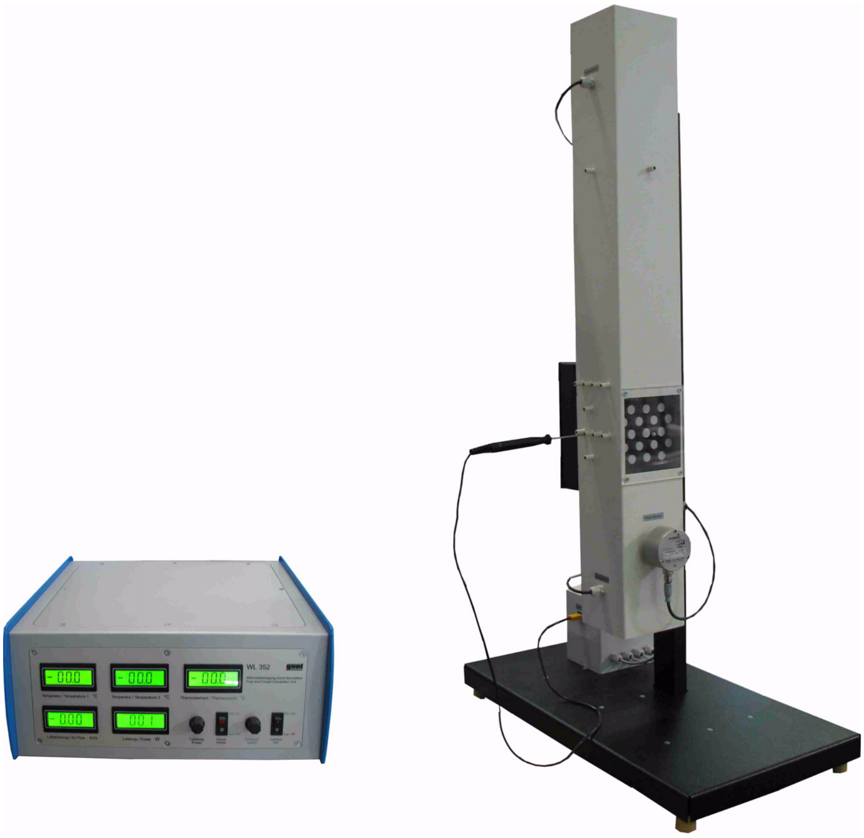
Experiment Instructions

WL 352 Free and Forced
Convection Unit



Experiment Instructions

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This manual must be kept by the unit.

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

Version 1.0

Table of Contents

1 Introduction

The field of heat transfer in industry and technology is a wide one. Machines that produce heat by converting energy are used in many fields. Whether this heat is dissipated as waste heat or re-used is not important in heat transfer. What is important here initially are the mechanisms that allow this form of energy to be transported. Convection is one of these mechanisms, alongside heat radiation and heat conduction. Convection can be differentiated from heat conduction by the flow of a fluid (gas, liquid). Thus the transport of particles results in heat transfer. Here we can differentiate between two types of convection. Firstly there is free convection, which gains its force by lift of the heated fluid (differences in density). Secondly there is forced convection, which uses technical means to force a flow. The Basic principles chapter goes into more details on the precise distinction between the mechanisms. Similarly, an insight is given into the calculation basis.

With the G.U.N.T. **WL 352 Free and Forced Convection Unit** you can conduct experiments to demonstrate a practical connection to the fundamentals of convection. Depending on the range of the subject matter you can cover levels from specialist technicians to students in the natural sciences.

The experiments focus on heat transfer in the variation of:

- Temperature difference
- Flow velocity
- Heat exchanger geometry

The students will therefore be able to learn about dependencies of heat transfer in an experiment and where necessary understand them with appropriate formulae. To this end, data acquisition with a PC provides a user-friendly interface to process recorded data further.

When reviewing the fundamentals and the supporting experiments, we have taken care to adhere to a didactically useful concept. Successful learning can be reviewed using the additional work sheets.

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 likelihood of occurrence and potential severity of injuries.

An additional symbol explains the type of danger or a command.

Signal word	Explanation
⚠ DANGER	Indicates a situation which, if not avoided, will lead to death or serious injury.
⚠ WARNING	Indicates a situation which, if not avoided, may lead to death or serious injury.
⚠ CAUTION	Indicates a situation which, if not avoided, may lead to light or moderate injury.
NOTICE	Indicates a situation which may lead to device damage or provides information on operating the device.

Symbol	Explanation
	Electric voltage
	Hot surface

Symbol	Explanation
	Wear gloves
	Notice

2.3 Safety instructions

⚠ WARNING

There is the possibility of electric shock when reaching into the open control and display unit.

- Disconnect the plug from the power supply before opening.
- All work must be performed by trained electricians only.
- Protect control and display unit against moisture.

⚠ WARNING

There is the possibility of electric shock when the heating elements' covers are open.

- Do not open the covers.

⚠ WARNING

There is a risk of burning if you come into contact with the housing and attachments.

Temperatures of around 120°C are reached.

- Do not touch housing during and after operation without wearing hand protection.
- Always wear heat-insulating gloves.
- Allow heating surfaces and inserts to cool before touching them.
- Leave the unit to cool before dismantling it.
- Do not leave the heated unit unattended.

⚠ WARNING

There is a risk of burning if you touch the star knob screws when installing/removing the heating elements.

- Leave the unit to cool before dismantling it.
- Always wear heat-insulating gloves.

⚠ WARNING

The heating inserts can burn.

- Leave heater inserts to cool before touching them.
- Always wear heat-insulating gloves.
- Label the dismantled heater insert with a warning sign using the same symbols as shown here.
- Do not leave the heated heater insert unattended.

NOTICE

Do not operate the fan in its lower range of adjustment, because even though there is voltage to the fan, the fan is stationary.

NOTICE

The fan and heating element connectors are fitted with identical plugs. The respective connector is marked on the reverse of the display and control unit. These two connectors may not be mixed up.

NOTICE

The speed sensor is extremely sensitive at the end of its probe and can easily be damaged.

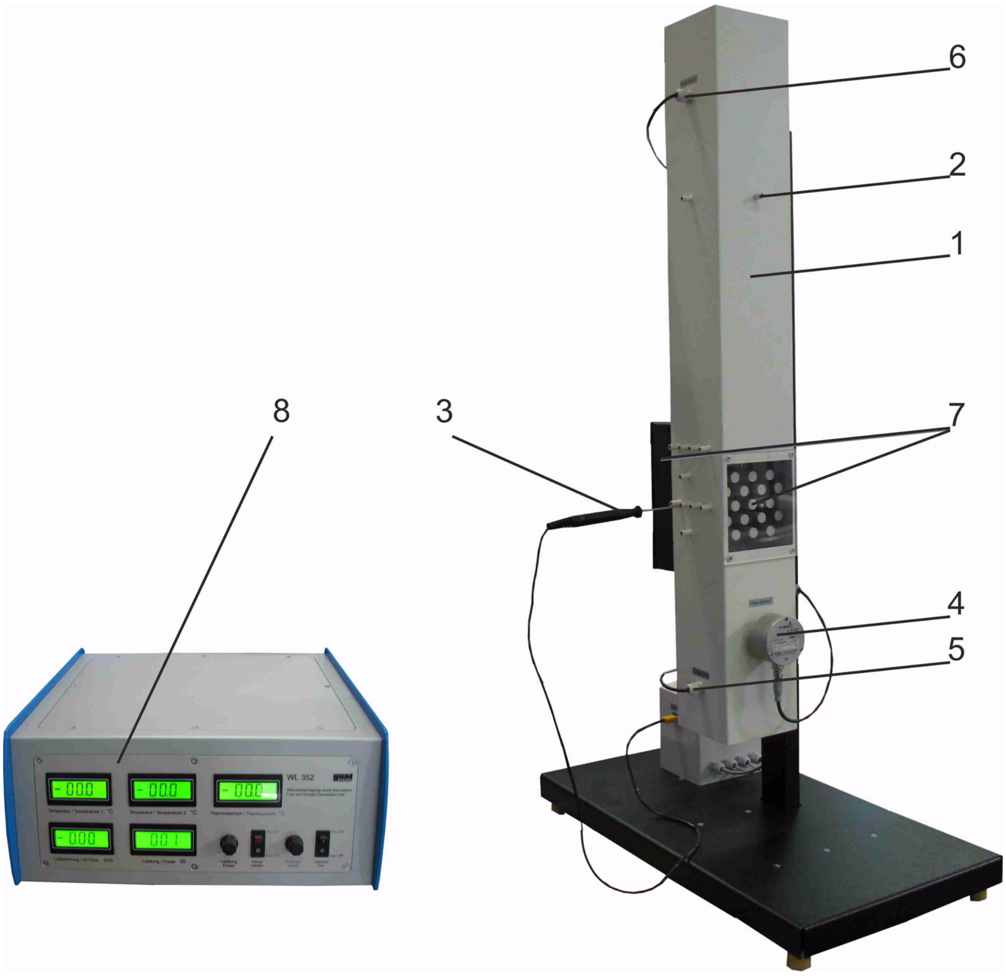
- Avoid contact.

NOTICE

When outputs are open (sensor or heating elements not connected) the digital display on the control and display unit will show incorrect values.

