Experiment Instructions

WL 377 Natural Convection and Radiation Apparatus

Experiment Instructions

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This manual must be kept by the unit.

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

Version 0.1

Subject to technical alterations

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1 Introduction

In the case of real heat transport between two bodies, the heat transfer generally takes place simultaneously through material-bound transport, such as convection or thermal conduction, and non-material-bound transport, such as radiation. It is difficult to determine the individual heat quantities in a particular kind of transfer.

With the WL 377 trainer, it is possible to allocate these individual heat quantities to the transfer types. The core component is a metal cylinder located in a pressure vessel. There is a temperature-controlled heating element in the middle of the cylinder. Sensors record the cylinder wall temperature, the heater temperature and the heater power. This metal cylinder is used to investigate the heat transfer between the heating element and the vessel wall.

The pressure vessel can be subjected to a vacuum or excess pressure. In a vacuum, the heat transport takes place primarily through radiation. If the vessel is filled with gas and subjected to excess pressure, the heat is additionally transferred through convection. It is possible to compare heat transfer in various gases. Nitrogen, helium or carbon dioxide are suitable for testing in addition to air.

A rotary pump generates vacuums of up to approx. 0,02 mbar. Excess pressure of up to approx. 1 bar can be generated with air pressure. Two pressure transducers with suitable measuring ranges are available for pressure measurement: the vacuum is recorded with a Pirani gauge, whereas a piezo-resistive sensor is used for tests where the cylinder is filled.

The measured values are read out on digital displays and can be simultaneously and directly transferred to a PC via a USB connection, where they can be analysed using the software supplied.

Learning content/exercises

Tests in a vacuum:

- Heat transfer through radiation
- Determination of the radiation coefficient

Tests at ambient pressure or excess pressure:

- Heat transfer through convection and radiation
- Determination of the heat quantities transferred through convection
- Determination of the heat transfer number from the measured values
- Theoretical determination of the heat transfer number using the Nusselt number
- Comparison of heat transfer in various gases

2 Safety

2.1 Intended use

The unit is to be used only for teaching purposes.

2.2 Structure of the safety instructions

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

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

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

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

2.3 Safety instructions

⚠ WARNING

Electrical connections are exposed when the switch cabinet is open.

Danger of electric shock.

- Disconnect the mains plug before opening the switch cabinet.
- Work should only be carried out by qualified electricians.
- Protect the switch cabinet against moisture.

⚠ CAUTION

Injuries are possible when opening the pressure vessel without pressure compensation.

- Before the cover is removed, the vacuum pump must be switched off and pressure compensation in the pressure vessel must be established.

⚠ CAUTION

Vacuum pump and heater become hot in operation.

There is a risk of burns from the hot surface of the heater, the vacuum pump and the vessel.

- Allow unit to cool down first.
- Do not touch hot surfaces, or only with protective gloves.

⚠ WARNING

High noise emissions.

High noise emissions may occur within a limited range around the vacuum pump. Danger of damage to hearing.

- Provide noise insulation or
- Wear ear protection.

NOTICE

There is a danger of overheating. Do not operate the trainer at more than 200°C. Plastic parts may be damaged.

NOTICE

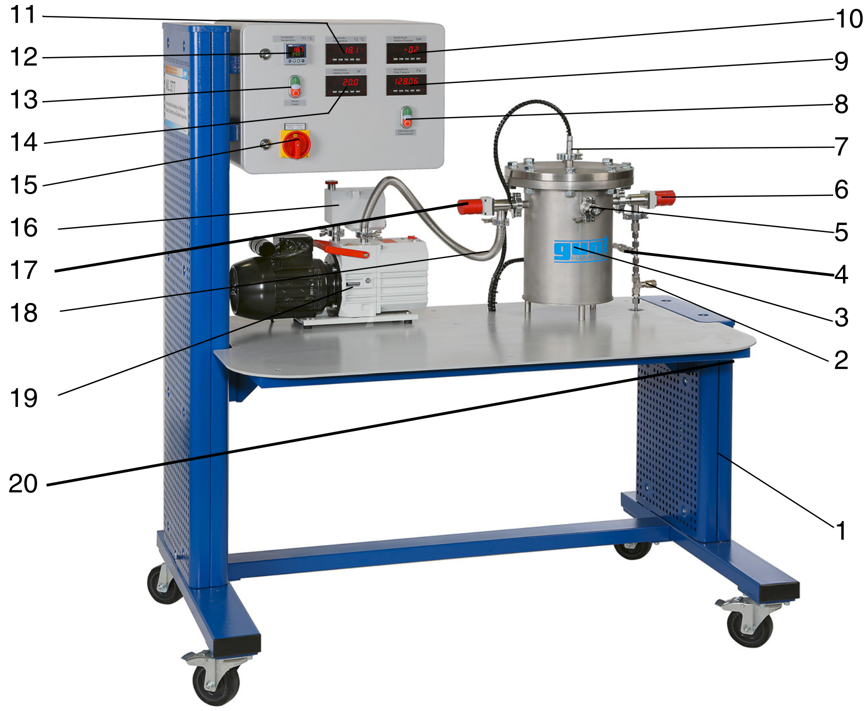
Switch off the trainer at the main switch prior to disconnecting or connecting power supply or data cables. The temperature transducers and other transducers may be irreparably damaged.

2.4 Ambient conditions for operation and storage location

- Enclosed space.
- Free of dirt and moisture.
- Even and stable standing surface.
- Frost-free.

3 Unit description

3.1 Unit layout



1 Moveable table frame with pressure vessel

2 Air inlet valve (V4)

3 Pressure vessel with heater

4 Pressure relief valve (V3)

5 Bleed valve (V5)

6 Feed valve (V2)

7 Connection for heater and thermocouple

8 Vacuum pump on/off (! The vacuum pump may have an additional switch at the rear of the electric motor)

9 Pressure display p_{abs} in Pa

10 Pressure display p_{rel} in bar

11 Temperature display of the vessel wall (T2)

12 Temperature controller with display (T1) (displays the heater temperature)

13 Heater on/off

14 Heater power display (E1)

15 Main switch

16 Oil separator on the outlet side

17 Valve on the intake side (V1)

18 Oil filter (with zeolite) on the intake side (not shown here)

19 Vacuum pump (P) with electric motor

20 Air or gas inlet

Both pressure transducers (P1) (P2) and the temperature transducer (T2) are located on rear of the pressure vessel.

