
Heat conduction in metals

1 heater, 2 sample, 3 storage for samples, 4 thermocouple; Peltier element concealed



Heat conduction through different metals: 1 temperature profile in metal with low thermal conductivity, 2 temperature profile in metal with medium thermal conductivity, 3 temperature profile in metal with high thermal conductivity; T temperature; red: hot, blue: cold



User interface of the powerful GUNT software

Specification

[1] investigation of the thermal conductivity of different metals
[2] continuously adjustable heater
[3] Peltier element as cooler
[4] 11 samples made of 5 metals, different lengths
[5] display of temperatures and power consumption in the software
[6] microprocessor-based instrumentation
[7] functions of the GUNT software: educational software, data acquisition, system operation
[8] GUNT software for data acquisition via USB under Windows 7, 8.1, 10

Technical data

Peltier element
- cooling capacity 56,6W

Heater
- heating power 30W
- temperature limitation: 150°C

Samples Ø 20mm
Length between measuring points
- 5x 20mm (copper, steel, stainless steel, brass, aluminium)
- 5x 40mm (copper, steel, stainless steel, brass, aluminium)
- 1x 40mm with turned groove (aluminium)

Measuring ranges
- temperature: 4x 0...325°C
- heating power: 0...50W

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase; 120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 670x350x480mm
Weight: approx. 18kg

Required for operation

PC with Windows

Scope of delivery

1 experimental unit
11 metal samples
1 CD with authoring system for GUNT educational software
1 GUNT software CD + USB cable
1 set of instructional material

WL 422
Heat conduction in fluids

Description

- **effect of different fluids on heat conduction**
- **functions of the GUNT software: educational software, data acquisition, system operation**
- **part of the GUNT-Thermoline: Fundamentals of Heat Transfer**

Heat conduction is one of the three basic forms of heat transfer. According to the second law of thermodynamics, heat is always transferred from the higher energy level to the low energy level.

WL 422 offers basic experiments for targeted teaching on the topic of heat conduction in fluids. Such teaching should discuss the fundamental differences between gases and liquids.

Two cylinders form the main component of the experimental unit: an electrically heated inner cylinder situated in a water-cooled outer cylinder. There is a concentric annular gap between the two cylinders. This annular gap is filled with the fluid being studied. The heat conduction occurs from the inner cylinder, through the fluid to the outer cylinder.

The narrow annular gap prevents the formation of a convective heat flux and allows a relatively large pass-through area while at the same time providing a homogeneous temperature distribution.

The experimental unit is equipped with temperature sensors inside and outside of the annular gap. Thermal conductivities for different fluids, e.g. water, oil, air or carbon dioxide can be determined in experiments.

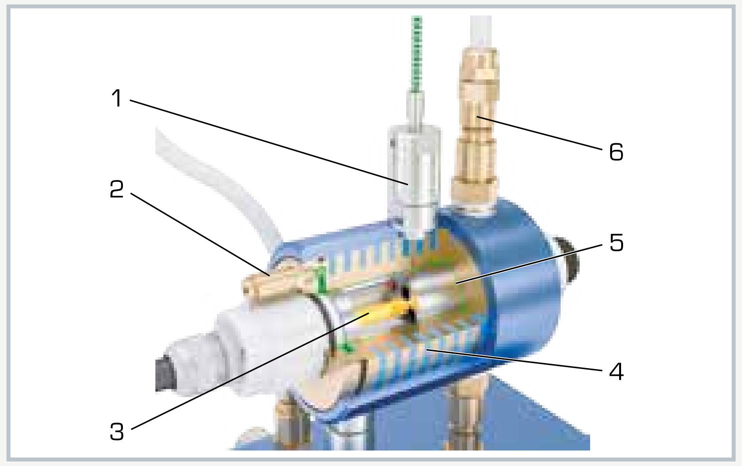
The microprocessor-based instrumentation is well protected in the housing. The GUNT software consists of a software for system operation and for data acquisition and an educational software. With explanatory texts and illustrations the educational software significantly aids the understanding of the theoretical principles. The unit is connected to the PC via USB.

Learning objectives/experiments

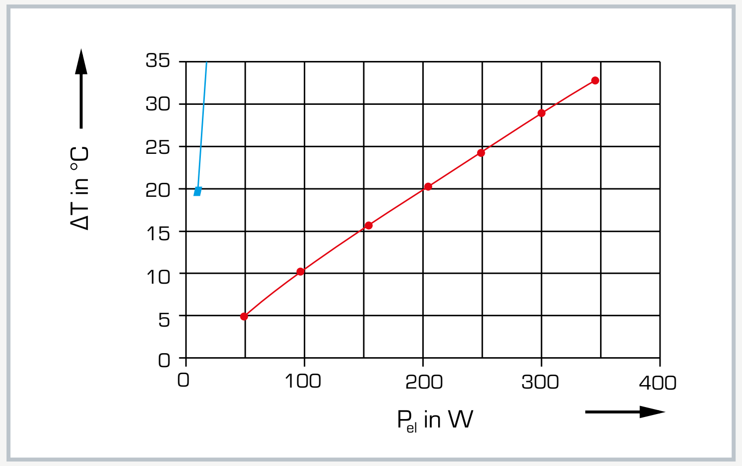
- steady heat conduction in gases and liquids:
  - determine the thermal resistance of fluids
  - determination of thermal conductivities k for different fluids at different temperatures
- transient heat conduction in fluids:
  - interpret transient states during heating and cooling
  - introduction to transient heat conduction with the block capacity model

WL 422
Heat conduction in fluids

1 temperature sensor, 2 connection for fluid to be examined, 3 inner cylinder, 4 valve for cooling water, 5 outer cylinder, 6 cooling water hose



Cross-sectional view of the experimental setup: 1 temperature sensor, 2 connection for fluid, 3 inner cylinder, 4 cooling channel, 5 annular gap, 6 cooling water connection; blue: cooling water, green: fluid



Differences in calculated values for water and air
ΔT temperature difference, P_{el} Electrical power; blue: air, red: water

Specification

[1] investigation of the thermal conductivity of common fluids, e.g. water, oil, air or carbon dioxide
[2] concentric annular gap between 2 cylinders containing the fluid being studied
[3] inner cylinder, continuously electrically heated
[4] water-cooled outer cylinder
[5] display of temperatures and heating power in the display
[6] microprocessor-based instrumentation
[7] functions of the GUNT software: educational software, data acquisition, system operation
[8] GUNT software for data acquisition via USB under Windows 7, 8.1, 10

Technical data

Heater
- heating power: 350W
- temperature limitation: 95°C

Heat transfer area: 0,007439m^2

Annular gap
- height: 0,4mm
- average diameter: 29,6mm

Inner cylinder
- mass: 0,11kg
- specific heat capacity: 890J/kg*K

Measuring ranges
- temperature: 2x 0...325°C
- heating power: 0...450W

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase; 120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 670x350x480mm
Weight: approx. 18kg

Required for operation

cold water connection max. 30°C, min. 1L/h
drain
PC with Windows

Scope of delivery

1 experimental unit
1 set of hoses
1 set of hoses with quick-release couplings
1 CD with authoring system for GUNT educational software
1 GUNT software CD + USB cable
1 set of instructional material

WL 430
Heat conduction and convection

Description

- **effect of heat conduction and convection on heat transfer**
- **experiments with still air on free convection**
- **functions of the GUNT software: educational software, data acquisition, system operation**
- **part of the GUNT-Thermoline: Fundamentals of Heat Transfer**

Heat conduction and convection are among the three basic forms of heat transfer and often occur together.

WL 430 allows basic experiments on both forms of heat transfer: heat conduction and convection.

At the heart of the unit are different metal samples. The samples are placed on a heater and are heated on one side. The heat is conducted through the sample and dissipated to the environment. The sample used behaves like a cooling fin. In addition there are fans below the sample. The flow rate of the fans is continuously adjustable in order to influence the convective heat transfer. The air flow is conveyed evenly around the sample. Consequently, besides conducting the experiment with still air (free convection), it is also possible to conduct experiments with flowing air (forced convection).