3 Device description

3.1 Device design



1	Air duct		6	Pt100 element for outlet temperature T_2
2	Measuring glands		7	Pipe bundle heater insert (fins & flat plate not shown)
3	Thermocouple, temperature T_3			
4	Flow sensor		8	Control and display unit
5	Pt100 element for inlet temperature T_1			

Fig. 3.1 Design of the WL 352 unit

- The **air duct** (1) with a flow cross-section of 120mm x 120mm and with a length of 1m is used to guide the flowing air.
- It has **measuring glands** (2), which allow it to detect the temperature at different points by inserting a **thermocouple** (3). In addition, a **flow sensor** (4) records the entry velocity of the air and each **Pt100 element** (5, 6) records the inlet and outlet temperatures.
- The **heater inserts** (7, fins and flat plate not shown) are inserted into the duct. They are attached with simple star knob screws. The different heat exchanger surfaces (flat plate, pipe bundle or fins) are each operated via four heating resistors with a maximum total output of approx. 170W. The applied voltage can be regulated so as to adjust the heating output. Bimetallic thermostats are used so that the temperature does not exceed a value of 120°C; these interrupt the current supply at a predefined limiting value. The current supply is switched back on at 105°C.
- The **control and display unit** (8) contains the power supply and control for the fan and the heater inserts. Furthermore, the unit displays the electrical output of the heating elements, the flow velocity, the inlet and outlet temperature of the air and the temperature of the thermocouple. A PC can be connected at the back to capture measurement data.

- A built-in adjustable speed **fan** conveys the air in experiments dealing with forced convection.

3.2 Positioning and commissioning

The device is designed so that it can be placed on a table. It is then possible for the observer to reach all the measuring glands and see the heater insert through a sight window. The control and display unit should be set up near to the air duct so that the measuring points can be reached by the thermocouple. The connection and measurement lines are up to 2m long. The connectors for the power supply and the outlets for heating elements and fan, as well as the thermocouple measurement input are located on the rear of the unit.

The air duct must be installed on a solid, flat surface. Furthermore, ensure that the air duct's entry and exit are freely accessible so that the flow is not adversely affected resulting in unexplained measurements.

The following points should be considered when setting up and commissioning:

- Position the trainer vertically.
- Keep the air duct inlet and outlet clear, so that the air flow is not restricted.
- Connect fan and heating element to the display and control unit via device cables with plug and / or coupling.

- Connect thermocouple to the display and control unit via a socket.
- Energy supply for the display and control unit via mains plug.

3.3 Measurement data collection program

3.3.1 Program installation

Required for installation:

- A ready-to-use PC with USB port (for minimum requirements see Chapter 8.1, Page 83).
- 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

The trainer must not be connected to the PC's USB port while the program is being installed. The trainer may only be connected after the software has been successfully installed.

- Start the PC.
- Insert GUNT CD-ROM.
- In the "Installer" folder, launch the "**Setup.exe**" installation program.
- Follow the installation procedure on screen.

- Installation will run automatically after starting it. The following program components are installed onto the PC:
  - Program for PC-based data acquisition.
  - Driver routines for the "LabJack®" USB converter.
- Once the installation program has finished, restart the PC.

3.3.2 Program operation

- Select the program and start via:
  Start / Programs / G.U.N.T. / WL 352.
- The first time you launch the software after installing it you will be asked which language you wish to operate the program in.

  The language may be changed at any time in the "**Language**" menu.
- For other functions various pull-down menus are available.
- For detailed instructions on use of the program refer to its Help function. You can get to the **help function** via the **"?"** pull-down menu and selecting **"Help"**.

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Bitte wählen Sie Ihre Sprache
please select your language
veuillez choisir une langue
seleccione su idioma por favor

Fig. 3.2 Language selection

4 Basic principles

This chapter lists some of the basic theoretical principles that should make it easier to understand and evaluate the subsequent experiments. Having said this, only a limited area of heat transfer is represented with respect to the trainer, since a complete theoretical analysis is too large a scope to cover.

Notes:
For variables in the basic principles the index corresponds to the measuring point of the respective unit of measurement.
A comparison of the variables used in software and instructions is provided in Chapter 8.2, Page 86.

4.1 Heat

Heat is energy bound in matter. It is a measure of motion at the atomic scale. What we refer to as heat is a form of energy that is present within the matter in the form of vibrational energy at the atomic level.

In thermodynamics we use Q in formulae to indicate the quantity of heat.

The temperature is directly related to the amount of stored heat of a body:

$$Q \sim T$$

If there is a temperature difference between two measuring points, then there is an exchange of heat. Heat can be transferred through a variety of different mechanisms.

4.2 Heat transfer by radiation

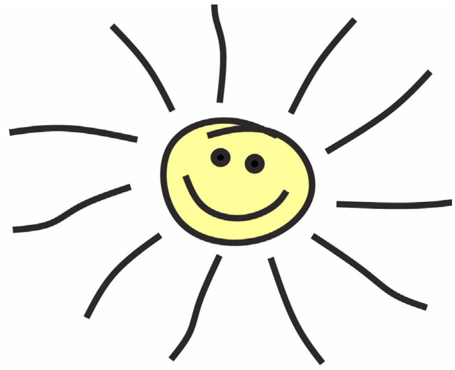


Fig. 4.1 The sun transfers its heat exclusively by radiation

Heat radiation is a transport mechanism for heat that doesn't require any materials for conduction or transport, as is the case in heat conduction or convection.

Heat radiation occurs everywhere where there is a temperature difference between bodies. Similarly, the bodies must be able to beam the radiation along a direct path. This is provided in a vacuum and in gases, and also in the Earth's atmosphere.

4.3 Heat transfer by conduction

Heat conduction is a heat transfer mechanism within solid bodies.

The heat is transferred through the vibrations of the particles of matter. Matter particles are bound to their location within the solid body. The heat is transferred through contact between the particles.

Metals, in which heat conduction is made possible through additional free electrons have a special place here. These are contained within the matter, but bound without a fixed position. This allows them to better absorb and emit the vibration. This is the reason why metals are generally better heat conductors than non-metals.

Heat conduction can also take place in fluids as well as solid bodies. This requires a still fluid in order to be differentiated from convection.

4.4 Heat transfer by convection

Convection is a heat transfer mechanism, during which a fluid absorbs heat. When in contact with a surface with a different temperature this occurs by heat conduction. The fluid can also absorb heat via radiation. This requires the radiation to be absorbed. The fact that the fluid does not have a fixed form compared to the solid body, the fluid particles can move freely, which means they can transport heat. Where such transport takes place, it is called convection.

Achieving a certain temperature difference in a body requires a certain amount of energy:

$$Q = m \cdot c_p \cdot \Delta T \qquad (4.1)$$

Here the mass m of the material to be heated up, and the specific thermal capacity c_{p_a} are significant. While the mass m describes the physical quantity of material, the specific thermal capacity c_p indicates how much energy is stored per temperature difference and mass.

Fig. 4.2 Hot gases rise

This instruction manual uses the measured temperature rise of the air mass flow rate to calculate the convective capacity.

In steady operating mode, flow passes through the trainer with a constant air mass flow rate. The observation of the heat flow with the measured air mass flow rate is:

$$\dot{Q} = \dot{m} \cdot c_p \cdot \Delta T \qquad (4.2)$$

The air mass flow rate $\dot{m}$ consists of:

$$\dot{m} = w \cdot A_{\dot{m}} \cdot \rho \qquad (4.3)$$

Below you can find details on the variables of Formula (4.2), Page 18 and Formula (4.3), Page 18:

- The temperature difference is calculated from:

$$\Delta T = T_2 - T_1 \qquad (4.4)$$

While T_1 roughly corresponds to the ambient temperature T_0, T_2 is simplified in that the measured value corresponds to the average temperature at the unit outlet. This simplification is important for the subsequent evaluation of results.

- The flow velocity w and the temperature difference ΔT are average variables over the entire flow cross-section. The flow cross-section $A_{\dot{m}}$ in the trainer is defined as constant at 0,0144 m^2. The cross-section is a result of the air duct dimensions of 120 mm x 120 mm.
- The density of air ρ can be derived from the general gas equation:

$$\rho = \frac{m}{V} = \frac{p}{R \cdot T} \tag{4.5}$$

The density of air to be used to calculate the mass flow rate depends on the temperature at the velocity measuring point. You can use relevant literature or the table in Chapter 8.3, Page 87 to form average values for the corresponding temperature.

- The universal gas constant R of the air depends on the relative humidity and temperature. The value of 287 $\frac{\text{KJ}}{\text{kg} \cdot \text{K}}$ of dry air can be used here with only negligible error.
- The specific thermal capacity of air c_{p_a} also depends on the air temperature. It increases with the temperature. In the later experiments the simplified value of 1,008 $\frac{\text{KJ}}{\text{kg} \cdot \text{K}}$ can be assumed. The error lies in the region of single

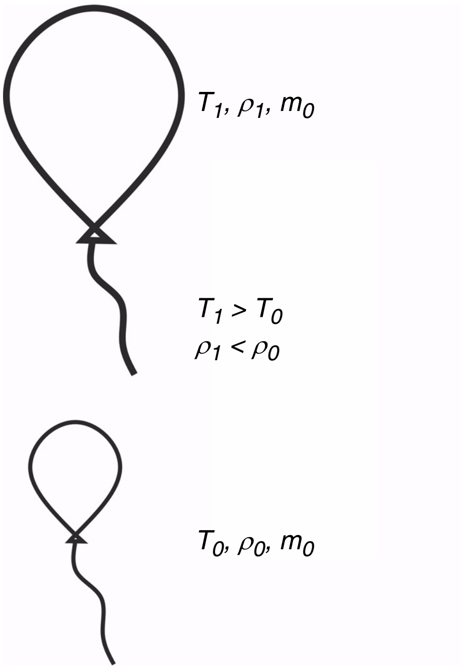


Fig. 4.3 Balloon with equal air mass and different temperatures

digit parts per thousand. You can use relevant literature or the table in Chapter 8.3, Page 87 to form average values for the corresponding temperature.