Fig. 3.1 WL 377 main view

3.2 Process schematic

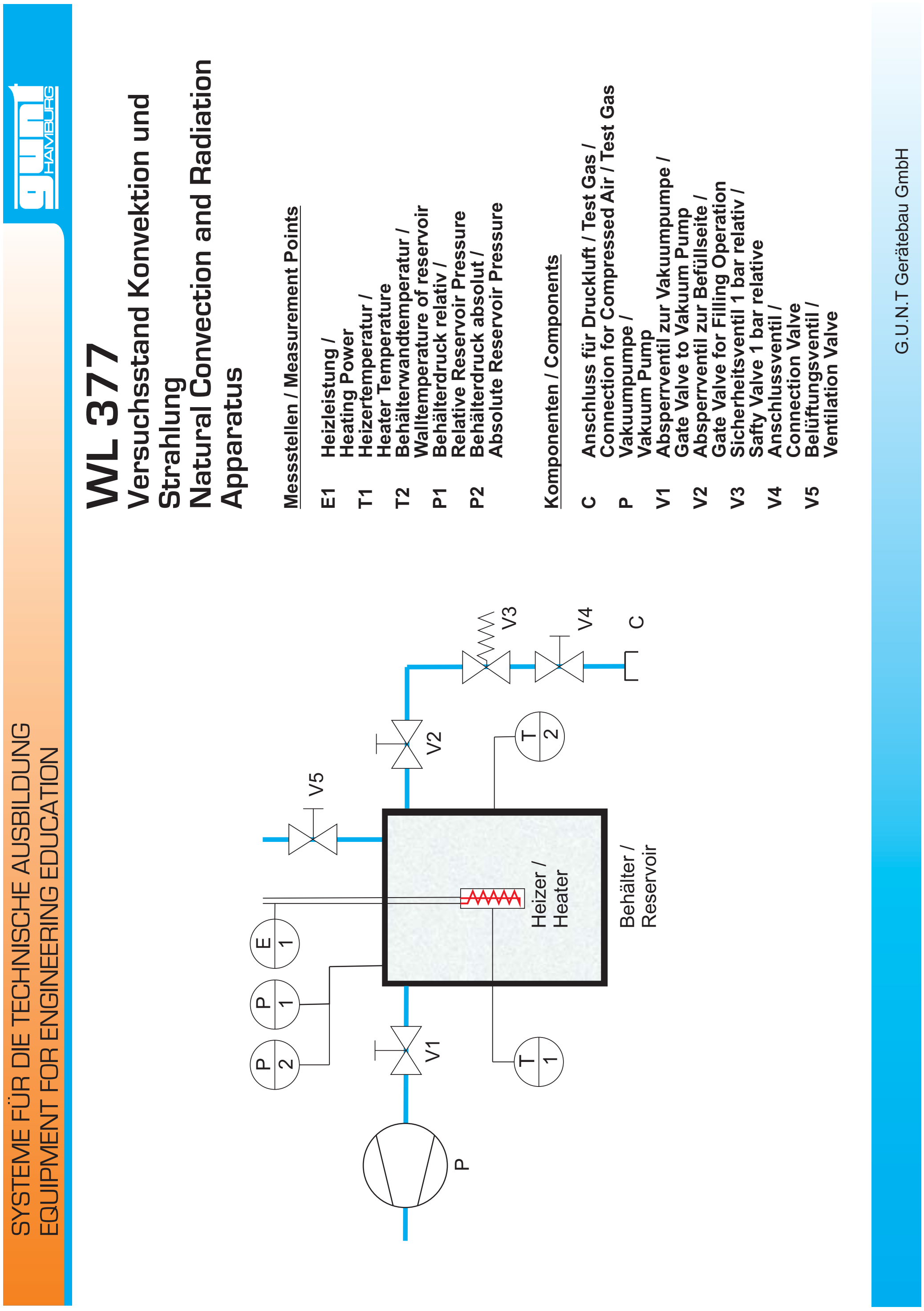


Fig. 3.2 WL 377 process schematic

3.3 Components

3.3.1 Operating and display elements

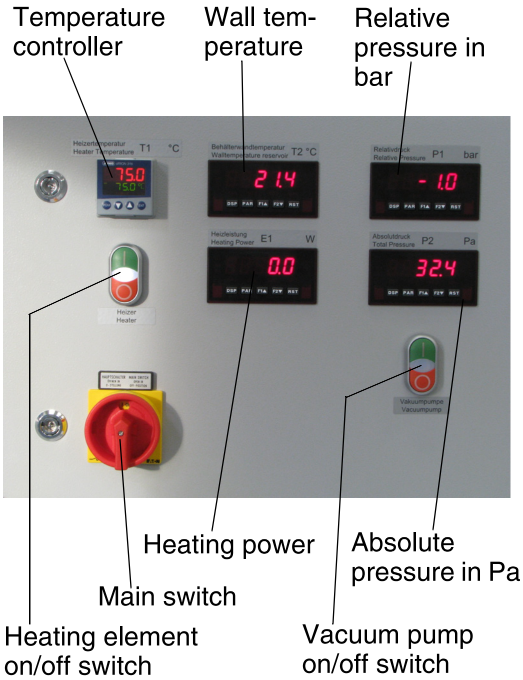


Fig. 3.3 Operating and display elements

The main switch and both on/off switches for the vacuum pump and heating element are located on the switch cabinet door.

The vacuum chamber pressure displays are above the vacuum pump switch. The upper pressure display shows the relative pressure to the environment in bar. The display range is from 1,5 bar to -1,0 bar.

The lower display shows the absolute pressure in Pa. The display range is from 0 Pa to 9999 Pa.

The wall temperature display is located at the top centre. The (actual) heating element temperature is indicated in red on the controller display. The heating element on/off switch is under the heating element controller.

3.3.2 The heating element

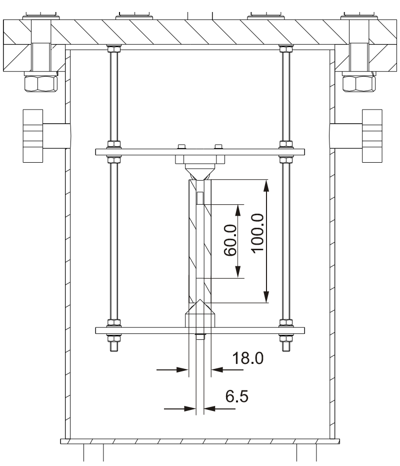


Fig. 3.4 Heating element in the pressure vessel

The heating element in question is an electrically-heated cartridge in a copper casing. The heating element is positioned vertically in the centre of the pressure vessel. The heating element casing is held by PTFE tips.

3.3.3 The temperature controller

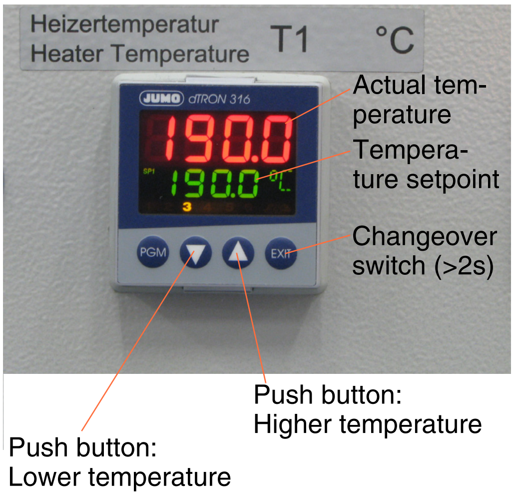


Fig. 3.5 Normal operation of the heater

The heater temperature is set and controlled using a temperature controller. The temperature can be set up to a maximum value of 190°C. The temperature controller can be operated in two modes.

Normal operation:

In normal operation, the temperature setpoint (green) in °C is adjusted with the upwards and downwards arrow buttons. If a value has been entered, then the controller adjusts the actual heater temperature (red) to this temperature setpoint. This temperature control is limited to a maximum of 190°C.

Manual operation:

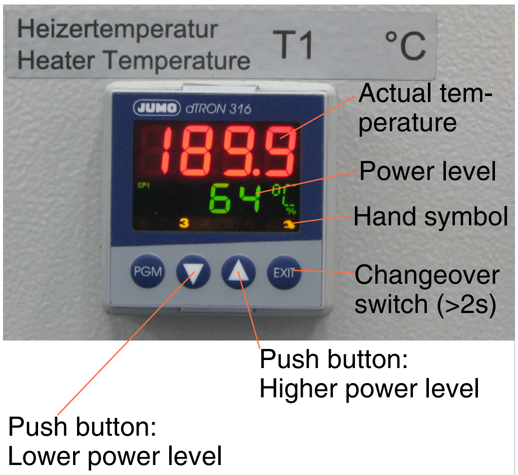


Fig. 3.6 Manual heater operation

In manual operation, the controller power level can be changed manually using the same arrow buttons. The heater power level can be set between 0% and 100% in manual operation. No temperature control takes place. The maximum attainable temperature is approx. 240°C in the vacuum.

