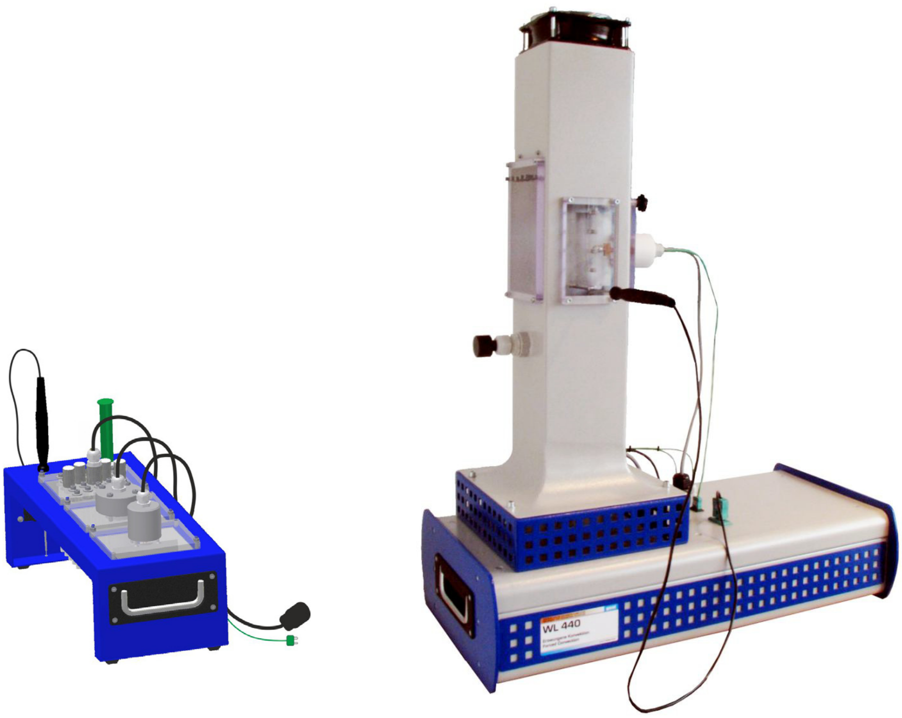
Experiment Instructions

WL 440 Free and Forced Convection



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.

Table of Contents

1 Introduction

WL 440 "Free and Forced Convection" is part of the **GUNT Thermoline Fundamentals of Heat Transfer** device series.

The **Fundamentals of Heat Transfer** device series allows experiments on heat conduction, convection and radiation.

The WL400 Thermoline device series consists of five devices and provides fundamental experiments on heat transfer:

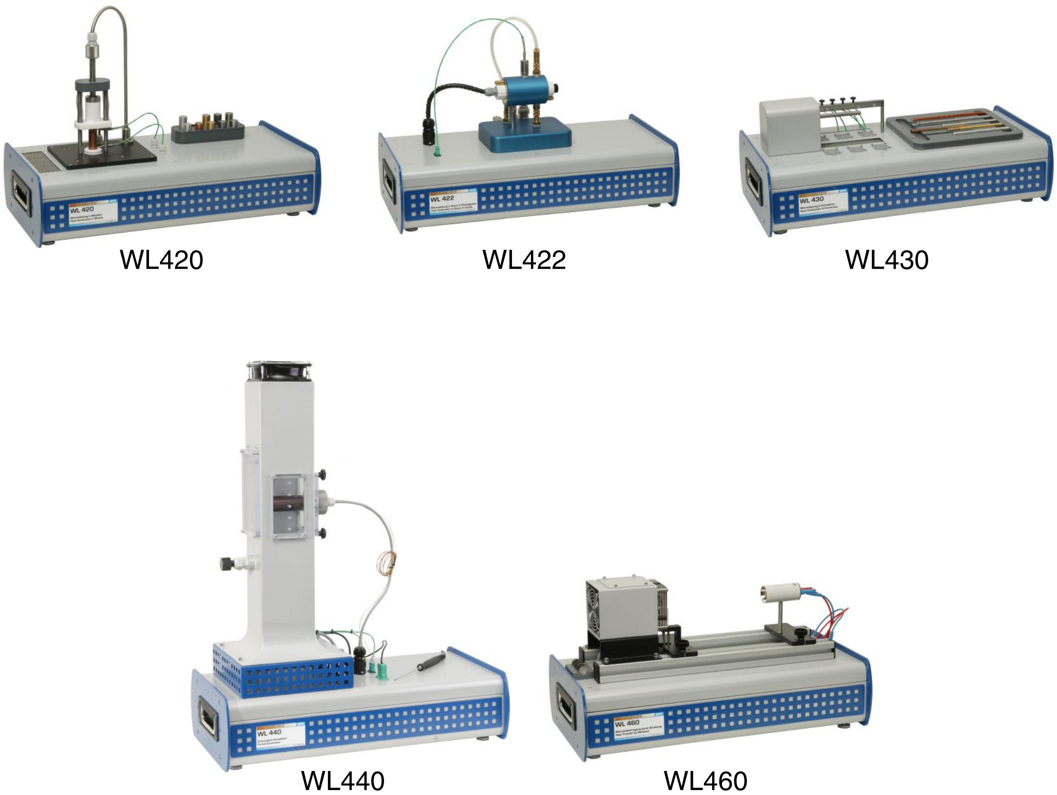

Fig. 1.1 WL400 Thermoline device series

The exhaustive range of experiments of this device family introduces students experimentally to the fundamentals of heat transfer.

All devices in the **GUNT Thermoline Fundamentals of Heat Transfer** range are equipped with electronic sensors for PC-based measurement data acquisition and are operated from a PC. Measurements can be represented graphically and characteristics can be recorded using the measurement data acquisition software provided. The **GUNT Thermoline** series of devices puts the HSI "Hardware-Software Integration" product approach into effect.

The experimental unit is designed as a tabletop device. The measurement data acquisition software supplied and a PC provided by the customer are required to operate the **WL 440** device.

The variation of operating points is made possible thanks to the adjustable heating and cooling capacity and the ability to study different samples.

Learning objectives for the experiments with the WL 440 "Free and Forced Convection" device are:

- Experiments on free and forced convection
- Describe the progression over time until the steady state is reached
- Calculate the heat transfer coefficient
- Determine the Nusselt number
- Determine the Reynolds number
- Relationship between flow formation and convective heat transfer
- Introduction to block capacity

1.1 Didactic notes for teachers

This device cannot be operated without measurement data acquisition software and a PC, since there are no separate, local measured value displays and control elements.

In addition to this device, the series includes comprehensive basic knowledge on "Fundamentals of Heat Transfer". This gives an overview of the field of heat transfer.

WL 440 can be employed both in the training of skilled workers and in engineering education.

Areas where the **WL 440** experimental unit can be employed include:

- **Demonstration experiments**
  The demonstrator operates the previously prepared experimental unit while a small group of five to eight students observes. Key effects can be demonstrated over an operating time of one class.
- **Practical experiments**
  Small groups of two or three students can carry out experiments for themselves. The time required to record measurements and some characteristic curves can be estimated at about two hours.
- **Project work**
  WL 440 is particularly well suited to carrying out project work. In addition to detailed investigations with **WL 440**, further experiments on heat transfer can be undertaken with devices from the **GUNT Thermoline Fundamentals of Heat Transfer** range. In this case a single, experienced student can operate the experimental units.

The accompanying educational software completes the picture by offering a browser-based course. This can be adapted to your own needs using the authoring system.

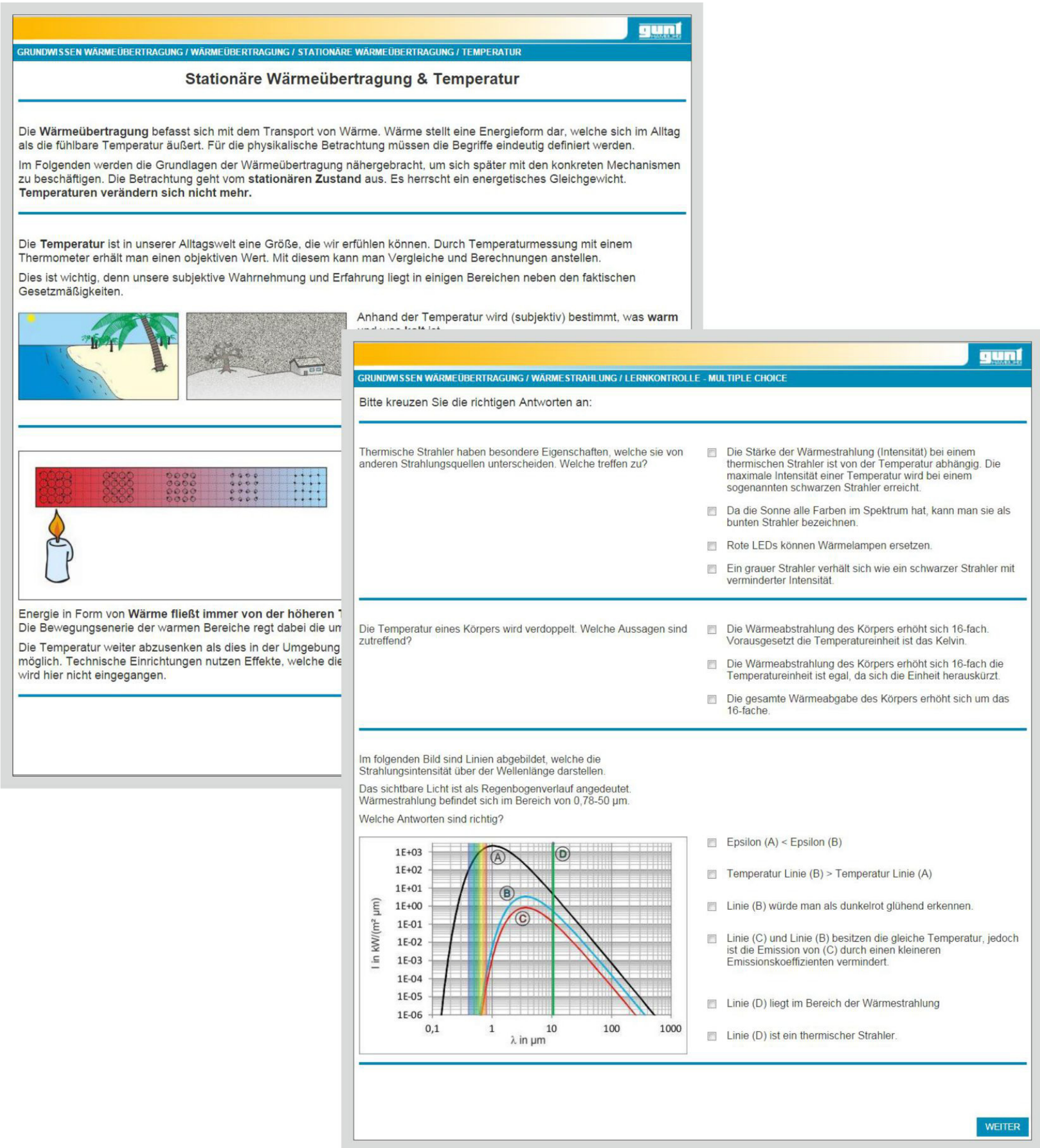

Fig. 1.2 Screenshots of a course

These materials are intended to be used to help you prepare your lessons. You can compile parts of the materials as information for students for use in the classroom.

We also provide these experiment instructions in pdf format on a CD to support your lessons. We grant you unlimited reproduction rights for use within the context of your teaching duties.

We hope that you enjoy using this experimental unit from the GUNT Thermoline range and wish you success in your important task of introducing students to the fundamentals of technology.

Should you have any comments about this device, please do not hesitate to contact us.

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2 Safety

2.1 Intended use

The unit is to be used only for teaching purposes.

2.2 Structure of 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
	Electric voltage
	Hot surface
	Wear ear defenders
	Harmful to the environment
	Note

2.3 Safety instructions

WARNING

Electrical connections are exposed when the housing is open.

Risk of electrical shock.

- Disconnect the plug from the power supply before opening the housing.
- All work must be performed by trained electricians only.
- Protect device against moisture.

⚠ WARNING

Hot surfaces while operating the heater.

Burns are possible.

- Do not touch during operation.

⚠ WARNING

Noise emissions > 80 dB(A).

Risk of hearing damage.

- Wear ear defenders.

NOTICE

Thermal paste

The thermal paste contains environmentally hazardous substances.

- Avoid releasing into the environment.
- Do not allow to get into the drains or waterways.
- Collect any spills.

2.4 Ambient conditions for the operating and storage location

- Enclosed space.
- Free from dirt and humidity.
- Level and fixed surface.
- Frost-free.

3 Description of the device

Fig. 3.1 Help function

For detailed instructions on use of the program refer to its Help function.

This can be found in the main screen of the software on the top right by clicking the icon as shown in the figure to the left.

3.1 Heat transfer device series - introduction to WL 440

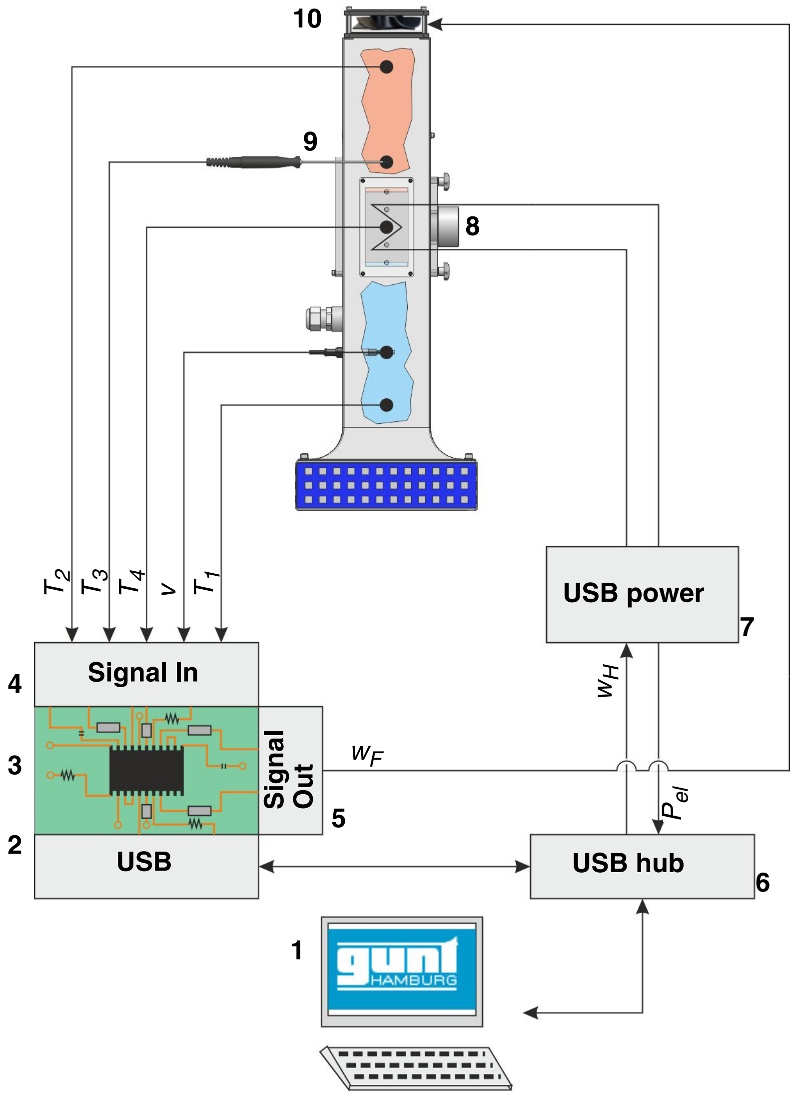
The **Fundamentals of Heat Transfer** device series allows for experiments on the different mechanisms of heat transfer.

The **WL 440** device is a fully functional stand-alone experimental unit.

The following chapters provide a detailed description of the **WL 440** experimental unit.

3.2 Operating concept and data communication

The WL 440 device offers a complete setup for investigating the thermal conductivity in metal samples. A PC with the measurement data acquisition program is required to operate the setup.



1	Measuring computer, PC	6	USB hub
2	USB interface	7	USB power supply for the heater
3	Microprocessor board	8	Heater insert
4	Inputs of the measured variables	9	Handheld temperature sensor
5	Outputs of the manipulating variables	10	Fan

Fig. 3.2 Data communication between PC and experimental setup

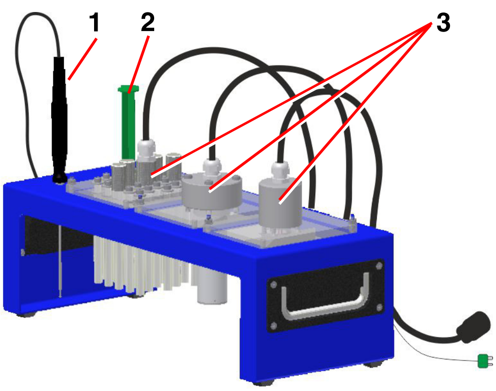
A microprocessor is used as the interface between the setup and the PC. It receives all measurement signals from the experimental setup and from these calculates the measured variables. These are sent to the PC via the USB interface and displayed on the PC.

The experiment is influenced with the PC by sending manipulating variables to the microprocessor which passes them on to the actuators. Effects are visible directly in the measured values.

A constant adjustment of the data flux allows the simultaneous display of measured values on the PC. If the USB connection between PC and device is interrupted, all manipulating variables are set to zero.

The software controls the power. It regulates the manipulating value of the USB power supply using the power supply's internal power measurement.

3.3 Device design



1 Handheld temperature sensor
2 Thermal paste
3 Heater inserts

Fig. 3.3 Storing the accessories

The WL 440 device is designed as a tabletop device.

The accessories can be kept in a separate holder. see Fig. 3.3.
Three heating elements, the handheld temperature sensor and the thermal paste can be stored in it.

The WL 440 device is shown in Fig. 3.4.

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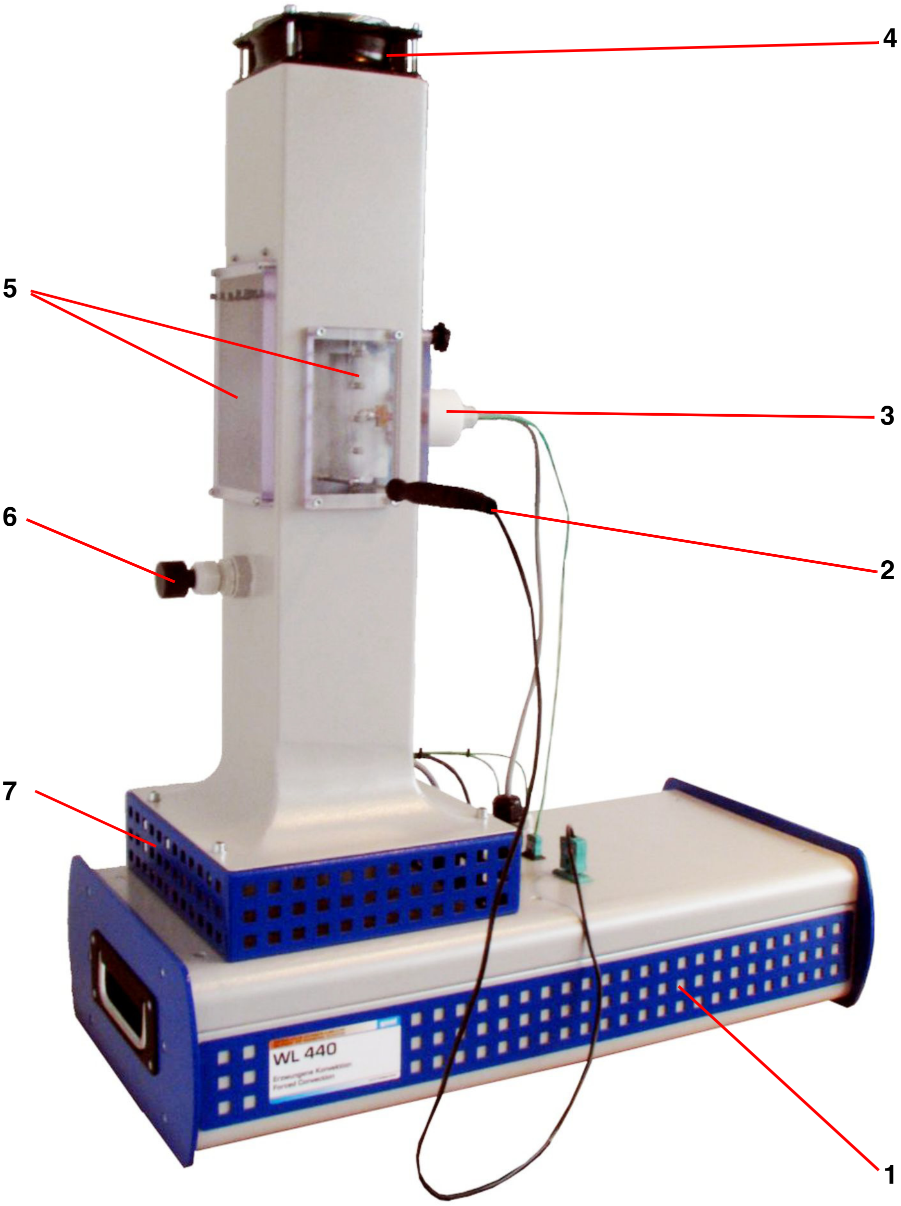
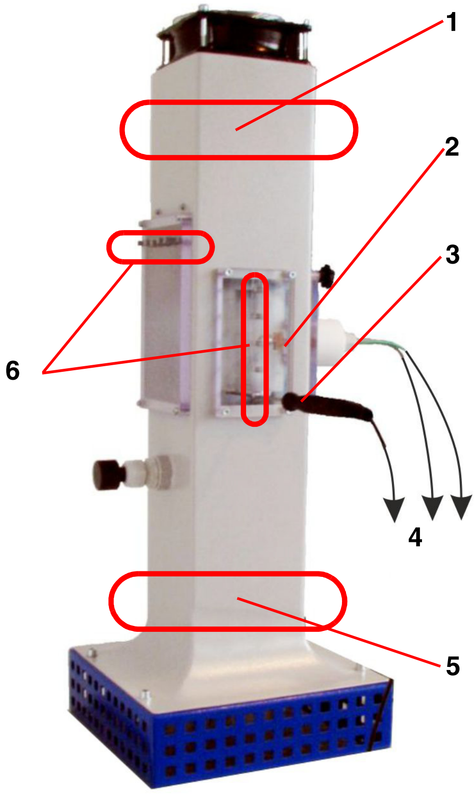


1	Basic housing	5	Sight glasses
2	Handheld temperature sensor	6	Turbulence generator
3	Heating element (flat plate)	7	Air inlet
4	Fan		

Fig. 3.4 The WL 440 tabletop device

3.4 Device function and components



1 Area of the measuring point T_2
2 Measuring point T_4 on the heater
3 Measuring point T_3
Handheld temperature sensor
4 Connections to the device housing
5 Area of the measuring point T_1
6 Measuring temperature fields

Fig. 3.5 Temperature measuring points

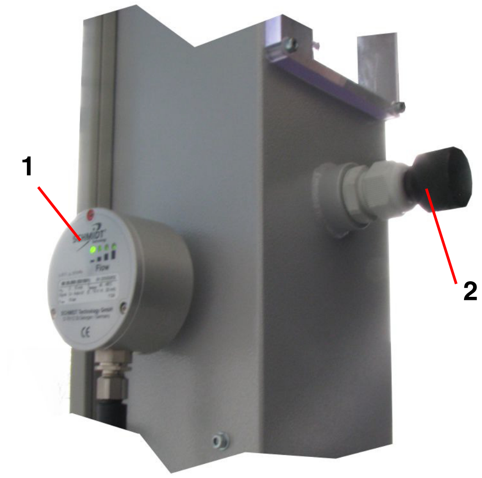
Air duct
The air duct is responsible for guiding the air. It is also used to hold all essential components such as measuring points, heater and fan.