4.5 Heat transfer coefficient

Another method for calculating the transferred heat is via the heat transfer coefficient α:

$$\dot{Q} = A_\alpha \cdot \alpha \cdot \Delta T \quad (4.6)$$

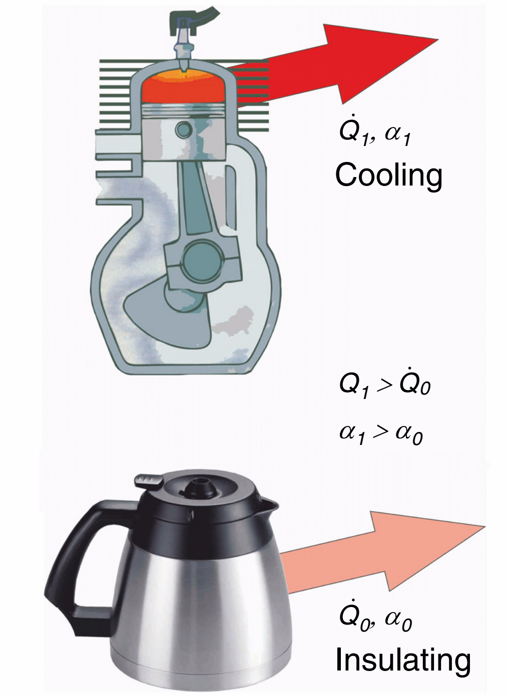


Fig. 4.4 Large and small intentional heat transfer

The area A_α is the surface of the heat exchanger and ΔT the temperature difference between the surface temperature T_4 of the heat exchanger and the temperature of the fluid, in this case equal to the ambient temperature which is nearly equal to T_1.

The heat transfer coefficient α can be determined experimentally using Formula (4.2), Page 18 and Formula (4.6), Page 20:

$$\alpha = \frac{\dot{m} \cdot c_p \cdot (T_2 - T_1)}{A_\alpha \cdot (T_4 - T_1)} = \mathrm{f}(Nu) \quad (4.7)$$

For select technically relevant applications it is possible to calculate the heat transfer coefficients by means of the theory of similarity. This is done through empirical formulae with ratios. A short overview of the theory of similarity is given below.

4.5.1 Theory of similarity

The method mentioned above for calculating the heat transfer coefficient α is based on the theory of similarity. This 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.

Example of scale: A model of the Cologne Cathedral looks similar to its original; it is similar in appearance (geometric similarity). However, it is different when we consider the interior or the building materials.

We use ratios in order to demonstrate and study similarities. These ratios are dimensionless, and their similarity only describes the parameters under consideration.

Fig. 4.5 Matryoshka dolls, similarity in form

Example: The Mach number is a ratio which is used in fast vehicles (e.g. aircraft) as a measure of velocity. The Mach number is defined as the ratio of current velocity to the velocity of sound.

Using the theory of similarity we can also perform calculations on heat flows. This often has advantages in technical handling, especially in construction matters.

The following ratios are essential when considering and assessing convection. Here we only refer to the mainly significant ratios. Calculating heat transfer is also based on formulae determined empirically from ratios obtained from models. Please refer to the relevant specialist literature for a deeper understanding of the subject.

4.5.2 Nusselt number

The Nusselt number is a measure of the heat transfer in convection. It is given by:

$$Nu = \frac{\alpha \cdot l}{\lambda} \tag{4.8}$$

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

According to this definition, *Nu* is always greater than one since each movement of fluid represents an additional transfer of heat for conduction.

The Greek letter λ stands for the coefficient of thermal conduction of air. This coefficient is dependent on temperature. The individual values can be found in the table in Chapter 8.3, Page 87.

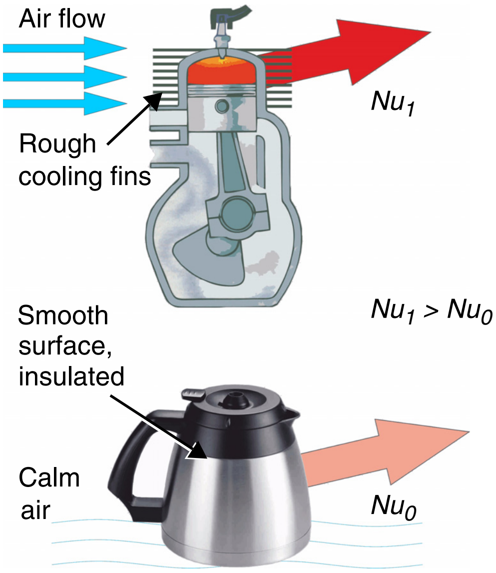


Fig. 4.6 Comparison of extreme Nusselt cases

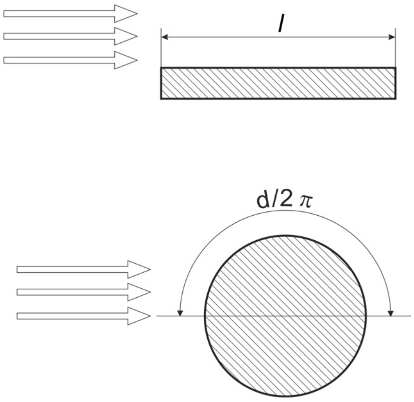


Fig. 4.7 Characteristic length

The length l is called the characteristic length. This length represents the geometric similarity. In a flat plate this is the overflowed length l, in a (quantity = 1)

overflowed cylinder it is $l = d \cdot \frac{\pi}{2}$.

The Nusselt number depends on other ratios. Empirical formulae have been created from experiments which reflect the ratios in different applications. It is only with the Nusselt number, which is calculated by an empirical formula, that we can later determine the heat transfer coefficient α using Formula (4.8), Page 22. The Nusselt number has to be re-calculated accordingly when the parameters are changed.

4.5.3 Reynolds number

The Reynolds number represents the ratio of the inertia force to the viscosity force of a fluid:

$$Re = \frac{w \cdot l}{\nu} \qquad (4.9)$$

w: Flow velocity

l: Characteristic length, refer to: Chapter 4.5.2, Page 22

υ: Kinematic viscosity, see table, Chapter 8.3, Page 87

The Reynolds number represents a ratio for the formation of the flow. We make a distinction between laminar and turbulent flow.

4.5.3.1 Laminar flow

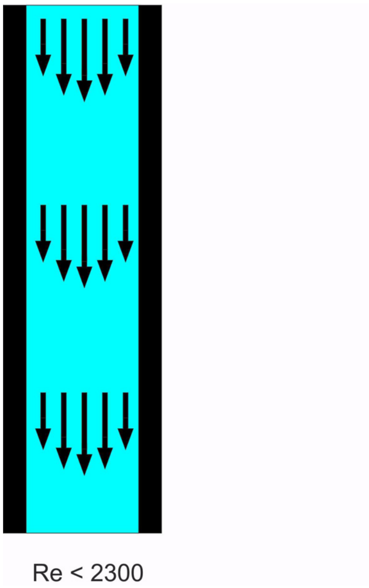


Fig. 4.8 Laminar pipe flow

Laminar flow means that the fluid particles have only one velocity value in the direction of flow.

Fluid particles in the vicinity of the heating element keep their distance from the surface as long as the flow is parallel to it. The heat transport occurs both by heat conduction and also by transport with the fluid particles. Heat conduction takes place in all directions. Transport with the particles of matter only in accordance with the direction of flow. Therefore a small transfer of heat takes place perpendicular to the flow as in the flow direction.

At low Reynolds numbers we assume laminar flow. The amount of the Reynolds number depends on the geometry. Other geometries mean other Reynolds numbers and also other Reynolds number variables for the laminar region. This must be determined by experiments for each problem case.

For pipes there is laminar flow at $Re < 2300$. In the flat plate this is the case at $Re < 10^5$.

We must make this distinction for areas of validity when calculating the Nusselt number, but in the subsequent calculation we only refer to one case by way of example.

4.5.3.2 Turbulent flow

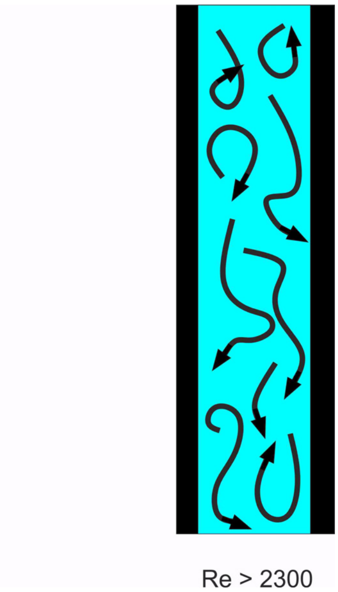


Fig. 4.9 Turbulent pipe flow

Turbulent flow occurs when turbulence causes other velocity components to be present in the flow in addition to the main direction of flow. This turbulence is irregular and random. For heat transfer, this means better mixing, since the heat is now also transported with the fluid particles, across the main flow.

Above a certain Reynolds number we can assume that the flow changes from laminar to turbulent. How big this Reynolds number is depends on the geometry of the body being flowed through.

With increasing flow velocity, after laminar flow there follows a transition area, designated by the range of the critical Reynolds number. The turbulent flow only develops fully at higher flow velocities. In the analytical calculations in industry and technology there is usually a set of formulae describing the areas of validity using ratios.

4.6 Free convection

As already mentioned, convection describes the transport of heat by moving fluid particles. In free convection, this motion is caused by the density differences resulting from warming.