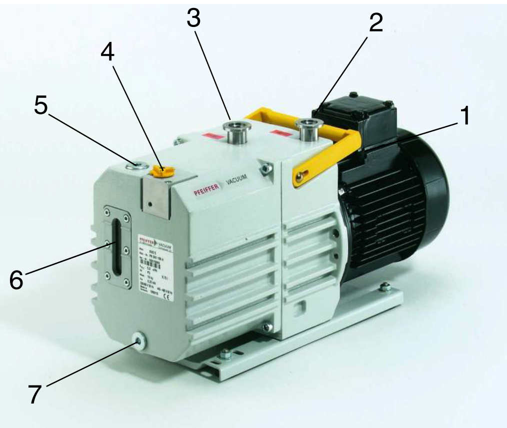
To switch between the modes, press and hold the "EXIT" key for more than 2 seconds. When set to manual operation, a small hand symbol appears in the bottom right-hand corner of the display.

The controller regulates the heating element between 0 and 100% using an impulse-pause signal. A 100% signal therefore corresponds to the maximum heating element power.

At the same time, the controller activates the power display with a signal from 0 to 10 V which corresponds to the regulation of 0 to 100%. The maximum heating element power has been specified and stored in the unit.

Using the stored power value and the analogue signal of between 0 and 10 V, the current power is established and displayed.

3.3.4 The vacuum pump



1 On/off switch
2 Exhaust flange
3 Vacuum flange
4 Gas ballast valve
5 Operating fluid filling screw
6 Sight glass
7 Operating fluid outlet screw

Fig. 3.7 Vacuum pump without oil separator

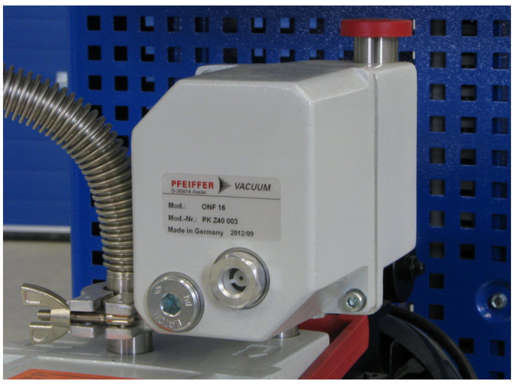


Fig. 3.8 Oil separator

The vacuum pump is a two-stage rotary pump with magnetic coupling. This pump is suitable for both rough and fine vacuums. The pumps are equipped with a vacuum safety valve, which seals the recipient vacuum-tight when the pump is not running, and also ventilates the pump. The incorporated magnetic coupling functions friction-free and contact-free. It is therefore not subject to mechanical wear and is completely maintenance-free.

An oil separator is located on the vacuum pump's air outlet (exhaust flange) which traps and collects the vacuum pump's separated oil. In order to prevent foreign particles from infiltrating the pump during long downtimes, the air outlet on the oil separator should be sealed with the red plastic cap (see Fig. 3.8). This should be removed during operation.

3.3.4.1 Before turning on

- The operating fluid level in the sight glass (6) must be checked before every start-up. Top up operating fluid (P3 standard operating fluid) if required. (See pump rating plate)
- Provide the pump with sufficient protection from the intake of contaminants by implementing suitable measures (e.g. dust filters), checking operating fluid regularly or replacing at shorter intervals as appropriate. Refer to the manufacturer's operating instructions.
- Remove red cap from the air outlet.

3.3.4.2 Gas ballast valve

Fig. 3.9 Closed gas ballast valve

In order to avoid condensation build-up in the pump when pumping out condensable vapours, air can be periodically channelled into the workspace at the start of the compression phase by the gas ballast valve (4). The gas ballast valve is closed when turned clockwise to the position 0 and open when turned anticlockwise to the position 1. An intermediate position is not possible.

3.3.5 The pressure vessel

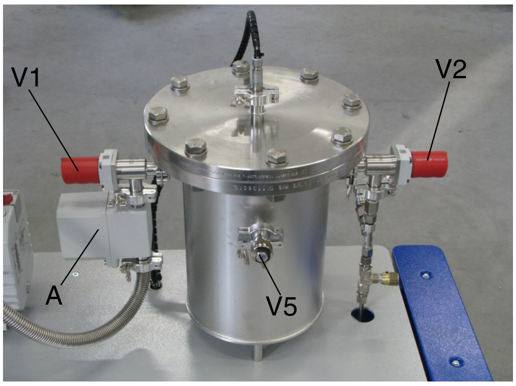


Fig. 3.10 Pressure vessel with zeolite trap

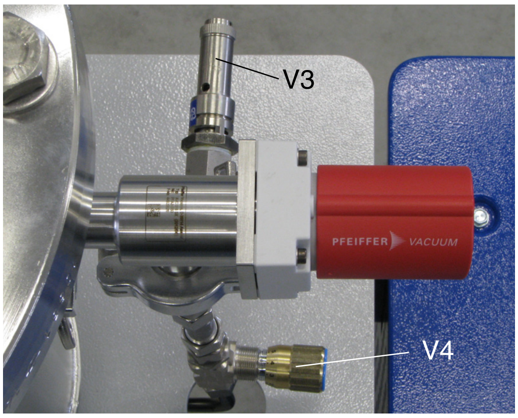


Fig. 3.11 Twist grip with embossed marking.

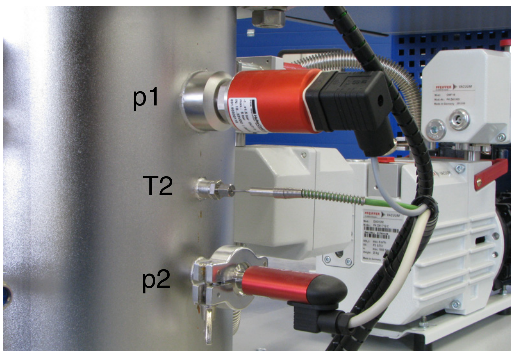


Fig. 3.12 Pressure and wall temperature sensors

The pressure vessel is intended for vacuums and excess pressures of up to 1 bar. At 1 bar, the pressure relief valve V3 activates on the supply air side. The shut-off valves V1 for the intake side and V2 for the supply air side are located at the sides of the pressure vessel. The valves have a red twist grip with an embossed marking. If this embossed marking is at the top, then the valve is closed (see Fig. 3.11). The valve is opened by turning this grip by approx. 180°. On the intake side to the vacuum pump, there is a container (A) which is filled with zeolite.

This is intended to prevent oil mist from the vacuum pump infiltrating the vacuum vessel and affecting or destroying the Pirani gauge which is located there.

On the supply air side, there is a fine regulating valve (V4) next to the safety valve (V3).

The supply for the electrical heating and the connection for the heater temperature transducer are both connected via the cover of the pressure vessel.

There is a ventilation and bleed valve (V5) on the front side of the pressure vessel.

The pressure transducers for relative and absolute pressure, in addition to the temperature transducer for the wall temperature, are located on the rear of the pressure vessel (Fig. 3.12).

3.4 Installing the data acquisition program

The following are needed for installation:

- A fully-operational PC with USB port (for minimum requirements see Chapter 6.1, Page 37).
- G.U.N.T. CD-ROM

All components necessary to install and run the program are contained on the CD-ROM supplied by G.U.N.T.

3.4.1 Installation procedure

NOTICE
The trainer must not be connected to the USB port on the PC during installation of the program. The trainer may only be connected after the software has been installed successfully.

- Start the PC.
- Insert the G.U.N.T. CD-ROM.
- Start the installation program "Setup.exe" in the "Installer" folder.
- Follow the installation procedure on screen.
- After starting, the installation runs automatically. The following program components are installed on the PC:
  - Program for PC-based data acquisition.
  - Driver routines for the "LabJack®" USB converter.
- When the installation program is finished, restart the PC.

3.4.2 Starting the program

Before the computer is switched on, the trainer must be connected to a power supply!