Temperature measuring points
The measured values from the temperature measuring points are used to develop the elementary knowledge of convection. There are four measuring points for the experiments.

Temperature *T1* and temperature *T2* are the air temperatures at the inlet and outlet of the air duct. Temperature *T3* is a handheld temperature sensor for measuring different surface and air temperatures. Temperature *T4* is the surface temperature of the respective heater. A more detailed definition is given in the description of the heating insert.

The plexiglass discs have holes which are used to measure temperature fields. For the plate in particular, it is possible to measure the profile along the surface in the direction of flow.

Device housing
The device housing is used to hold the air duct and contains the necessary measuring instruments as well as the hardware for communication with the PC.



1 Speed sensor
2 Turbulence generator

Fig. 3.6 Speed sensor and turbulence generator

Speed sensor

The speed sensor is located at the rear of the air duct and measures the velocity of the air according to the principle of a hot-wire anemometer.

Turbulence generator

The turbulence generator is a fluid mechanics component that illustrates the effect of different, distinctive flow in the experiment. In the picture it is inserted into the flow. If it not going to be used in the experiments, it should be retracted until it is flush with the wall.

Fig. 3.7 Fan on top of the air duct

Fan

The fan ensures the flow in the air duct. It is strong enough to accelerate the air to sufficient velocity through the experimental section.

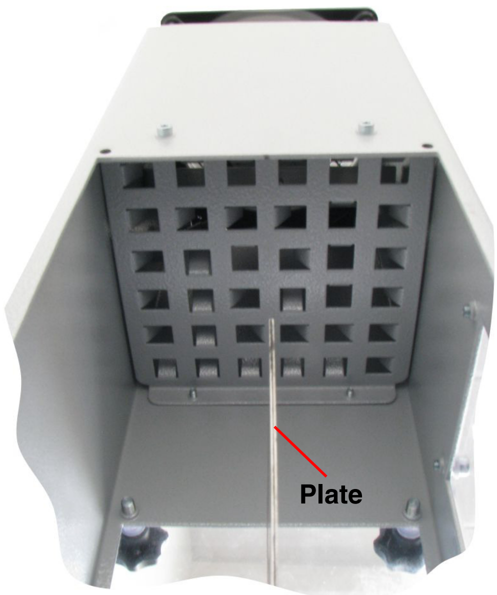


Fig. 3.8 Vortex lattice. Photographed with disc removed and the "Plate" heater insert.

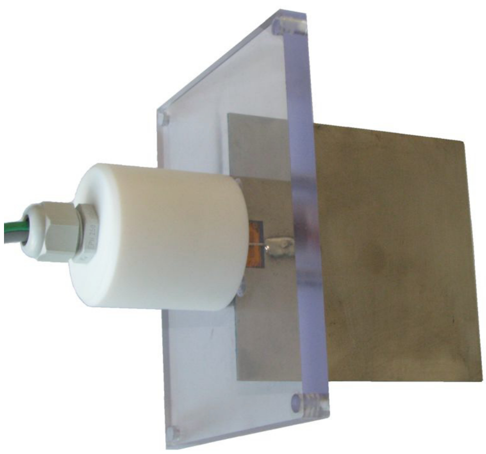


Fig. 3.9 Heater insert: Plate

Vortex lattice

The vortex lattice is used to mix the air so that the temperature is distributed over the cross-section as evenly as possible.

Heater inserts

The various heater inserts show the different effects of shape on the heat-up time and convection. The heating power is set and controlled by the software.

The heaters are protected against overheating by being switched off when they reach 90°C.

The **plate** is a heating foil with stainless steel sheet glued on both sides. The even heat dissipation (heat area load) of the foil means the temperature settles according to convective heat transfer.

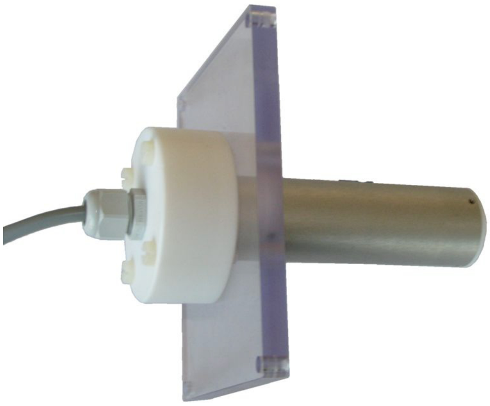


Fig. 3.10 Heater insert: Cylinder

The **cylinder** is heated by a heating cartridge which is located centrally in a hole. The good heat conduction ensures an even temperature at the surface.

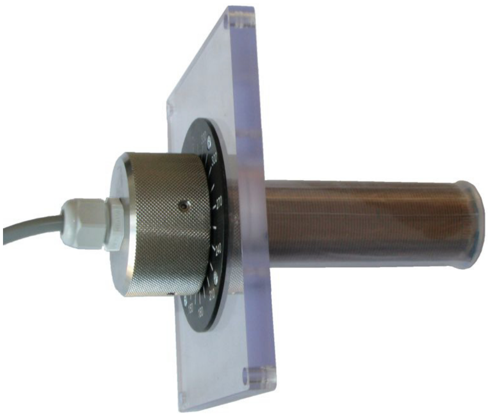


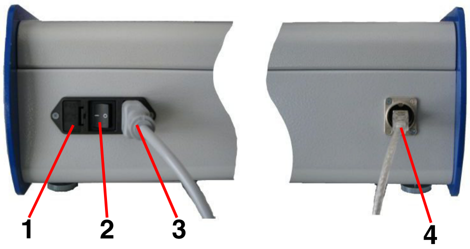
Fig. 3.11 Heater insert: Cylinder for circumferential measurement

The **cylinder for circumferential measurement** is a Teflon cylinder that is wrapped in a heating foil. The even heat dissipation (heat area load) of the foil results in temperature distribution according to the local convective heat transfer. This is made possible because the heat exchange of the Teflon cylinder (by conduction) is negligibly small. The cylinder can be rotated so that a thermocouple can detect the temperature at the desired point of the circumference.

Fig. 3.12 Heater insert: Tube bundle

The **tube bundle** consists of 5 x 5 rods. The heated rod can be brought to the centre position of the individual rows. The convective heat transfer can be determined in each row by heating the rod and measuring the temperature difference.

3.5 Operation and measurement data acquisition



1 Fuse holder
2 Main switch
3 Power supply
4 USB connection

Fig. 3.13 Connections and switches on the rear of the device

Rear:

The **main switch** is used to turn the power supply on and off. It uses a I/0 rocker switch design.

The connection socket for the **power supply** is located next to the main switch. The **fuse holder** holds the two **microfuses**. The socket for the USB connection is on the other side of the device.

The integrated **microcontroller board** is used to control the device and for measurement data acquisition.

The **measurement data acquisition program** provided is used both to operate the experimental unit and to record and display the measurement data. The measurement data acquisition program (referred to simply as the program below) is installed on a PC provided by the customer (see Chapter 3.5.2, Page 22).

The experimental unit and the PC are connected via the USB interface.

The program allows you to **operate** the heater (specify the electrical power) and the fan (specify the fan power as a percentage). The program offers the following options for displaying the current **measured values** and calculated values:

- **System diagram.**
  This contains a view of the device with the user interface
- **Chart recorder.**
  Shows the path over time of the measured values.
- **Data logger.**
  Used to record sequences over time.
- **Data viewer.**
  Used to display data recorded by the data logger.
- The available measured values and calculated values are recorded in **measurements files**. These measurements files can be imported into a spreadsheet program (e.g. MS Excel®) for further processing.

The program's help feature explains how to use the program (see also Chapter 3.5.3, Page 23).

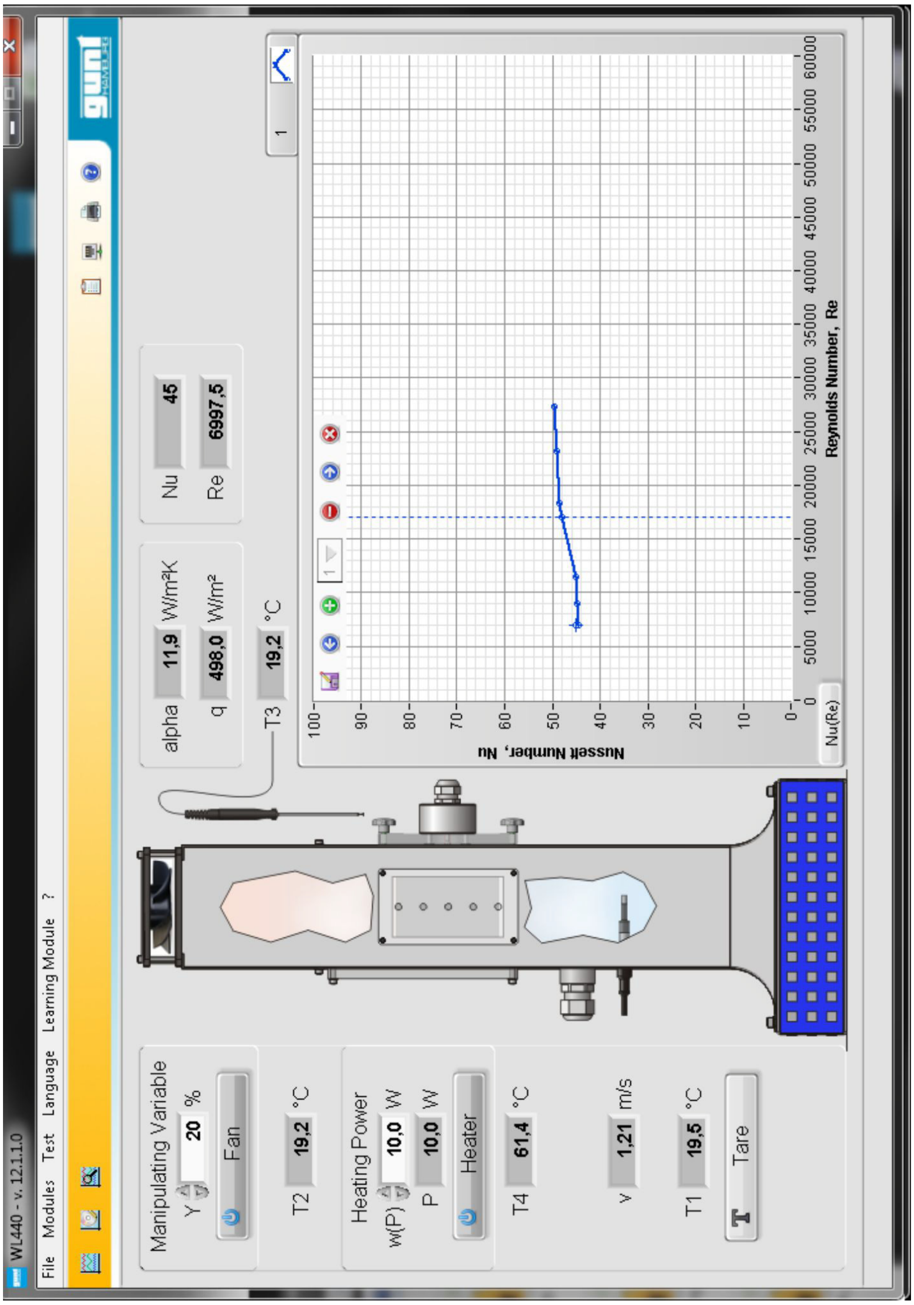


Fig. 3.14 System diagram of WL 440 with inserted plate

3.5.1 Authoring system and learning module

The authoring system and the learning module are included and documented separately. A course is included in the **Fundamentals of Heat Transfer** series. This can be adapted and expanded according to your own requirements.

3.5.2 Installing the software

Required for installation:

- A ready-to-use PC with USB port (for minimum requirements see Chapter 6.1, Page 75).
- G.U.N.T. CD-ROM

  All components required to install and operate the program are included on the CD-ROM provided by GUNT.

Installation procedure

NOTICE
While installing the software, the experimental unit may not be connected to the USB port on your PC. The trainer may only be connected after the software has been successfully installed.

- Start the PC.
- Insert GUNT CD-ROM.
- Start the installation software "**Start.bat**".
- Follow the installation procedure on screen.
- Installation will run automatically after starting it. The following software components are installed onto the PC:

- Software for PC-based acquisition of measurement data.
- LabVIEW runtime and driver routines.
- G.U.N.T. libraries.

- Once the installation program has finished, restart the PC.

3.5.3 Using the software

- Select the program and launch it via: **Start / Programs / G.U.N.T. / WL440**
- The language may be changed at any time in the "**Language**" menu.
- Various pull-down menus are available for other functions.
- For detailed instructions on use of the program refer to its Help function. The **help function** is accessed by the **"?"** button.

Saved measurement data can be imported into a spreadsheet program (e.g. MS Excel®) where the data can be processed further.

3.6 Initial commissioning

NOTICE

Risk of damage to the device.

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

– Set up the device in a location with as little air movement as possible.

– Establish the power supply with a rubber connector.

– Establish connection between PC and device with USB cable.

3.7 Commissioning / Preparation for the experiments

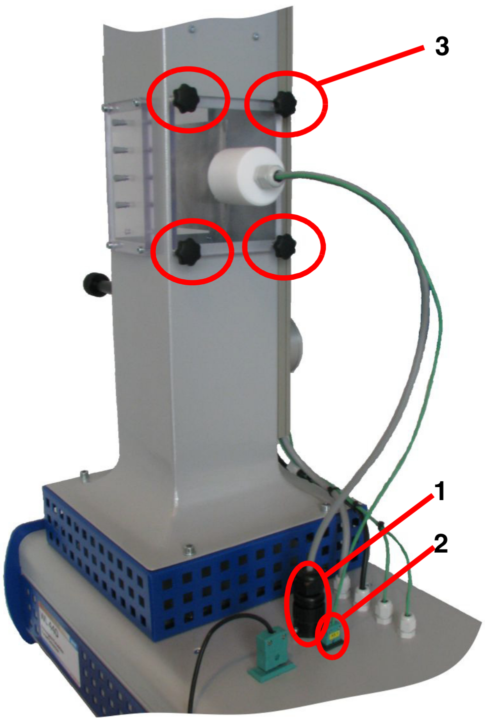
3.7.1 Positioning and connection

Two things are essential in order to obtain values that are as constant as possible:

1. Avoid increased air movement.
   Strong air-conditioning units, ceiling fans and similar strong air movements can have a negative impact on the measurements. This is reflected in a fluctuation of the measured values and is especially apparent on the flow velocity indicator.
2. Uniform temperature in the room.
   Free convection means there is stratification of the temperature in the room. Furthermore, heat sources in the room can cause a non-uniform

distribution of temperatures. Examples include machinery and equipment. However, on sunny days large window areas can also contribute to larger temperature differences in the room.
The flow generated by the device causes mixing. The temperatures may drift the longer the measurement lasts and with increasing flow velocity. This does not affect the generated temperature differences.

3.7.2 Changing the heater inserts



1 Energy supply
2 Temperature measurement
3 Mounting screws

Fig. 3.15 Changing the inserts

To change the heater inserts, first remove the **power supply** cable and the **temperature detection** from the sockets. By removing the **fastening screws** it is possible to remove the heater and replace it with another one.

The insert is ready for operation once the cables have been connected and tightened.

Both plugs can only be plugged into the sockets in one way, so it is impossible to connect them incorrectly.

If **free convection** is being studied, the heater insert must be attached to the air duct as shown in Fig. 3.16. This is intended for the plate and cylinder.

Free convection requires free inflow and outflow. This is disturbed by:

- The fan and the vortex lattice decelerate the outflow of the heated air so that a larger volume of heated air accumulates over the heater than is the case during undisturbed free convection.

- When installed in the air duct, the outflow of the heated air sucks in new air at the same time. This is known as the chimney effect. Due to the flow configuration it leads to a defined incident flow of the heater.

Measurement of free convection is made possible by the following type of assembly:

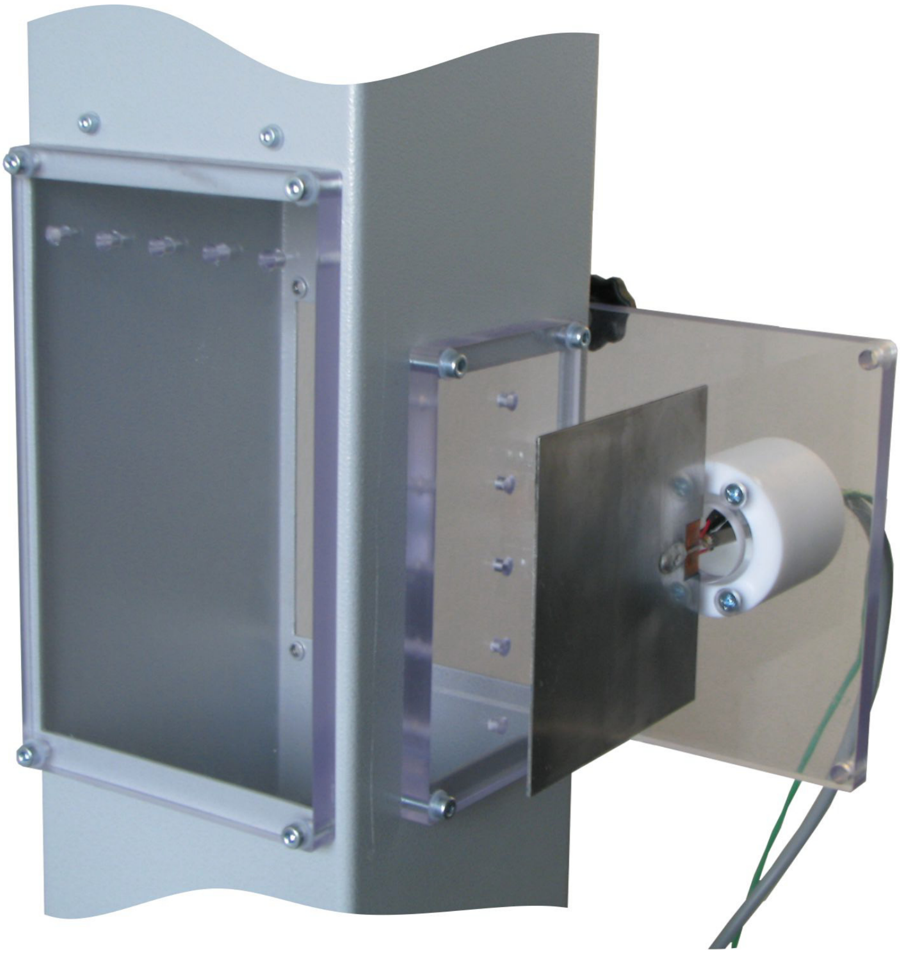


Fig. 3.16 Installation of the plate to study free convection

NOTICE

Free convection assumes a fluid at rest. If this condition is not present due to the ambient conditions (e.g. due to air-conditioning units, fans etc.) the results may vary significantly from expectations.

3.7.3 Calibrating the temperature measuring points

The temperature measuring points used are thermocouples. These have the advantage that they react very quickly to changes in temperature and consequently shorten the measurement time. They are somewhat less accurate than resistance thermometers, although this is negligible in the measurement values of the experiments.

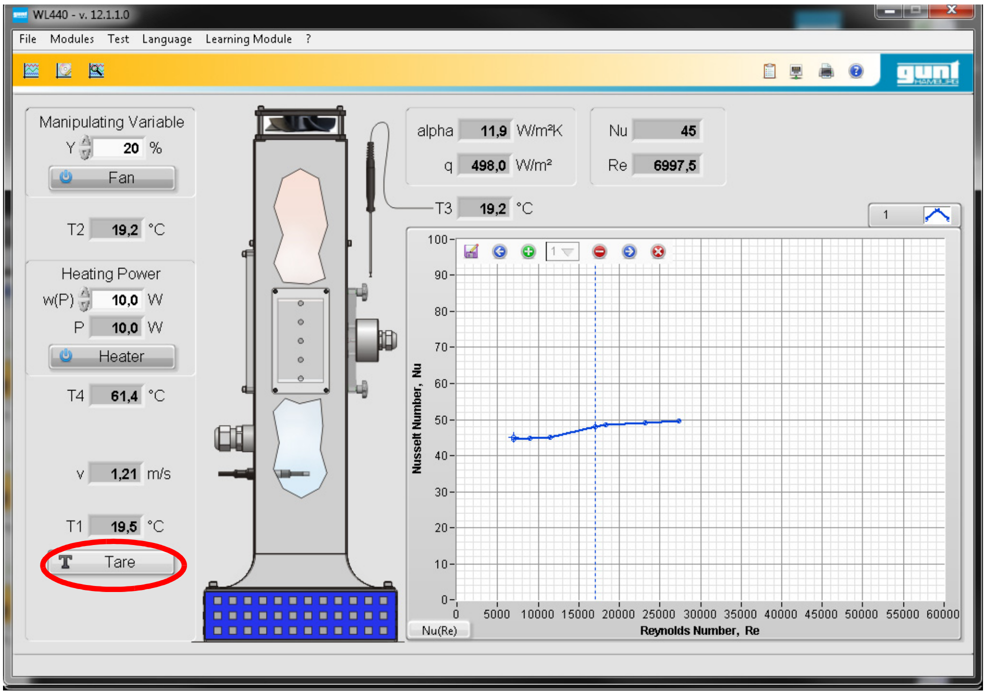


Fig. 3.17 Taring the temperatures

The temperature measurements can be calibrated against each other. This is best done with the heater switched off and after the ventilation has run for a few minutes. Once the measured values settle down (see Chapter 3.7.4) it is apparent when it makes sense to press the tare button. To calibrate all temperatures, the heater must be switched off and project into the air duct, as shown in Fig. 3.15.

Calibrating sets the temperature T_2 to T_4 to the value of the ambient temperature T_1.

Calibrating the temperature measuring points is recommended before commencing the experiments if an even temperature can be expected after a longer break.

3.7.4 Starting up measuring points

In order to take accurate measurements, steady values are needed. This means that no temperature change is detectable during the time in the operating point. Small fluctuations due to measurement accuracy and environmental factors due to air flows etc. cannot be excluded.

Fig. 3.18 shows the chart recorder with measured values that reach this steady state.

If the temperatures are no longer changing, the steady state is reached - area shaded green.