The effect of different materials on heat conduction is demonstrated by comparing different samples.

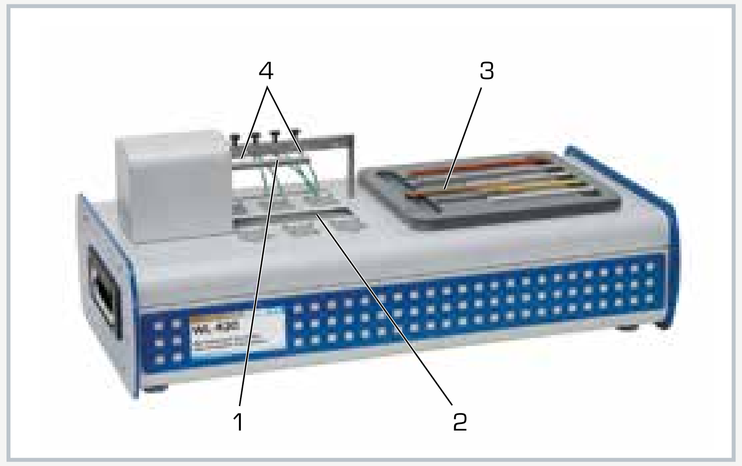
The experimental unit is equipped with five temperature sensors. Heating power and flow velocity of the air flow are adjusted and displayed via the software.

The microprocessor-based instrumentation is well protected in the housing. The GUNT software consists of a software for system operation and for data acquisition and an educational software. With explanatory texts and illustrations the educational software significantly aids the understanding of the theoretical principles. The unit is connected to the PC via USB.

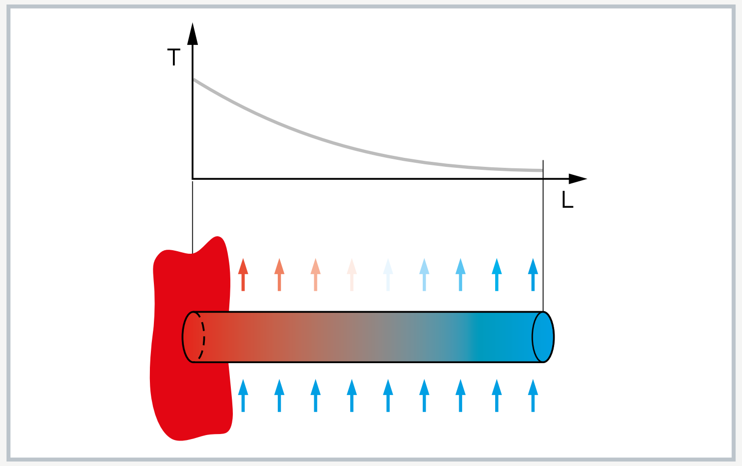
Learning objectives/experiments

- effect of heat conduction and convection on heat transfer
- effect of free and forced convection on heat transfer
- calculate convective heat transfers
- effect of different materials on heat conduction
- effect of sample length on heat transfer

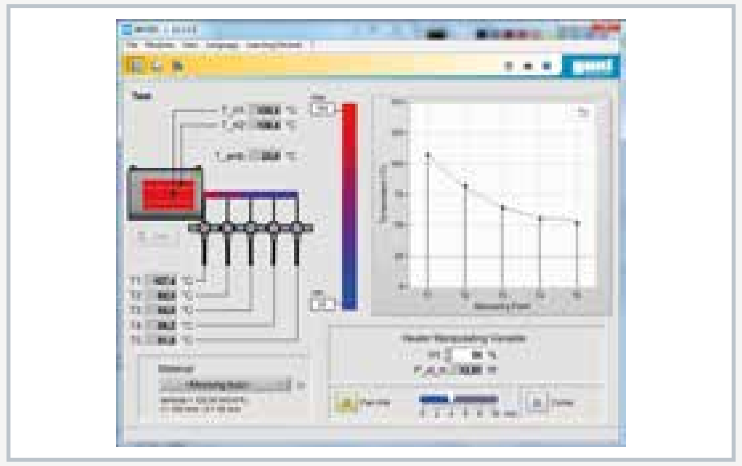
WL 430
Heat conduction and convection



1 sample, 2 air vent, 3 storage for samples, 4 thermocouple



Temperature profile along a sample: red: hot, blue: cold; T temperature, L length of the sample; arrows: air flow



User interface of the powerful GUNT software

Specification

[1] investigate heat conduction and convection using the example of a cooling fin
[2] cooling fin: sample heated at one end, made of metal
[3] 6 samples made of different materials and with different lengths
[4] 6 fans for experiments with forced convection
[5] continuously adjustable heating power and fan power
[6] display of temperatures, heating power and air velocity in the software
[7] microprocessor-based instrumentation
[8] functions of the GUNT software: educational software, data acquisition, system operation
[9] GUNT software for data acquisition via USB under Windows 7, 8.1, 10

Technical data

Heater
- heating power 30W
- temperature limitation: 160°C

6x fan
- max. flow rate: $40m^3/h$
- nominal speed: $14400min^{-1}$
- power consumption: 7,9W

4x samples, short
- length dissipating heat: 104mm
- heat transfer area: $32,6cm^2$
- copper, aluminium, brass, steel

2x samples, long
- length dissipating heat: 154mm
- heat transfer area: $48,4cm^2$
- copper, steel

Measuring ranges
- flow velocity: 0...10m/s
- temperature: 8x 0...325°C
- heating power: 0...30W

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase; 120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 670x350x280mm
Weight: approx. ca. 17kg

Required for operation

PC with Windows

Scope of delivery

1 experimental unit
7 metal samples
1 CD with authoring system for GUNT educational software
1 GUNT software CD + USB cable
1 set of instructional material

WL 440
Free and forced convection

Learning objectives/experiments

- free and forced convection
- calculation of convective heat transfer at different geometries
  - flat plate
  - cylinder
  - tube bundle
- experimental determination of the Nusselt number
- calculation of typical characteristic variables of heat transfer
  - Nusselt number
  - Reynolds number
- investigation of the relationship between flow formation and heat transfer during experiments
- description of transient heating process

Description

- **free and forced convection using the example of various heating elements**
- **functions of the GUNT software: educational software, data acquisition, system operation**
- **part of the GUNT-Thermoline: Fundamentals of Heat Transfer**

Convection is one of the three basic forms of heat transfer. Material-bound heat transport takes place. During convection the fluid is in motion.

The WL 440 offers basic experiments for targeted teaching on the topic of free and forced convection on various heating elements.

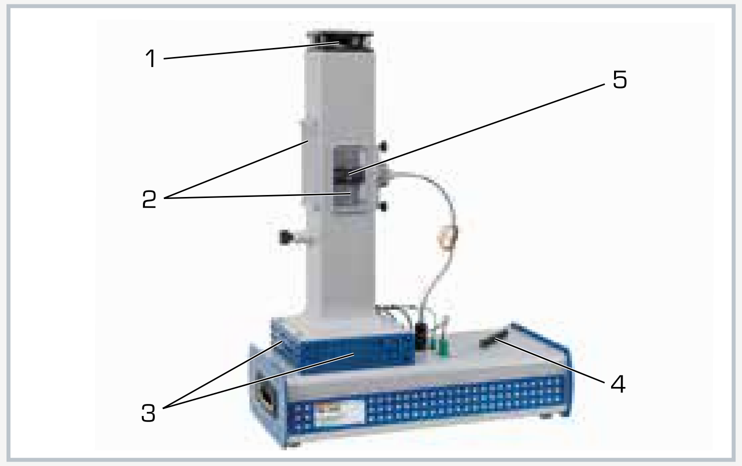
At the heart of the experimental unit is a vertical air duct into which various heating elements are inserted.