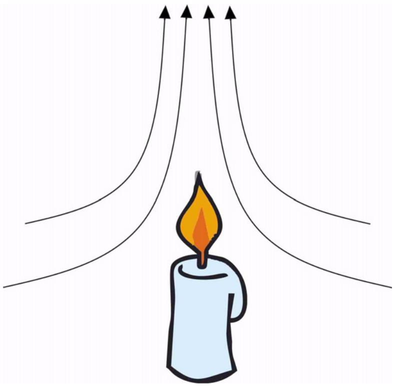


Fig. 4.10 Free convection

The heater element gives off its heat to the air. This occurs in the heating element by heat conduction to the surface. The heated air flows upwards through the resulting difference in density. Since the outflow proceeds faster than the heat transfer, we can note an increased velocity and temperature, especially in the vicinity of the warm surface.

4.7 Forced convection

In forced convection, the flow is made possible by an outside technical device, such as a fan. This results in an increased speed compared to free convection. The quicker transport of the fluid causes a higher temperature gradient from the warm surface to the fluid and thus a better heat transfer.

If the velocity is so high that the flow changes from laminar to turbulent, the additional fluid movement across the main direction (turbulence) provides improved heat transfer - away from the surface. This can also only happen locally (e.g. between the fins on the fin heater), since the local Reynolds number can vary over the cross-section.

5 Experiments

5.1 Notes for instructors

The experiments discussed in this chapter are only a selection of experiments that can be carried out. The subsequent exercises in Chapter 6, Page 47 are mainly based on the experiments described being carried out.

Environmental conditions and manufacturing tolerances of the device may cause deviations between your own measurements and the measured values shown here.

The time taken to reach steady state largely depends on the mass to be heated and the heat flow coming off. The better the heat is transferred by convection, the longer the time needed until the final state is reached. Therefore the heating time is conditional on physical conditions.

Because of the relatively long time needed to achieve a steady state the exercises in this chapter are handled separately. Alternatively, it is possible to process and present individual experiments in group work.

It is down to the instructor to judge how later exercises are handled in theory and practice. A guideline is proposed in the structure of the exercises.

5.2 Notes on conducting the experiments

1. If you are intending to evaluate efficiency, make sure that the device is not operated in hysteresis mode (switching off the heat output at maximum temperature). This leads to values

being distorted, as there is no quasi-stationary operation and the actual heat output remains unknown!

2. Due to physical conditions the temperature sensor requires a certain amount of time before the temperature value of the flowing air is displayed correctly. In factory experiments, we determined a measurement time $T_{5\%}$ from about 2.5 min. For large temperature changes, it is even more important to observe the measuring time in order to keep absolute errors small.
3. Analogous to no. 2:
   It will take some time before the heating element reaches steady operation. It is recommended that the software provided is used to regulate reaching the steady state over the course of time. This can be assumed for a temperature change in the heater of less than 0,5° C/min. If no computer is available we recommend not falling below the following times:

Heating element	Air velocity in m/s	Recommended hold time in min
Flat plate	min	70
Flat plate	max	45
Fin heater	min	45
Fin heater	max	20
Pipe bundle	min	45
Pipe bundle	max	15

Tab. 5.1 Recommended heating times for various heating elements in minimum and maximum heat output

5.3 Preparation of experiments

To obtain correct results, it is necessary to determine and save the heater temperature. The surface temperature T_4 is measured with the thermocouple. This happens with the heating element installed and after a steady operation has been reached. The temperature of the heating elements can be measured with the thermocouple through measuring holes. The menu item "Edit - Initialize Surface Temperature" is used to transfer the temperature from the thermocouple.

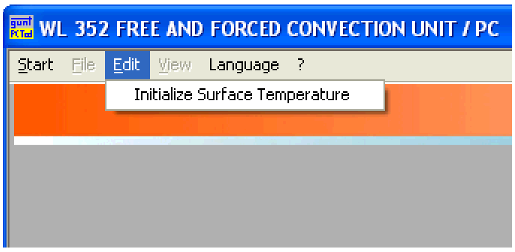


Fig. 5.1 Recording T_4

If the fin heater or the pipe bundle is used, an average value can be formed from all measuring ports on the trainer. These can be entered in the software manually as heating element surface temperature. Alternatively, the middle measuring port can be selected as a temperature reference.

Furthermore, the ambient temperature, air pressure and relative humidity have to be entered manually.

If a new measuring point is approached after a measurement, this procedure has to be repeated upon reaching the steady point.

5.4 GUNT measurement data

The following charts show measurements by GUNT on the WL 352 trainer. The curves shown are trend lines through point clouds (point clouds not shown). The curves represent an orientation of the expected values. Variations in conditions (input power, physical properties) must be taken into account.