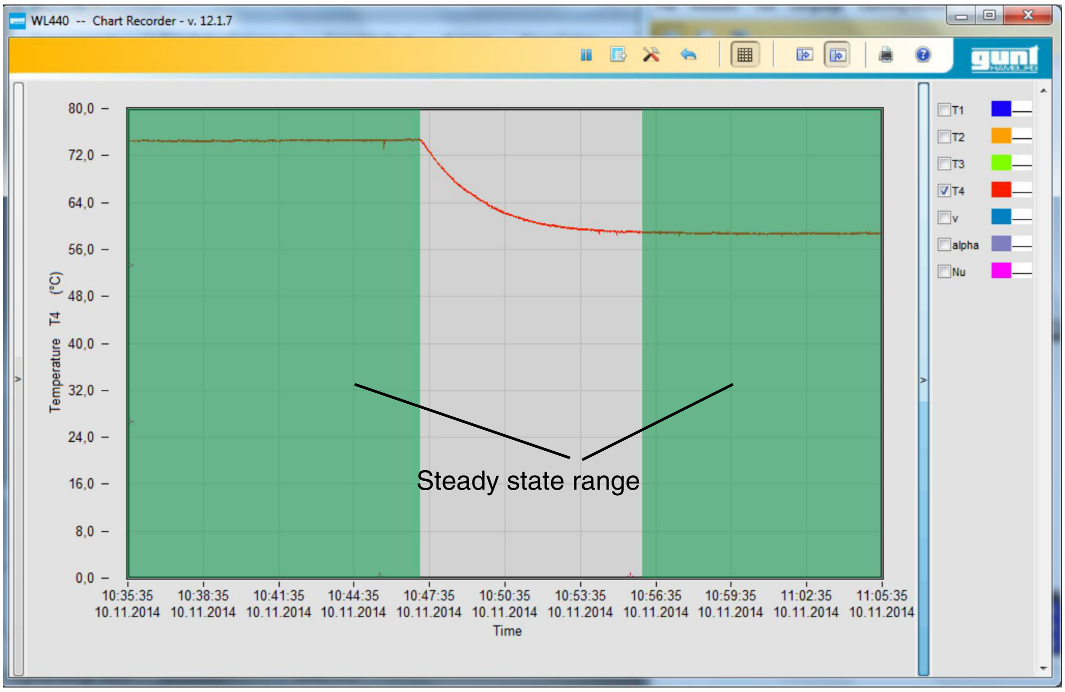


Fig. 3.18 Steady state operating point (highlighted green)

4 Fundamentals

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

Convection is the heat transfer between a surface and a fluid (gas or liquid). To demarcate this from conduction, it is decisive that this fluid transports the heat through motion.

In the following, it is tacitly assumed that we are dealing with the heating of the fluid. The fundamentals are identical when cooling, except for the algebraic sign.

4.1.1 Definition of free convection

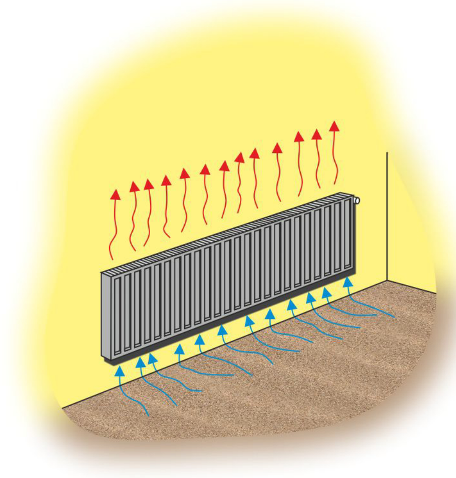


Fig. 4.1 Free convection at a heater

Convective heat transfer is the transfer of heat through fluid particles in motion. In free convection, the motion of the fluid is caused by the density differences resulting from warming. The heated fluid develops a free, vertical and upward-pointing flow. New, cool fluid from the surroundings flows in. An equilibrium occurs. The inward flow and the outward flow must be unimpeded for free convection.

A large temperature difference arises due to the increased transport of heat vis-a-vis conduction. The equalisation effort increases, and the convective heat transfer increases.

4.1.2 Definition of forced convection

Fig. 4.2 Forced convection at blown cooling fins

In forced convection, there is an incident flow of the heat transferring surface. This can be facilitated by an external technical device, such as a fan. But it can also be exploited, for instance, by the head wind of vehicles. This results in an increased speed compared to free convection. The quicker transport of the hot fluid causes a higher temperature gradient from the warm surface to the fluid, and thus a better heat transfer.

4.2 General procedure

There are similarities in convection, irrespective of the exact procedure.

The hot surface transfers heat to the fluid. This occurs directly at the boundary layer by conduction into the adjacent fluid.

The heat now flows in two directions:

Vertical to the surface into the fluid.

Parallel to the surface with the motion of the fluid.

If convective heat transfer is to be influenced, then these two heat fluxes must be influenced. This cannot be done separately.

Flow formation is directly linked to this topic.

4.2.1 Heat transport - laminar flow

The flow at a surface can form differently. When the speed of the fluid is relatively low, the movement is in layers parallel to the surface. The layer that covers the surface does not move. This effect is know as the no-slip condition. Adhesion prevents motion.

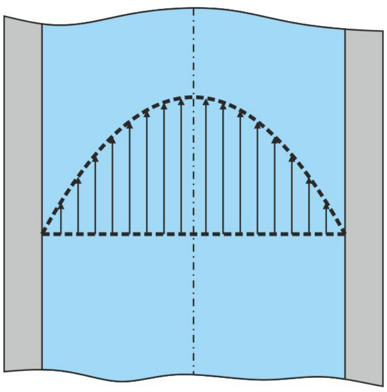


Fig. 4.3 Laminar pipe flow

Fig. 4.3 shows the flow within a pipe. The speed is zero directly at the edge. The speed increases with increased wall clearance, with the maximum in the middle.

In this type of flow, the fluid layers flow off from each other. The flow is ordered, the velocity vector is always aligned in the axial direction. Heat penetrates into the more removed layers due to conduction.

4.2.2 Heat transport - turbulent flow

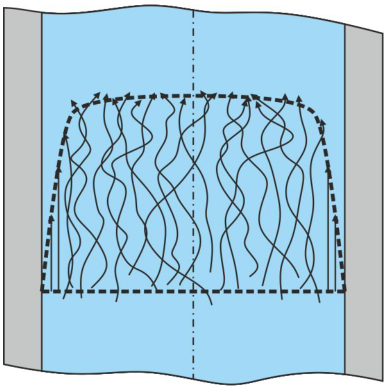


Fig. 4.4 Turbulent pipe flow

If the speed increases, a different velocity profile becomes apparent after a certain point.

The first fluid layer once more adheres to the surface at speed zero (no-slip condition). This is followed by a very narrow area in which the layers show laminar slip; this is the laminar sublayer.

The most significant difference for convection begins behind this. The flow is turbulent. This means that there is indeed a main flow direction, but this is covered by random velocity elements in other directions. For the pipe flow shown in Fig. 4.4, the median is indicated by the dotted velocity profile. Due to the random flow elements, there is also motion transverse to the surface. Turbulence over the thin laminar sublayer causes the layers to mix with each other.

Heat is transported away from the surface by the motion of the fluid particles. In comparison to laminar flow, therefore, there is an improved heat transfer from the wall to the fluid.

4.3 Processes during free convection

Due to conduction of the fluid, the temperature of the fluid drops the further away it is from the surface. The following illustration shows a vertical plate that transfers heat to the surrounding fluid. The temperature is shown by the colour gradient:

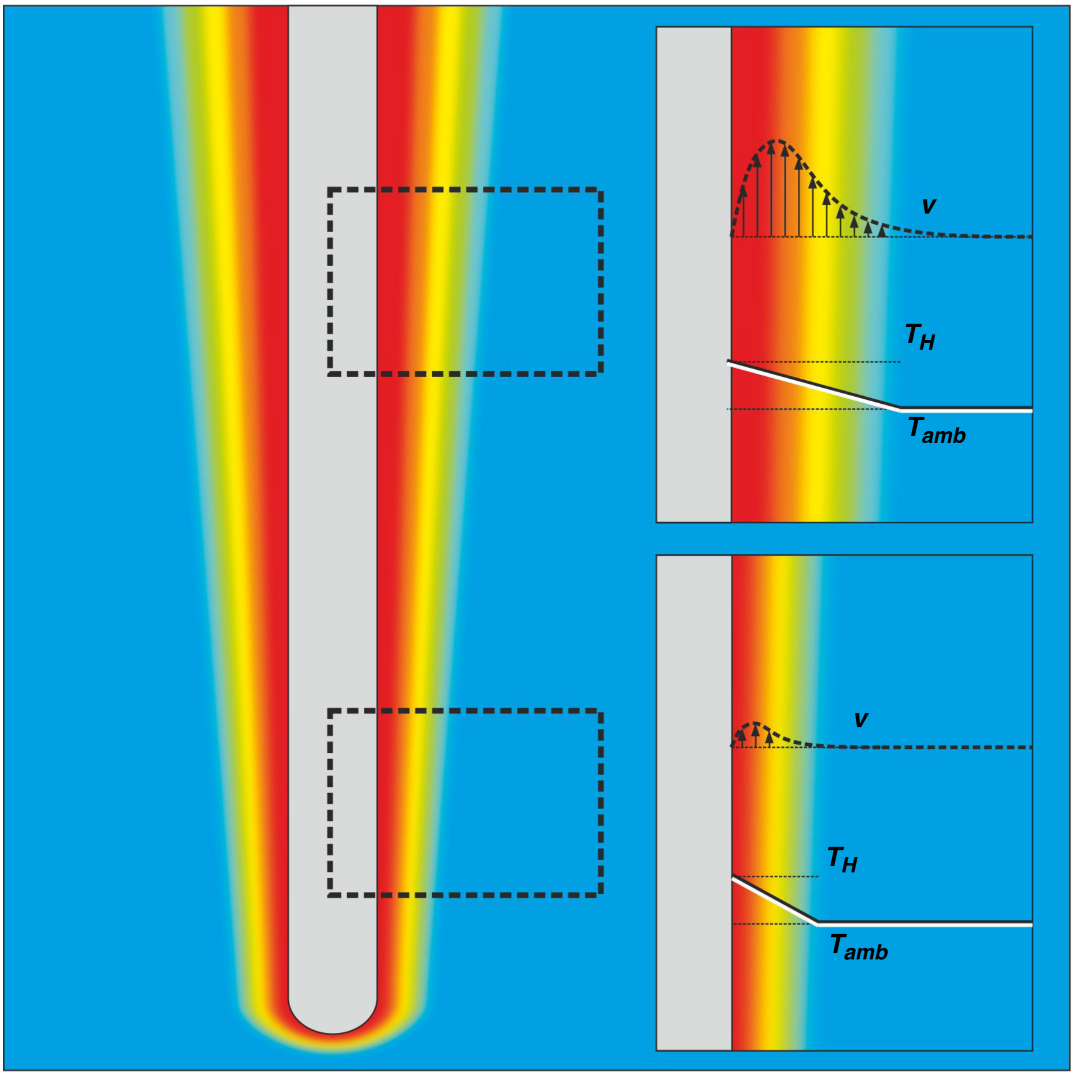


Fig. 4.5 Boundary layers under free convection at the vertical flat plate

Fig. 4.6 Positioning of the heater for free convection, see Chapter 3.7.2, Page 25

A layer is formed in which the heat penetrates into the fluid. This is called the temperature boundary layer.

There is also an additional velocity boundary layer caused by buoyancy forces. The buoyancy forces only affect the heated fluid layers. Due to the no-slip condition, the hottest fluid layer on the surface is stationary. In the adjacent fluid layers, the velocity increases up to a maximum and then decreases. This viscosity of the fluid influences the thickness of the velocity boundary layer. It ranges up to the undisturbed fluid.

Only fluid layers that rise due to heating can transport the heat. Temperature and velocity boundary layers have a significant influence.

4.4 Processes in forced convection

The flow velocity of the fluid over the exothermic wall is induced by technical means. The heated fluid is therefore moved faster over the exothermic surface. The heat-dissipating mass flow is thereby higher than in free convection. The temperature difference to the surroundings drops due to improved heat dissipation.

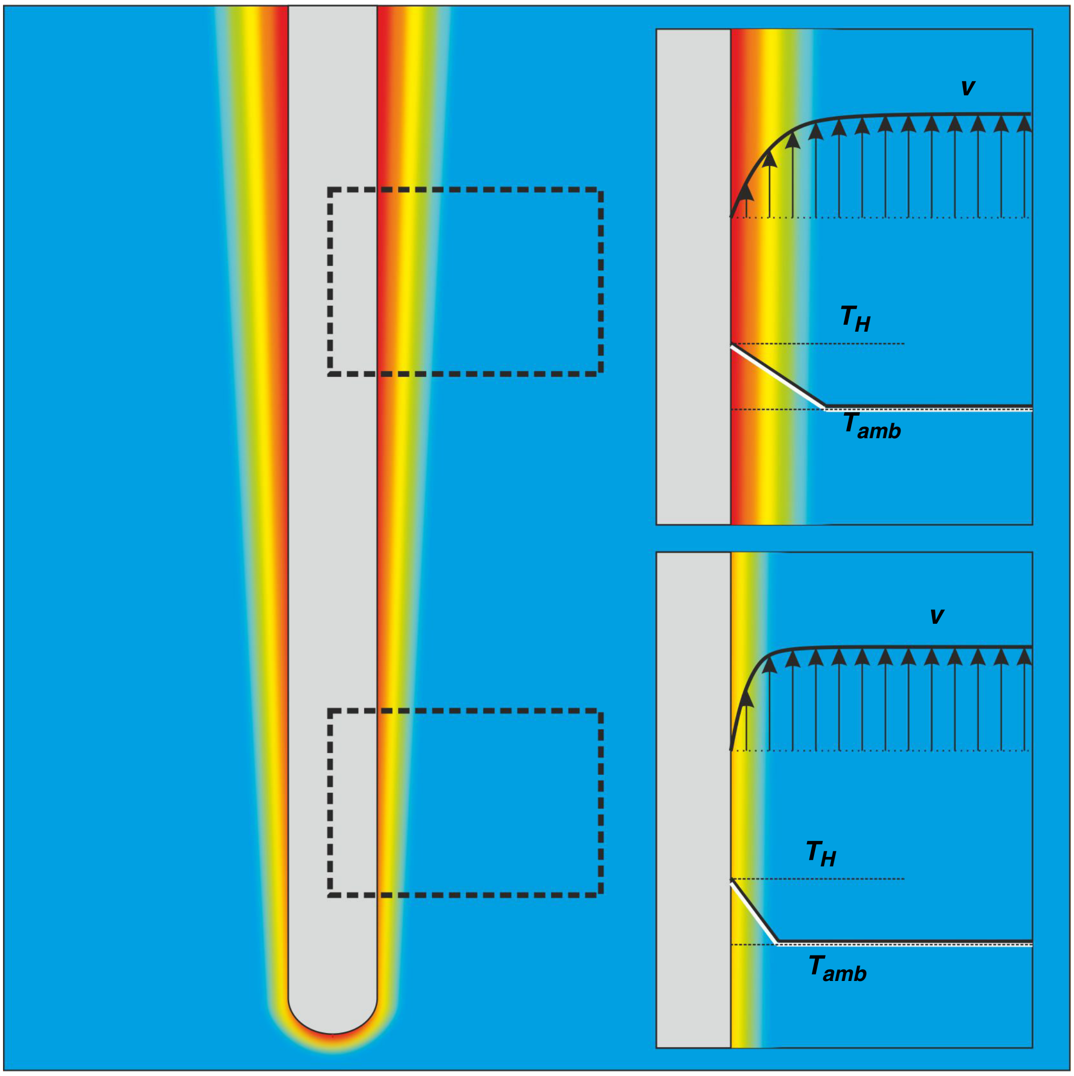


Fig. 4.7 Boundary layers under forced convection

The temperature drop vertical to the surface is nevertheless greater than in free convection. This results in a higher equalisation effort, and convective heat transfer improves.

4.5 Calculations for convection

4.5.1 Amount of heat

When a body is heated up, this requires a certain amount of energy:

$$Q = m \cdot c \cdot (T_{t2} - T_{t1}) \quad (4.1)$$

Q = Amount of energy
m = Mass
c = Specific heat capacity
T_{t1} = Temperature of the body at time *t1*
T_{t2} = Temperature of the body at time *t2*

4.5.2 Heat flux: Temperature increase of the mass flow

The heat flux of the heater increases the temperature of the fluid. The convection power can be calculated from the mass flow of the fluid and the resulting temperature difference.

$$\dot{Q} = \dot{m} \cdot c \cdot (T_2 - T_1) \quad (4.2)$$

$\dot{Q}$ = Heat flux
$\dot{m}$ = Mass flow
c = Specific heat capacity
T_1 = Input fluid temperature at inlet
T_2 = Output fluid temperature

4.5.3 Heat flux: Temperature difference between heater and fluid

In most practical applications the temperature increase of the heat-absorbing fluid is not measured. The temperature difference between the surface and the fluid also makes it possible to derive a relation to the dissipated heat.

$$\dot{Q} = A_s \cdot \alpha \cdot (T_H - T_{amb}) \qquad (4.3)$$

$\dot{Q}$ =Heat flux
A_s =Heat-dissipating surface
α =Heat transfer coefficient
T_{amb} =Ambient temperature
T_H =Heater temperature

The heat transfer coefficient can be taken from tables for some cases. These values often suffice for an initial estimate.

4.5.4 Heat fluxes: Equating, deviations

The Formula (4.2) and Formula (4.3) listed above can be equated. However, the mass flow and the temperature difference are often difficult to identify, since for example there is no clear flow area. There is a forced distribution of more or less heated mass flow. Similarly, it is difficult to identify an average temperature increase since there is a distribution here.

Nevertheless, if we equate the formulae mentioned in Chapter 4.5.4, we get deviations.

Formula (4.3), $\dot{Q} = A_s \cdot \alpha \cdot (T_H - T_{amb})$

The heat transfer coefficient depends mainly on the flow velocity. The temperature differences between the surface and the surrounding fluid are quite large. An error due to low temperature differences is therefore small. The heat flux can be determined with a small error.

Formula (4.2), $\dot{Q} = \dot{m} \cdot c \cdot (T_2 - T_1)$

Here the temperature difference is rather small. Small deviations in the temperature measurement lead to a large error. Reducing the flow velocity does indeed minimise this effect, although the accuracy of the flow sensor decreases at lower velocities. The result is that this measurement tends to be subject to larger errors.

4.5.5 Heating surface load

For the heating surface load $\dot{q}$ we can transpose the formula. We get:

$$\dot{q} = \frac{\dot{Q}}{A_s} = \alpha \cdot (T_H - T_{amb}) \qquad (4.4)$$

$\dot{q}$ = Heating surface load

4.5.6 Thermal resistance

Formula (4.3) can be transposed so that we get the relation of the temperature increase to the heat flux. We call this ratio the thermal resistance "R".

$$\frac{T_H - T_{amb}}{\dot{Q}} = \frac{1}{A_s \cdot \alpha} = R \qquad (4.5)$$

$\dot{Q}$ = Heat flux
A_s = Heat-dissipating surface
α = Heat transfer coefficient
T_{amb} = Ambient temperature of fluid
T_H = Surface temperature
R = Thermal resistance

4.6 Theory of similarity

The theory of similarity is used in many fields of physics and is a particularly important foundation in heat transfer. Physical similarity means that the model is similar to its original in a certain property.

Fig. 4.8 Section of a city map

Example of a map:
A map describes a given area as a two-dimensional model. Its special feature is that it shows the position and distances between buildings, roads, streams, mountains, etc. In this example, the scale is the key indicator by which it is possible to transfer the conditions on the map to reality.

The processes during convection can be expressed using the Nusselt number.

4.7 Nusselt number, Indicator of heat transfer

The Nusselt number is the improvement of heat transfer in convection compared to the heat transfer, which 'only' takes place by the heat conduction of the fluid.

It is calculated from:

$$Nu = \frac{\alpha \cdot L}{\lambda} \tag{4.6}$$

L = characteristic length
Nu = Nusselt number
α = heat transfer coefficient
λ = thermal conductivity

The length swept by the fluid is called the characteristic length. Fig. 4.9 shows two examples.

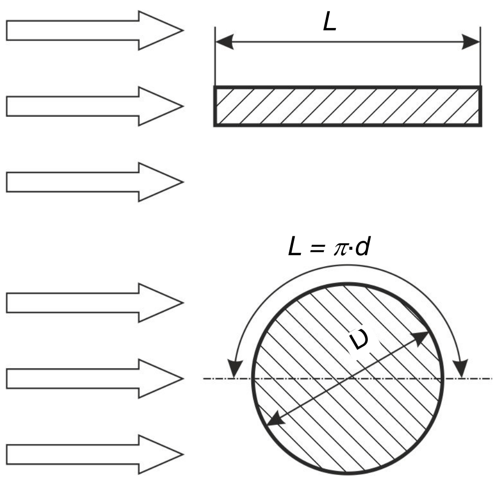


Fig. 4.9 Characteristic length

The higher the Nusselt number, the better is the heat transferred by convection to the surrounding fluid.

The lowest Nusselt number is when air is at rest. The convective heat transfer is then of the same order as the conduction. This hardly ever happens due to density differences caused by heating, or due to naturally occurring air movement.

The Nusselt number changes along the surface flowed over. This is due to the change in the boundary layers, as can be seen in Fig. 4.5, Page 35 and Fig. 4.6, Page 36. The median Nusselt number, indexed as ‘m’, suffices for many applications: Nu_m.

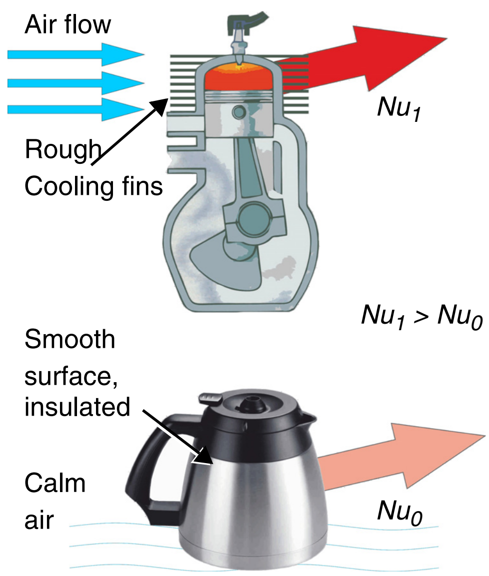


Fig. 4.10 Comparison of extreme Nusselt cases

For some geometries (e.g. plate, cylinder), the Nusselt number can be calculated from additional key indicators. Nusselt numbers can only be compared between identical geometries.

This allows a rough theoretical estimate to be made. Free and forced convection as well as laminar and turbulent flow must be differentiated in the calculation.

Besides characteristics that describe the material properties of the fluid, the Reynolds number under forced convection or the Grashof number under free convection is the variable with the most significant influence.

The fundamentals listed here should be understood as an introduction to the theory of similarity. For a more detailed study of heat transfer on the basis of the theory of similarity, please refer to the specialist literature.

In the experiments on the **WL 440** device, the Nusselt number is determined solely from measured values. The heat transfer coefficient α can be determined using Formula (4.6) and the Nusselt number.

4.7.1 Rayleigh number: Inciting free convection

Free convection takes place in a fluid at rest. Heated fluid rises due to change in density. Fluid from the environment flows in to replace it, heats up and keeps the process moving.

The characteristic is a ratio of several material variables and process parameters.

The Rayleigh number is calculated as follows:

$$Ra = \frac{g \cdot \gamma \cdot \Delta T \cdot L^3}{a \cdot \upsilon} \quad (4.7)$$

a = Thermal diffusivity
g = Gravitational acceleration
L = Characteristic length, see Fig. 4.9, Page 43
Ra = Rayleigh number
ΔT = Temperature difference T_H - T_{amb}
γ = Volumetric expansion coefficient
υ = Kinematic viscosity

The Rayleigh number is a measure of the convection. The greater it is, the stronger the heated fluid is compelled to rise. The convection heat flux and the Rayleigh number behave non-linearly.