- Start Windows™
- Select and launch the program using: Start / All Programs / G.U.N.T. / WL377 or double click on the corresponding icon of the GUNT software.
- When the software is launched for the first time after installation, you will be prompted to select the language to be used for the program.
  The language can subsequently be changed at any time in the "Language" menu.
- Various pull-down menus are provided for additional functions.
- For detailed instructions on use of the program, refer to its "Help" function. This "Help" function can be accessed by opening the "?" pull-down menu and selecting "Help".

Saved measurement data can be imported into a spreadsheet program (such as Microsoft Excel) where it can be edited.

3.4.3 Start menu

Fig. 3.13 "Menu" screen

Fig. 3.13 shows the start menu which is only displayed once after starting the program. One of four languages can be selected here. The language can also be changed at a later stage under the "Language" menu point.

3.4.4 Schematic diagram

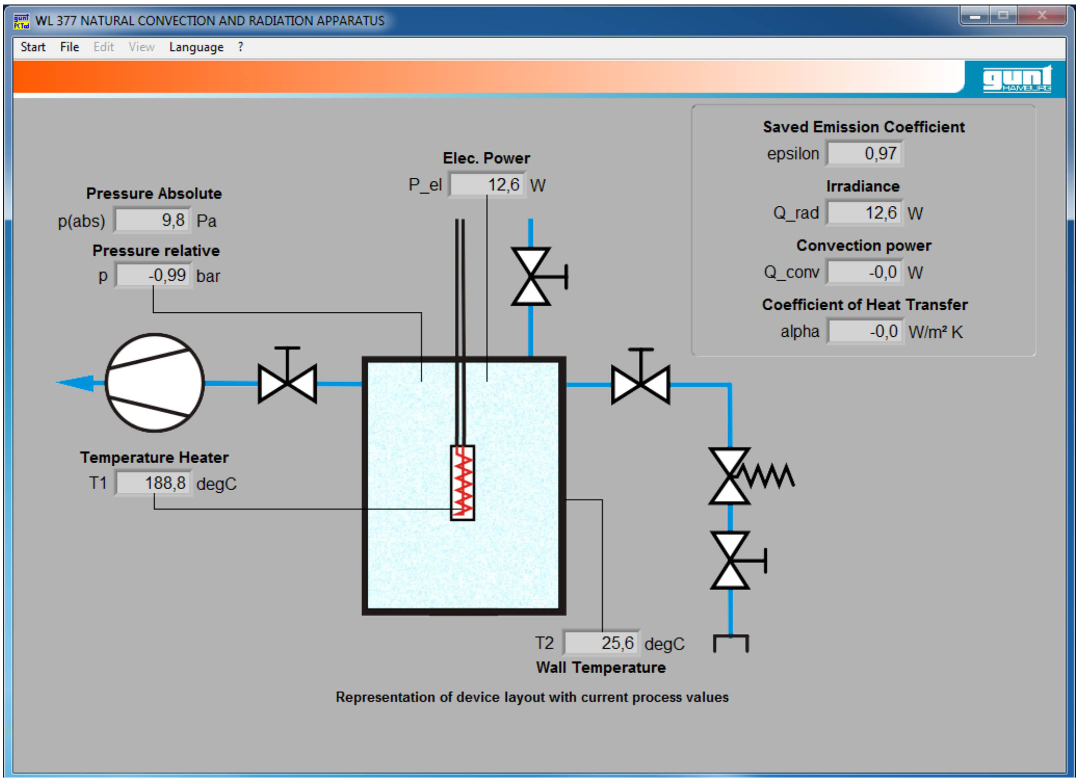


Fig. 3.14 Schematic diagram of device layout with current process values

The device layout is displayed schematically in this window. The current measured values (pressure in vessel, temperature at heating element, temperature at the wall and electrical heating power) are shown.

Calculated values are displayed slightly recessed in the top right-hand corner. It is necessary for the emission coefficient to have been determined in advance for this calculation.

3.4.5 Determination of the emission coefficient

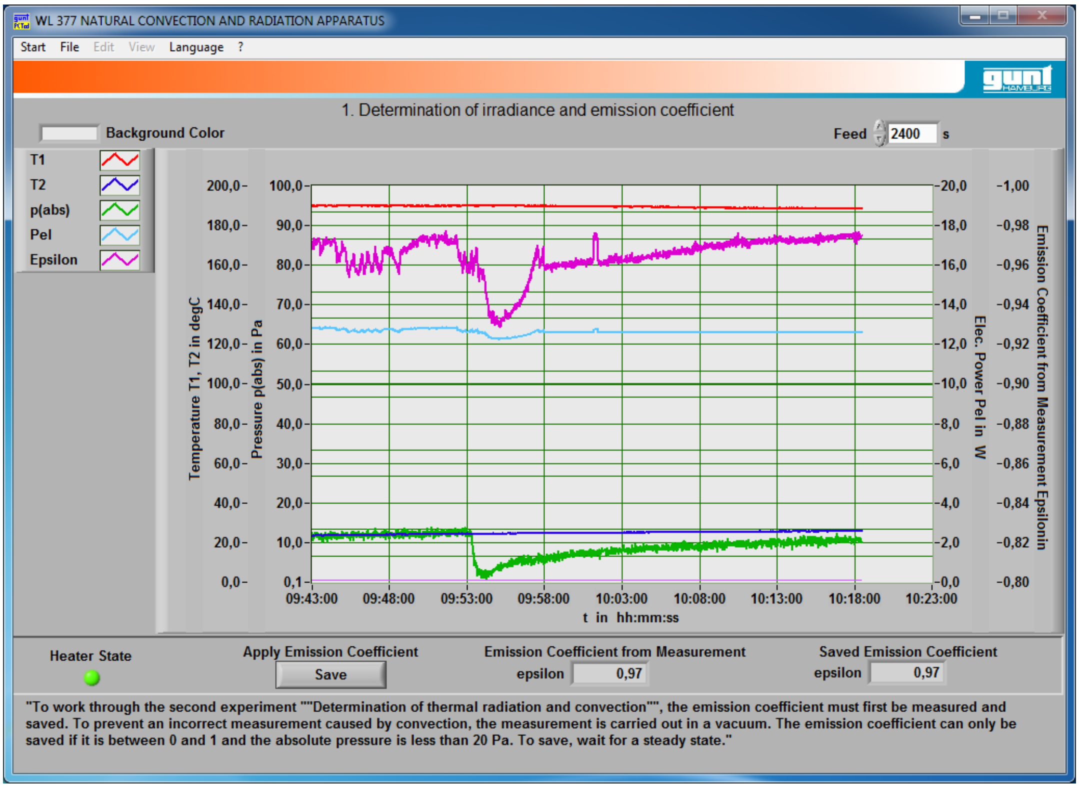


Fig. 3.15 Window for determining emission coefficient

In this window, the values for vessel pressure, temperature and the heater's electrical heating power are plotted over time.

The emission coefficient is calculated and can only be saved for subsequent calculations for pressures < 20 Pa. The emission coefficient is required for the later determination of the heat quantity transferred through convection and the heat transfer number.