An axial fan is located on top of the air duct. The fan draws in ambient air and guides it through the air duct. The air flows past a heating element and absorbs heat. Four heating elements with different geometries are available to be selected. In order to investigate free convection, two of the four heating elements can be operated outside of the air duct. The heating elements are designed in such a way to release heat only at their surface. The compact design ensures rapid heating and a short time for experiments.

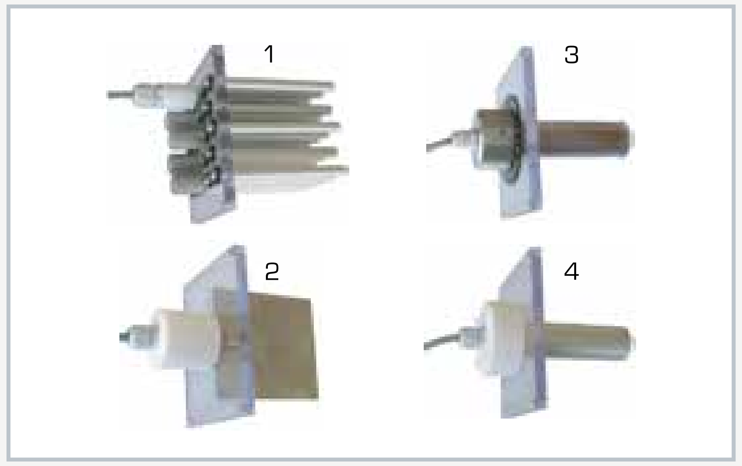
The experimental unit is equipped with temperature sensors at the inlet and outlet of the air duct. The air velocity is measured to determine the air flow rate. Heating power and flow rate are adjusted and displayed via the software.

The microprocessor-based instrumentation is well protected in the housing. The GUNT software consists of a software for system operation and for data acquisition and an educational software. With explanatory texts and illustrations the educational software significantly aids the understanding of the theoretical principles. The unit is connected to the PC via USB.

WL 440
Free and forced convection



1 fan, 2 sight window, 3 air inlet, 4 hand-held meter for temperature, 5 heating element



Various interchangeable heating elements: 1 tube bundle, 2 plane plate, 3 cylinder with heating foil to examine the local heat transfer, 4 cylinder with an even temperature at the surface

User interface of the powerful GUNT software

Specification

[1] investigate heat transfer in the air duct by forced convection
[2] study of free convection
[3] air duct with axial fan
[4] 4 heating elements with different geometries
[5] continuously adjustable heating power and fan power
[6] display of temperatures, heating power and air velocity in the software
[7] microprocessor-based instrumentation
[8] functions of the GUNT software: educational software, data acquisition, system operation
[9] GUNT software for data acquisition via USB under Windows 7, 8.1, 10

Technical data

Air duct
- flow cross-section: 120x120mm
- height: approx. 0,6m

Heating elements, temperature limitation: 90°C
- tube bundle
  - number of tubes: 23
  - one tube in variable postion is heated
  - heating power: 20W
  - heat transfer area: 0,001m^2
- cylinder with an even temperature at the surface
  - heating power: 20W
  - heat transfer area: 0,0112m^2
- plate
  - heating power: 40W
  - heat transfer area: 2x 0,01m^2
- cylinder with heating foil to investigate the local heat transfer
  - heating power: 40W
  - heat transfer area: 0,0112m^2

Axial fan
- max. flow rate: 500m^3/h
- max. pressure difference: approx. 950Pa
- power consumption: 90W

Measuring ranges
- air velocity: 0...10m/s
- temperature: 4x 0...325°C
- heating power: 0...50W

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase; 120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 670x350x880mm; Weight: approx. 25kg

Required for operation

PC with Windows

Scope of delivery

1 experimental unit
1 GUNT software CD + USB cable
1 set of instructional material

WL 460
Heat transfer by radiation

Description

- **effect of different surfaces on heat transfer by radiation**
- **functions of the GUNT software: educational software, data acquisition, system operation**
- **part of the GUNT-Thermoline: Fundamentals of Heat Transfer**

Heat radiation is one of the three basic forms of heat transfer. In radiation the heat transfer takes place via electromagnetic waves. Unlike heat conduction and convection, heat radiation can also propagate in a vacuum. Heat radiation is not bound to a material.

WL 460 offers basic experiments for targeted teaching on the topic of heat transfer by radiation. At the heart of the experimental unit is a metallic sample heated by a concentrated light beam. The light beam is generated by a continuously adjustable halogen lamp and a parabolic reflector. The reflector concentrates the radiation to a focal point. A sample is placed on a thermocouple located at the focal point. The thermal radiation emitted by the sample is measured by a thermopile. In order to be able to measure the radiation at different distances, the thermopile is mounted on a moveable carriage.

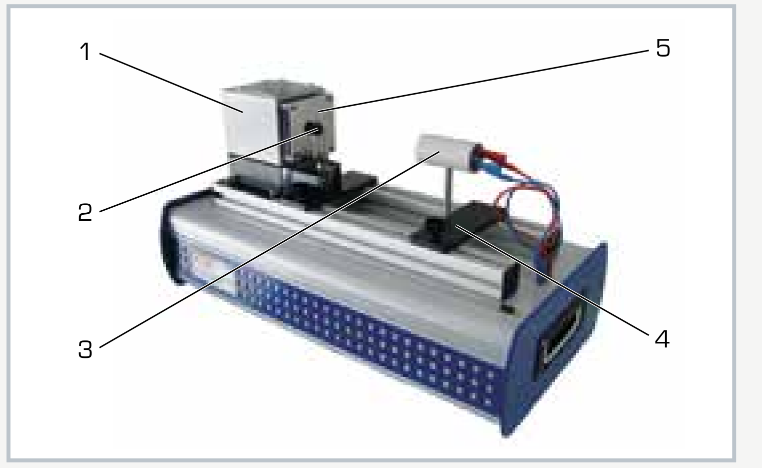
Samples with different surfaces are available to be selected. Perfectly matched components ensure rapid heating and trouble-free measurements.

The microprocessor-based instrumentation is well protected in the housing. The GUNT software consists of a software for system operation and for data acquisition and an educational software. With explanatory texts and illustrations the educational software significantly aids the understanding of the theoretical principles. The unit is connected to the PC via USB.

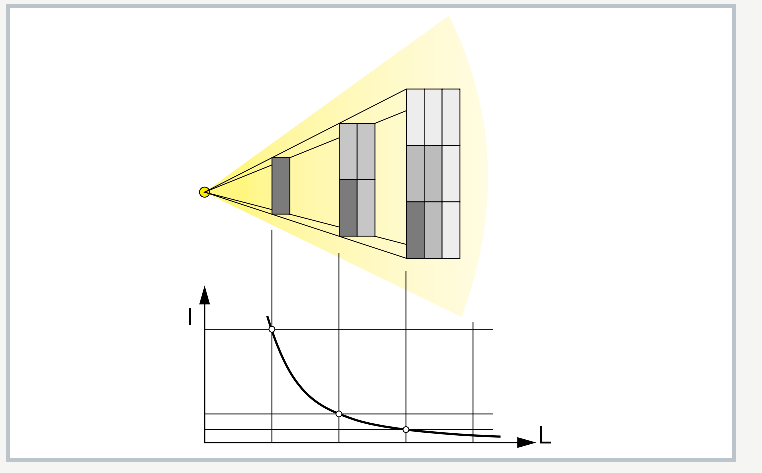
Learning objectives/experiments

- verify Lambert's inverse-square law
- verify Stefan-Boltzmann law
- verify Kirchhoff's law
- study transient behaviour
- create power balances
- produce logarithmic diagrams for evaluations