The Rayleigh number can only be used to compare equal geometries.

Since on the temperature difference can be varied in the subsequent experiment, the calculation method with the Rayleigh number is not described here. For the sake of completeness, the effects when changing the parameters will be discussed.

Influence of free convection due to the Rayleigh number:

Changes in the meter

The values listed in the meter affect the lift force of the fluid. The **characteristic length** is used as a scale and is a measure for the surface at which convection takes place. Therefore, the fact that heating takes place in the fluid at this surface results in a heated fluid volume (third power).

The **volumetric expansion coefficient** and the temperature difference give a calculated volume increase. Since the mass remains equal, the density changes. The **gravitational acceleration** results in a change in the gravitational force, which changes the lift force.

An increase in the denominator results in a stronger lift force. Free convection is thereby incited.

Changes in the denominator

An increase in the denominator reduces the lift force. Two different effects are responsible for this.

The **thermal diffusivity** is a value that states how quickly the heat penetrates into a material. If this value is relatively large, the heat is introduced into the fluid more by heat conduction. The heating of the fluid thus remains rather small. The lift-increasing change in volume remains small. Thermal diffusivity is a physical property.

The **viscosity** of the fluid creates resistance against the flow process. The tougher this viscosity, the more the flow process is decelerated by friction in the fluid.

4.7.2 The Reynolds number
Flow formation under forced convection

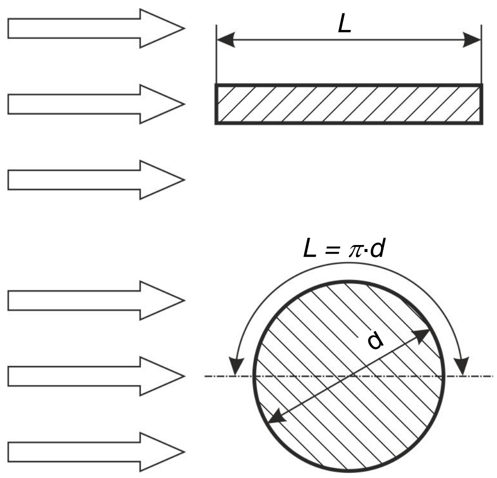


Fig. 4.11 Characteristic length in the plate and the cylinder

The Reynolds number is the ratio which is formed from the flow velocity, size of the body being studied and the viscosity of the fluid. It is calculated from:

$$Re = \frac{v \cdot L}{\upsilon} \tag{4.8}$$

L = Characteristic length
Re = Reynolds number
v = Flow velocity
υ = Kinematic viscosity

The use of flow velocity shows the relationship to forced convection.

The characteristic length is the length swept by the flow, see figure to the left.

The kinematic viscosity is a material variable. Since it depends on the temperature, it is formed from the mean temperature between environment and wall temperature.

While the velocity can be taken directly for the individual bodies, for a body such as the tube bundle it is increased due to the large volume displacement. The measured velocity must therefore be offset against the so-called void fraction.

$$v_{\psi} = \frac{v}{\psi} \tag{4.9}$$

v = Flow velocity
v_{ψ} = Mean velocity in the tube bundle
ψ = Void fraction of the tube bundle

Void fraction, see Formula 6.1, Page 121.

With similar geometries (scale!) and the same Reynolds number, the flow formation is the same.

Consequently for example, the Reynolds number can be indicative of flow formation within a tube. If $Re < 2300$, the flow is laminar, as in Fig. 4.3, Page 33. Vortices degenerate.

If $Re > 2300$, it is no longer possible for laminar flow to form with vortices present.

The transition point from laminar to turbulent flow is described as the critical Reynolds number Re_{krit}. This number depends on the geometry and is determined by experiment. Common geometries such as plate, tube and cylinder are sufficiently studied.

Even if the Reynolds number is the same, different geometries cannot be compared to each other. Therefore the statement $Re_{krit} = 2300$ only applies to pipe flow.

Influence of forced convection due to the Reynolds number:

The **flow velocity** determines the volume of heat-absorbing fluid.

The **size** can be used to change the heat-transferring area that is flowed over by the fluid.

The selection of the **fluid** influences the formation of the temperature and velocity boundary layer, although in practice it often can't be selected.

The **geometry** of the flow control can **agitate** or **calm** the flow. Configuration of the parameters mentioned allow the **flow formation** to be influenced (**laminar / turbulent**).

4.7.3 Forced convection
Heat transfer of the plate subject to flow

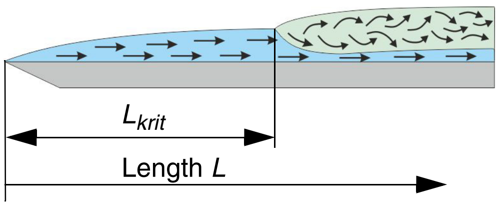


Fig. 4.12 Plate subject to flow

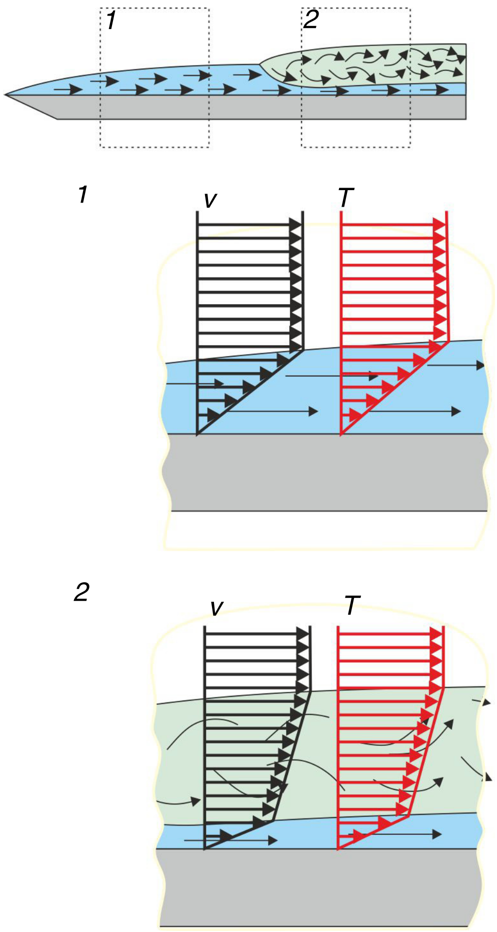


Fig. 4.13 Boundary layers at the plate

In the case of laminar flow over the plate, the flow boundary layer forms over the plate. With increasing length, this becomes thicker until transition to turbulent flow occurs at a certain length.

This happens at the critical length L_{krit} with the critical Reynolds number of about: $Re_{krit} \sim 300000$ (this cannot be achieve with the WL 440 device).

A laminar sub-layer is maintained.

Due to the characteristics the processes described are independent of the size - geometrically similar bodies can be compared to each other taking into account similarities.

Fig. 4.13 shows laminar and turbulent flow formation and heat transfer in both cases. The velocity in the flow boundary layer is zero at the surface.

1. The heat is dissipated from the surface and migrates with the air and perpendicularly. The velocity increases with increasing distance from the wall.
2. In the laminar sub-layer, the velocity increases and remains parallel until is also contains vertical velocity components in the turbulent layer. The illustration only shows the components proportional to the surface.
   If the flow is turbulent, the heat in the turbulent region is transported away much more effectively than is the case in laminar flow. The temperature drop is lower for the same heat flux.

Temperature boundary layers form. Their profile under forced convection is very similar to the velocity boundary layers.

A turbulent formation of the boundary layer can not be demonstrated by velocity with WL 440. The turbulent incitation of the flow before the plate can however demonstrate this effect during heat transfer.

4.7.4 Forced convection
Heat transfer on the cylinder

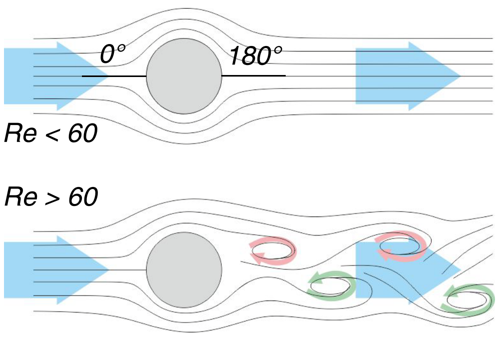


Fig. 4.14 Varying levels when flowing around the cylinder

Up to a Reynolds number of about 60 flow around a cylinder is laminar. From *Re*~60 a typical flow formation takes place, the Karman vortex street. Local flow separations (return flow at the surface) cause regular vortices. The flow separations are turbulent components in the flow. Typically the flow separations occur at around 90°.

The regular vortices are used in WL 440 to achieve turbulent flow through a cylinder, the turbulence generator.

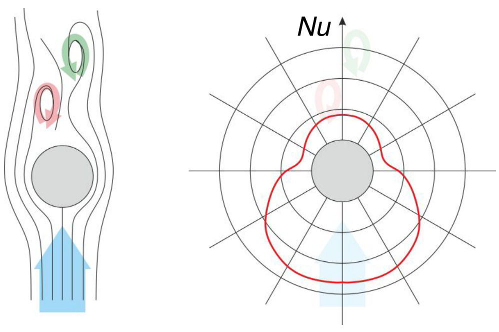


Fig. 4.15 Nusselt number on cylinder under surrounding flow

As with the plate, local values for convective heat transfer can be formed at any point on the cylinder. This results in a profile of the values around the cylinder, see Fig. 4.15.
It is a characteristic of the heat transfer at the cylinder that there is a drop in the heat transfer if we move along the surface away from the upstream side.

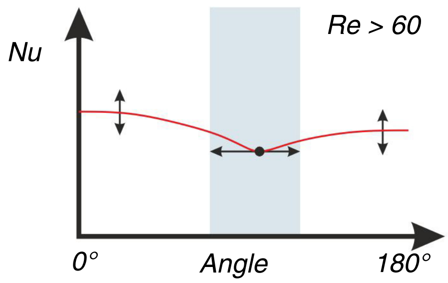


Fig. 4.16 Characteristic profile of the Nusselt number on cylinder under surrounding flow

At this point of the smallest heat transfer, flow separations occur (see Chapter 4.7.3). This is directly related to the flow, see Fig. 4.16. The minimum is in the range of the shaded zone. Depending on the flow formation, slightly before or after 90°.

Similarly, the convective heat transfer before and after depends on the flow velocity.

4.7.5 Forced convection Heat transfer on the tube bundle

Tube bundles are often used in heat exchangers to deliver heat to the flowing fluid. In this case a number of tubes are positioned so that the flow sweeps over all tubes. This is typically done in arrangements with lots of rows.

What matters here is a different heat transfer depending on the row subject to flow.

This difference can again be attributed to different flow formation. Depending on which row is subject to flow, the flow is characterised somewhat differently. The characterisation can be controlled to a certain extent by the structural shape. Generally speaking, there is a sharper increase of heat transfer in the first rows, which then remains at its high level.

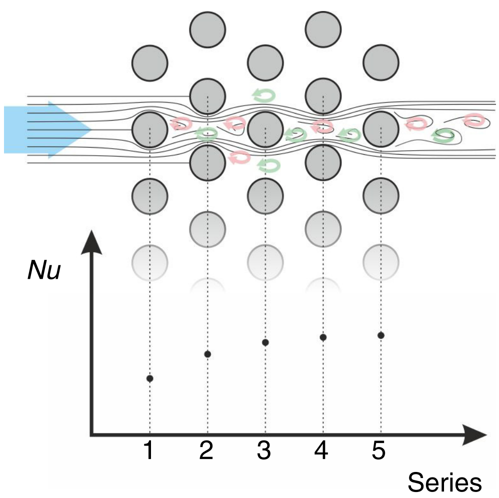


Fig. 4.17 Convective heat transfer in the tube bundle

The first row is subject to flow by calmer air. The surrounding flow is similar to the single cylinder, in that differences occur due to the flow control of the tube rows, especially in tube bundles that are close together. The flow in the subsequent rows is more turbulent.

4.8 Transient behaviour

Transient heat conduction denotes a temperature profile which varies over time. The **WL 440** device offers an experiment on behaviour over time.

This experiment looks at the temperature of the core over time. It is assumed to be distributed evenly over the body. Heating and cooling are considered in more detail.

A heated body is immersed in a liquid and gives off its heat.

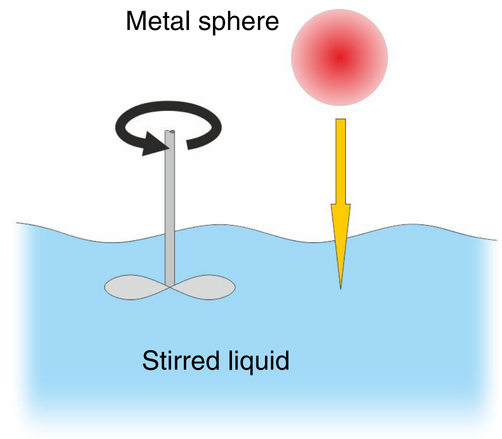


Fig. 4.18 Stirred tank

In order that the computational model provides sufficiently accurate results, the following basic conditions must be met:

- The body must have a compact shape.
- The surrounding fluid must have a constant and uniform temperature. This ideal is best satisfied by the "stirred tank".
- The heat is better conducted (distributed) in the body being studied than the heat flows outward. Therefore a uniform temperature of the body can be assumed.

Two formulae of the heat flux are essential for transient heat conduction.

The heat flux of the body can be calculated by deriving from Formula (4.5), Page 41:

$$\dot{Q} = m \cdot c \cdot \frac{\Delta T_H}{\Delta t} \quad (4.10)$$

$\dot{Q}$ = Heat flux
m = Heated mass
c = Specific heat capacity
ΔT_H = Temperature change of the body
Δt = Time difference

This heat flux must flow out via thermal resistance, Formula (4.4), Page 40

$$\dot{Q} = A_s \cdot \alpha \cdot (T_H - T_{amb}) = \frac{1}{R} \cdot (T_H - T_{amb}) \quad (4.11)$$

A_s = Heat-dissipating surface
α = Heat transfer coefficient
R = Thermal resistance
T_{amb} = Ambient temperature
T_H = Heater temperature

4.8.1 Time constant

When used later, the variables of the two formulae are combined as a time constant τ:

$$\tau = \frac{1}{\alpha \cdot A_s} \cdot c \cdot m = R \cdot c \cdot m \tag{4.12}$$

A_s = Heat-transferring surface
c = Heat capacity
m = Mass
R = Thermal resistance
α = Heat transfer coefficient
τ = Time constant

The greater the mass or the specific heat capacity or the thermal resistance, the greater the time constant.

4.8.2 Cooling, block capacity

The example shown in Fig. 4.18, Page 54 is called block capacity.

The hot body is immersed in the stirred tank and releases its stored thermal energy. The temperature drop is the system's response to the cooling environment.

Formula (4.10), Page 55 and Formula (4.7), Page 45 are equated:

$$\frac{dT_H}{dt} \cdot m \cdot c = -\frac{1}{R} \cdot (T_H - T_{amb}) \qquad (4.13)$$

$$\frac{dT_H}{dt} \cdot \tau = -(T_H - T_{amb}) \qquad (4.14)$$

T_H = Temperature of the body
T_{amb} = Ambient temperature
m = Heated mass
c = Specific heat capacity
R = Thermal resistance
τ = Time constant
dT_H/dt = Temperature rise, heat-up rate

The largest temperature difference is **at the start**. The heat flux is the greatest here.

At the end the body has reached ambient temperature. The heat flux is zero.

The solution to the differential equation of Formula (4.14) is:

$$T_H(t) = T_{amb} + K \cdot e^{\left(\frac{-t}{\tau}\right)} \qquad (4.15)$$

K = Total temperature jump
$T_H(t)$ = Temperature of the body at time t
T_{amb} = Ambient temperature
t = Time
τ = Time constant

The **temperature jump *K*** is equal to the temperature difference at the beginning of the experiment:

$$K = T_H - T_{amb} \qquad (4.16)$$

4.8.3 Heating up

A very similar trend to block capacity is obtained when the heater of **WL 422** is heated by a constant heat flux. Heat is dissipated to the cooling water via heat conduction.

Formula (4.10), Page 55 and Formula (4.7), Page 45 are equated with the electrical power:

$$P_{el} = \frac{dT_H}{dt} \cdot m \cdot c + \frac{1}{R} \cdot (T_H - T_{amb}) \qquad (4.17)$$

P_{el} = Electrical power
m = Heated mass
c = Specific heat capacity
R = Thermal resistance
T_H = Temperature of the core
T_{amb} = Ambient temperature
dT_H/dt = Temperature rise

At the start, all energy flows into the heater, which heats up at the rate $\frac{\Delta T}{\Delta t}$. As the temperature difference to the environment increases, the heat flux to the environment increases too.

At the end the heater has reached its final temperature. The input energy is dissipated to the cooling water.

The solution to the differential equation Formula (4.17) is:

$$T_H(t) = T_{amb} + K \cdot \left(1 - e^{\left(-\frac{t}{\tau}\right)}\right) \quad (4.18)$$

$T_H(t)$ = Temperature of the body at time t
K = Total temperature jump
T_{amb} = Ambient temperature
t = Time
τ = Time constant

The **temperature jump *K*** is equal to the achievable temperature difference after a long dwell time.

$$K = T_H - T_{amb} = \frac{\dot{Q}}{\alpha \cdot A_s} = \dot{Q} \cdot R \quad (4.19)$$

T_{amb} = Ambient temperature
T_H = Final temperature of the body
A_s = Heat-dissipating surface
α = Heat transfer coefficient
$\dot{Q}$ = Heat flux
R = Thermal resistance

4.8.4 Typical profile of the temperature jump

By normalising the two interdependent variables of time t and temperature T, all variables can be traced on a single chart.

The normalisation of time is done by tracing back to the time constant τ. The maximum temperature jump can be normalised to "one".

$$\theta = \frac{T_H(t) - T_{amb}}{T_H - T_{amb}} \tag{4.20}$$

$T_H(t)$ = Temperature of the body at time t
T_H = Final temperature of the body
T_{amb} = Ambient temperature
θ = Dimensionless temperature

Using the formulae shown, we can calculate the temperature jump and illustrate it graphically:

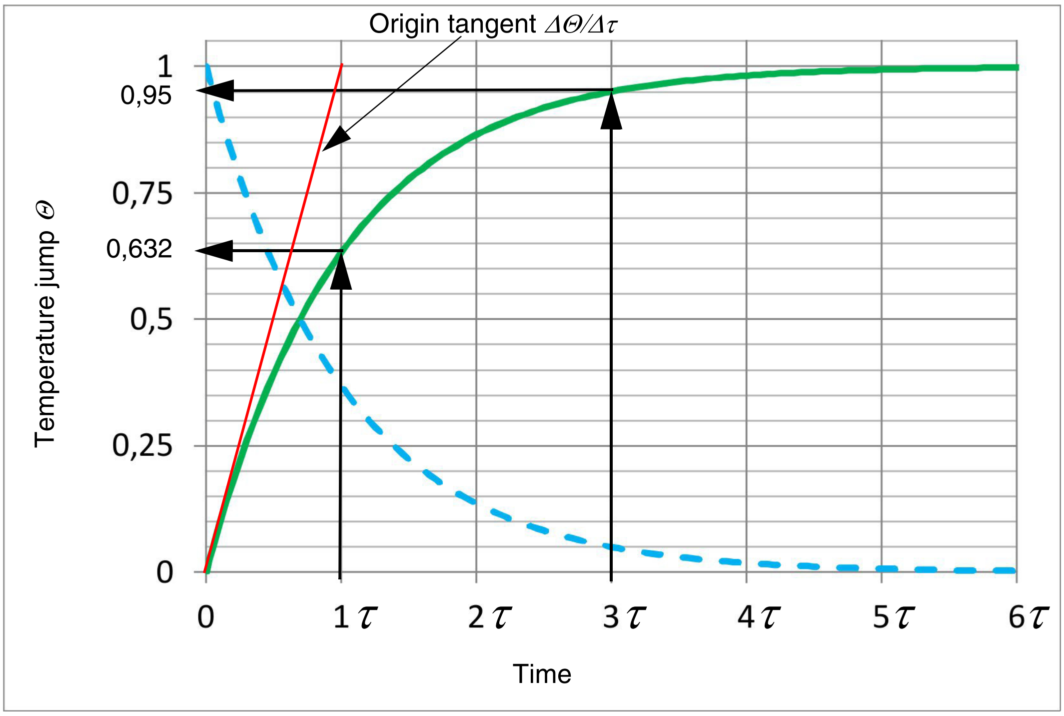


Fig. 4.19 Temperature jump over the time constants
Heating green / cooling blue dashed

Fig. 4.19, Page 60 shows the temperature jump. After a while the temperature jump has approximated the final temperature. There is then practically no more change in the temperature.

This form of the illustration clearly shows the influence of the time constants τ. The initial gradient passes through the origin and the point [Θ; τ]. In another illustration this corresponds to [*K; R m c*]

The dimensionless temperature after time τ reaches 63.2% of the total jump of θ. After $3 \cdot \tau$ 95% is achieved.

Variations in the temperature jump or the time constants compress or stretch the curve, provided the temperature jump θ or the time constant τ is not selected as the illustration. Fig. 4.20 shows these illustration options. All stated laws are preserved.