3.4.6 Convection

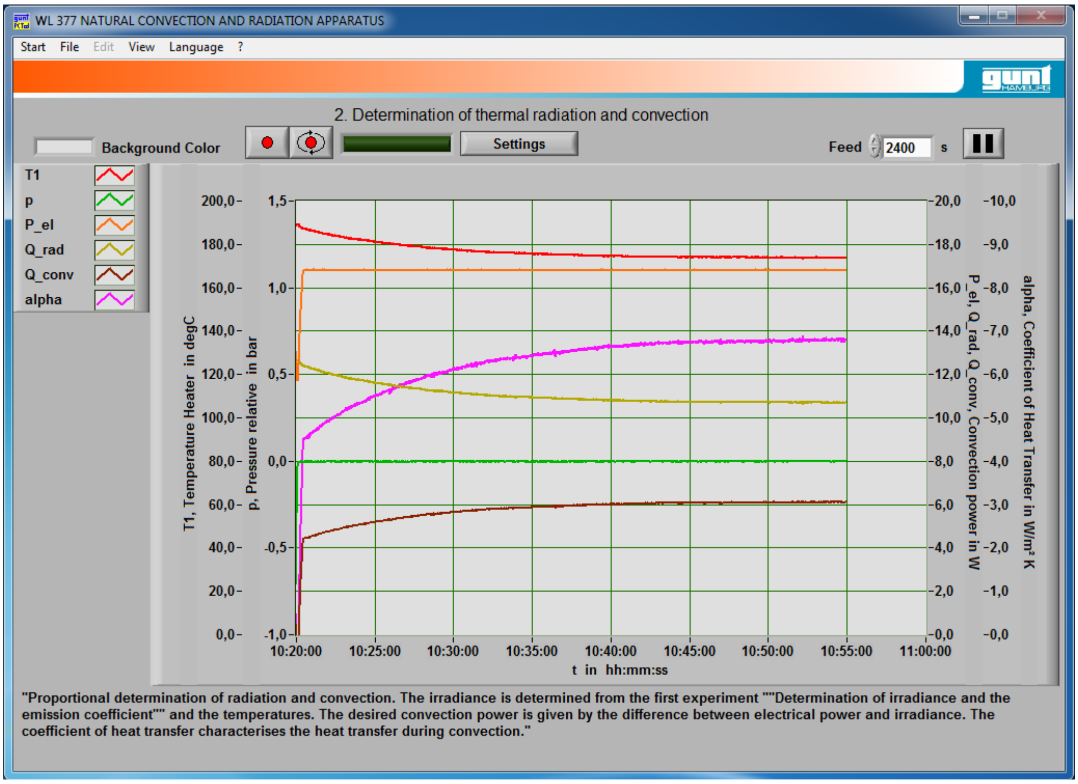


Fig. 3.16 Window for determination of the heat quantity transferred through convection and the heat transfer number

In this window, the proportion of heat transferred through convection and the heat transfer number are calculated using the previously determined emission coefficient. The read-out of the values should only take place once a stationary state has been reached.

The values for the heat transfer number, convection power and irradiance can also be read out in the system diagram window.

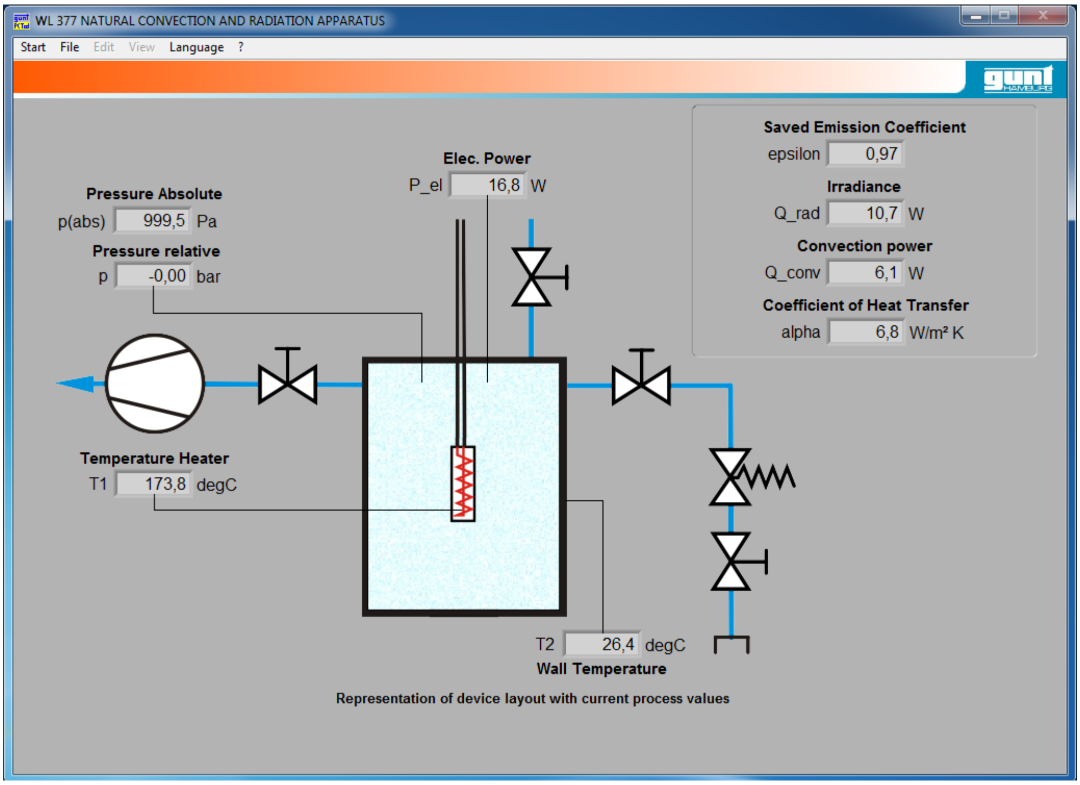


Fig. 3.17 Window with the power values for convection and radiation calculated with ε and the determined coefficient of heat transfer.

3.5 Setting up and connection

The unit is fitted with wheels and is therefore mobile. The front wheels are fitted with brakes in order to fix the unit in place on an even surface.

3.6 Commissioning

– Check oil level of vacuum pump.

– Check gas ballast valve is in position "0".

– Connect the unit to the power supply.

NOTICE

Danger of damage to the device.

- Before connecting to the electrical supply: Make sure that the power supply in the laboratory corresponds to the specifications on the unit's rating plate.

3.6.1 Operation - turning on the unit

1. Turn on the main switch (15).
2. Close ventilation valve (V5).
3. Close inlet valve (V2).
4. The valve (V1) to the vacuum pump on the intake side must be open.
5. Turn on the vacuum pump (P) with the switch (8). (The pressure on displays (9) and (10) must now fall.)
6. Switch on the heater with the switch (13) and set the setpoint for the temperature to be controlled on the controller (12). Use the push buttons "Down arrow" and "Up arrow" to do so.

The controller shows the heater temperature (green: temperature setpoint; red: actual temperature).

7. After attaining the temperature, the controller should be switched to manual operation. The controller has been configured so that the last control variable is transferred when switching to the manual range. The point at which the transient oscillation occurs can be monitored on the time scale on the computer.
8. In addition to the actual temperature on the controller display, the controller also shows the power used by the heater on a separate display (14).
9. The WL 377 unit is ready for measurement when the pressure display is stable.

3.7 Maintenance and care

Check the oil level in the vacuum pump and top up if necessary. Refer to manufacturer’s instructions for oil specifications.

3.8 Shutting down, storage and disposal

– Switch off the unit
– Compensate the pressure in the pressure vessel
– Disconnect the unit from the power supply.

4 Fundamental principles

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

4.1 Convection

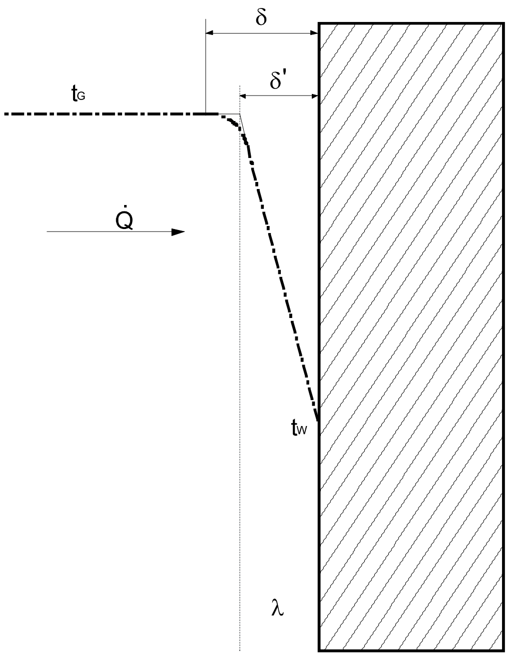


Fig. 4.1 Convection

In the case of heat transfer by means of convection, the heat is transferred to flowing liquids or gas particles. This energy is carried along by the particles as a flow. If the flow is itself caused by the heat transfer, as for example in the case of air flowing past a central heating radiator, the movement is termed free convection. If the movement is due to pumps or fans independent of the heat transfer, e.g. for the cooling of an engine, the movement is termed forced convection.