5.4.1 Flat plate

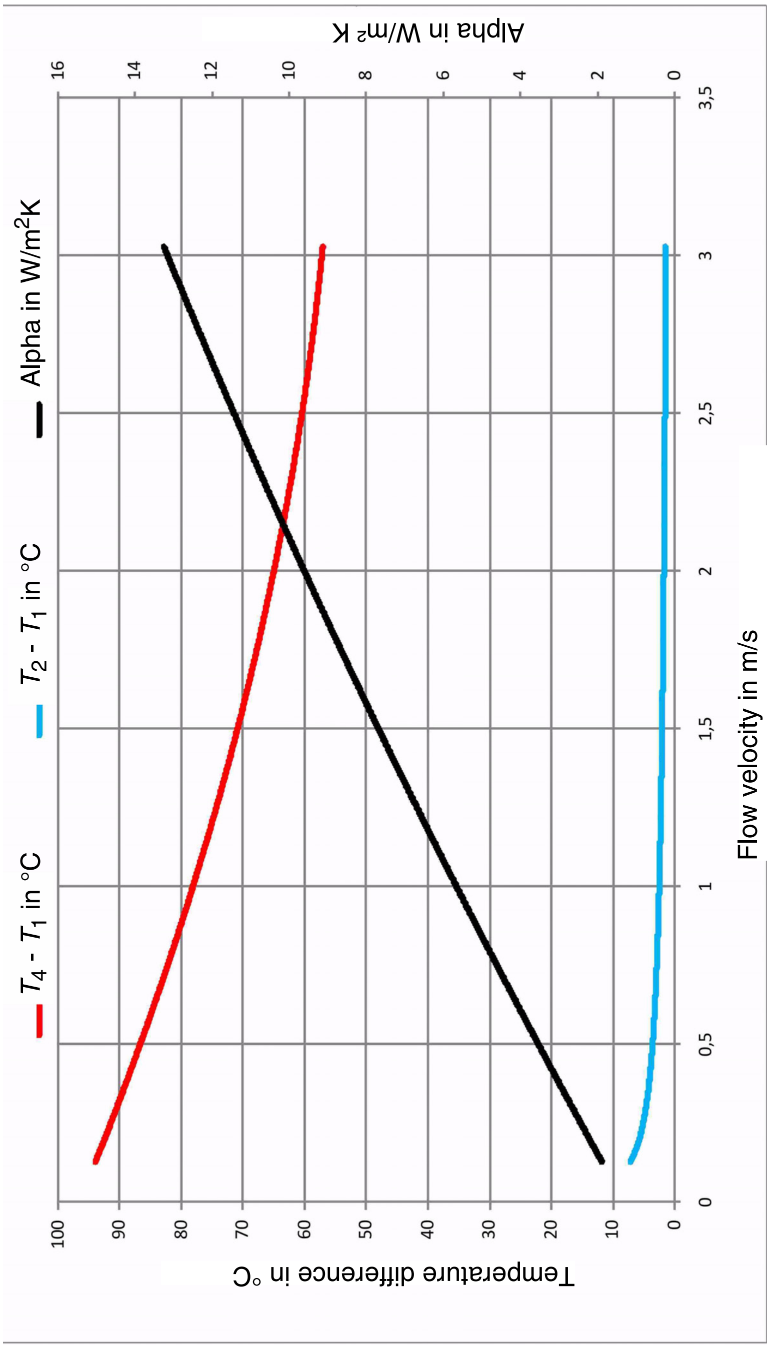


Fig. 5.2 Flat plate at 55 watts

5.4.2 Fin heater

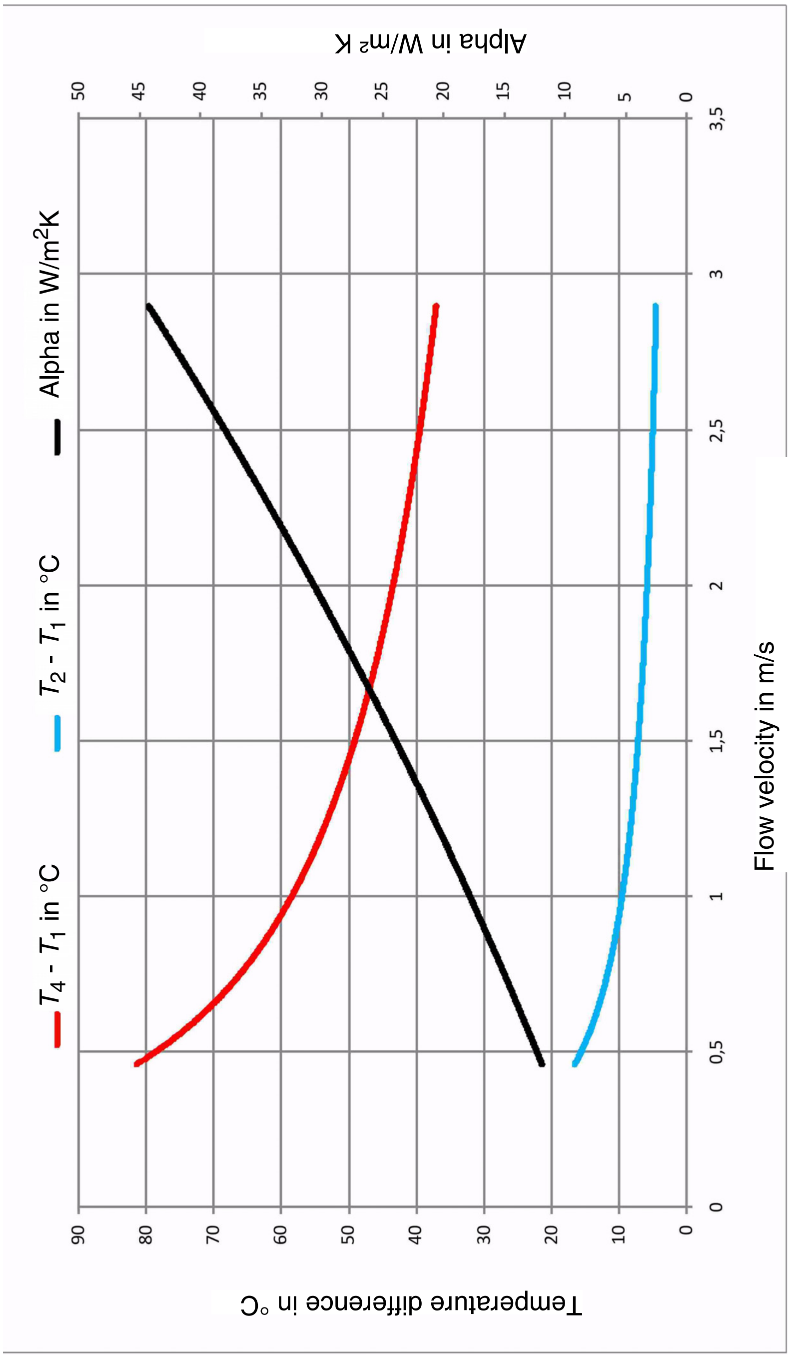


Fig. 5.3 Fin heater at 180 watts

5.4.3 Pipe bundle

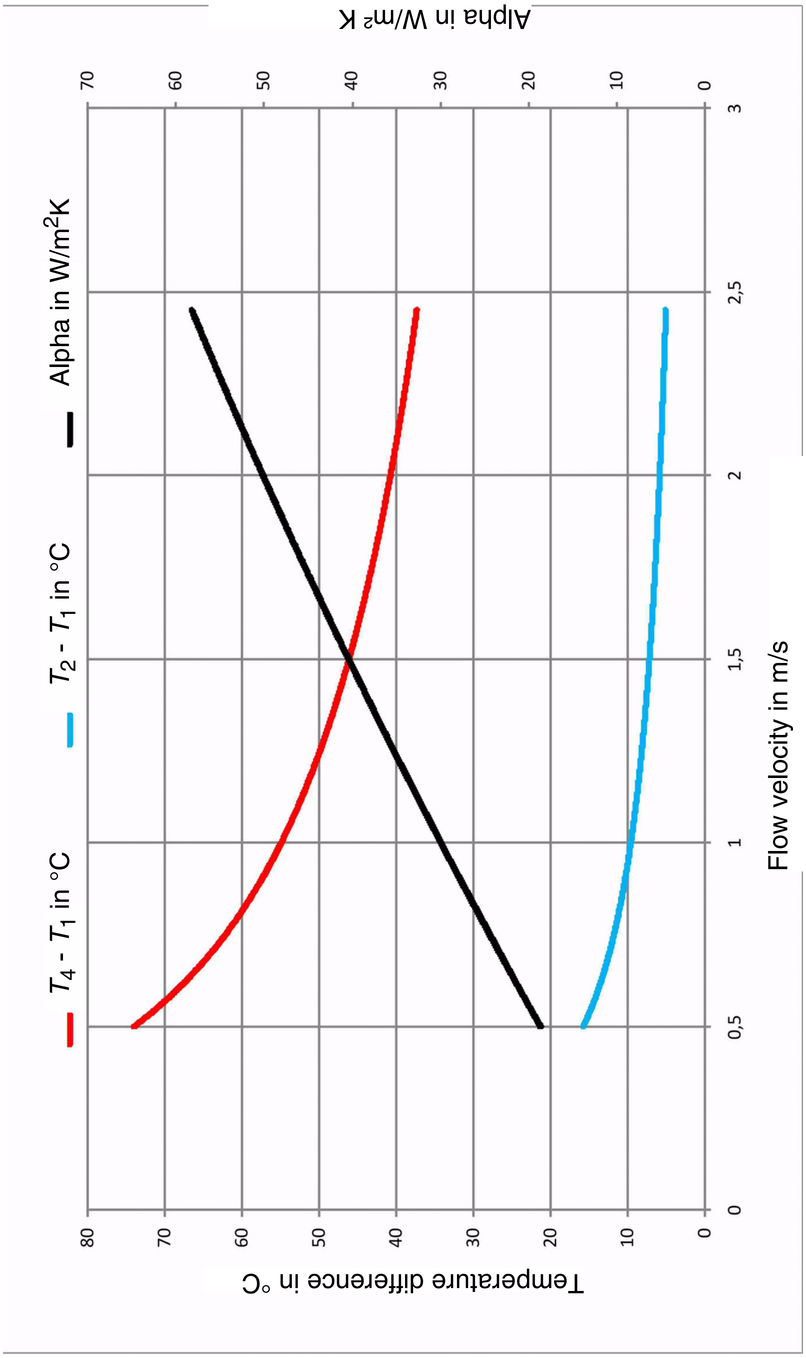
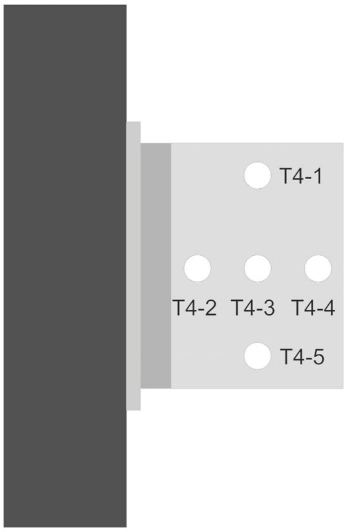


Fig. 5.4 Pipe bundle at 180 watts

5.4.4 Fin heater and pipe bundle temperature distribution



T4-1: 110,6°C

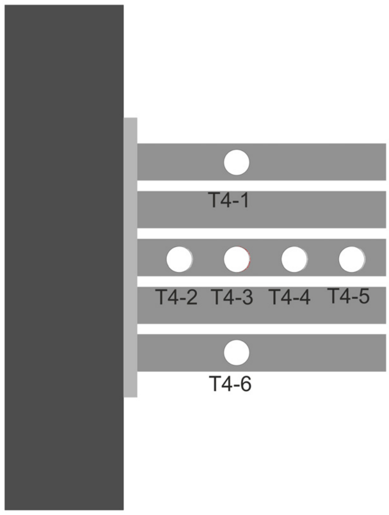
T4-2: 112,5°C

T4-3: 109,8°C

T4-4: 108,2°C

T4-5: 108,8°C

Fig. 5.5 Fin insert with temperature distribution in free convection, 160W



T4-1: 106,5°C

T4-2: 107,8°C

T4-3: 105,3°C

T4-4: 102,8°C

T4-5: 101,8°C

T4-6: 102,1°C

Fig. 5.6 Pipe bundle insert with temperature distribution in free convection, 145W

5.5 Possible educational opening question / experiment

The 'flat plate' heating element is presented on a table without the trainer and operated with the control panel. The heated plate gives off heat to the environment. First we will discuss which mechanisms are used to emit heat. After an overview of the mechanisms our main focus will be convection. Another learning objective is measures for increasing the heat discharge, for example to dissipate process heat.

The other experiments are intended to strengthen this understanding.

5.6 Experiment 1: Evaluation of free convection

Note for free convection:

If, following a period of downtime that allows a uniform temperature distribution in the room and the device, the trainer indicates a temperature difference from T1 to T2, then there is temperature layering present in the room air in the experiment space. This temperature difference must be subtracted from the subsequent value of air heating, because it means an increase in energy level, which is already given by the space.

5.6.1 Experiment 1a: Evaluation of the flat plate

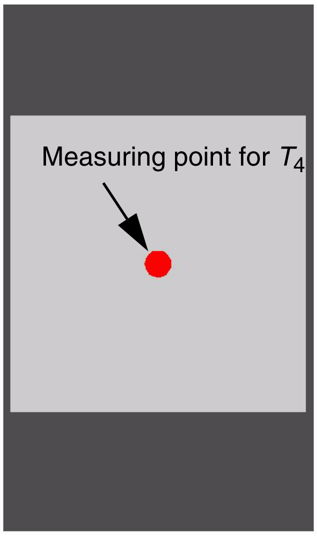


Fig. 5.7 Measuring point for T_4 with the 'flat plate' heater insert

At the start of the experiment, the 'flat plate' heating element is attached to the control and display unit and installed in the trainer. The heating output is adjusted so as to set a temperature between 105...115°C on the surface of the flat plate. In factory experiments this was achieved at 55 watts. The surface temperature T_4 is measured by the thermocouple in the centre of the plate as shown in Fig. 5.7. For this purpose a hole is added in the front Plexiglas plate.

The values can be recorded on the computer or in the respective sub-chapter using the experiment documentation.

The measurements can be documented via data acquisition or using the following prepared sheets.

Learning objectives:

- Familiarisation with the experimental unit.
- Record readings.
- Calculate convection characteristic values.
- Interpret convection characteristic values.