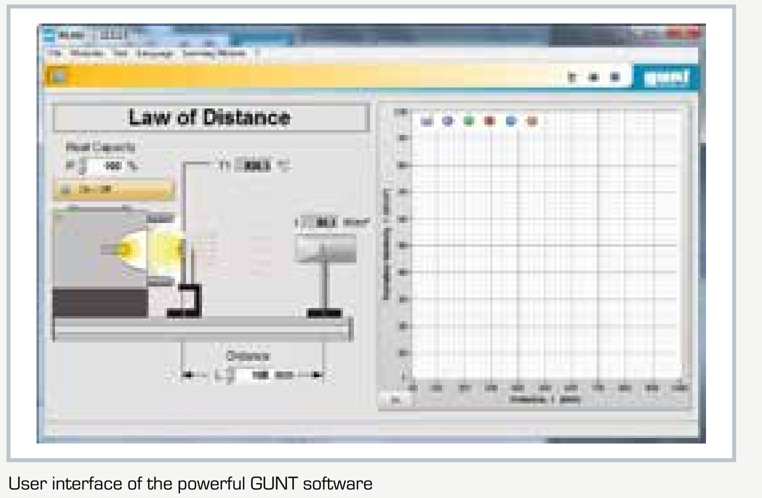
WL 460
Heat transfer by radiation



1 lamp housing, 2 sample placed on thermocouple, 3 thermopile, 4 movable carriage, 5 orifice plate



Radiation intensity with point-based radiation source: I intensity of the radiation, L distance to the radiation source (Lambert's inverse-square law)



User interface of the powerful GUNT software

Specification

[1] investigation of heat radiation on different surfaces heated by a concentrated beam of light
[2] generation of the concentrated beam of light with a continuously adjustable halogen lamp and a parabolic reflector
[3] 6 different metallic samples
[4] thermopile on a movable carriage for measuring the heat radiation
[5] display of temperature and radiation intensity in the software
[6] microprocessor-based instrumentation
[7] functions of the GUNT software: educational software, data acquisition, system operation
[8] GUNT software for data acquisition via USB under Windows 7, 8.1, 10

Technical data

Halogen lamp
- electrical power 150W
- max. temperarature: approx. 560°C

Aluminium samples, Ø 20mm
- 1x matt anodized on both sides
- 1x painted on both sides (high-temperature paint)
- 1x matt anodized with one painted side

Copper samples, Ø 20mm
- 1x nickel-plated
- 1x heavily oxidized

Steel sample, Ø 20mm
- 1x heavily oxidized

Measuring ranges
- temperature: 0...780°C
- radiation intensity: 0...1250W/m^2

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase; 120V, 60Hz, 1 phase
UL/CSA optional
LxWxH:LxBxH: 670x350x370mm
Weight: approx. 18kg

Required for operation

PC with Windows

Scope of delivery

1 experimental unit
6 different metal samples
1 CD with authoring system for GUNT educational software
1 GUNT software CD + USB cable
1 set of instructional material

WL 900
Steady-state and non-steady-state heat conduction

Learning objectives/experiments

- steady heat conduction
- transient heat conduction
- temperature/time profiles
- calculate thermal conductivity λ of different metals

Description

- **steady and transient heat conduction in metals**
- **12 temperature measurement points in every sample**
- **regulated temperature of the heat source**

Heat conduction is the transport of heat between the individual molecules in solid, liquid and gaseous media under the influence of a temperature difference. Steady heat conduction is the term used when heat transport is maintained permanently and uniformly by adding heat. In transient heat conduction, the temperature distribution in the body is dependent on location and time.

Thermal conductivity λ is a temperature-dependent property of a material that indicates how well the heat propagates from a point in the material.

WL 900 can be used to study both steady and transient heat conduction. The trainer consists of a heat source and a heat sink, between which cylindrical samples made of different metals are inserted. Each sample is fitted with 12 temperature measurement points. The temperature measurement points are designed to has as little influence on the temperature as possible and the core temperature of the sample is measured.

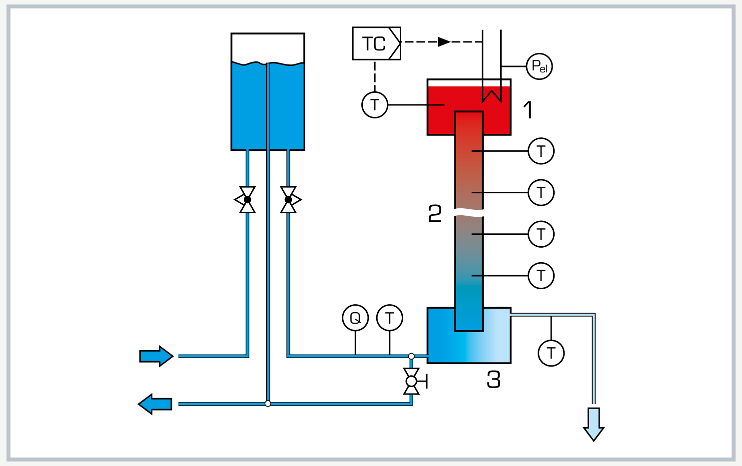
The heat source consists of an electrically heated hot water circuit. An electronic controller ensures the heating water is kept at a constant temperature. The heat sink is realised by means of a water cooling system. An elevated tank ensures a constant cooling water flow rate.

A temperature jump can be generated by appropriate regulation of the cooling water flow. A PC can be used to display the transient temperature distribution in the sample over time and place.

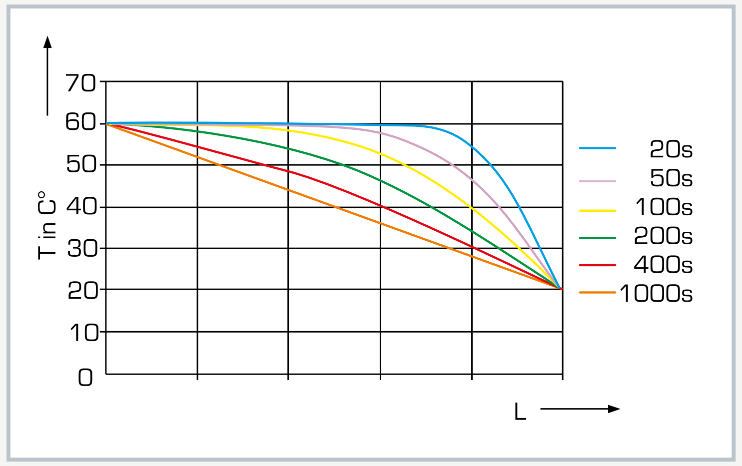
The temperatures of the sample, heating and cooling water, as well as the electrical heating power and the cooling water flow rate are displayed digitally on the switch cabinet and can be transmitted simultaneously via USB directly to a PC where they can be analysed using the software included. The thermal conductivity λ can be calculated from the measured data.

WL 900
Steady-state and non-steady-state heat conduction

1 elevated tank for constant cooling water initial pressure, 2 heat source with heater, 3 sample, 4 water-cooled heat sink, 5 displays and controls



1 heater, 2 sample, 3 heat sink; T temperature, Q flow rate, TC heating water temperature controller, P_{el} electric heating power, blue cooling water, red heating water



Transient temperature profile along a rod with sudden cooling
T temperature, L length of the rod, coloured lines: temperature profile at different points in time

Specification

[1] investigation of steady and transient heat conduction in metals
[2] determining the thermal conductivity λ
[3] heating water circuit as heat source, electronically regulated
[4] electric heater with PID controller
[5] elevated tank with overflow for generating a constant cooling water flow rate
[6] samples made of 5 different metals
[7] cooling water temperature and flow rate measurement
[8] digital displays: electric heating power, temperatures, cooling water flow rate
[9] GUNT software for data acquisition via USB under Windows 7, 8.1, 10

Technical data

Heater
- output: 800W
- temperature: 20...85°C

Samples, Ø 40mm
- 3x 450mm (copper, aluminium, brass)
- 2x 300mm (steel, stainless steel)

Heating tank: ca. 2L
Cooling tank: ca. 0,5L
Elevated tank: ca. 6L

Temperature sensors
- 12x thermocouple type K, along the sample
- 2x Pt100, in the cooling water
- 1x Pt100, in the heating water