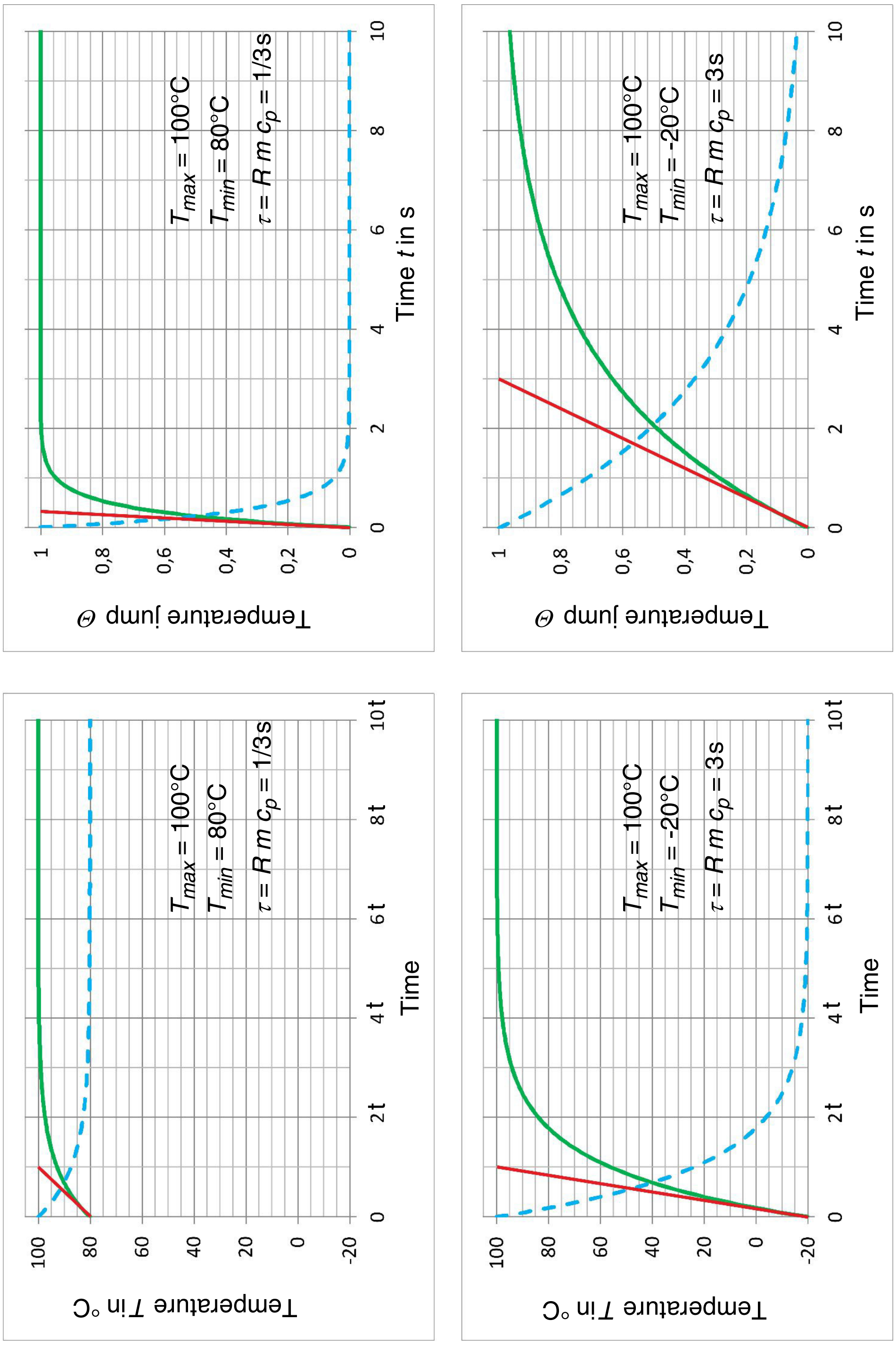


Fig. 4.20 Variations of the exponential function

4.9 Effects when measuring with the handheld temperature sensor

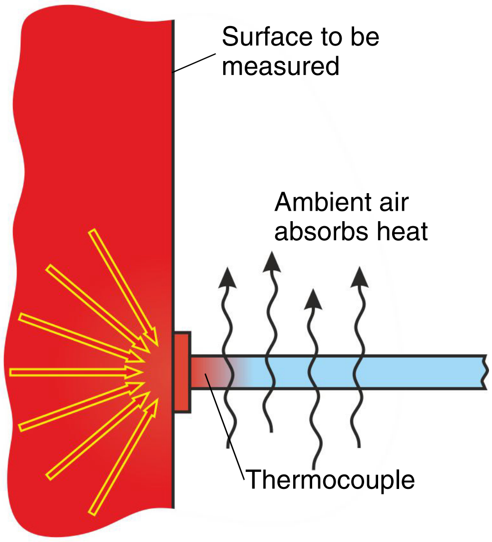


Fig. 4.21 Flow of heat when measuring the temperature produces a small measurement error

Temperature measurement with the handheld temperature sensor takes place through a thermocouple. This has a small measuring point, which is pressed onto the point to be measured.

In order to measure the surface temperature, the heat must be conducted to the thermocouple by heat conduction.

This results in two error sources that distort the temperature:

- Heat conduction at the contact point. This effect can be minimised by using thermal paste.
- The thermocouple works like a small cooling fin and discharges heat to the surrounding air.

Both effects lead to a somewhat lower measured temperature than the actual surface temperature without the thermocouple applied.

Nevertheless it is possible to clearly demonstrate the profile of temperature fields.

5 Experiments

The selection of experiments makes no claims of completeness but is intended to be used as a stimulus for your own experiments.
The results shown are intended as a guide only. Depending on the construction of the individual components, experimental skills and environmental conditions, deviations may occur in the experiments. Nevertheless, the laws can be clearly demonstrated.

All specifications for electrical power and flow velocity are recommendations that deliver good results. Other settings are possible.

The analysis is performed in part with Excel® in order to compare measured values.

5.1 Experiment 1: Free convection at the plate

5.1.1 Learning objective

I. The student can describe what happens when the heater is operated with different electric powers.

In addition to the measured variables, the software also shows calculated values of heat transfer. Calculating the values shows relationships which are studied in more detail in subsequent experiments.

II. The student can calculate the following variables from the measured values:
   a) Heat transfer coefficient
   b) Heating surface load
   c) Thermal resistance
   d) Nusselt number
   The student can judge the significance of the calculated value.

III. The student can feel the heat in the vicinity of the heater.

IV. The student can explain why the flow velocity / Reynolds number are not relevant to the experiment.

V. The student analyses the curves of:
   a) Temperature difference over power
   b) Nusselt number over temperature difference

5.1.2 Conducting the experiment

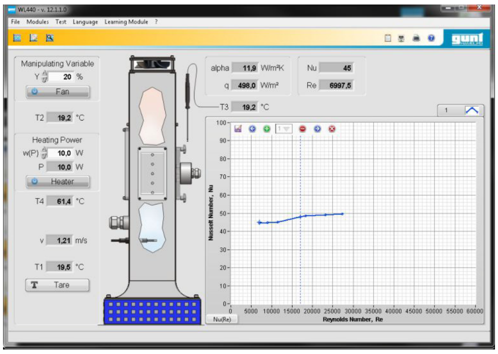


Fig. 5.1 Experiment screen

Fig. 5.2 Positioning of the plate for free convection

1. Start the device and software.
2. If necessary, tare the measurements, see Chapter 3.7.3, Page 28.
3. Attach the "Plate" heater insert to the device, see Chapter 3.7.2, Page 25 and Fig. 5.2.
4. In the "Modules" menu, open "Chart recorder".
5. Supply 2 W to the heater insert.
6. Once the measured values in the graph of the chart recorder have stopped fluctuating (see Chapter 3.7.4, Page 29), record the measuring point.
7. Increase heating power (4, 6, 8, 10, 12W)
8. Repeat steps 7 and 8.
   A minimum of 4 measuring points are recommended for a meaningful illustration.
9. Save the measured values.
   Save/print the chart using the print function as required.

NOTICE
The experiment is sensitive to air movements. Air flows in the room may affect the results.

5.1.3 Measured values

Power P_{el} [W]	T_1 [°C]	T_4 [°C]	α [W/m²K]	$\dot{q}$ [W/m²]	*Nu*
2	24,9	38,1	7,5	99	29
4	24,6	48	8,5	199,2	32
6	24,4	58,4	8,8	300,6	34
8	24,3	69	8,9	397,7	34
10	24,1	78,1	9,2	498,4	35
20	25,1	86,4	9,8	601,5	37

Tab. 5.1 Measured values from experiment 1

The values used for further calculations are highlighted grey.

5.1.4 Analysis of the experiment

Learning objective I

Processes when supplying different electrical powers.

If the heater insert is supplied with power, the temperature of the heater rises. This rise is directly measured at the surface.

The temperature difference between the heater insert and air causes thermal energy to be transferred to the air.

After enough time has passed, an equilibrium is established where the values no longer change. This can be seen in the curve over time of the measured values.

In the experiment it is clear that the temperature increases with increasing electrical power to the heater insert.

Learning objective II

Re-calculating heat transfer variables.

Re-calculate some heat-related variables (physical properties of air from Chapter 6.2, Page 124):

Learning objective II (a)

Heat transfer coefficient

The **heat transfer coefficient** α. See also Formula (4.3), Page 39. Transposed:

$$\alpha = \frac{\dot{Q}}{A_s \cdot (T_4 - T_1)} \tag{5.1}$$

$\dot{Q}$ = Heat flux
A_s = Heat-dissipating surface
α = Heat transfer coefficient
T_1 = Ambient temperature
T_4 = Surface temperature

$$\alpha = \frac{6\text{W}}{2 \cdot (0{,}1\text{m})^2 \cdot (58{,}4 - 24{,}4)\text{K}} = 8{,}8 \frac{\text{W}}{\text{m}^2 \cdot \text{K}} \tag{5.2}$$

The heat transfer coefficient indicates how well the heat is transferred from the surface to the air.

There are no deviations to the stored value, since the internal calculation is performed with the same numbers. Small deviations due to rounding may occur with other measurements.

Learning objective II b)

Surface loading

The **heating surface load** $\dot{q}$. See also Formula (4.4), Page 40.

$$\dot{q} = \frac{\dot{Q}}{A_s} = \alpha \cdot (T_4 - T_1) \tag{5.3}$$

$\dot{Q}$ = Heat flux
$\dot{q}$ = Heating surface load
A_s = Heat-dissipating surface
α = Heat transfer coefficient
T_1 = Fluid ambient temperature
T_4 = Surface temperature

Heat flux and the heat-dissipating surface give:

$$\dot{q} = \frac{6\mathrm{W}}{2 \cdot (0{,}1\,\mathrm{m})^2} = 300\frac{\mathrm{W}}{\mathrm{m}^2} \tag{5.4}$$

Deviations to the stored value of 300,6 W/m² can be explained by the rounding of the electric power measurement.

Learning objective II c)

Thermal resistance

The **thermal resistance *R***. See also Formula (4.5), Page 41. Transposed:

$$R = \frac{1}{A_s \cdot \alpha} = \frac{T_4 - T_1}{\dot{Q}} \tag{5.5}$$

R = Thermal resistance

(5.6)

$$R = \frac{1}{0{,}02\mathrm{m}^2 \cdot 8{,}8\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}}} = 5{,}68\frac{\mathrm{K}}{\mathrm{W}} \tag{5.7}$$

The thermal resistance indicates how well the heat is transferred from the surface to a fluid in convection.

The smaller the thermal resistance, the better the heat can be transferred to the fluid. The higher the thermal resistance, the stronger the heating effect.

Learning objective II d)

Nusselt number

The **Nusselt number Nu**, Formula (4.6), Page 43:

$$Nu = \frac{\alpha \cdot L}{\lambda} \tag{5.8}$$

L = Characteristic length
Nu = Nusselt number
α = Heat transfer coefficient
λ = Thermal conductivity

With the thermal conductivity of air of about 0,026 W/m K (depending on temperature) we get:

$$Nu = \frac{8{,}8\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}} \cdot 0{,}1\,\mathrm{m}}{0{,}026\frac{\mathrm{W}}{\mathrm{m} \cdot \mathrm{K}}} = 33{,}8 \tag{5.9}$$

The Nusselt number is a dimensionless number for convective heat transfer. It is much more general than for example the heat transfer coefficient or thermal resistance. It represents the fluid being studied as a comparison to thermal conductivity.

Learning objective III

Detecting the temperature rise in the vicinity of the plate.

By carefully moving your finger close to the surface of the plate it is clear that the heat transfer only takes place in a very narrow range, see Fig. 5.3.

Fig. 5.3 Feeling the heat at the surface of the plate - without touching

By supporting the outside of your hand on the air duct, you can prevent shaking and get closer to the surface.

Through careful observation it becomes clear that the area is only a few millimetres thick. This area is the thermal boundary layer. All variables discussed in this manual are directly related to the formation of this area.

⚠ WARNING

Hot surfaces while operating the heater.

Burns are possible.

- Do not touch during operation.

Learning objective IV

Explain why the flow velocity / Reynolds number is not relevant to the experiment on free convection.

The experiments on free convection should take place in the stationary fluid. In this case the ambient air should remain as still as possible. A generated flow is therefore undesirable.

The indicated air velocity may well fluctuate in small ranges. This is always a given due to unavoidable air movements in conventional rooms.

Learning objective Va

Analyse the temperature difference over the electric power

If we create a chart in which the temperature difference is plotted over the electrical power, we can see a steady increase, see Fig. 5.4.

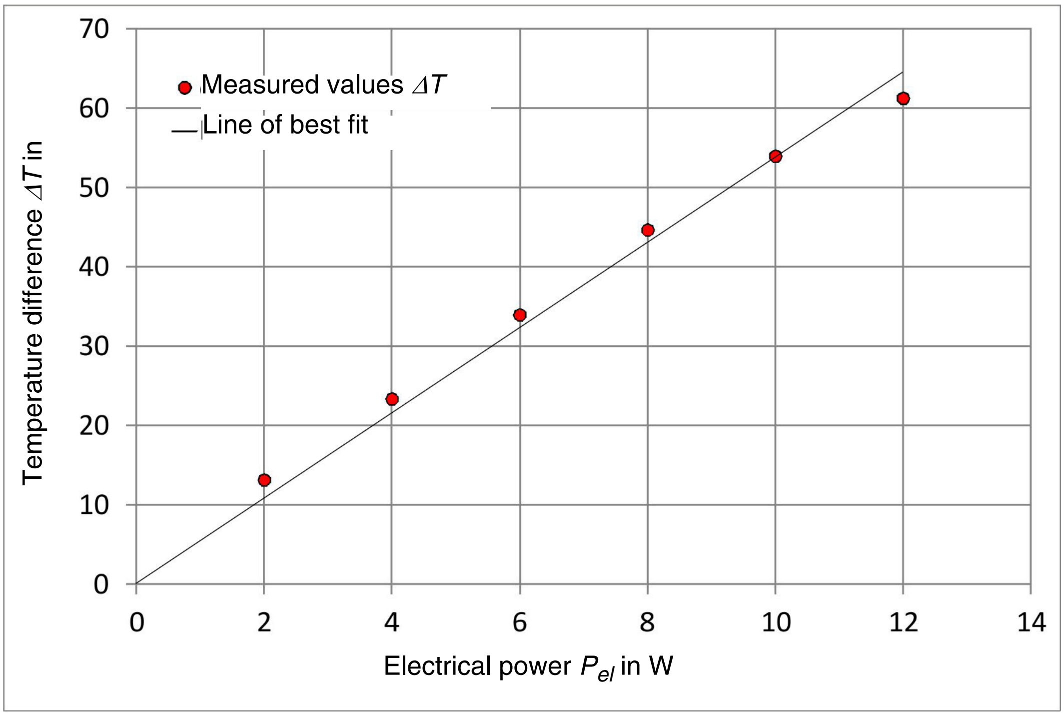


Fig. 5.4 Temperature difference ΔT over the electrical power P_{el}

A trend line is added to the measured values. This has its source in the origin. The measured values are not exactly on this line, but tend to be slightly above it at low power.

The added trend line correspond to a constant thermal resistance. If the measured value is above it, the thermal resistance at this point is also higher ($R = \Delta T / P_{el}$).

Learning objective Vb

Evaluate the Nusselt number over the temperature difference

If we create a chart in which the Nusselt number is plotted against the temperature difference, we get the following:

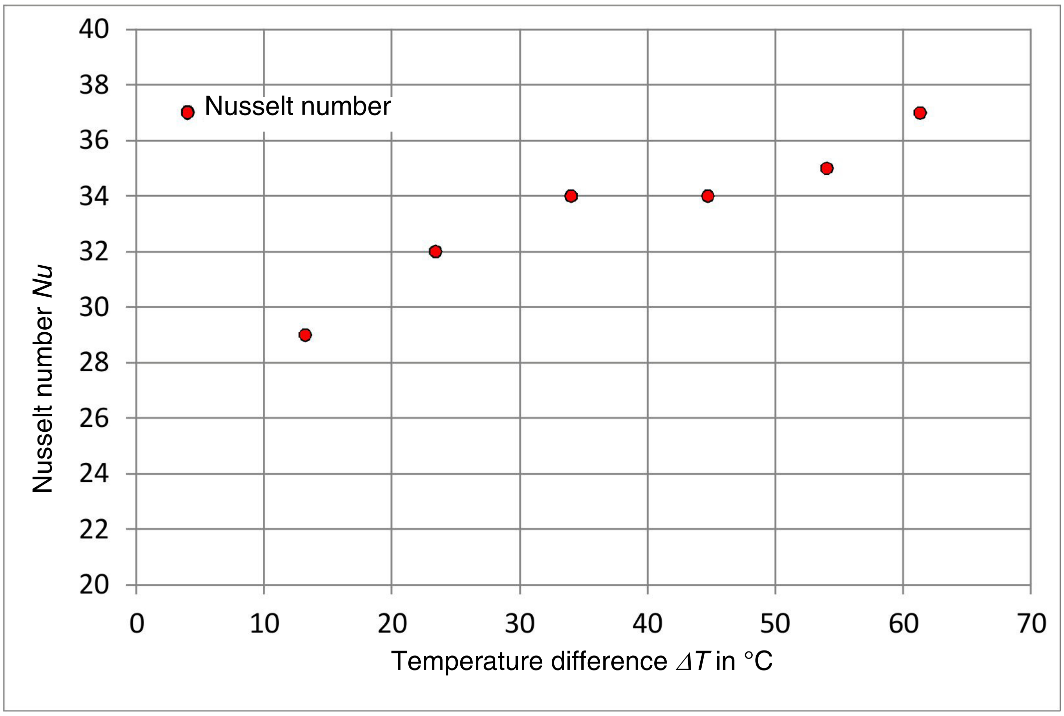


Fig. 5.5 Nusselt number over temperature difference

The Nusselt number increases with increasing temperature difference. There is a higher equalisation effort.

The air heats up more sharply than at low temperature. This results in a stronger lift. The heated air flows upwards and is replaced by air from the environment.

This process increases the convective heat transfer with rising temperature, the heat is better conducted from the plate into the surrounding air.

5.2 Experiment 2: Free convection on the cylinder

5.2.1 Learning objective

VI. The student can calculate the following variables from the measured values:
   a) Heat transfer coefficient
   b) Heating surface load
   c) Thermal resistance
   d) Nusselt number

VII. The student compares the values with the results which were obtained with the plate. The student provides explanations for any deviations.

5.2.2 Conducting the experiment

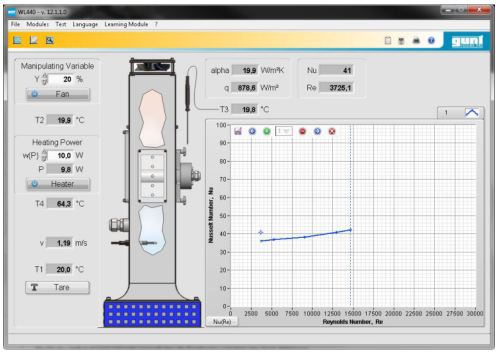


Fig. 5.6 Experiment screen

1. Start the device and software.
2. If necessary, tare the measurements, see Chapter 3.7.3, Page 28.
3. Attach the "Cylinder" heater insert to the device, similar to Chapter 3.7.2, Page 25 and Fig. 5.2.
4. In the "Modules" menu, open "Chart recorder".
5. Supply 2 W to the heater insert.
6. Once the measured values in the graph of the chart recorder have stopped fluctuating (see Chapter 3.7.4, Page 29), record the measuring point.

Fig. 5.7 Positioning of the plate for free convection

7. Increase heating power (4, 6, 8, 10, 12 W)
8. Repeat steps 7 and 8.
   A minimum of 4 measuring points are recommended for a meaningful illustration.
9. Save the measured values.
   Save/print the chart using the print function as required.

NOTICE

The experiment is sensitive to air movements. Air flows in the room may affect the results.

5.2.3 Measured values

Power P_{el} [W]	T_1 [°C]	T_4 [°C]	α [W/m²K]	$\dot{q}$ [W/m²]	*Nu*
2	24,6	35,5	16,4	178,1	34
3,9	24,5	45,4	16,8	350,2	35
5,9	24,4	54,3	17,7	528,1	37
7,9	24,8	64,6	17,8	706,5	37
10	24,7	73	18,4	888,7	38
11,9	24,5	80,9	18,9	1063,8	39

Tab. 5.2 Measured values from experiment 2

The values used for further calculations are highlighted grey.

5.2.4 Analysis of the experiment

Learning objective VI

Re-calculating heat transfer variables.

Re-calculate some heat-related variables (physical properties of air from Chapter 6.2, Page 124). The calculation is done in the same was as the calculations from experiment 1.

Learning objective VI a)

Heat transfer coefficient

Heat transfer coefficient α, Formula (4.3), Page 39. Transposed:

$$\alpha = \frac{\dot{Q}}{A_s \cdot (T_4 - T_1)} \tag{5.10}$$

$\dot{Q}$ = Heat flux
A_s = Heat-dissipating surface
α = Heat transfer coefficient
T_1 = Ambient temperature of fluid
T_4 = Surface temperature

$$\alpha = \frac{5{,}9\mathrm{W}}{0{,}0112\mathrm{m}^2 \cdot (58{,}4 - 24{,}4)\mathrm{K}} = 17{,}6\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}} \tag{5.11}$$

Learning objective VI b)

Surface loading

Heating surface load $\dot{q}$, Formula (4.4), Page 40.

$$\dot{q} = \frac{\dot{Q}}{A_s} = \alpha \cdot (T_4 - T_1) \tag{5.12}$$

$\dot{Q}$ = Heat flux
$\dot{q}$ = Heating surface load
A_s = Heat-dissipating surface
α = Heat transfer coefficient
T_1 = Fluid ambient temperature
T_4 = Surface temperature

$$\dot{q} = \frac{5{,}9\mathrm{W}}{0{,}0112\mathrm{m}^2} = 526{,}8\frac{\mathrm{W}}{\mathrm{m}^2} \tag{5.13}$$

Learning objective VI c)

Thermal resistance

Thermal resistance *R*, Formula (4.5), Page 41. Transposed:

$$R = \frac{1}{A_s \cdot \alpha} = \frac{T_4 - T_1}{\dot{Q}} \tag{5.14}$$

R = Thermal resistance

$$R = \frac{1}{0{,}0112\,\text{m}^2 \cdot 17{,}6\frac{\text{W}}{\text{m}^2 \cdot \text{K}}} = 5{,}07\frac{\text{K}}{\text{W}} \tag{5.15}$$

Learning objective VI d)

Nusselt number

Nusselt number *Nu*, Formula (4.6), Page 43

$$Nu = \frac{\alpha \cdot L}{\lambda} \tag{5.16}$$

L = Characteristic length
Nu = Nusselt number
α = Heat transfer coefficient
λ = Thermal conductivity

$$Nu = \frac{17{,}6\frac{\text{W}}{\text{m}^2 \cdot \text{K}} \cdot 0{,}055\,\text{m}}{0{,}026\frac{\text{W}}{\text{m} \cdot \text{K}}} = 37{,}2 \tag{5.17}$$

Learning objective VII

Comparison of heat transfer variables between plate and cylinder

	Plate	Cylinder
Heat transfer coefficient α **in W/(m²K)**	8,8	17,7
Heating surface load $\dot{q}$ **in W/m²**	300,6	528,1
Thermal resistance R **in K/W**	5,67	5,07
Nusselt number Nu	33,8	37,2

Tab. 5.3 Comparison of values from experiment 1 and 2, free convection

The values are compared in Tab. 5.3.

If we compare the values obtained, it is noticeable that the values for the heat transfer coefficient and the heating surface load are around factor 2. This is due to the fact the area of the plate is nearly double that of the cylinder.

Due to the different area or geometry, these cannot be used to compare the convective heat transfer.

The thermal resistance or the Nusselt number are better suited for this purpose. The thermal resistance shows that the heating for the plate is higher than for the cylinder at the same power. This can be explained by the improved heat convective heat transfer. The Nusselt number is a measure of this improvement.

The improved convective heat transfer at the cylinder is due to two effects. Firstly, it is assumed that vortices arise at the upper side of the cylinder surface which better transport the heat away. This effect is described in more detail below under forced convection.