5.6.2 Experiment 1a experiment documentation

Type of experiment: Evaluation of the flat plate

Type of convection: free convection
Heading element: flat plate

Measurements:

Measuring point - measured values	**Unit**	**Value**
Electrical power P_{el}		
Flow velocity w		
Inlet temperature T_1		
Outlet temperature T_2		
Flat plate heating element T_4		
Values for calculation	**Unit**	**Value**
Temperature difference T_2 - T_1		
Temperature difference T_4 - T_1		
Table value of air density ρ		
Table value of spec. thermal capacity c_p		
Thermal energy $\dot{Q}$		
Heating element area A		
Heat transfer coefficient α		
Nusselt number Nu		
Heating surface load $\dot{q}$		

Tab. 5.2 Measurements

Notes:

5.6.3 Experiment 1b: Comparison of different heating elements

The trainer is operated as in the previous experiment, however, the heating element is replaced by the fin heater or the pipe bundle.

As in experiment 1a, the maximum surface temperature at the back wall of the heating element should be between 105...115°C, in order to produce the power for continuous output. In factory experiments, this was the case of at 160 watts for the fin heater and 145 watts for the pipe bundle.

The measurements can be documented via data acquisition or using the following prepared sheets.

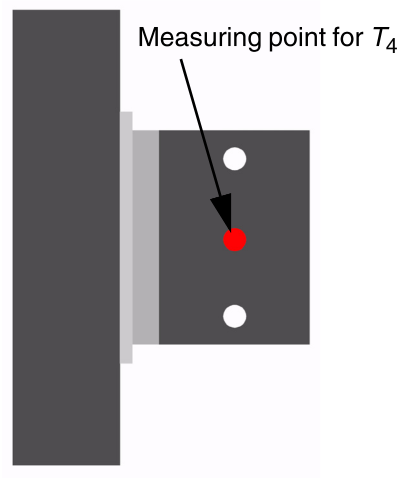


Fig. 5.8 Measuring point for T_4 with the 'fin heater' heater insert

To make things simpler, the surface temperature of the heater can be measured through the side measuring points as shown in Fig. 5.8 and Fig. 5.9.

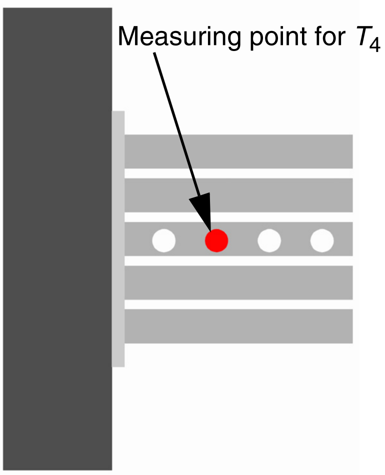


Fig. 5.9 Measuring point for T_4 with the 'pipe bundle' heater insert

Learning objectives:

- To recognise how the heater surface affects heat transfer

5.6.4 Experiment 1b experiment documentation

Type of experiment: Evaluation of fin heater & pipe bundle

Type of convection: free convection
Heating element: fin heater / pipe bundle

Measurements:

Measuring point - measured values	**Unit**	**Fin heater value**	**Pipe bundle value**
Electrical power P_{el}		approx. 160	approx. 145
Flow velocity w			
Inlet temperature T_1			
Outlet temperature T_2			
Surface temperature T_4			
Values for calculation	**Unit**	**Fin heater value**	**Pipe bundle value**
Temperature difference T_2 - T_1			
Temperature difference T_4 - T_1			
Table value of air density ρ			
Table value of spec. thermal capacity c_p			
Thermal energy $\dot{Q}$			
Heater surface A			
Heat transfer coefficient α			
Nusselt number Nu			
Heating surface load $\dot{q}$			

Tab. 5.3 Measurements

Notes:

5.6.5 Experiment 1c: Varying the heater temperature

In this experiment the fin model is used as a heating element. The efficiency of convection is much better here than in the flat plate, thus the learning objectives can be more clearly seen.

The following experiment has to be distinguished from the pipe bundle.

Start-up takes place as in the previous experiments.

The measurements can be documented via data acquisition or using the following prepared sheets.

Learning objectives:

- To recognise the relationship between surface temperature to heat transfer

5.6.6 Experiment 1c experiment documentation

Type of experiment: Evaluation of the fin heater

Type of convection: free convection
Heating element: fin heater

Measurements:

Measuring point - measured values	**Unit**	**Value**	**Value**	**Value**	**Value**
Electrical power P_{el}		approx. 75	approx. 100	approx. 125	approx. 150
Flow velocity w					
Inlet temperature T_1					
Outlet temperature T_2					
Surface temperature T_4					
Values for calculation	**Unit**	**Value**	**Value**	**Value**	**Value**
Temperature difference T_2 - T_1					
Temperature difference T_4 - T_1					
Table value of air density ρ					
Table value of spec. thermal capacity c_p					
Thermal energy $\dot{Q}$					
Heater surface A					
Heat transfer coefficient α					
Nusselt number Nu					
Heating surface load $\dot{q}$					

Tab. 5.4 Measurements

Notes:

5.6.7 Experiment 1d: Influence of the heating element's overflow

This experiment is designed as a follow-up to experiment 1c.

The pipe bundle is used as a heating element.

Start-up takes place as in the previous experiments.

The measurements can be documented via data acquisition or using the following prepared sheets.

Learning objectives:

- To recognise what affect flow mixing has.

5.6.8 Experiment 1d experiment documentation

Type of experiment: **Evaluation of the pipe bundle**

Type of convection: free convection
Heading element: pipe bundle

Measurements:

Measuring point - measured values	**Unit**	**Value**	**Value**	**Value**	**Value**
Electrical power P_{el}		approx. 75	approx. 100	approx. 125	approx. 150
Flow velocity w					
Inlet temperature T_1					
Outlet temperature T_2					
Surface temperature T_4					
Values for calculation	**Unit**	**Value**	**Value**	**Value**	**Value**
Temperature difference T_2 - T_1					
Temperature difference T_4 - T_1					
Table value of air density ρ					
Table value of spec. thermal capacity c_p					
Thermal energy $\dot{Q}$					
Heater surface A					
Heat transfer coefficient α					
Nusselt number Nu					
Heating surface load $\dot{q}$					

Tab. 5.5 Measurements

Notes:

5.7 Experiment 2: Flow velocity in forced convection

This experiment is intended to demonstrate what effect flow velocity has on the trainer system.

The fundamentals of the influence of flow velocity on convection can be found in the "Basic principles" chapter.

Start-up takes place as in the previous experiments.

The measurements can be documented via data acquisition or using the following prepared sheets.

Learning objectives:

- To identify the influence of velocity on the heater insert
- To identify the influence of velocity on heat transfer

5.7.1 Experiment 2 experiment documentation

Type of experiment: **Influence of flow velocity**

Type of convection: forced convection
Heading element: fin heater

Measurements:

Measuring point - measured values	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Electrical power P_{el}							
Flow velocity w		approx. 0,5	approx. 1,0	approx. 1,5	approx. 2,0	approx. 2,5	approx. 3,0
Inlet temperature T_1							
Outlet temperature T_2							
Surface temperature T_4							
Values for calculation	**Unit**	**Value**	**Value**	**Value**	**Value**	**Value**	**Value**
Temperature difference T_2 - T_1							
Temperature difference T_4 - T_1							
Table value of air density ρ							
Table value of spec. thermal capacity c_p							
Thermal energy $\dot{Q}$							
Heater surface A							
Heat transfer coefficient α							
Nusselt number Nu							
Heating surface load $\dot{q}$							

Tab. 5.6 Measurements

Notes:

5.7.2 Experiment 3: Heat distribution on the pipe bundle

This experiment looks at the qualitative evaluation of the influence of heat transfer in the pipe bundle.

Learning objective:

- To identify the temperature gradient in the pipe bundle
- To identify the relationship to convection

5.7.3 Experiment 3 experiment documentation

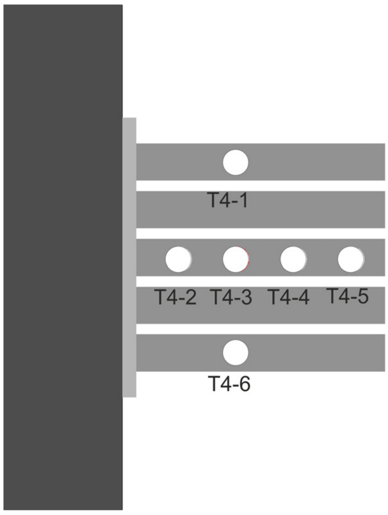
Type of experiment: **Temperature distribution on the pipe bundle**

Type of convection: **free convection / forced convection**
Heating element: **pipe bundle**

Measurements:

Measuring point - measured values	**Unit**	**Value**
Electrical power P_{el}		
Flow velocity w		
Inlet temperature T_1		
Outlet temperature T_2		

Tab. 5.7 Measurements



T4-1: ____________

T4-2: ____________

T4-3: ____________

T4-4: ____________

T4-5: ____________

T4-6: ____________

Notes: ____

____

____

6 Tasks

Tasks / exercises	Topic
Worksheet 1	Layout and function of the trainer
Worksheet 2	Basic questions on free convection
Worksheet 3	Basic questions on forced convection
Worksheet 4	Basic questions on measurement practice and the theory of similarity

6.1 Worksheet 1: Layout and function of the trainer

Page 1

Learning objectives:

- To be able to explain the mechanism of convection and differentiate from other types of heat transfer
- To discover the possibilities of the trainer
- Practical familiarisation with the trainer
- To develop proficiency for conducting measurements
- To identify and describe differences in the heating elements
  - in geometry
  - in operation
- To be able to state influences on the thermal energy transferred
- To understand and be able to explain the influence of the temperature gradient in the calculation

Worksheet 1, Page 2

1. What type of heat transfer is present in each example?

a) Heat transfer from cooking pot on hob:

How is the heat transferred?