Measuring ranges
- temperature: 14x 0...100°C
- power: 0...1000W
- flow rate: 0,1...2,5L/min

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase, 120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 1240x800x1670mm
Weight: approx. 150kg

Required for operation

water connection, drain
PC with Windows recommended

Scope of delivery

1 trainer
1 set of accessories
1 set of instructional material

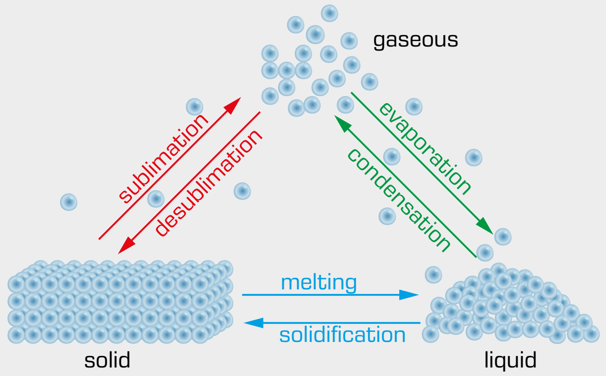
Basic knowledge

Phase transition

Phase transition

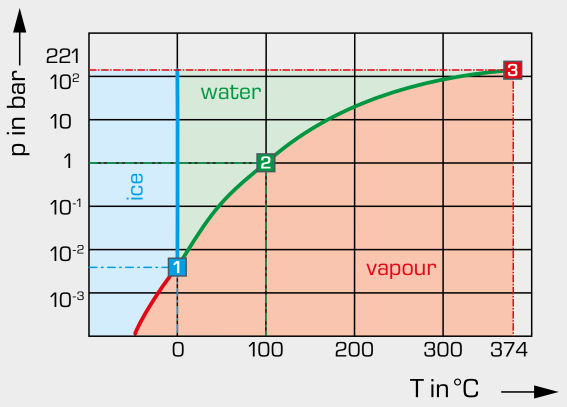
A gaseous, liquid or solid state in a homogeneous system of substances is called a phase. The phase depends on the thermodynamic state variables pressure **p** and temperature **T**.

The conversion from one phase to another is called a phase transition:



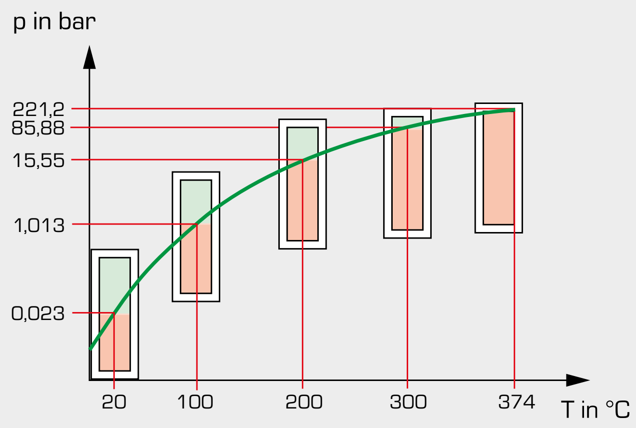
Above the critical point 3 the gaseous and liquid phases of some systems of substances, e. g. water, cannot be differentiated anymore. The physical properties of the fluid lie somewhere between the two phases: The density corresponds to the density of the liquid phase, the viscosity to that of the gaseous phase. This phase is known as the "supercritical" phase. In this phase, the fluid can neither evaporate nor condense.

Another particularity in some systems of substances, such as water, is known as the triple point 1. At this point the solid, liquid and gaseous phase are in equilibrium. All six phase changes occur simultaenously.



Phase diagram of water

sublimation curve,
vaporisation curve,
fusion curve;
1 triple point, **2** boiling point, **3** critical point



Closed system along the vapour pressure curve of water

vaporisation curve,
water,
vapour;
p pressure, **T** temperature

In a closed system filled with liquid, a thermodynamic equilibration sets in between the liquid and its vaporised phase. This state is called the saturation state. The prevailing pressure is referred to as vapour pressure, in case of water steam pressure or saturated steam pressure, and the temperature is known as saturation temperature. The vapour pressure curve can be derived from both. This curve is shown in the phase diagram of water.

Evaporation process

Steam is used for a variety of processes in engineering. The most common applications are heating processes as well as steam turbines in power plants.

Typical applications of steam in processes include:

- heating: e.g. shell-and-tube heat exchangers to heat up a product
- propulsion: e.g. steam turbines, steam engines
- propellant: e.g. steam ejectors to separate process gases
- atomization: steam for the mechanical separation of fluids, e.g. in gas flares, to reduce soot particles in the exhaust gas
- cleaning: steam cleaners to loosen dirt
- product moistening: paper production
- air humidification: steam humidifiers in air ducts

We distinguish between ideal gas, real gas and vapour. In an ideal gas, pressure and volume are exactly inversely proportional, in a real gas only by approximation. In vapours, the pressure changes only slightly with the volume, depending on the degree of saturation.

Steam occurs in various forms:

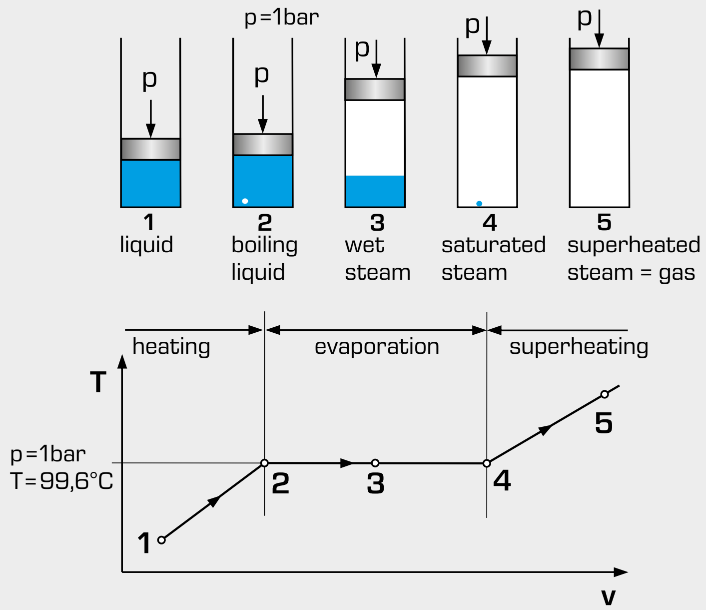
Wet steam: Liquid and gaseous state of the water molecules in a system, some water molecules have released their evaporation heat and condense into fine water droplets.

Saturated steam: Boundary area between wet steam and hot steam, state in which the last drop of water changes from liquid to gaseous. The addition of further heat beyond the boiling point produces hot steam or superheated steam.

Hot steam: A distinction is made between **superheated steam** and **supercritical steam.**

Superheated steam: Steam with a temperature above the boiling temperature, purely gaseous state of the water molecules. Real gas is present.