The heat is absorbed by the air directly at the surface and conducted into the more distant layers. With the plate this surface remains almost the same with increasing distance from the plate. With the cylinder, we can imagine this as lots of hollow cylinder around the fixed cylinder surface. The surface increases with increasing distance. The temperature in the adjacent fluid therefore drops more quickly than with the plate. This larger temperature drop causes a better equalisation effort. The convective heat transfer is improved.

This improved convective heat transfer persists in the entire measurement range:

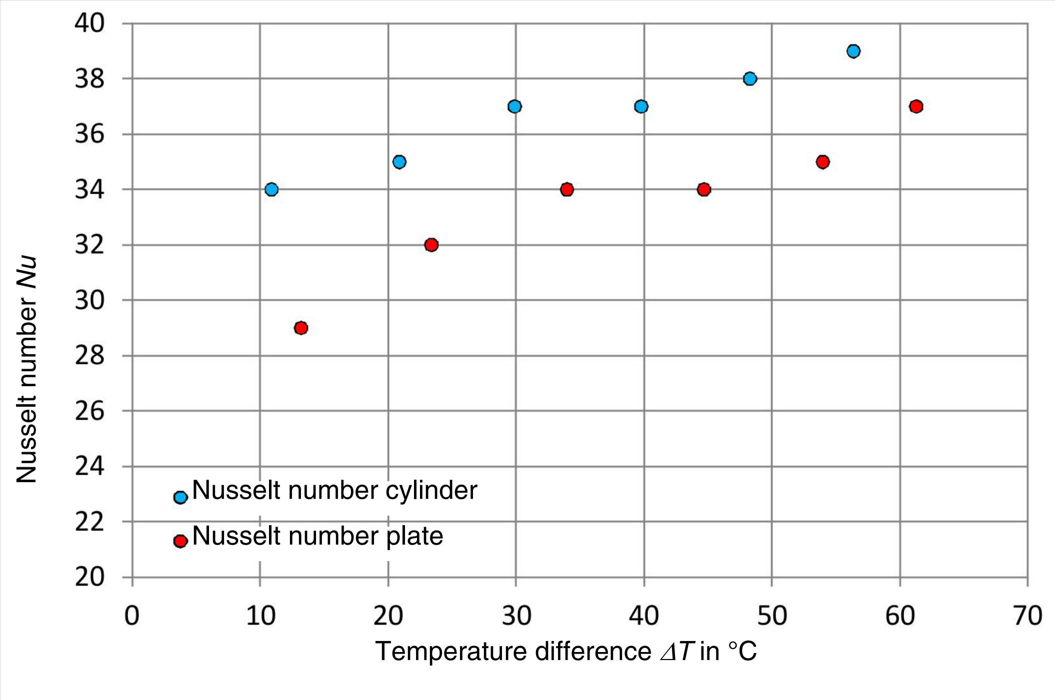


Fig. 5.8 Comparison of the convective heat transfer at plate and cylinder with the Nusselt number *Nu*

The curves are very similar, with better convective heat transfer with the cylinder.

5.3 Experiment 3: Forced convection
Heat transfer at the plate

5.3.1 Learning objective

VIII. The student compares the values of free and forced convection.

IX. Differences in the measurement results are attributed to and explained by the differences in the experiment.

5.3.2 Conducting the experiment

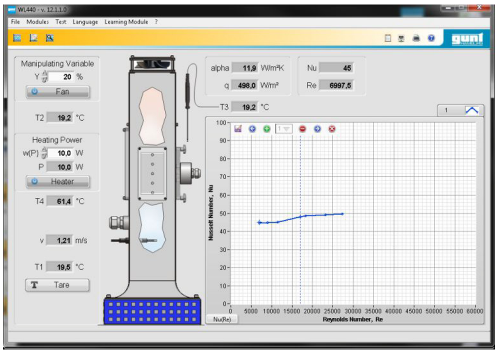


Fig. 5.9 Experiment screen

1. Start the device and software.
2. Attach the "Plate" heater insert to the device, see Chapter 3.7.2, Page 25.
3. Pull the turbulence generator out of the flow.
4. If necessary, tare the measurements, see Chapter 3.7.3, Page 28.
5. Set low fan power, e.g. 20%.
6. In the "Modules" menu, open "Chart recorder".
7. Supply 5W to the heater insert.
8. Once the measured values in the graph of the chart recorder have stopped fluctuating (see Chapter 3.7.4, Page 29), record the measuring point.
9. Increase heating power (10, 15, 20W)
10. Repeat steps 7 and 8.
    Four measuring points are often sufficient for a meaningful illustration.
11. Save the measured values.
    Save/print the chart using the print function as required.

5.3.3 Measured values

Power P_{el} [W]	T_1 [°C]	T_2 [°C]	T_4 [°C]	α [W/m²K]	v [m/s]	$\dot{q}$ [W/m²]	Nu
5	21,6	21,8	38,2	15	1,23	249,4	57
10,1	21,8	22,4	54,5	15,4	1,28	504	59
15	21,2	22,2	70,1	15,3	1,26	747,6	58
20	21	22,2	84,4	15,7	1,29	998,5	60

Tab. 5.4 Measured values from experiment 3

5.3.4 Analysis of the experiment

Learning objective VIII

Comparison of free and forced convection.

In order to be able to compare free and forced convection, the temperature difference and Nusselt number are plotted against the electrical heating power.

This results in the following two charts:

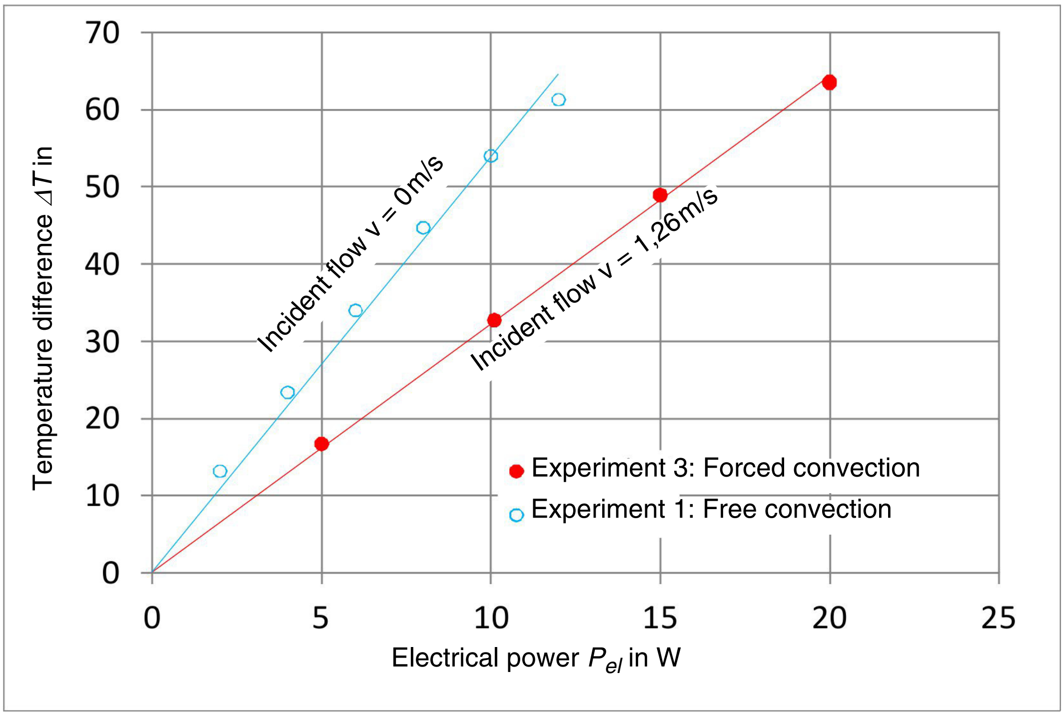


Fig. 5.10 Comparison of the temperature difference over the electric power

The curve for free convection has a steeper rise of the temperature difference.

Trend lines from the origin are inserted. The values for forced convection are near to this line, for free convection there are deviations as already described in experiment 1.

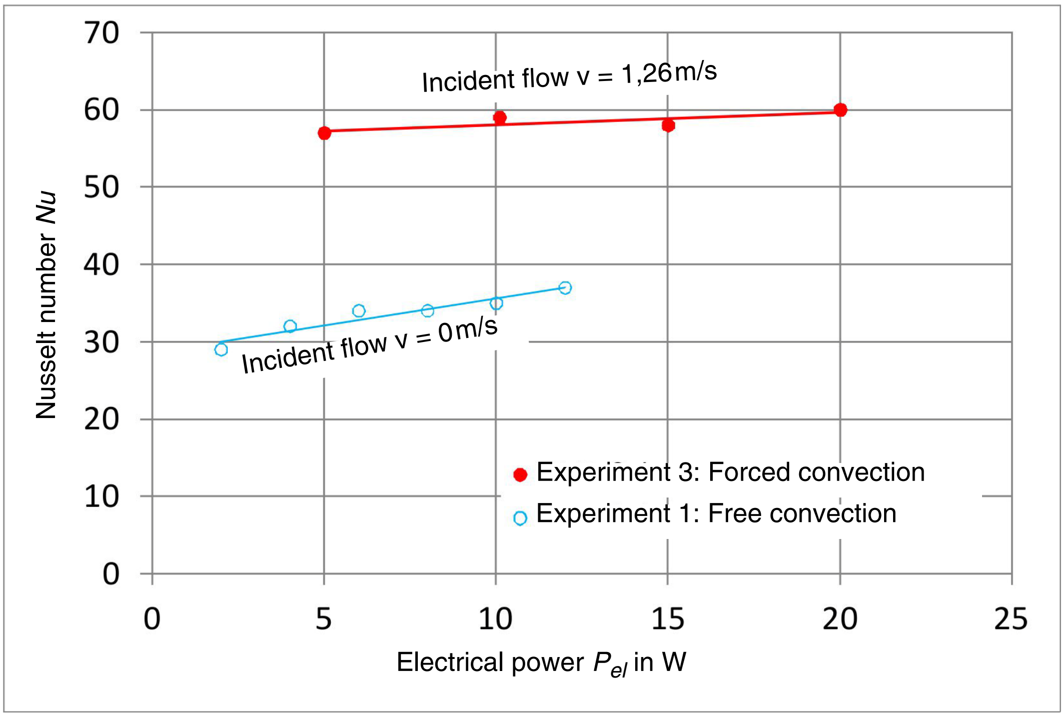


Fig. 5.11 Comparison of the Nusselt number over the electric power

When comparing the Nusselt number the higher values are striking. Furthermore, a much larger increase can be seen with free convection.

Learning objective IX

Description of the effect from incident flow.

The two charts show the better convective heat transfer of forced convection. The gradients in Fig. 5.10 correspond to different thermal resistances ($R = \Delta T / P_{el}$). The higher thermal resistance of free convection leads to a higher temperature rise at the same heat flux.

The comparison of the Nusselt number in Fig. 5.11 confirms the better convective heat transfer.

The deviations to the trend line inserted in Fig. 5.10, and the different gradients in Fig. 5.11 can both be attributed to a temperature influence during heat transfer. A high temperature difference favours convective heat transfer - as already described in experiment 1. However, the effect is particularly noticeable during free convection. At even higher flow velocities, this effect is negligible compared to the flow velocity.

The essential improvement in the convective heat transfer under forced convection is the deliberate removal of the heat by the layer of heated air. This removal means the gradient of the temperature drop from the surface to the adjacent fluid rises sharply. The thermal boundary layer is smaller.

The equalisation effort is increased due to the stronger temperature gradients and thus the convective heat transfer.

5.4 Experiment 4: Forced convection Temperature fields at the plate

5.4.1 Learning objective

X. The student can explain why the measured temperature field forms over the plate as in the measurement.

XI. The student can derive and explain that this has an impact on an optimum distance when using several fins.

XII. The student can explain why the measured temperature field forms at the plate as in the measurement.

5.4.2 Conducting the experiment

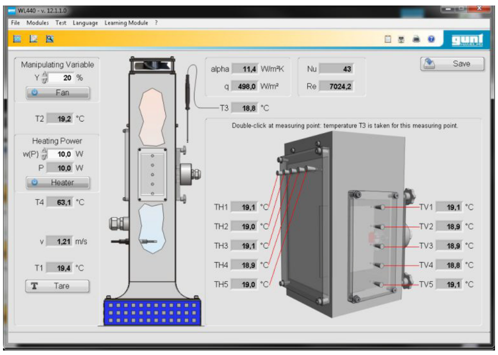


Fig. 5.12 Experiment screen

1. Start the device and software.
2. Attach the "Plate" heater insert to the device, see Chapter 3.7.2, Page 25.
3. Pull the turbulence generator out of the flow.
4. If necessary, tare the measurements, see Chapter 3.7.3, Page 28.
5. Set fan power to 10%.
6. In the "Modules" menu, open "Chart recorder".
7. Set the heating power to 15 W.
8. Wait until the steady-state operating point is reached.
9. Use the handheld temperature sensor to record the indicated measuring points. Once the measured values in the graph of the chart recorder have stopped fluctuating (see Chapter 3.7.4, Page 29), record the measuring

point.
(Use thermal paste when measuring surface temperatures)

10. Move the temperature sensor to the next point and repeat from step 9 until you have measured 10 measuring points.

11. Save the measured values.
Save/print the chart using the print function as required.

5.4.3 Measured values

Measured values as screenshot:

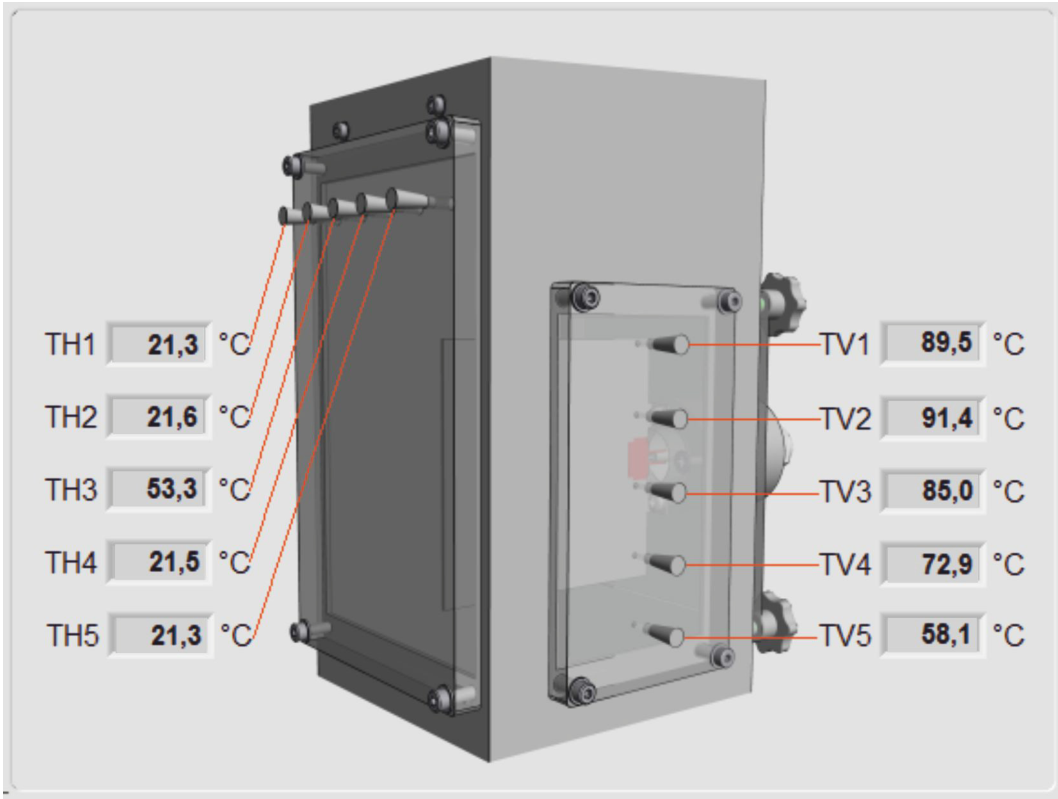


Fig. 5.13 Screenshot of the values from experiment 2

The measured value of the surface temperature is 86,7°C. This matches the measured value that was recorded at the centre of the plate.

5.4.4 Analysis of the experiment

Learning objective X

Formation of the temperature field.

In the screenshot it can be seen that the temperature profile of the outflow has a significant temperature increase above the plate. Within 20 mm (distance between the holes) this peak has fallen to almost room temperature. The slight difference in the outer measuring points is lost in the noise.

The thickness of the zone of increased temperature mainly depends on the flow velocity. The entire transferred is located in this zone.

The wall area of the air duct does not carry any heat away from the plate. Measuring the average air temperature is only possible with an ideal mixture of the flow after the heater insert, due to this limited temperature increase. The vortex lattice is intended to approximate this ideal state.

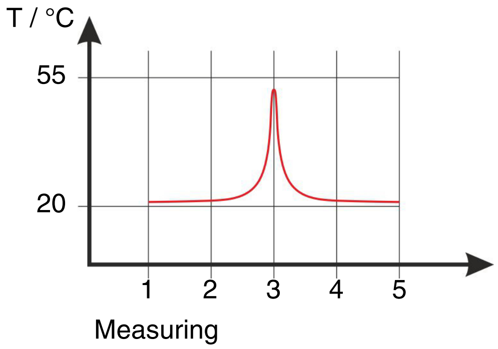


Fig. 5.14 Schematic representation of the temperature distribution

Learning objective XI

Obstruction of heat transfer with plate distances that are too close.

The heat exchange perpendicular to the plate occurs through heat conduction. If this heat transfer is not prevented, there must be a sufficient gap from the surface. In the case of several parallel plates (e.g. heat sink fins) this gap is important.

The flow velocity has an effect on this gap. The entire heat transfer from the plate to the air takes place within the heated layer. This thickness is the thermal boundary layer. The thermal boundary layer starts with the flow to the plate.

If the diffusion of the thermal boundary layer is disturbed, the heat transfer to the air is obstructed.

From these conclusions it follows that there is a minimum distance in the case of cooling fins arranged in parallel. This distance depends on the flow velocity and the temperature difference between the heater surface and the fluid.

The fluid and the structural size also have an effect.

Learning objective XII

Formation of the temperature profile along the plate

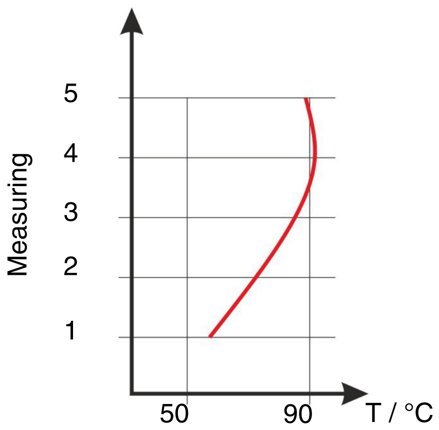


Fig. 5.15 Schematic representation of the temperature distribution

The plate cools in the lower section more than in the upper section.

The heat transfer in the lower section is better. This can be explained by the incident flow with ambient temperature. The air passes over the plate and absorbs heat by heating up itself. Due to the air heating up, the temperature difference at the top of the plate is less, the thermal boundary layer grows and the heat transfer decreases.

Both upper measured values are close together, although with slightly cooler temperature at the plate end.

During the entire measurement error influences due to effects as listed in Chapter 4.9, Page 63 should not be forgotten.

Fig. 5.16 Measuring across the flow. White blobs of thermal paste can be seen on the plate

NOTICE

Measuring the outflowing temperature field as in the figure on the left leads to lower temperatures because the handheld temperature sensor measures across the thermal boundary layer and thereby records an average temperature. This type of measurement is less accurate.

5.5 Experiment 5: Forced convection Influence of flow velocity

5.5.1 Learning objective

XIII. The student can describe the measurement results of the experiment.

XIV. The student can explain why the heat transfer improves.

5.5.2 Conducting the experiment

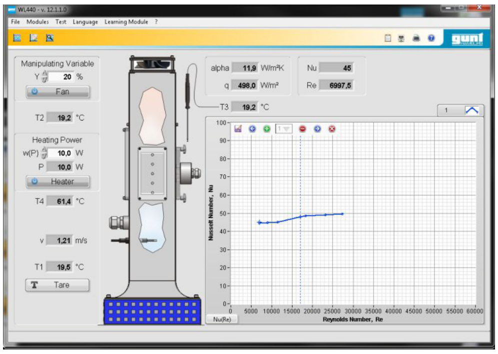


Fig. 5.17 Experiment screen

1. Start the device and software.
2. Attach the "Plate" heater insert to the device, see Chapter 3.7.2, Page 25.
3. Pull the turbulence generator out of the flow.
4. If necessary, tare the measurements, see Chapter 3.7.3, Page 28.
5. Set the fan to 10%.
6. In the "Modules" menu, open "Chart recorder".
7. Supply 15W to the heater insert.
8. Once the measured values in the graph of the chart recorder have stopped fluctuating (see Chapter 3.7.4, Page 29), record the measuring point.
9. Increase fan power (e.g. in 10% increments)
10. Repeat steps 8 and 9.
    Six measuring points are often sufficient for a meaningful illustration.
11. Save the measured values.
    Save/print the chart using the print function as required.

5.5.3 Measured values

Power P_{el} [W]	T_1 [°C]	T_4 [°C]	α [W/m²K]	*v* [m/s]	Re	*Nu*
15	17,3	82,1	11,6	0,38	2032	44
14,9	17,2	78	12,3	0,56	3112	47
15	17,2	72,7	13,5	0,81	4568	51
15	17,1	65,8	15,5	1,28	7361	59
15	17,6	57,1	18,9	2,1	12362	72
15	17,1	49,9	22,9	2,99	18003	88
15,1	17,3	44,7	27,5	3,92	24001	105
14,9	17,1	38,5	34,9	5,49	34245	133
15	17,2	36,2	39,7	6,21	38977	151
15	17,1	34,9	42,2	7,06	44417	161

Tab. 5.5 Measured values from experiment 5

5.5.4 Analysis of the experiment

Learning objective XIII

Description of the measurement results

The heat transfer improves with increasing velocity. This can be recognised by the increase of the heat transfer coefficient α and the Nusselt number *Nu*. In the chart the Nusselt number *Nu* is plotted over the Reynolds number *Re*. A nearly perfect straight line can be seen in the chart.