Where is this type of heat transfer present on the device?

b) Heat transfer from Sun to Earth:

How is the heat transferred?

Where is this type of heat transfer present on the device?

Worksheet 1, Page 3

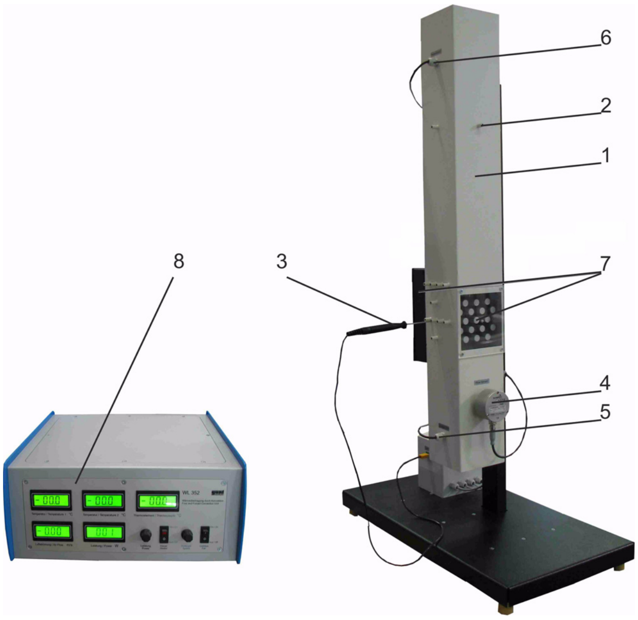
c) Heat transfer from filament to air in a hair dryer:

How is the heat transferred?

Where is this type of heat transfer present on the device?

Worksheet 1, Page 4

Exercise: Name the numbered items on the WL 352 trainer. What function does each element have?



No.	Description	Function
1		
2		
3		
4		
5		
6		
7		
8		

Tab. 6.1 Description of the trainer

6.2 Worksheet 2: Basic questions on free convection

Page 1

Learning objectives:

- Familiarisation with the trainer in operation with free convection
- Reference to everyday heating equipment should be created
- The physical function should be identified

Exercises:

Answer the following questions on the WL 352 trainer

1. Compare (several possibilities):
   What technical devices also transfer heat to air?

2. Which components in you comparison do the named components of the WL 352 trainer correspond to?

Heating element:

Power cable:

Air duct:

Worksheet 2, Page 2:

3. a) Describe the heat transfer in conduction:

a) Describe the heat transfer in convection:

c) How are solids different to gases/liquids in heat transfer?

Worksheet 2, Page 3:

on experiment 1a, free convection:

4. What happens during free convection? Describe the processes involved in free convection.

- What physical variables of the air does the heater insert change when the air flows through the air duct?

- What property change in the air is the reason for flowing through the air duct?

on experiment 1b, flat plate - fin heater comparison:

5. Explain the improvement of heat transfer when comparing the flat plate to the fin heater and/or the pipe bundle.

Worksheet 2, Page 4:

on experiment 1c, variation of T4:

6. The surface temperature T4 is increased.

- Where can the higher heater temperature be noticed in the air?

- How does this become apparent in the uplift?

on experiment 1d, fin heater - pipe bundle comparison:

7. Although the pipe bundle has a smaller surface area, the calculated values for heat transfer show comparable or better values for heat transfer. What effect can explain this?

6.3 Worksheet 3: Basic questions on forced convection:

Page 1:

Learning objectives:

- Distinction between forced and free convection
- To develop an understanding of the variable parameters
- To be able to describe how flow velocity affects the transferred thermal energy

Exercise:

Answer the following questions on the WL 352 trainer

1. How are forced and free convection different?

2. What technical devices operate on the principle of forced convection?

Worksheet 3, Page 2:

on experiment 2:

3. How can the transferred thermal output be calculated: (Formula)

Using mass flow:

Using the surface area:

4. In forced convection and where the heater and inflow temperatures are equal, the outflow temperatures are smaller than in free convection. Nevertheless, in comparison there are higher heat transfer coefficients. How can this be explained?

Analogous to experiment 1d:

5. How can the heat transfer coefficient be increased further using the flow and the heater insert?

Worksheet 3, Page 3:

on experiment 3: Temperature distribution on the pipe bundle

6. The pipes protrude vertically into the flow. During operation, we can measure a lower temperature at the end of the pipe compared to the beginning of the heater plate. How can we explain this decrease in temperature in the pipe direction?

7. In the direction of flow the air passes through the series of pipe bundles. During operation we can measure a lower temperature at the lower row of pipes (near T1) compared to the upper row of pipes (near T2). How can we explain this difference in temperature in the direction of flow?

6.4 Worksheet 4: Basic questions on measurement practice and the theory of similarity:

Page 1:

Learning objectives:

- To be able to describe physical similarity
- To be able to explain the importance of the Nusselt ratio's statement
- To be able to critically evaluate measurements and the values calculated from them

Exercise:

Answer the following questions on the theory of heat transfer WL 352

1. When do we talk about physical similarity?

2. Explain the statement of the Nusselt number for heat transfer.

Worksheet 4, Page 2

on the experiments:

3. What ratio characterises the flow?

4. What statements can we use it to make?

5. How can ratios for heat transfer be used?

Worksheet 4, Page 3:

Considering the measuring points

6. In a comparison of the temperature measuring points it is evident that the handheld temperature sensor (thermocouple) is slightly different to the other two measurement points (Pt100). What could the explanation be?

7. When measuring surface temperatures with the handheld temperature sensor it is evident is that this is much quicker than measuring the air flowing out. How can this be explained?

8. The measurement point T2 is located roughly in the centre of the air duct. What error has to be taken into consideration when the air is only heated up on one side of the duct wall due to the use of the 'flat plate' heater insert?

Worksheet 4, Page 4

9. The flow sensor protrudes into the flow of the air duct. Measurement is done at the end of the probe. What assumption is made in the calculation?

10. What conclusion must be drawn from the knowledge of measurement uncertainties for resulting findings?

Worksheet 4, Page 5

Considering efficiency:

11.Calculate the efficiency of your selected measurement using the formula: $\eta = \frac{\dot{Q}}{P_{el}}$. The factor η indicates how much of the heat output used is transferred to the fluid (here: air).

Experiment: ______________________
Heating element: ______________________
Electrical power P_{el}: ______________________
Flow velocity w: ______________________
Inlet temperature T1: ______________________
Outlet temperature T2: ______________________

Calculation:

12.The electric power applied is fully converted into heat. When calculating the efficiency only one of the three heat transfer mechanisms is considered. What does this mean for the efficiency?

____
____
____
____

7 Solutions

Tasks / exercises	Topic
Worksheet 1	Layout and function of the trainer
Worksheet 2	Basic questions on free convection
Worksheet 3	Basic questions on forced convection
Worksheet 4	Basic questions on measurement practice and the theory of similarity

7.1 Worksheet 1: Layout and function of the trainer

Page 1

Learning objectives:

- To be able to explain the mechanism of convection and differentiate from other types of heat transfer
- To discover the possibilities of the trainer
- Practical familiarisation with the trainer
- To develop proficiency for conducting measurements
- To identify and describe differences in the heating elements
  - in geometry
  - in operation
- To be able to state influences on the thermal energy transferred
- To understand and be able to explain the influence of the temperature gradient in the calculation

Worksheet 1, Page 2

1. What type of heat transfer is present in each example?

a) Heat transfer from cooking pot on hob:

How is the heat transferred?

Heat conduction. Transfer of heat through a substance.

Where is this type of heat transfer present on the device?

The heating element conducts heat to the heater housing via the attachment. Heat is also transferred to the air duct by conduction through contact points with the air duct.

b) Heat transfer from Sun to Earth:

How is the heat transferred?

Heat radiation. Heat transfer by electromagnetic radiation.

Where is this type of heat transfer present on the device?

All bodies emit thermal radiation at their surface. The heating element emits radiation to the surrounding air duct. The influence of heat transferred by radiation is negligible.

Worksheet 1, Page 3

c) Heat transfer from filament to air in a hair dryer:

How is the heat transferred?

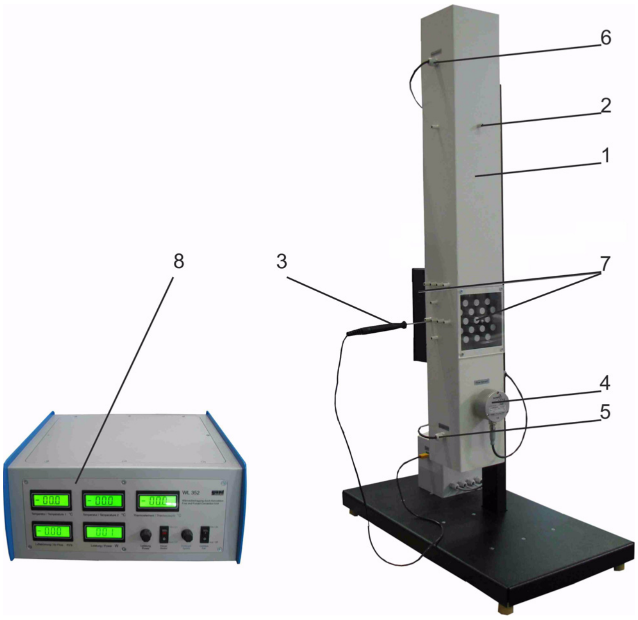
Convection Conduction from a surface to the fluid, then
further heat transfer through the fluid particles themselves.