Supercritical steam: Phase at temperatures above the critical point



Evaporation of water: change of state when heating water under constant pressure **p** = 1 bar

T temperature,
v specific volume;
1 liquid,
2 boiling liquid,
3 unsaturated (wet) steam,
4 saturated steam,
5 superheated steam (gas)

WL 210
Evaporation process

Learning objectives/experiments

- observation of typical forms of evaporation
  - single phase liquid flow
  - sub-cooled boiling
  - slug flow
  - annular flow
  - film boiling
  - dispersed flow
  - single phase vapour flow
  - wet steam
- effect on the evaporation process by
  - flow rate
  - temperature
  - pressure

Description

- **demonstration of evaporation in a double-wall pipe evaporator made of glass**
- **operation with harmless, special low boiling point liquid**

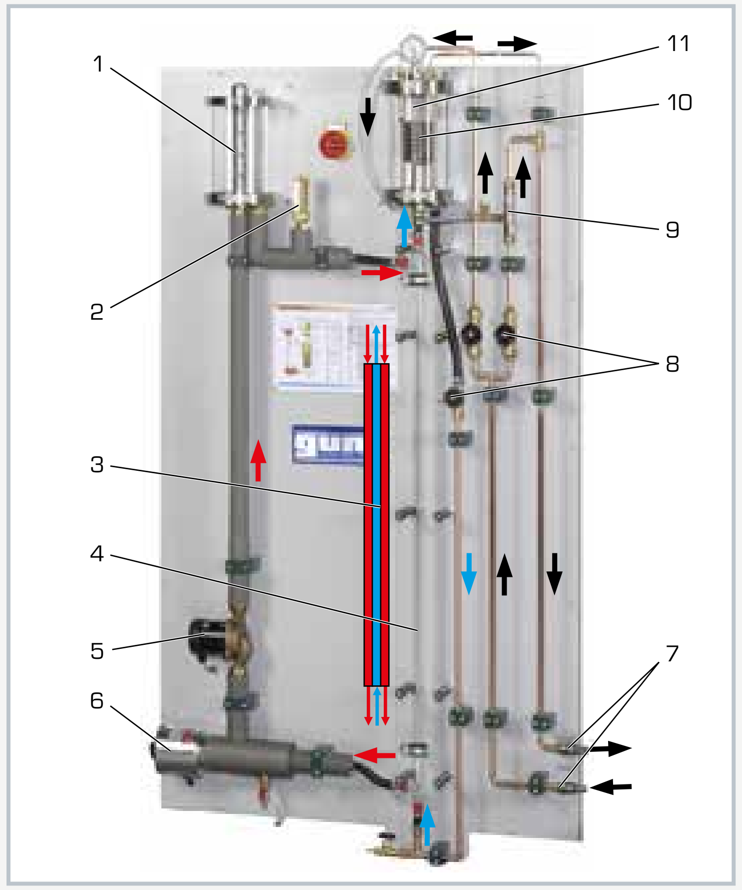
During the generation of vapour, the medium that is to evaporate runs through different flow forms dependent on the heat transfer area. The medium flows into a tube evaporator as a fluid and exits the tube evaporator as superheated vapour.

In practice, the water vapour generated in big systems is used e.g. for heating plants or machine drives. To design steam generators, it is important to have knowledge of the evaporation process with the boiling crises in order to ensure reliable operation. Boiling crises are caused by a sudden deterioration of the heat transfer, whereby the high heat flux density leads to a dangerous increase in the wall temperature.

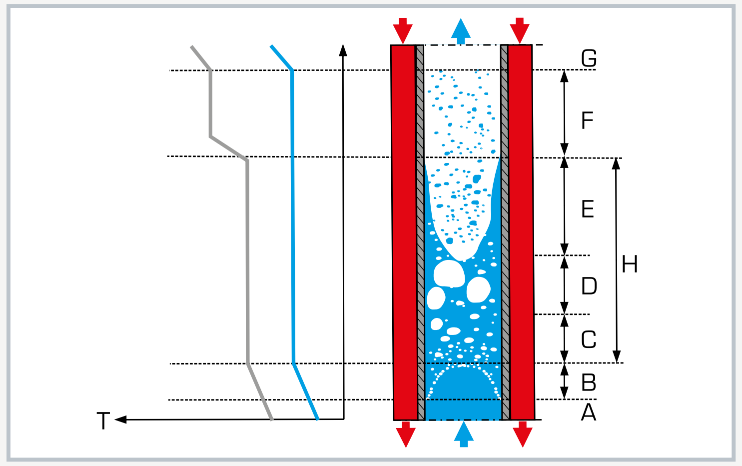
The WL 210 experimental unit can be used to examine and visualise the evaporation process in its various flow forms. This is done by heating evaporating liquid, Solkatherm SES36, in a tube evaporator made of glass.

Compared with water, this liquid has the advantage that its boiling point is at 36,7°C (1013hPa), whereby the entire evaporation process takes place at much lower temperatures and a lower heating power. The pressure can be varied via the cooling circuit. A water jet pump evacuates the evaporation circuit.

WL 210
Evaporation process



1 heating circuit tank, 2 thermometer, 3 tube evaporator, schematic drawing, 4 tube evaporator, 5 pump, 6 heater, 7 cooling water connection, 8 valves, 9 water jet pump, 10 tube coil, 11 collector with manometer and safety valve; red: heating circuit, blue: evaporation circuit, black: cooling circuit



Evaporation in a tube evaporator:
A subcooled fluid, B initial boiling point, C bubbly flow, D slug flow, E annular flow, F dispersed flow, G superheated vapour, H boiling range; blue: fluid temperature, grey: heating surface temperature

Specification

[1] visualisation of evaporation in a tube evaporator
[2] heating and cooling medium: water
[3] tube evaporator made of double-wall glass
[4] heating circuit with heater, pump and expansion vessel
[5] safety valve protects against overpressure in the system
[6] water jet pump to evacurate the evaporation circuit generate negative pressure (vacuum)
[7] evaporation circuit with CFC-free evaporating liquid Solkatherm SES36

Technical data

Heater
- power rating: 2kW
- temperature range: 5...80°C

Heating and cooling medium: water

Pump
- 3 stages
- max. flow rate: 1,9m^3/h
- max. head: 1,5m
- power consumption: 58W

Tube evaporator
- length: 1050mm
- inner diameter: 16mm
- outer diameter: 24mm

Condenser: coiled tube made of copper

Measuring ranges
- pressure: -1...1,5bar relativ
- temperature: 0...100°C

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase
120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 1250x790x1970mm
Weight: approx. 170kg

Required for operation

water connection: 500mbar, min. 320L/h, drain

Scope of delivery

1 trainer
1 kg refrigerant Solkatherm SES36
1 set of hoses
1 set of instructional material

WL 220
Boiling process

Description

- **visualisation of boiling and evaporation**
- **software for data acquisition**

Heating a liquid over a heating surface produces different modes of boiling dependent on the heat flux density. They can accelerate the evaporation process (nucleate boiling) or impair it (film boiling). In practice, a limitation of the heat flux density must be assured in order to prevent damage to the heating surface. This knowledge is applied in practice e.g. when designing steam boilers for steam-powered drives.

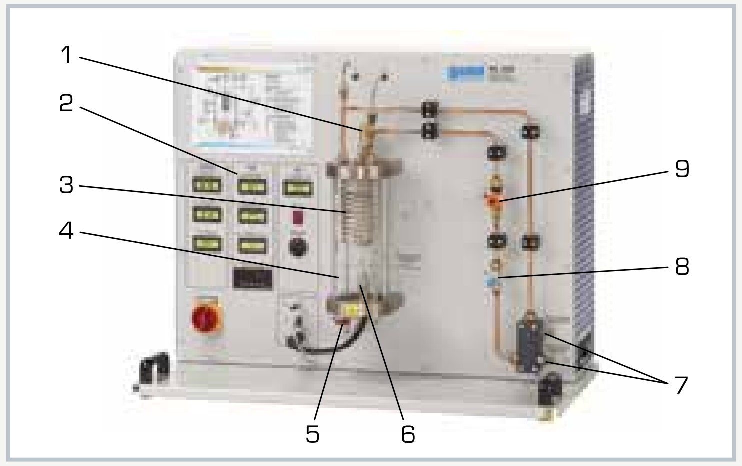
The WL 220 experimental unit can be used to demonstrate boiling and evaporation processes in a straightforward manner. The processes take place in a transparent tank. A condenser in the form of a water-cooled tube coil ensures a closed circuit within the tank. Solkatherm SES36 is used as evaporating liquid. Compared with water, this liquid has the advantage that its boiling point is at 36,7°C (1013hPa), whereby the evaporation process takes place at much lower temperatures and a lower heating power.