The heat transferred by convection is referred to the area of the material to which the heat is transferred. If, for example, the heat is transferred from a gas like air to a solid medium like a wall, then the heat flow can be calculated as follows:

$$\dot{Q} = \alpha \cdot A \cdot (t_G - t_W) \tag{4.1}$$

Here:

$\dot{Q}$	The heat flow being transferred in W
α	The coefficient of heat transfer in W/m^{2}K
A	The surface of the wall in m^2
t_G	The temperature of the gas in °C
t_W	The wall temperature in °C

The coefficient of heat transfer α can be calculated as:

$$\alpha = \frac{\lambda}{\delta} \text{ in W/m}^2\text{K} \tag{4.2}$$

Here:

λ Thermal conductivity ($\lambda_{L20\,°C}$ = 0,026W/mK)

δ Thickness of boundary layer (Fig.:4.1)

From the relationship of equation 4.2 and 4.1, the heat flow transferred by convection can be calculated as:

$$\dot{Q} = \frac{\lambda}{\delta} \cdot A \cdot (t_G - t_W) \tag{4.3}$$

The coefficient of heat transfer depends on a complex relationship of a wide range of factors that are defined by the physical properties and flow state of the fluid, as well as the geometrical shape of the heated areas. In the following, a few general figures for the coefficient of heat transfer are given.

Coefficients of heat transfer for air vertical to the metal wall	Unit in W/m²K
Stationary	3,5...35
Moving gently	23...70
Moving strongly	58...290

Tab. 4.1

For the calculation of the heat transfer by convection, the coefficient of heat transfer for stationary air is to be assumed. These values assume dry air, as the air α changes depending on the humidity.

4.2 Radiation

Temperature radiation is termed heat radiation or thermal radiation. There are two approaches for the theoretical description of the emission, transmission and absorption of radiation: the classic theory of electromagnetic waves and the quantum theory of photons.

The radiation addressed here can be explained as the sum of the contributions of many small amounts of energy emitted. Although the movements and the position of the individual photons cannot be given, the behaviour of a large number can be described as an electromagnetic wave. We will address radiation by means of its wave character.

The waveband for thermal radiation is between:
$\lambda = (0{,}35...10)\,\mu\text{m}$

The radiation incident on a body divides into three parts:

$$a + r + d = 1 \qquad (4.4)$$

Here:
- a Absorption coefficient
- r Reflection coefficient
- d Permeability or transmission coefficient

4.3 Black body

For a black body $a = 1$, for a white body $r = 1$. Both bodies are theoretical boundary cases, the black body can however be realised approximately by means of a hollow space with a small opening; the radiation entering the opening is completely absorbed. Solid and liquid bodies as a rule only allow a small amount of radiation to pass through (d=0). The majority of bodies are grey; they absorb the same portion of all wavelengths of the radiation ($a < 1$). Here the emission capacity of a body is the same as its absorption capacity (Kirchhoff's law).

$$\varepsilon = a \tag{4.5}$$

In the following, several emission coefficients are listed for the angle $\varphi = 90°$:

Surface	Temperature in °C	ε_n
Copper (polished)	20	0,030
Aluminium (bright rolled)	170	0,039
Iron (polished)	20	0,24
Iron (rusty)	20	0,85
Radiator paint	100	0,925
Black paint, matt	80	0,970

Tab. 4.2

The flow of energy radiated from a black body into the half-space from Stefan-Boltzmann's law is:

$$\dot{E} = \sigma \cdot T^4 \tag{4.6}$$

Here:

$\dot{E}$ The energy per unit area

σ Stefan-Boltzmann constant $5{,}67 \cdot 10^{-8}$ W/m²K⁴

T Temperature of the medium (to the power of four)

As the majority of radiation is emitted from grey bodies, the reduction in the radiation is taken into account with the emission coefficient. Furthermore, by rearranging the Stefan-Boltzmann constant, the radiation constant is found to be:

$$C_s = 10^8 \cdot \sigma = 5{,}67 \text{ in W/m}^2\text{K}^4 \tag{4.7}$$

Formula (4.6) and (4.7) result in:

$$\dot{E} = \varepsilon \cdot C_s \cdot \left(\frac{T}{100}\right)^4 \tag{4.8}$$

In Tab. 4.2, Page 26, the emission coefficients for the direction φ 90° are given. To arrive at the total radiation as described in Formula (4.8), the following must be set:

$$\dot{E} = \pi \cdot \dot{E}_n \tag{4.9}$$

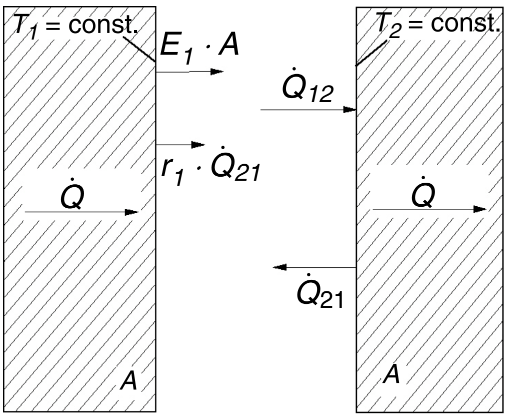


Fig. 4.2 Heat transfer through radiation

Two bodies of different temperatures that exchange heat in the form of radiation are now considered. Here, the total radiation comprises emitted and reflected radiation.

For body 1, the following applies:

$$\dot{Q}_{12} = \dot{E}_1 \cdot A + r_1 \cdot \dot{Q}_{21} \tag{4.10}$$

For body 2, the following applies:

$$\dot{Q}_{21} = \dot{E}_2 \cdot A + r_2 \cdot \dot{Q}_{12} \tag{4.11}$$

If equation Formula (4.10) and (4.11) are now brought together, by rearranging, the transferred heat flow is found to be:

$$\dot{Q} = \frac{C_s}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \cdot A \cdot \left[\left(\frac{T_1}{100}\right)^4 - \left(\frac{T_2}{100}\right)^4\right] \qquad (4.12)$$

4.3.1 Path of radiation in cylinders

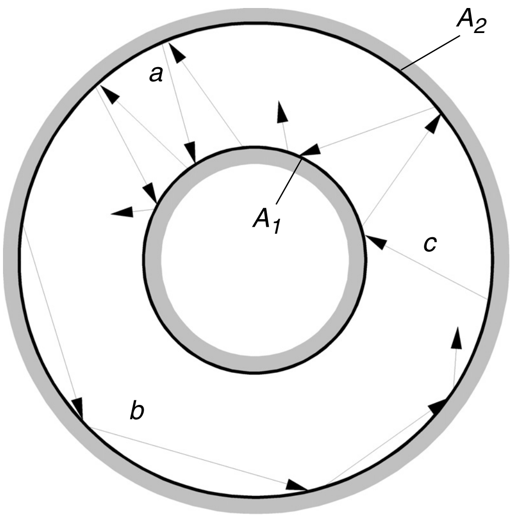


Fig. 4.3 Path of radiation in the cylinder

Fig. 4.3 shows the path of radiation between two concentric cylinders that reflect like mirrors. The radiation (*a*) emitted by the inner surface A_1 is incident on the outer surface A_2 and is reflected there by the mirror-like surface such that it is again incident on surface A_1. This is a case of diffuse reflection where the radiation continues to be reflected between the two surfaces until it is completely absorbed. In the case of radiation (*b*), the surface A_2 is never left and the radiation always moves along the wall. This radiation does not contribute to the exchange of heat. The radiation (*c*) emitted from the outer surface A_2 is reflected by the inner surface A_1, reduced by the area 2-1 , until it is completely absorbed.