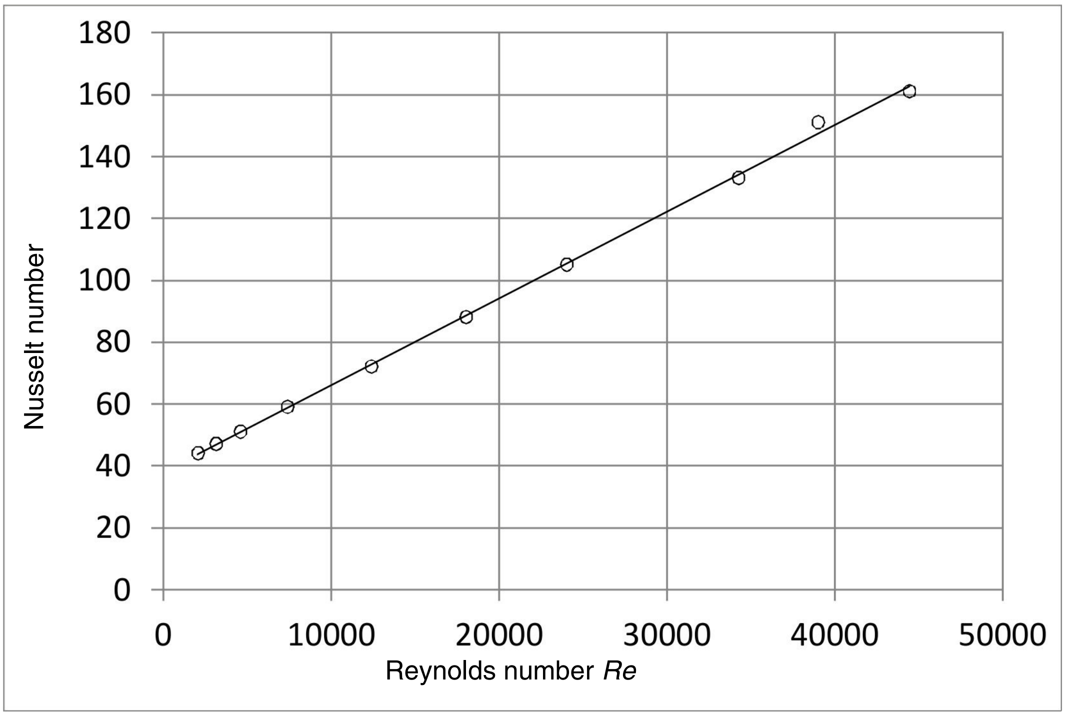


Fig. 5.18 Measured values of *Nu* and *Re* from experiment 4

Learning objective XIV

Improvement of the heat transfer

The heat transfer increases with the Reynolds number. The increased flow velocity allows a better removal of the heat. The thermal boundary layer becomes thinner, the temperature gradient increases. The temperature difference between the heater surface and the air is smaller, the heat transfer coefficient α and the Nusselt number *Nu* rise.

5.6 Experiment 6: Forced convection Disturbed incident flow at the plate

5.6.1 Learning objective

XV. The student can describe what happens with the measured values in the disturbed incident flow comparison to the undisturbed incident flow.

XVI. The student can explain the cause of these differences.

5.6.2 Conducting the experiment

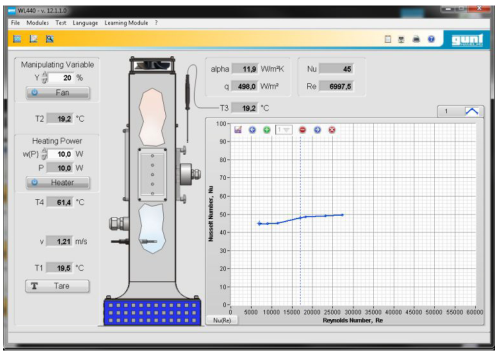


Fig. 5.19 Experiment screen

1. Start the device and software.
2. Attach the "Plate" heater insert to the device, see Chapter 3.7.2, Page 25.
3. Slide the turbulence generator into the flow.
4. If necessary, tare the measurements, see Chapter 3.7.3, Page 28.
5. Set the fan power as in experiment 1 (20%).
6. In the "Modules" menu, open "Chart recorder".
7. Set the heating power as in experiment 1 (5/10/15/20W).
8. Once the measured values in the graph of the chart recorder have stopped fluctuating (see Chapter 3.7.4, Page 29), record the measuring point.
9. Save the measured values.
   Save/print the chart using the print function as required.

5.6.3 Measured values

Power P_{el} [W]	T_1 [°C]	T_2 [°C]	T_4 [°C]	α [W/m²K]	v [m/s]	$\dot{q}$ [W/m²]	Nu
5	20,5	20,8	20,2	17,5	1,23	17,5	67
10	20,6	21,1	48,5	17,9	1,23	499,2	68
15	21,1	21,9	62,7	18	1,25	749,5	69
20	21,6	22,6	75,9	18,4	1,28	1000	70

Tab. 5.6 Measured values from experiment 6

5.6.4 Analysis of the experiment

Learning objective XV

Description of the results

The experiment provides results that represent an improvement in the heat transfer compared to the experiment without turbulence generator.

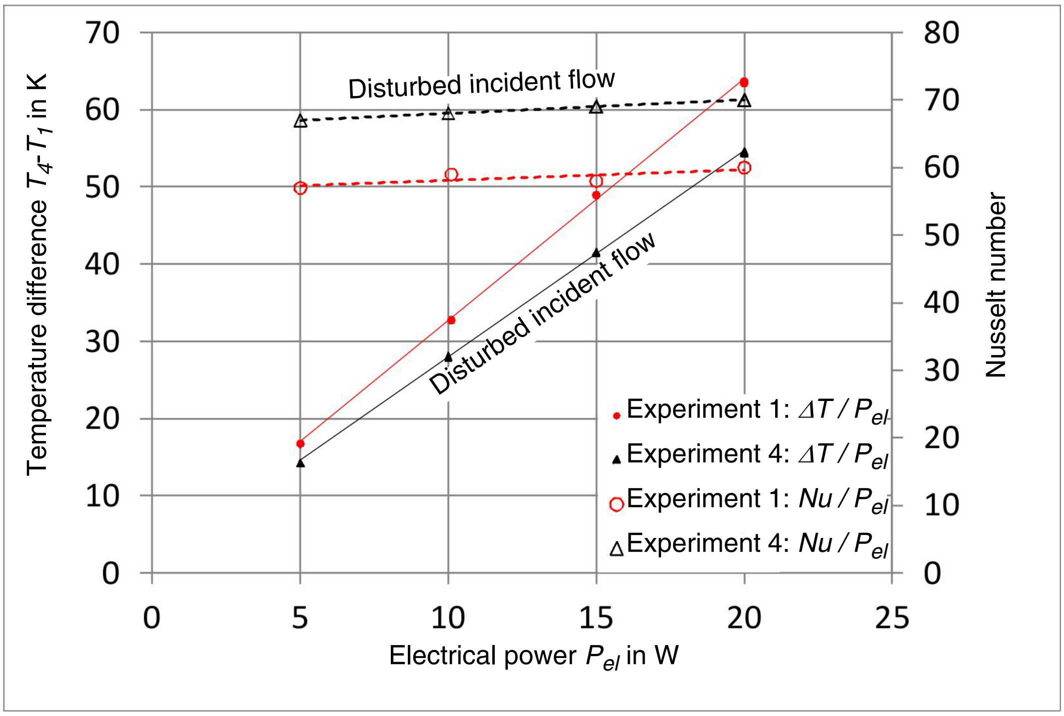


Fig. 5.20 Comparison of the heat transfer at the flat plate with undisturbed and disturbed incident flow.

Learning objective XVI

Representation of the results

The heat transfer is improved by a better removal of the heat. Downstream of the turbulence generator, the flow is turbulent. Vortices form whose axis is parallel to the axis of the turbulence generator.

Due to the vortices, flow movements occur perpendicular to the plate surface. These improve the heat transfer, because the removal is improved compared to heat conduction from fluid layer to fluid layer, see Chapter 4.7.2, Page 48.

5.7 Experiment 7: Forced convection Transient behaviour

5.7.1 Learning objective

XVII. The student can use a heating curve to explain what happens at the beginning.

XVIII. The student can also explain the causes of the main differences to the subsequent steady state.

XIX. The student can calculate the measurement at any given time *t*.

5.7.2 Conducting the experiment

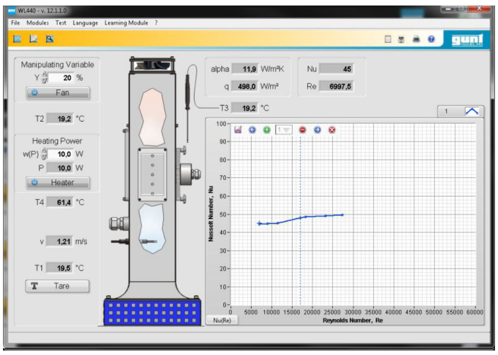


Fig. 5.21 Experiment screen

1. Start the device and software.
2. Attach the "Plate" heater insert to the device, see Chapter 3.7.2, Page 25.
3. Pull the turbulence generator out of the flow.
4. If necessary, tare the measurements, see Chapter 3.7.3, Page 28.
5. Set the fan power, e.g. 10-30% (experiment analysed here: 20%)
6. In the "Modules" menu, open "Chart recorder".
7. Start continuous measurement.
8. After a moment, supply power to the heater insert. (This analysis: 15 W)
9. Once the measured values in the graph of the chart recorder have stopped fluctuating (see Chapter 3.7.4, Page 29), the continuous measurement can be stopped.
10. Open the measurement with the Data Viewer and save it. If necessary, save/print the chart with the print function, after the relevant area has been brought into view.

5.7.3 Measured values

The values are shown in Excel® due to the subsequent processing. The temperature rise over time shows the following curve:

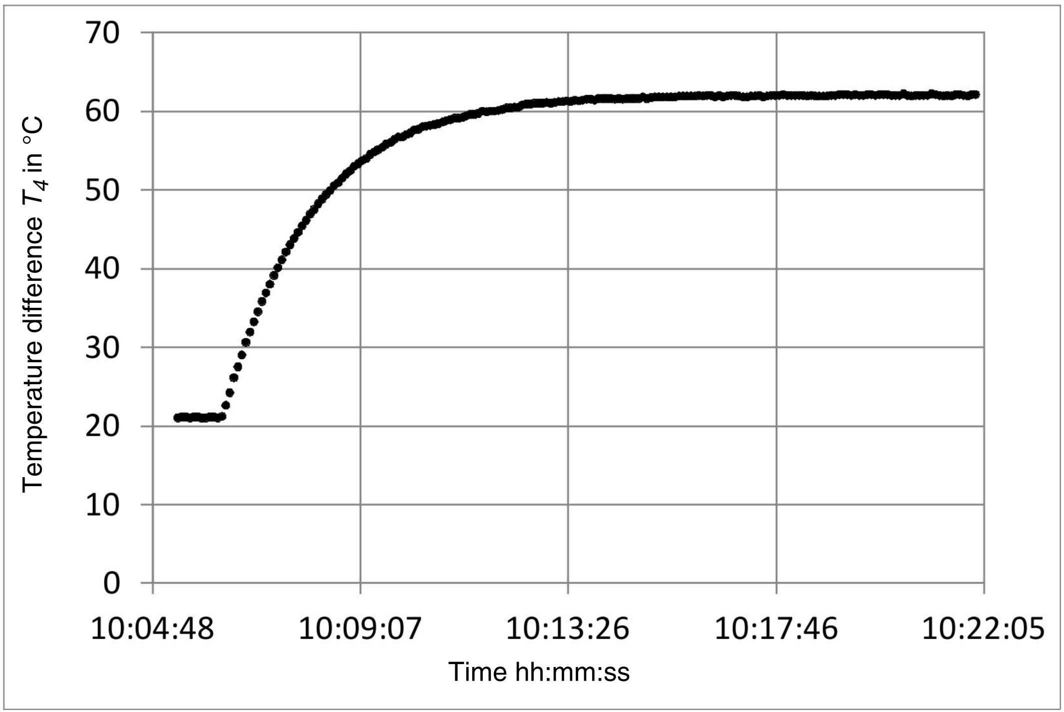


Fig. 5.22 Measured values when heating the plate at P_{eF}=14,9W and v=1,25m/s

Differences in the representation of time can occur due to different format settings. Deviations may occur due to manufacturing tolerances.

Further **important data** of the measurement can be extracted **at the end of the file** once the **final value** has settled in. In the experiment shown here, this is the **heat transfer coefficient** α of 18,2 W/m²K.

For the calculation, the **temperature jump** K = 41°C and the **start temperature** T_1 of 21,2°C must be noted.

5.7.4 Analysis of the experiment

Learning objective XVII

Processes at the start of the experiment

The temperature at the measuring point increases most quickly at the beginning. Due to the small temperature difference, the heat flux that is transferred to the air still very low. The heating power used mainly heats the heater at the beginning.

Learning objective XVIII

Processes upon reaching the steady final value

Towards the end of the experiment the heater reaches the steady final temperature. The electrical power is converted into heat and is transferred directly to heating the air.

Learning objective XIX

Calculating the heating curve

In order to start the analysis, the time axis must be shown in seconds. This can be converted in Excel® using the function below:

"=Hour(cell reference)*3600+Minute(cell reference)*60+Second(cell reference)" (5.18)

The transient temperature curve can be calculated with Formula (4.18), Page 59:

$$T_H(t) = T_{amb} + K \cdot \left(1 - e^{\left(-\frac{t}{\tau}\right)}\right) \tag{5.19}$$

$T_H(t)$ = Temperature of the body at time t
K = Total temperature jump
T_{amb} = Ambient temperature
t = Time
τ = Time constant

For the calculation, the time constant τ is needed, Formula (4.12), Page 56:

$$\tau = \frac{m \cdot c}{\alpha \cdot A_s} = R \cdot c \cdot m \tag{5.20}$$

The time constant can be calculated from the measured values and the technical data for the heater from the appendix, Chapter 6, Page 121:

$$\tau = \frac{m \cdot c}{\alpha \cdot A_s} = R \cdot c \cdot m \tag{5.21}$$

$$\tau = \frac{0{,}08\,\mathrm{kg} \cdot 480\,\frac{\mathrm{J}}{\mathrm{kg} \cdot \mathrm{K}}}{18{,}2\,\frac{\mathrm{W}}{\mathrm{m}^2 \cdot \mathrm{K}} \cdot 2 \cdot (0{,}1\,\mathrm{m})^2} = 105{,}5\,\mathrm{s} \tag{5.22}$$

Furthermore, the temperature jump from the measurement is K=41°C.

With Formula (5.19) and the starting temperature, we can now calculate the temperature at time t:

$$T(t) = T_1 + K \cdot \left(1 - e^{\left(\frac{-t}{\tau}\right)}\right) \tag{5.23}$$

For the calculation, an offset must be applied to the time axis so that the electrical power is inserted at the "zero" time point. The calculation gives the following curve, here in comparison to the measurement:

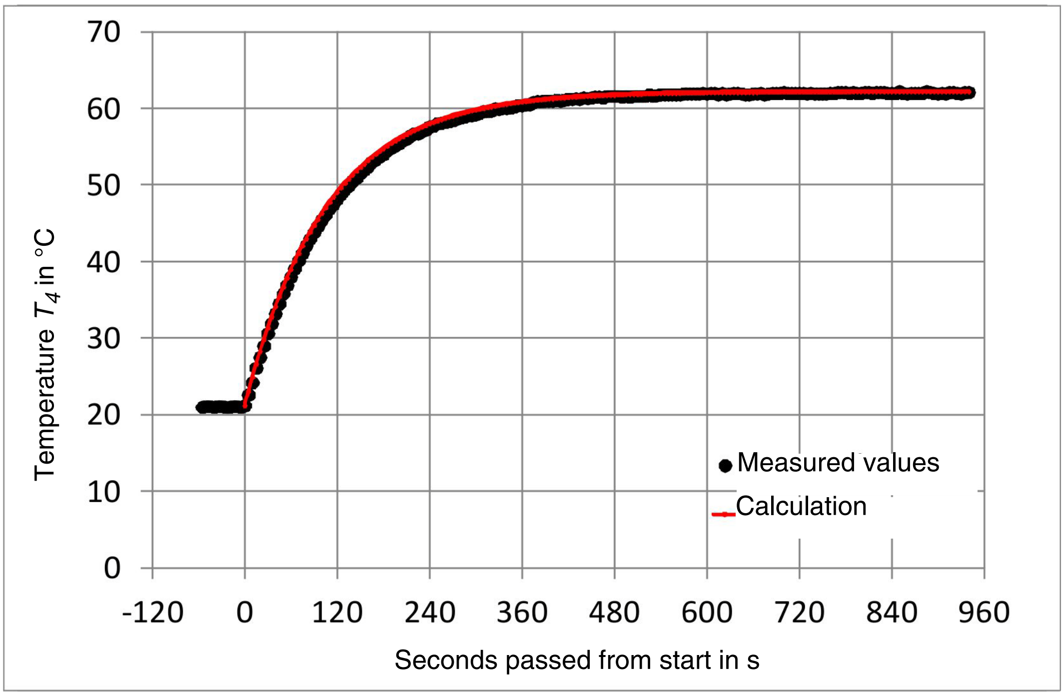


Fig. 5.23 Comparison of measured values to calculated values for experiment 5

The calculation result of the experiment coincides remarkably well. In the calculation of the time constants, only values for the glued plates were used. The thermal values of the heating film and the glue were not taken into account. Omitting this heat storage means a deviation should be expected, in which the calculation shows a slightly shorted heating time compared to the measured values.

5.7.5 Option for more in-depth investigation

Learning objective:

The cooling curve is studied in the same way as the experiment.

or

Learning objective:

The student is able to calculate in advance the heating curve at any heat transfer coefficient α for plate or cylinder.

The subsequent experiment confirms the prediction or is used to discuss deviations.

or:

Learning objective:

The time constant is determined from the experiment. Using the structural data of the heater, the heat transfer coefficient is calculated and deviations discussed.

5.8 Experiment 8: Forced convection Heat transfer on the cylinder

5.8.1 Learning objective

XX. The student can calculate the following variables from the measured values:
  a) Heat flux at the air
  b) Heat transfer coefficient
  c) Thermal resistance
  d) Heating surface load
  e) Nusselt number

XXI. The student compares the values with the results which were obtained with the plate. The student provides explanations for any deviations.

5.8.2 Conducting the experiment

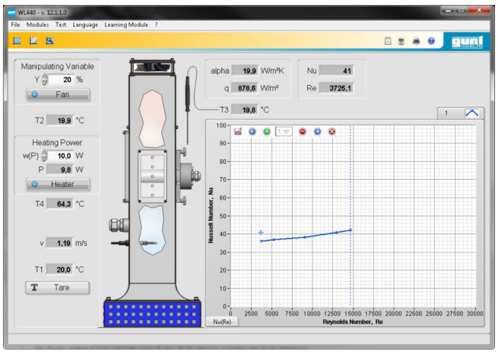


Fig. 5.24 Experiment screen

1. Start the device and software.
2. Attach the "Cylinder" heater insert to the device, see Chapter 3.7.2, Page 25.
3. Pull the turbulence generator out of the flow.
4. If necessary, tare the measurements, see Chapter 3.7.3, Page 28.
5. Set the fan power from experiment 1 (20%).
6. In the "Modules" menu, open "Chart recorder".
7. Set the heating power as in experiment 1 (5; 10; 15; 20 W).
8. Once the measured values in the graph of the chart recorder have stopped fluctuating (see Chapter 3.7.4, Page 29), record the measuring point.

9. Save the measured values.
   Save/print the chart using the print function as required.

5.8.3 Measured values

Power P_{el} [W]	T_1 [°C]	T_2 [°C]	T_4 [°C]	α [W/m²K]	v [m/s]	$\dot{q}$ [W/m²]	Nu
4,9	20,3	20,3	35,9	28,2	1,3	439,9	58
9,9	21,9	22,1	50,8	30,7	1,31	885	64
14,9	21,3	21,8	63,4	31,6	1,33	1328,9	65
17,1	19,5	20,4	67,2	32,1	1,31	1527,2	66

Tab. 5.7 Measured values from experiment 8

The line highlighted grey was calculated according to the learning objectives.

5.8.4 Analysis of the experiment

Learning objective XX

Re-calculating heat transfer variables

The calculated values are re-calculated in the same way as the calculations in experiment 1, see: Chapter 5.3.4, Page 83.

Learning objective XX a-e)

Calculated values at the cylinder

The **heat flux** $\dot{Q}$ to be measured by the heating of the air is:

$$\dot{Q} = 11{,}4\ \text{W}$$

The deviation to the electrical power P_{el} of 14,9 W can be explained by the measurement uncertainty caused by the temperature field above the heater (learning objective X, Chapter 5.4, Page 87).

The **heat transfer coefficient** α.

$$\alpha = 32{,}2\ \text{W/m}^2\text{K}$$

The deviation to the software value of 31,6 W/m²K is caused by rounding of measured values.

The **heating surface load** $\dot{q}$.

$$\dot{q} = 1355{,}1\ \text{W/m}^2$$

The deviation to the software value of 1328,9 W/m² is caused by rounding of measured values.

The **thermal resistance** ***R***.

$$R = 2{,}8\ \text{K/W}$$

The **Nusselt number** ***Nu***.

$$Nu = 68$$

Small deviations can be attributed to the rounding of values.

Learning objective XXI

Comparison of cylinder and plate

	Plate	Cylinder
Heat flux $\dot{Q}$ **in W**	15	14,9
Heat transfer coefficient α **in W/(m²K)**	15,3	31,6
Heating surface load $\dot{q}$ **in W/m²**	747,6	1328,9
Thermal resistance ***R*** **in K/W**	3,3	2,8
Nusselt number Nu	58	65

Tab. 5.8 Comparison of the values from experiment 3 and 8, forced convection

Heat transfer coefficient α.
At the same electrical power, halving the surface means the product of temperature difference and heat transfer coefficient must be doubled, see Formula (4.3), Page 39.

The value is higher compared to the plate (α = 15,3 W/m²K). This is due to the flow around the cylinder. With the plate the flow is next to the surface. The heat is removed perpendicularly to the surface by heat conduction.

With the cylinder there is a flow separation at the outflow side, see Chapter 4.7.2, Page 48. Consequently the heat removal to the fluid is better and the heat transfer coefficient rises.

Heating surface load $\dot{q}$.
In terms of structure, half the surface is available compared to the plate. When specifying the same electrical power, we get around half the heating surface load.

The **thermal resistance *R***.
The thermal resistance drops compared to the plate. This is due to the better heat dissipation due to flow formation.

The **Nusselt number *Nu***.
The Nusselt number compares the heat transfer properties. The cylinder has a higher value than the plate due to the better heat dissipation. In previous comparisons the relation to the surface area or to temperature differences was always give. The comparison with the Nusselt number is independent of these.

5.8.5 Possible further experiments

The cylinder can be studied in the same way as the plate.

- The temperature distribution, see Chapter 5.4, Page 87
- The heat transfer depending on the flow velocity, see Chapter 5.5, Page 92
- Disturbed incident flow of the cylinder, see Chapter 5.6, Page 95
- Transient behaviour of the cylinder, see Chapter 5.7, Page 98

5.9 Experiment 9: Forced convection
Heat transfer on the cylinder with circumferential measurement

5.9.1 Learning objective

XXII. The student can explain how the Nusselt number behaves on the cylinder.

XXIII. The student explains that the calculation of alpha is possible due to the even heating surface load of the heated foil.

XXIV. The student can explain the different temperature distribution on the heat dissipation through different flow formation.

5.9.2 Conducting the experiment

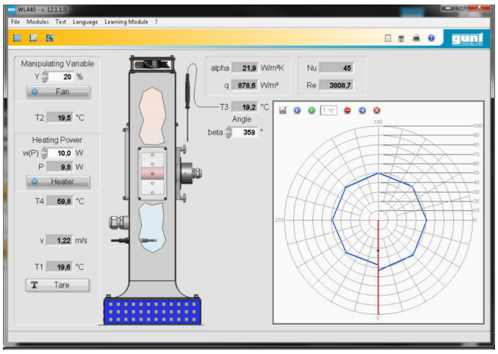


Fig. 5.25 Experiment screen

1. Start the device and software.
2. Attach the "Cylinder with circumferential measurement" heater insert to the device, see Chapter 3.7.2, Page 25.
3. Pull the turbulence generator out of the flow.
4. If necessary, tare the measurements, see Chapter 3.7.3, Page 28.
5. Set the fan power to any level. (In the analysis below, 80% gives Re ~ 20000).
6. In the "Modules" menu, open "Chart recorder".
7. Set heating power.
   (Value of the following analysis: 25 W)
8. Enter the position of the measuring point in the input screen.
9. Once the measured values in the graph of the chart recorder have stopped fluctuating (see

Chapter 3.7.4, Page 29), record the measuring point.