Sensors record the flow rate of the cooling water, the heating power, pressure and temperatures at all relevant points. The measured values can be read on digital displays. At the same time, the measured values can also be transmitted directly to a PC via USB. The data acquisition software is included.

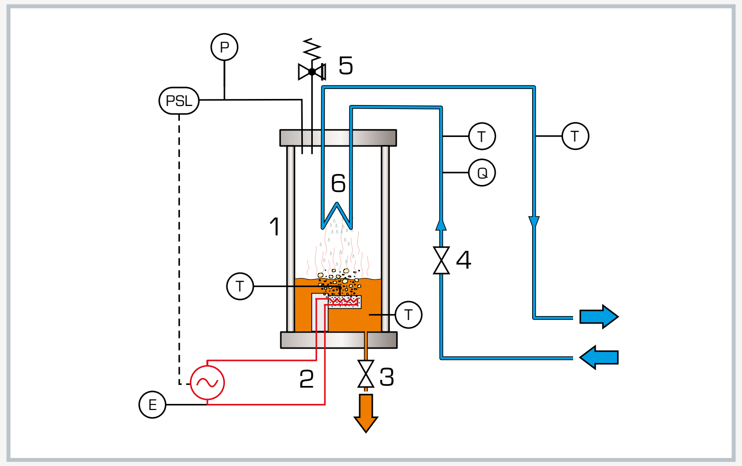
Learning objectives/experiments

- visualisation of different forms of evaporation
  - free convection boiling
  - nucleate boiling
  - film boiling
- heat transfer
- effect of temperature and pressure on the evaporation process

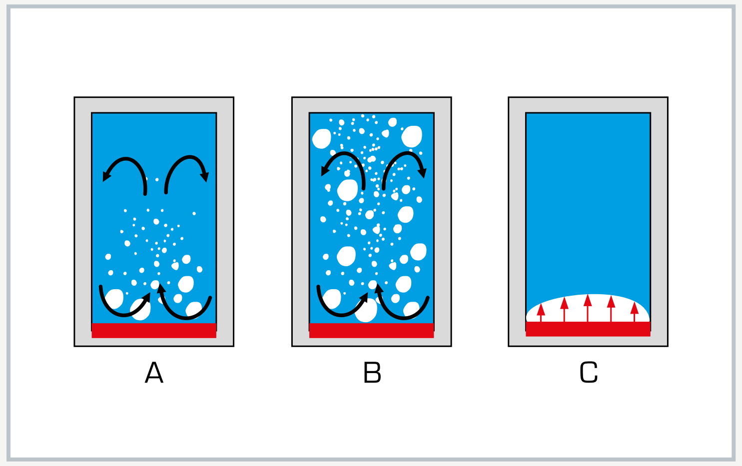
WL 220
Boiling process



1 safety valve, 2 displays for temperature, flow rate and pressure, 3 condenser, 4 pressure vessel, 5 drain valve for the evaporating liquid, 6 heater, 7 cooling water connection, 8 valve for adjusting the cooling water, 9 cooling water flow rate sensor



1 pressure vessel, 2 heater, 3 drain valve, 4 cooling water valve, 5 safety valve, 6 condenser; orange: evaporating liquid, red: heater, blue: cooling circuit; PSL pressure switch, E output, T temperature, Q flow rate, P pressure



Different modes of boiling: A free convection boiling, B nucleate boiling, C film boiling; red: heater, blue: evaporating liquid, white: steam, black: convection flow

Specification

[1] visualisation of boiling and evaporation in a transparent pressure vessel
[2] evaporation with heating element
[3] condensation with tube coil
[4] safety valve protects against overpressure in the system
[5] pressure switch for additional protection of the pressure vessel, adjustable
[6] sensors for pressure, flow rate and temperature with digital display
[7] GUNT software for data acquisition via USB under Windows 7, 8.1, 10
[8] CFC-free evaporating liquid Solkatherm SES36

Technical data

Heater
- power: 250W, continuously adjustable

Safety valve: 2bar rel.
Pressure vessel: 2850mL
Condenser: coiled tube made of copper

Measuring ranges
- tank pressure: 0...4bar abs.
- power of heater: 0...300W
- flow rate (cooling water): 0,05...1,8L/min
- temperature: 4x 0...100°C

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase
120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 1000x550x800mm
Weight: approx. 65kg

Required for operation

water connection, drain
PC with Windows recommended

Scope of delivery

1 experimental unit
2 kg refrigerant Solkatherm SES36
1 GUNT software CD + USB cable
1 set of hoses
1 set of instructional material

WL 204
Vapour pressure of water - Marcet boiler

Learning objectives/experiments

- recording the vapour pressure curve of water
- presentation of the relationship between pressure and temperature in a closed system
- temperature and pressure measurement

Description

- **recording the vapour pressure curve of water**
- **saturation pressure of water vapour as a function of the temperature**

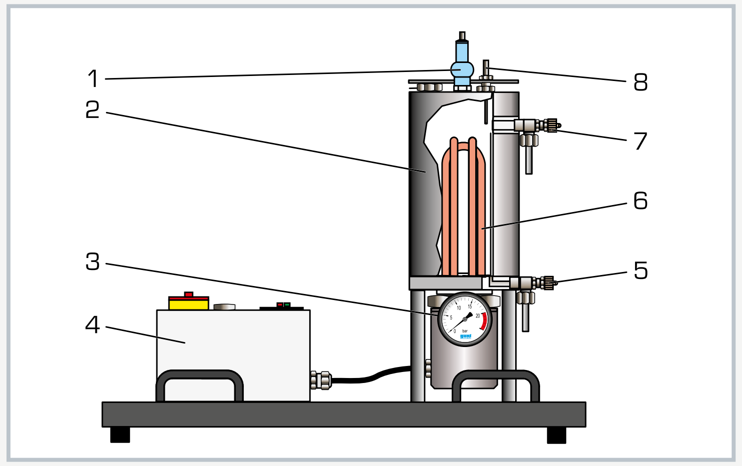
In a closed system filled with fluid, a thermodynamic equilibrium sets in between the fluid and its vaporised phase. The prevailing pressure is called vapour pressure. It is substance-specific and temperature-dependent.

When a fluid is heated in a closed tank, the pressure increases as the temperature rises. Theoretically, the pressure increase is possible up to the critical point at which the densities of the fluid and gaseous phases are equal. Fluid and vapour are then no longer distinguishable from each other. This knowledge is applied in practice in process technology for freeze drying or pressure cooking.

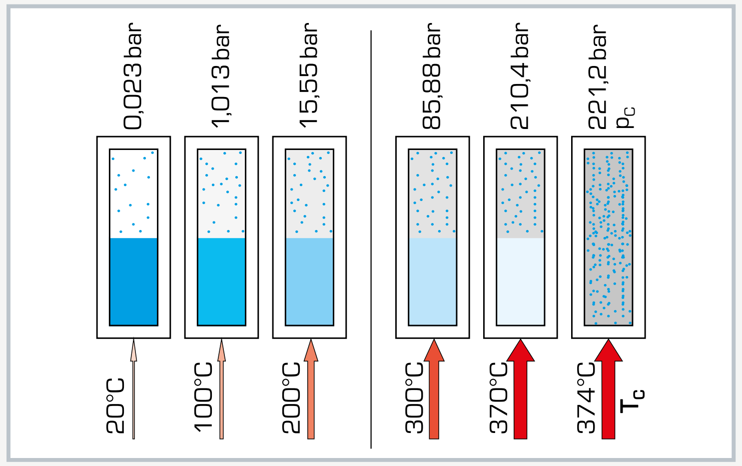
The WL 204 experimental unit can be used to demonstrate the relationship between the pressure and temperature of water in a straightforward manner. Temperatures of up to 200°C are possible for recording the vapour pressure curve. The temperature and pressure can be continuously monitored via a digital temperature display and a Bourdon tube pressure gauge.

A temperature limiter and pressure relief valve are fitted as safety devices and protect the system against overpressure.