If the outer surface A_2 reflects like a mirror, the equation Formula (4.12) becomes:

$$\dot{Q} = \frac{\sigma \cdot (T_1^4 - T_2^4)}{\frac{1 - \varepsilon_1}{\varepsilon_1 A_1} + \frac{1}{A_1} + \frac{1 - \varepsilon_2}{\varepsilon_2 A_2}} \qquad (4.13)$$

If, in the third resistance of the denominator, the area A_2 is replaced by the effective area A_1, the following is found:

$$\dot{Q} = \frac{A_1 \cdot \sigma \cdot (T_1^4 - T_2^4)}{\frac{1}{\varepsilon_1} + \frac{1}{\varepsilon_2} - 1} \tag{4.14}$$

From this relationship, it can be seen that the outer surface A_2 has no significance for the exchange of radiation.

5 Experiments

5.1 Aim of experiment

Determination of the emission coefficient

5.1.1 Preparing the experiment

- Check the on/off switch on the vacuum pump. The switch must be turned on.
- Close valve V2.
- Open valve V1.

5.1.2 Performing the experiment

- Turn on the main switch.
- Turn on the vacuum pump.
- Check gas ballast valve. This should be set to "0".
- Close ventilation valve V5. The pressure must now fall.
- Turn on the heater with the switch (13) and set the setpoint on the controller (12) for the temperature to be regulated. Use the push buttons "Down arrow" and "Up arrow" to do so. The controller shows the heater temperature (green: temperature setpoint; red: actual temperature).
- After reaching the temperature setpoint and after the transient oscillation of temperature and heating power, the controller can be switched over to manual operation so that no power fluctuations occur due to changing the

controller which may have a negative impact on the calculation of the emission coefficient.

– When the indications on the temperature displays no longer change and the pressure is below 20 Pa, measurement can commence.

5.1.3 Measured values

Vacuum							
Measurement	**Temperature setpoint T_1 in °C**	**Power level in %**	**Pressure p_1 in Pa**	**Temperature T_1 in °C**	**Temperature T_2 in °C**	**Heater power E_1 in W**	**Emission coefficient ε**
1	190	75	9,8	188,8	25,6	12,6	0,97
2	170	58	9,3	168,3	26,6	9,8	0,95
3	150	46	15,6	149,7	26,4	7,7	0,94
4	130	37	13,2	131,7	23,5	6,2	0,94

Tab. 5.1

5.1.4 Evaluation of the experiment

The following applies for the electrical power of the heater:

$$\dot{Q}_{Ele} = \dot{Q}_{Rad} + \dot{Q}_{Con} \tag{5.1}$$

As there is no convection in the vacuum, the entire electrical power is converted into radiation.

$$\dot{Q}_{Ele} = \dot{Q}_{Rad} \tag{5.2}$$

Calculation of the emission coefficient using Stefan-Boltzmann's law:

$$\dot{Q}_{Rad} = \varepsilon \cdot \sigma \cdot A_1 \cdot (T_1^4 - T_2^4) \tag{5.3}$$

Here: $T_1 = 273{,}15\ \text{K} + T_{1(\text{gemessen})}$

$T_2 = 273{,}15\ \text{K} + T_{2(\text{gemessen})}$

By rearranging, the following is given for the emission coefficient:

$$\varepsilon = \frac{\dot{Q}_{Rad}}{A_1 \cdot \sigma \cdot (T_1^4 - T_2^4)} \tag{5.4}$$

The mean value can be determined in order to gain an emission coefficient which applies for the temperature range.

5.1.5 Analysis

According to the VDI Heating Atlas, the expected ε values lie in the range from 0,92 (oil paint, black) to 0,97 (matt paint, black).

5.2 Aim of experiment

Determination of the heat quantities transferred through convection and radiation and calculation of the coefficients of heat transfer α_{Con} and α_{Rad}.

5.2.1 Preparing the experiment

– Check the on/off switch on the vacuum pump. The switch must be turned on.

– Close valve V2.

– Open valve V1.

5.2.2 Performing the experiment

– Turn on the main switch.

– Switch on the vacuum pump.

– Check gas ballast valve. It must be set to "0".

– Close ventilation valve V5. The pressure must now fall.

– Turn on the heater with the switch (13) and set the setpoint on the controller (12) for the temperature to be regulated. Use the push buttons "Down arrow" and "Up arrow" to do so. The controller shows the heater temperature (green: temperature setpoint; red: actual temperature).

– After reaching the temperature setpoint and after the transient oscillation of temperature and heating power, the controller should be switched over to manual operation so that no power fluctuations occur due to changing the controller which would have a negative impact on the calculation of the emission coefficient.

- If the temperature displays do not indicate any changes, and if the pressure is under 20 Pa, then the measured values can be read out and the transfer button for the epsilon value can be pressed.
- Afterwards, the vacuum vessel can be ventilated by opening the valve V2.
- In the window with the graphical representation of radiation and convection power, the values can be read out and it can also be observed when a stationary state was achieved.
- In the system diagram window, the values are displayed as numerical values.

5.2.3 Measured values

Vacuum							
Measurement	Temperature setpoint T_1 in °C	Manual power level in %	Pressure p_1 in Pa	Temperature T_1 in °C	Temperature T_2 in °C	Heater power E_1 in W	Emission coefficient ε
1	190	75	9,8	188,8	25,6	12,6	0,97
2	170	58	9,3	168,3	26,6	9,8	0,95
3	150	46	15,6	149,7	26,4	7,7	0,94
4	130	37	13,2	131,7	23,5	6,2	0,94

Tab. 5.2

Air, p_1 = 0 bar (rel.)									
Measurement	Temperature set-point T_1 in °C	Manual power level in %	Temperature T_1 in °C	Temperature T_2 in °C	Power Heater E_1 in W	Irradiance $\dot{Q}_{Rad}$ in W	Convection power $\dot{Q}_{Con}$ in W	Coefficient of heat transfer α_{Con} in W/m²K	Coefficient of heat transfer α_{Rad} in W/m²K
1	190	100	173,8	26,4	16,8	10,7	6,1	6,8	11,8
2	170	100	174,6	27,8	16,8	10,4	6,4	7,1	11,7
3	150	78	150	26,7	13,1	7,7	5,4	7,2	10,4
4	130	64	130	24,4	10,8	6,1	4,6	7,1	9,4

Tab. 5.3

5.2.4 Evaluation of the experiment

The electrical power yielded is shared between irradiance and the thermal power which is conveyed from the heater by convection.

$$\dot{Q}_{Ele} = \dot{Q}_{Rad} + \dot{Q}_{Con}$$

Using the emission coefficient determined in the previous experiment, the irradiance can now be calculated.

$$\dot{Q}_{Rad} = \varepsilon \cdot \sigma \cdot A \cdot (T_1^4 - T_2^4)$$

The following applies for the thermal power transferred through convection:

$$\dot{Q}_{Con} = \dot{Q}_{Ele} - \dot{Q}_{Rad}$$

From the equation for the thermal power transferred through convection,

$$\dot{Q}_{Con} = \alpha_{Con} \cdot A \cdot (T_1 - T_2)$$

the coefficient of heat transfer for convection can be obtained:

$$\alpha_{Con} = \frac{\dot{Q}_{Con}}{A \cdot (T_1 - T_2)}$$

The coefficient of heat transfer for radiation is as follows:

$$\alpha_{Rad} = \frac{\dot{Q}_{Rad}}{A \cdot (T_1 - T_2)}$$

where the value for irradiance should be inserted for the thermal power.

$$\alpha_{Rad} = \varepsilon \cdot \sigma \cdot \frac{(T_1^4 - T_2^4)}{T_1 - T_2}$$

The radiation proportion sinks considerably due to the influence of the convection. It can generally be stated that the fall in the radiation proportion increases with falling temperature.