10. Rotate the position of the measuring point by a few degrees and repeat steps 8 and 9
(we recommend at least 5 measuring points)

11. Save the measured values.
Save/print the chart using the print function as required.

5.9.3 Measured values

Power P_{el} [W]	T_1 [°C]	T_4 [°C]	α [W/m²K]	v [m/s]	Re [-]	Nu [-]	β [°]
25	18,2	47,5	76,5	6,32	20695	158	0
25	18,4	48,5	74,3	6,25	20399	154	15
25	18,2	50	70,2	6,22	20281	145	30
25	18,2	53,3	63,5	6,28	20221	131	45
24,8	18,2	61,5	43,2	6,24	19656	106	60
24,9	18,1	67,8	44,8	6,25	19286	93	75
25	18,3	74,2	40	6,27	19023	83	90
25	17,8	75,3	38,8	6,25	19018	80	105
25	18,2	77,7	37,6	6,22	18783	78	110
25	18,2	77,9	37,4	6,27	18801	77	115
25	17,9	76,6	38,1	6,31	19093	79	120
25	18,1	70,3	42,9	6,29	19117	89	135
25	18,1	65,3	47,4	6,28	19452	98	150
25	18,2	62,7	50,2	6,38	19999	104	165
25	18	63	49,7	6,25	19614	103	180

Tab. 5.9 Measured values from experiment /

5.9.4 Analysis of the experiment

Learning objective XXII

Profile of the convective heat transfer at the cylinder

The experiment shows the convective heat transfer at the cylinder depending on the angle. The Nusselt number in the polar diagram looks as follows:

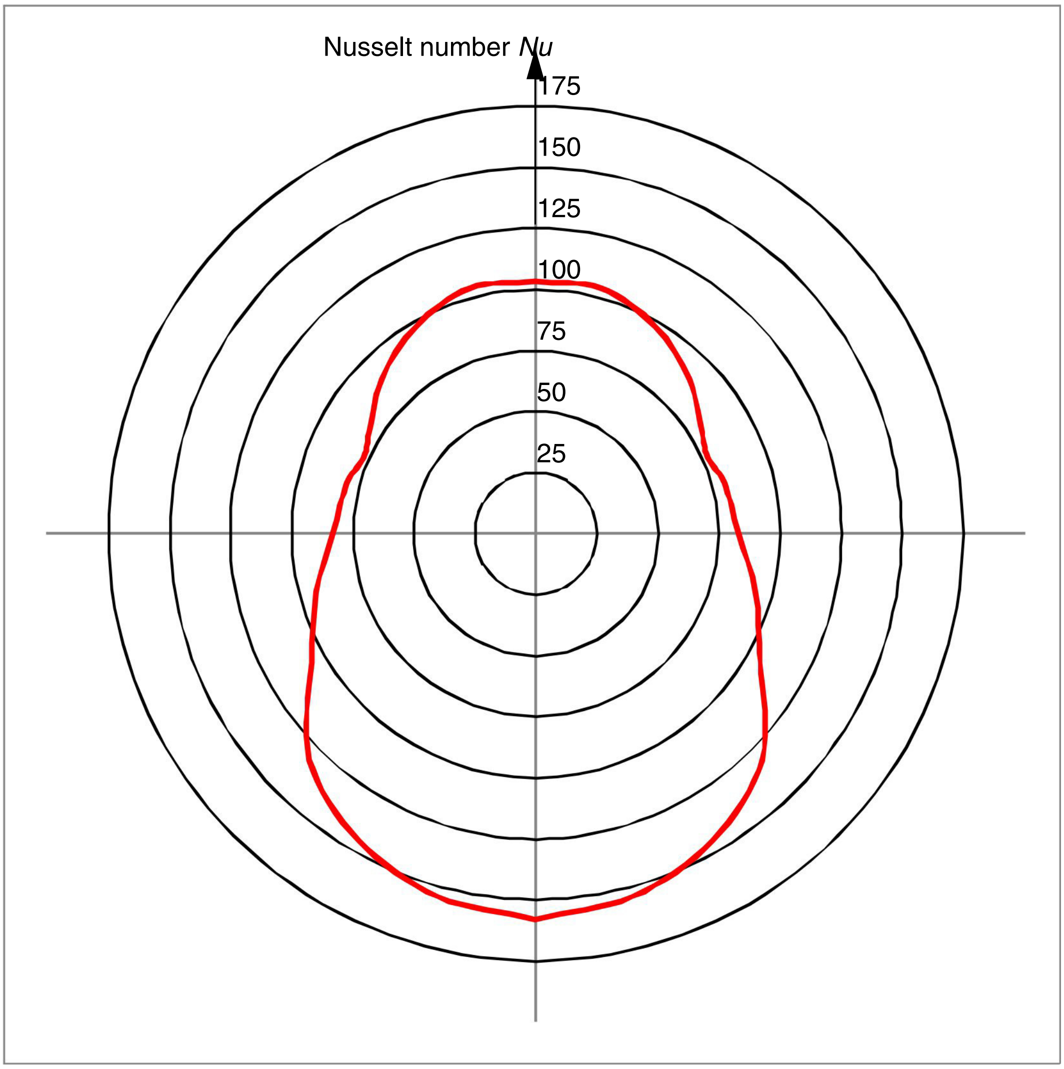


Fig. 5.26 Polar diagram of the Nusselt number from experiment

It is visibly largest in the area of the cylinder subject to flow. The values decrease slightly at the sides and drop to a minimum shortly after. Then the values rise again, but are not as large as achieved during incident flow.

Learning objective XXIII

Performing the measurement

In the calculation it is assumed that the heat heating surface load is constant. On this basis, the heat is dissipated evenly over the entire circumference. Since the Teflon cylinder conducts heat very poorly, it is dissipated to the environment directly at the surface of the heating foil. Heat fluxes through the cylinder can be ignored.

Learning objective XXIV

Explaining the different heat dissipation

There are various flow formations on the cylinder subject to surrounding flow. These dissipate the heat to different extents. The best heat dissipation is at the coolest place, incident flow at 0°. Here the heat is dissipated with the fresh air. The air flow is split in both directions. The laminar boundary layer is next to the surface and heats up. As a result, the temperature difference becomes smaller in the direction of flow. The equalisation effort to dissipate heat is therefore lower.

At the side away from the direction of flow, the flow separates. Turbulence occurs here, which promotes heat dissipation. However, the values do not reach the same levels as for incident flow.

The end points of the flow separation are at the points of the smallest heat dissipation. Here vortices separate, the flow briefly stops at these points and consequently does not remove the heat as well.

5.9.5 Option for more in-depth investigation:

Learning objective:

Convective heat transfer at different flow velocities

5.10 Experiment 10: Forced convection Convective heat transfer at the tube bundle

5.10.1 Learning objective

XXV. The student can explain why the heat transfer behaves as it does in the experiment for the different rows.

5.10.2 Conducting the experiment

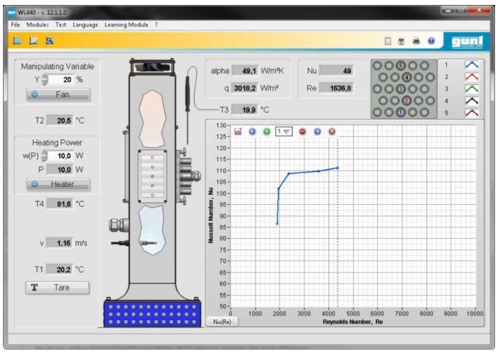


Fig. 5.27 Experiment screen

1. Start the device and software.
2. Attach the "Tube bundle" heater insert to the device, see Chapter 3.7.2, Page 25.
3. Insert the heated rod into the bottom row (row 1).
4. Pull the turbulence generator out of the flow.
5. If necessary, tare the measurements, see Chapter 3.7.3, Page 28.
6. Set the fan power, e.g. 20%.
   (The analysis took place at 20%-80%).
7. In the "Modules" menu, open "Chart recorder".
8. Supply power to the heater insert.
   (The analysis took place at 12W and 11,5W)
9. Once the measured values in the graph of the chart recorder have stopped fluctuating (see Chapter 3.7.4, Page 29), record the measuring point. Ensure the rows are assigned correctly.
10. Increase the fan power.
11. Repeat steps 8 and 9.
    We recommend at least 4 fan power levels.
12. Insert the heated rod into the next row and repeat the measurement from step 6.

13. Save the measured values.
14. Save/print the chart using the print function as required.

5.10.3 Measured values

Power P_{el} [W]	T_1 [°C]	T_2 [°C]	T_4 [°C]	α [W/m²K]	v [m/s]	Re	*Nu*
Row 1							
11,5	25,9	26,4	89,5	54,7	1,25	1264	38
11,4	25,9	26,2	75,0	70,5	2,65	2789	50
11,4	25,9	26,1	67,1	84,2	3,9	4215	60
11,4	25,8	25,9	61,2	97,8	5,19	5763	71
11,4	25,7	25,8	57,8	108,1	6,62	7414	79
Row 2							
12	25,8	26,2	85,5	60,8	1,24	1309	43
12	25,5	25,7	69,9	82,3	2,63	2921	59
12	25,2	25,4	60,9	101,5	3,94	4431	74
12	25,3	25,4	56,2	117,2	5,3	5990	85
12	25,3	25,4	52,9	131,6	6,68	7505	96
Row 3							
12	25,7	26,2	82,2	64,2	1,23	1321	45
12	25,5	25,8	65,5	90,7	2,65	2888	65
12	25,6	25,7	57,4	113,7	3,88	4291	83
12	25,6	25,7	52,6	134,7	5,22	5978	99
12	25,3	25,4	49,2	152,1	6,56	7607	112
Row 4							
12	25,7	26,1	80,1	66,6	1,19	1287	47
11,9	25,4	25,6	64,2	93,1	2,56	2911	67
12	25,3	25,4	57,5	112,7	4,03	4486	82
12	25,2	25,4	52,6	132,5	5,21	6018	97
12	25,2	25,3	49,4	149,9	6,46	7375	110
Row 5							
12	25,8	26,2	82,1	64,5	1,24	1300	45
12	25,6	25,8	67,2	87,1	2,64	2874	63
12	25,4	25,6	59,2	107,4	3,82	4316	78
12	25,3	25,5	53,9	127,2	5,2	5961	93
12	25,3	25,4	50,3	145,1	6,51	7413	107

Tab. 5.10 Measured values from experiment 10

5.10.4 Analysis of the experiment

Learning objective XXV

Comparison of the values for different rows

The heat transfer increases in the first three rows. At the fourth and fifth row, no improvement can be noticed. The curves are clearly visible in the chart:

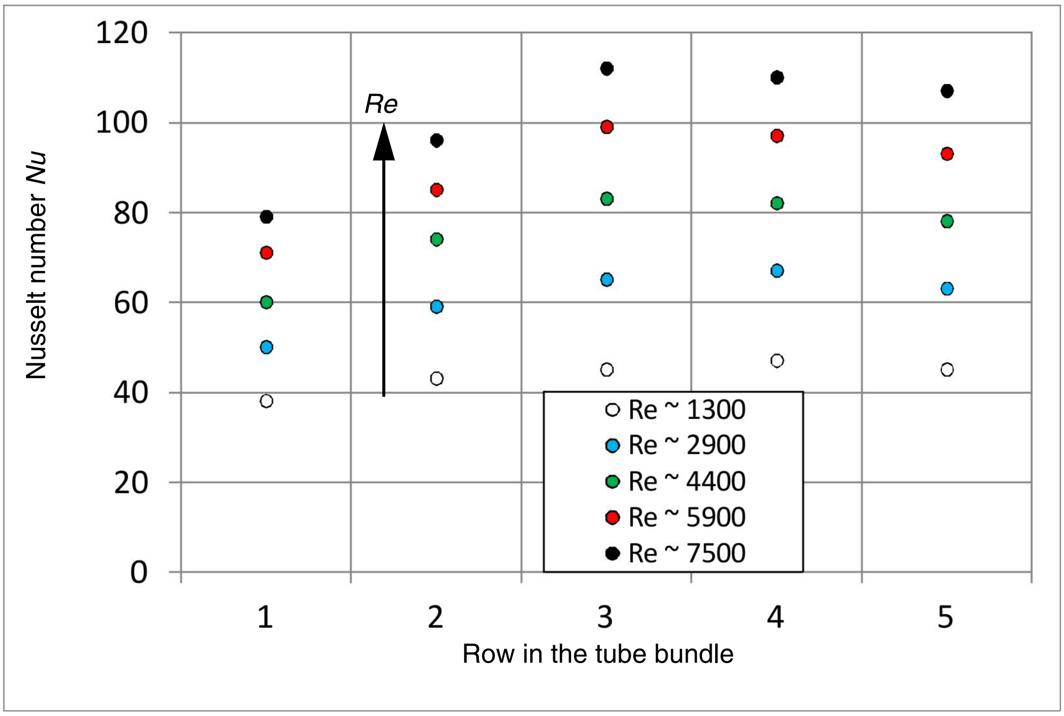


Fig. 5.28 Chart *Nu* over *Re* of the measurement

The increasing at the beginning is due to the increasing turbulence caused by the first two rows of tubes.

Flow passes through row 1 undisturbed. Flow through row 2 passes through the voids of row 1. Row 2 is not yet in the vortices of an outflow. This is only the case from row 3. The Nusselt numbers of rows 1 and 2 are therefore lower than for row 3. Row 4 is comparable to that of the flow around row 3. The results are close together.

At the last row, row 5, another outflow is present because the flow is not forcibly deflected.

There is always a correlation between the formation of surrounding flow and the heat transfer.

For completeness, the chart from Fig. 5.28, Page 118 in the illustration of the Nusselt number over the Reynolds number:

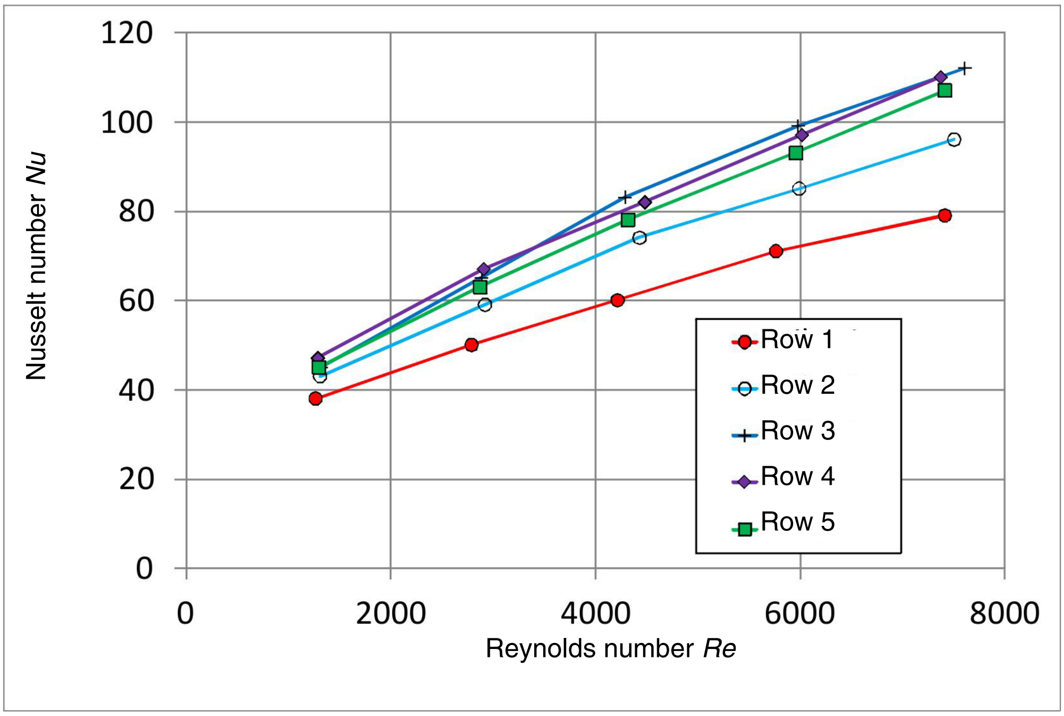


Fig. 5.29 Chart *Nu* over *Re* of the measurement

6 Appendix

6.1 Technical data

Dimensions

Length x Width x Height	780 x 350 x 880 mm
Weight	approx. 24.8 kg

Air duct

Flow cross-section	120 x 120 mm

Power supply

Voltage	230 V
Frequency	50 Hz
Phases	1
Nominal consumption (output):	approx. 190 W
2 x microfuse, each	1A at 230 V
Alternatives optional, see rating plate	

Noise

	up to >80 dB(A)

Heater data

Plate (stainless steel):

Thickness of a plate:	0,0005 m
Heat-dissipating length x width:	0,1 x 0,1 m
	= 2 x 0,01 m^2
Mass of both plates:	0,08 kg
Specific heat capacity of stainless steel:	480 J/kg K

Cylinder:

Heat-dissipating length:	0,101 m
Diameter:	0,035 m
	= 0,0112 m²
Characteristic length:	π/2 x 0,035 m = 0,055 m
Mass of the aluminium cylinder without heater:	0,2 kg
Specific heat capacity of aluminium:	890 J/kg K

Tube bundle:

Diameter of the heater:	10 mm
Heat-dissipating length:	100 mm
	= 0,001 m²

Void fraction ψ:

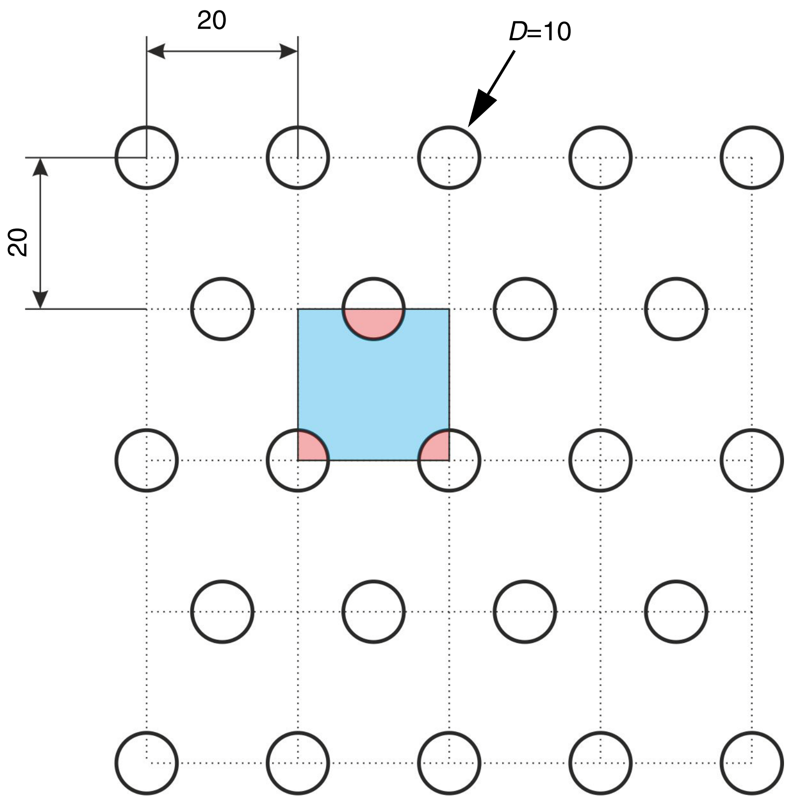


Fig. 6.1 Diagram for calculating the void fraction

Calculating void fraction:

$$\psi = \frac{V_{free}}{V} = \frac{(20 \cdot 20)\text{mm}^2 - \left(\frac{\pi}{4} \cdot (10\text{mm})^2\right)}{(20 \cdot 20)\text{mm}^2} = 0{,}804$$

Heating foil of cylinder for circumferential measurement and plate:

Electrical power consumption max. 40 W

Heater of cylinder and tube bundle:

Electrical power consumption max. 20 W

To be provided by customer:

Measurement computer with minimum requirements for:

Measurement data acquisition:

Software environment:

LabVIEW Runtime

System requirements:

PC with Pentium IV processor, 1 GHz

Minimum 2048 MB RAM

Minimum 1 GB free hard disk space

1 CD-ROM drive

1 USB port

Graphic card resolution min. 1024 x 768 pixels, True Color

Windows Vista / Windows 7 / Windows 8

Accessories supplied:

WL 440 device with instruction manual

Rubber connector

USB cable

4 different heater inserts

6.2 Physical properties of dry air at 1 bar

T in °C	ρ in $\frac{kg}{m^3}$	*c* in $\frac{kJ}{Kg \cdot K}$	λ in $\frac{W}{K \cdot m}$	η in $10^{-6} \cdot \frac{kg}{m \cdot s}$	ν in $10^{-6} \cdot \frac{m^2}{s}$	*a* in $10^{-6} \cdot \frac{m^2}{s}$	*Pr*
-20	1,3765	1,004	0,02301	16,15	11,73	16,6	0,71
0	1,2754	1,004	0,02454	17,10	13,41	19,1	0,70
20	1,1881	1,007	0,02603	17,98	15,13	21,8	0,70
40	1,1120	1,008	0,02749	18,81	16,92	24,5	0,69
60	1,0452	1,009	0,02894	19,73	18,88	27,4	0,69
80	0,9859	1,010	0,03038	20,73	21,02	30,5	0,69
100	0,9329	1,012	0,03181	21,60	23,15	33,7	0,69
120	0,8854	1,014	0,03323	22,43	25,33	37,0	0,68

Tab. 6.1 Physical properties of dry air at 1 bar

6.3 List of formula symbols and units

Formula symbols	Mathematical/physical variable	Value/unit
A	Area, cross-section	m²
a	Thermal diffusivity	m²/s
c	Specific thermal capacity	J/(kg K)
D	Diameter	m
dT	Temperature differential	°C / K
dt	Time differential	s
g	Gravitational acceleration	9,81 m/s²
K	Temperature jump	°C / K
L	Length	m
m	Mass	kg
$\dot{m}$	Mass flow	kg/s
Nu	Nusselt number, dimensionless heat transfer	-
P	Power	W
Q	Heat	J
$\dot{q}$	Heat flux density	W/m²
$\dot{Q}$	Heat flux	W
R	Thermal resistance /	K/W
Ra	Rayleigh number	
Re	Reynolds number, dimensionless speed	-
T	Temperature	K
t	Time	s
v	Flow velocity	m/s
w	Manipulating variable	here: %

Greek characters

Formula symbols	Mathematical/physical variable	Value/unit
α	Heat transfer coefficient	W/(m² K)
β	Angle	°
Δ	Difference	-
θ	Dimensionless temperature jump	-
λ	Thermal conductivity	W/m K
ν	Kinematic viscosity	m²/s
π	Pi	3,14
ρ	Density	kg/m³
τ	Time constant	s
Ψ	Void fraction	Here: 0,6073

Indices

Abbreviation	Meaning
1	Input
2	Outlet
amb	Ambient
el	Electrical
F	Fan
H	Heater
krit	Critical, denotes a transition point
s	Surface
t1	Start
t2	End
y	Void fraction