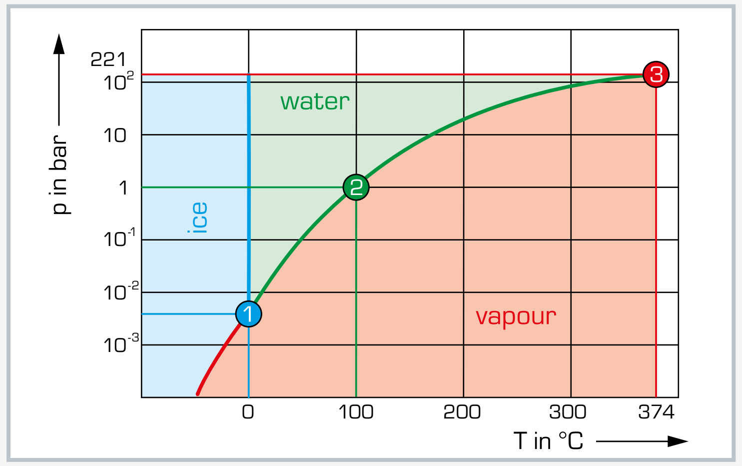
WL 204
Vapour pressure of water - Marcet boiler



1 safety valve, 2 pressure boiler with insulating jacket, 3 Bourdon tube pressure gauge, 4 switch cabinet with temperature display, 5 drain valve, 6 heater, 7 overflow, 8 temperature sensor



Heating up water in a closed tank: the pressure and temperature increase proportionally up to the critical point, at which fluid and vapour are no longer distinguishable from each other; critical point at T_c=374°C, p_c=221bar, dotted line: temperature limit of the experimental unit



Temperature-pressure diagram of water
red: sublimation curve, green: boiling point curve, blue: melting point curve; 1 triple point, 2 boiling point, 3 critical point

Specification

[1] measuring a vapour pressure curve for saturated vapour
[2] pressure boiler with insulating jacket
[3] temperature limiter and safety valve protect against overpressure in the system
[4] Bourdon tube pressure gauge to indicate pressure
[5] digital temperature display

Technical data

Bourdon tube pressure gauge: -1...24bar
Temperature limiter: 200°C
Safety valve: 20bar
Heater: 2kW
Boiler, stainless steel: 2L

Measuring ranges
- temperature: 0...200°C
- pressure: 0...20bar

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase
120V, 60Hz, 1 phase
UL/CSA optional
LxWxH: 600x400x680mm
Weight: approx. 35kg

Scope of delivery

1 experimental unit
1 funnel
1 set of tools
1 set of instructional material

WL 230
Condensation process

Description

- **visualisation of different condensation processes**
- **software for data acquisition**

Condensation forms when steam meets a medium with a lower temperature than the saturation temperature for the existing partial pressure of the steam. Factors such as the material and surface roughness of the medium influence the heat transfer and thus the type of condensation. In practice, it is usually film condensation. Dropwise condensation only forms when the cooling surface is very smooth and poorly wettable, e.g. Teflon. Knowledge of condensation processes is applied e.g. in steam power plants or at distillation processes.

The WL 230 experimental unit can be used to demonstrate the different condensation processes using two tubular shaped water-cooled condensers made of different materials. Dropwise condensation can be demonstrated by means of the condenser with a polished gold-plated surface. Film condensation forms on the matt copper surface of the second condenser, thus making it possible to examine film condensation.

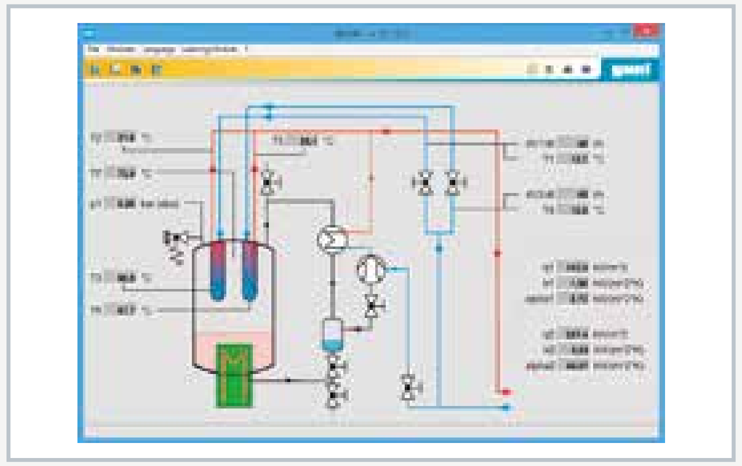
The tank can be evacuated via a water jet pump. The boiling point and the pressure in the system are varied by cooling and heating power. Sensors record the temperature, pressure and flow rate at all relevant points. The measured values can be read on digital displays. At the same time, the measured values can also be transmitted directly to a PC via USB. The data acquisition software is included. The heat transfer coefficient is calculated from the measured values. The influence of non-condensing gases, pressure and the temperature difference between the surface and steam can be examined in further experiments.

Learning objectives/experiments

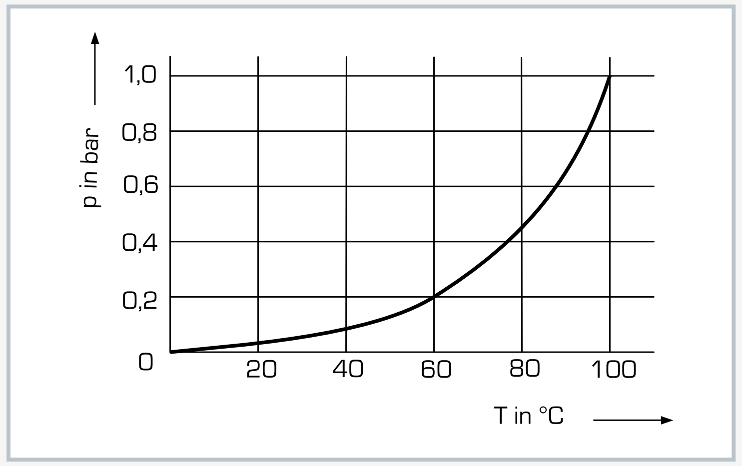
- dropwise and film condensation
- determination of the heat transfer coefficient
- effect of pressure, temperature and non-condensable gases on the heat transfer coefficient

WL 230
Condensation process

1 condensers, 2 heat exchanger, 3 steam trap, 4 displays for temperature, flow rate and pressure, 5 heater, 6 cooling water connections, 7 water jet pump, 8 temperature sensor, 9 valve for adjusting the cooling water, 10 cooling water flow rate sensor



Software screenshot



Vapour pressure curve for water: p pressure, T temperature

Specification

[1] visualisation of the condensation process of water in a transparent tank
[2] two water-cooled tubes as condensers with different surfaces to realise film condensation and dropwise condensation
[3] controlled heater to adjust the boiling temperature
[4] water jet pump to evacuate the tank
[5] pressure switch and safety valve for safe operation
[6] sensors for temperature, pressure and flow rate with digital display
[7] GUNT software for data acquisition via USB under Windows 7, 8.1, 10

Technical data

Heater
- output: 3kW, freely adjustable

Condenser
- 1x tube with matt copper surface
- 1x tube with a polished gold-plated surface

Water jet pump
- flow rate: 4...12L/min
- pressure: 16mbar

Safety valve: 2200mbar absolute

Measuring ranges
- pressure: 0...10bar absolute
- flow rate: 0,2...6L/min
- temperature: 4x 0...100°C, 3x 0...200°C

230V, 50Hz, 1 phase
230V, 60Hz, 1 phase
230V, 60Hz, 3 phases
UL/CSA optional
LxWxH: 1000x550x790mm
Weight: approx. 85kg

Required for operation

water connection: 1bar, max.1000L/h, drain
PC with Windows recommended

Scope of delivery

1 experimental unit
5L distilled water
1 set of hoses
1 GUNT software CD + USB cable
1 set of instructional material