In the case of rising temperature, the convective proportion of the heat transfer will fall.

5.3 Expected results in an experiment with a relative excess pressure of 1 bar

As the pressure increases, the temperatures fall. This is the consequence of a higher molecule density. Here, there is a greater number of molecules available to accelerate heat transport. The effect is that the coefficient of heat transfer for convection increases.

Power transfer by radiation decreases with increased pressure, whilst the power transfer through convection increases.

6 Appendix

6.1 Technical data

Dimensions

Length x Width x Height	1340 x 790 x 1500	mm
Weight	115	kg

Power supply

Voltage	230	V
Frequency	50	Hz
Phases	1	Phase
Nominal consumption (power)	0,6	kW
Optional alternatives, see rating plate		

Vacuum pump

Nominal suction capacity	5	m^3/h
Ultimate pressure total	$5 \cdot 10^{-3}$	mbar
Motor power	370	W
Speed	1390	1/min

Heater cartridge

Nominal rating	20	W
Voltage	24	VDC
Diameter	6,5	mm
Length	60	mm

Casing around the heater cartridge

Diameter	18	mm
Length	100	mm
Material	Copper	Cu
Surface	matt black	
Heater sleeve surface area:	$5{,}655 \cdot 10^{-3}$	m^2
Total surface area of the cartridge casing:	$6{,}097 \cdot 10^{-3}$	m^2
Thermocouple made of Kapton	Type K	
Self-adhesive thermocouple	Type K	

Pressure vessel

Internal diameter	211 mm
Height	316 mm
Surface	matt black
Vessel internal sleeve surface area:	0,20957 m^2

Emission coefficients

Oil paint, black ε :	0,92
Paint, matt black ε_n:	0,97

Relative pressure transducer

Measuring range:	-1...+1,5 bar
Accuracy:	<±0,3% of ultimate value for measuring range

Absolute pressure transducer (Pirani)

Measuring range:	0,05 Pa...10000 Pa
Accuracy:	2% of measured value

If the ambient conditions should change or if necessary for other reasons, calibration should be carried out according to the manufacturer's instructions (TPR 280, TPR 281).

As the Pirani pressure gauge is a thermal conductivity sensor, the heat conductivity of gases other than air should be considered.

Data acquisition

Program environment:

- LabVIEW Runtime

System requirements:

- PC with processor Pentium IV, 1 GHz
- Minimum 1024 MB RAM
- Minimum 1 GB available memory on hard disk
- 1 CD-ROM drive
- 1 USB port
- Graphics card resolution min. 1024 x 768 pixels, True Color
- Windows XP / Windows Vista / Windows 7

6.2 Worksheet for recording measured values

Date:..

Characteristic values

Emission coefficients

Paint, matt black:	$\varepsilon_n = 0{,}97$
Oil paint, black:	$\varepsilon_n = 0{,}92$
Iron, polished:	$\varepsilon_n = 0{,}24$

Stefan-Boltzmann constant: $\sigma = 5{,}67 \cdot 10^{-8}\ \mathrm{W/m^2K^4}$

Radiation surface areas

Heater sleeve surface area: $0{,}00609743\ \mathrm{m^2}$

Vessel internal sleeve area: $0{,}20957\ \mathrm{m^2}$

Coefficient of heat transfer

Air to iron: $\alpha = 3{,}5...35\ \mathrm{W/m^2K}$

Calculation formulas:

Radiation

$$\dot{Q}_{Rad} = \varepsilon \cdot A \cdot \sigma \cdot (T_1^4 - T_2^4) \tag{6.1}$$

$$\alpha_{Rad} = \frac{\dot{Q}_{Rad}}{A \cdot (T_1 - T_2)} \tag{6.2}$$

$$\alpha_{Rad} = \varepsilon \cdot \sigma \cdot \frac{T_1^4 - T_2^4}{T_1 - T_2} \tag{6.3}$$

Convection

$$\dot{Q}_{Kon} = \alpha_{Kon} \cdot A \cdot (t_1 - t_2) \tag{6.4}$$

$$\alpha_{Kon} = Nu_m \cdot \frac{\lambda}{d} \tag{6.5}$$

6.3 Measured value table

Measurement	Pressure p in Pa or mbar	Temperature T_1 in °C	Temperature T_2 in °C	Heater power P in W
Vacuum p_{abs} < 20 Pa				
1				
2				
3				
4				
Convection p_{abs} = ...mbar				
1				
2				
3				
4				
Convection p_{abs} = ... mbar				
1				
2				
3				
4				

Tab. 6.1 Measured values

Measurement	Emission coefficient ε	Radiation power $\dot{Q}_{Rad}$ in W	Convection power $\dot{Q}_{Con}$ in W	α_{Con} in W/m²K	α_{Rad} in W/m²K
Vacuum p_{abs} < 20 Pa					
1					
2					
3					
4					
Convection p_{abs} = ...mbar					
1					
2					
3					
4					
Convection p_{abs} = ... mbar					
1					
2					
3					
4					

Tab. 6.2 Calculated values

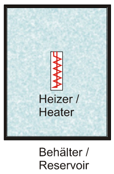
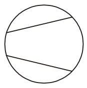
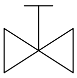
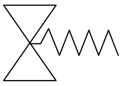
6.4 List of abbreviations

Abbreviation	Meaning
Ele	Electrical
Rad	Radiation
Con	Convection

6.5 List of key symbols and units used

Symbol	Mathematical/physical variable	Unit
A	Area	
A_1	Heating element surface	
A_2	Surface	
a	Absorption coefficient	
C_s	Radiation constant 5,67	W/m^2K^4
d	Permeability or transmission coefficient	
r	Reflection coefficient	
T	Medium temperature	K
T_1	Temperature body 1	K
T_2	Temperature body 2	K
t_G	Temperature of the gas	°C
t_W	Temperature of the wall	°C
$\dot{E}$	Energy per unit area	
$\dot{Q}$	Heat flow	W
α	Coefficient of heat transfer	W/m^2K
δ	Thickness of the boundary layer	
δ	Thickness of the boundary layer	
λ	Thermal conductivity	W/mK
λ	Wavelength	µm
σ	Stefan-Boltzmann constant: $5{,}67 \cdot 10^{-8}$	W/m^2K^4
π	Pi 3,1415	
ε_1	Emission coefficient body 1	
ε_2	Emission coefficient body 2	

6.6 List of symbols in process schematic

Symbol	Name
	Vessel with heater
	Compressor
	Valve
	Safety valve
	Coupling

6.7 List of code letters in process schematic

Code letter	Name
Equipment and machines	
P	Pump
V	Compressor, vacuum pump, fan
Fittings	
V	Fitting, general

Tab. 6.3 Code letters for equipment, machines, fittings and pipes

Code letter	Measured variable or other input variable, actuator		Processing
	As first letter	As additional letter	As following letter (sequence I, R, C)
E	Electrical variables		Sensor function
I			Display
P	Pressure		
T	Temperature		Measuring transducer function

Tab. 6.4 Code letters for measuring points

6.8 Tables and diagrams

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

Tab. 6.5 Conversion table for units of volume

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

Tab. 6.6 Conversion table for volumetric flow units

Unit	bar	mbar	Pa	hPa	kPa	mm WS *
1 bar	1	1.000	100.000	1.000	100	10.000
1 mbar	0,001	1	100	1	0,1	10
1 Pa	0,00001	0,01	1	0,01	0,001	0,1
1 hPa	0,001	1	100	1	0,1	10
1 kPa	0,01	10	1.000	10	1	100
1 mm WS *	0,0001	0,1	10	0,1	0,01	1

Tab. 6.7 Conversion table for pressure units
* Rounded values