Where is this type of heat transfer present on the device?

Heating elements transfer their heat output to the air flowing by.

Worksheet 1, Page 4

Exercise: Name the numbered items on the WL 352 trainer. What function does each element have?



No.	Description	Function
1	air duct	Guiding the air flow
2	Measuring glands	Opening to pass the thermocouple through
3	Thermocouple	Measuring air and surface temperatures T3
4	Flow sensor	Measuring the flow velocity
5	Temperature sensor	Measuring the inlet temperature T1
6	Temperature sensor	Measuring the outlet temperature T2
7	Heater insert	Transferring heat to air
8	Control and display unit	Controlling the trainer and displaying measured values

Tab. 7.1 Description of the trainer

7.2 Worksheet 2: Basic questions on free convection

Page 1

Learning objectives:

- Familiarisation with the trainer in operation with free convection
- Reference to everyday heating equipment should be created
- The physical function should be identified

Exercises:

Answer the following questions on the WL 352 trainer

1. Compare (several possibilities):
   What technical devices also transfer heat to air?

Building heating / car radiator / hair dryer, etc

2. Which components in you comparison do the named components of the WL 352 trainer correspond to?

Heating element: Radiator / radiator frame / heating coil

Power cable: Water supply / water supply / power cable

Air duct: room to be heated / not applicable / case for guiding air

Worksheet 2, Page 2:

3. a) Describe the heat transfer in conduction:

In heat conduction the heat is passed on due to individual matter particles coming into contact with each other.

a) Describe the heat transfer in convection:

In convection there is also motion of the heat-transporting particles. As a result, heat is absorbed by a gas or a liquid and carried along.

c) How are solids different to gases/liquids in heat transfer?

Only heat conduction can take place in solids, because the particles are bound and unable to move. In liquids or gases heat transport by the movement of the material is also possible. The transfer directly to a surface in a fluid occurs by heat conduction.

Worksheet 2, Page 3:

on experiment 1a, free convection:

4. What happens during free convection? Describe the processes involved in free convection.

- What physical variables of the air does the heater insert change when the air flows through the air duct?

The temperature difference causes heat to be transferred to the air. The air

warms up, temperature increases.

- What property change in the air is the reason for flowing through the air duct?

Warming up causes the air to expand. The density decreases compared to

the

ambient air. This results in lift forces, which cause the heated air

to flow through the air duct.

on experiment 1b, flat plate - fin heater comparison:

5. Explain the improvement of heat transfer when comparing the flat plate to the fin heater and/or the pipe bundle.

Compared to the flat plate, the fin heater has a larger surface

area. Convection can only take place where heat is transferred

to a fluid. This can only happen at the surface of a fluid.

The larger surface area means greater implementation of heat

output is possible.

Worksheet 2, Page 4:

on experiment 1c, variation of T4:

6. The surface temperature T4 is increased.

- Where can the higher heater temperature be noticed in the air?

If the heating element temperature increases, the temperature difference to the ambient air also increases to the same extent. The higher temperature difference results in a higher equalisation effort; more heat is transferred to the air. The heat transport is improved.

- How does this become apparent in the uplift?

The better heat transfer from the warmer heating element causes to heat up more quickly. This creates a greater uplift force, resulting in an increase in flow velocity. The heat transport is improved.

on experiment 1d, fin heater - pipe bundle comparison:

7. Although the pipe bundle has a smaller surface area, the calculated values for heat transfer show comparable or better values for heat transfer. What effect can explain this?

The geometry of the pipe bundle forces the flowing air to mix together. This is not the case in the fin heater. The mixing of the air ensures better transfer of the heat across the main flow and a better transfer away from the pipe wall.

7.3 Worksheet 3: Basic questions on forced convection:

Page 1:

Learning objectives:

- Distinction between forced and free convection
- To develop an understanding of the variable parameters
- To be able to describe how flow velocity affects the transferred thermal energy

Exercise:

Answer the following questions on the WL 352 trainer

1. How are forced and free convection different?

In forced convection the movement of the fluid is produced by a technical device, e.g. a fan. This means that the mass flow rate of the heat-absorbing medium is higher in free convection.

2. What technical devices operate on the principle of forced convection?

Hair dryers, any type of cooler with fan (e.g. automotive, CPU cooler), condensers in process engineering

Worksheet 3, Page 2:

on experiment 2:

3. How can the transferred thermal output be calculated: (Formula)

Using mass flow: $\dot{Q} = \dot{m} \cdot c_{p_a} \cdot \Delta T$

Using the surface area: $\dot{Q} = \alpha \cdot A \cdot \Delta T$

4. In forced convection and where the heater and inflow temperatures are equal, the outflow temperatures are smaller than in free convection. Nevertheless, in comparison there are higher heat transfer coefficients. How can this be explained?

The amount of heat increases with increasing temperature difference and increasing mass: $Q = m \cdot c_{p_a} \cdot \Delta T$

In the case of forced convection the recorded temperature decreases, the dwell time of the fluid particles on the heater surface is lower, yet there is a much greater mass flow, which more than compensates for this effect.

Analogous to experiment 1d:

5. How can the heat transfer coefficient be increased further using the flow and the heater insert?

The flow-through geometry allows you to influence the flow. Heat transfer can be increased by deliberate mixing.

Worksheet 3, Page 3:

on experiment 3: Temperature distribution on the pipe bundle

6. The pipes protrude vertically into the flow. During operation, we can measure a lower temperature at the end of the pipe compared to the beginning of the heater plate. How can we explain this decrease in temperature in the pipe direction?

The heat flows in the heating element by conduction. The heat is transferred from the heater plate to the pipes and further passed on into the ends of the pipes. Heat is continuously given off by the pipe surface. Thus, not all heat is conducted to the end of the pipe, which leads to the temperature difference described.

7. In the direction of flow the air passes through the series of pipe bundles. During operation we can measure a lower temperature at the lower row of pipes (near T1) compared to the upper row of pipes (near T2). How can we explain this difference in temperature in the direction of flow?

While the lower pipes emit their heat to cooler air, the upper pipes only have the already heated air available to them. The smaller temperature difference cancels out the cooling, so that we can measure a temperature difference in the direction of flow at the pipes.

7.4 Worksheet 4: Basic questions on measurement practice and the theory of similarity:

Page 1:

Learning objectives:

- To be able to describe physical similarity
- To be able to explain the importance of the Nusselt ratio's statement
- To be able to critically evaluate measurements and the values calculated from them

Exercise:

Answer the following questions on the theory of heat transfer WL 352

1. When do we talk about physical similarity?

Physical similarity exists when certain properties of one scale can be transferred to another scale.
This requires a ratio to be defined (despite the different scale):

2. Explain the statement of the Nusselt number for heat transfer.

The Nusselt number states by what factor heat transfer is better through convection compared to pure thermal conductivity of the fluid.

Worksheet 4, Page 2

on the experiments:

3. What ratio characterises the flow?

The Reynolds number is the ratio used to compare flows.

4. What statements can we use it to make?

If the flow formation in a model at a certain Reynolds number is known, then the results (laminar, turbulent flow, turbulence) can be transferred to other scales of the same Reynolds number.

5. How can ratios for heat transfer be used?

Unknown, new devices can be designed safely, whereby findings from model-based experiments on small models can be extrapolated up.

Worksheet 4, Page 3:

Considering the measuring points

6. In a comparison of the temperature measuring points it is evident that the handheld temperature sensor (thermocouple) is slightly different to the other two measurement points (Pt100). What could the explanation be?

The measurement principles of the two different temperature measurement points are different. As a result, small variances have to be expected.

7. When measuring surface temperatures with the handheld temperature sensor it is evident is that this is much quicker than measuring the air flowing out. How can this be explained?

The handheld temperature sensor indicates the temperature at the point. This temperature must be adjusted to the temperature of the point being measured. In good heat transfer (heat conduction to the metallic surface) this works more quickly than a worse one (convection of air).

8. The measurement point T2 is located roughly in the centre of the air duct. What error has to be taken into consideration when the air is only heated up on one side of the duct wall due to the use of the 'flat plate' heater insert?

The temperature sensor measures one point in the temperature profile. This point does not correspond to the mean value. In reality there is a temperature distribution in the cross-section being flowed through.

Worksheet 4, Page 4

9. The flow sensor protrudes into the flow of the air duct. Measurement is done at the end of the probe. What assumption is made in the calculation?

As with measurement point T2, there is also a distribution over the entire flow cross-section here. It is assumed that the flow velocity is constant over the entire cross-section and that the average velocity is equal to the velocity at this point.

10. What conclusion must be drawn from the knowledge of measurement uncertainties for resulting findings?

Measurement uncertainties are propagated through the calculations. The resulting findings also contain this uncertainty.

Worksheet 4, Page 5

Considering efficiency:

11. Calculate the efficiency of your selected measurement using the formula: $\eta = \frac{\dot{Q}}{P_{el}}$. The factor η indicates how much of the heat output used is transferred to the fluid (here: air).

Examples from factory experiment:

Experiment: 2

Heating element: Fin heater

Electrical power P_{el}: 180 W

Flow velocity w: 0,9 m/s

Inlet temperature T1: 25,4°C

Outlet temperature T2: 35,8°C

Calculation:

$$\dot{Q} = \dot{m} \cdot c_p \cdot (T_2 - T_1) = \rho \cdot w \cdot (0{,}12\mathrm{m})^2 \cdot c_p \cdot (T_2 - T_1)$$

$$\dot{Q} = 1{,}15\frac{\mathrm{kg}}{\mathrm{m}^3} \cdot 0{,}9\frac{\mathrm{m}}{\mathrm{s}} \cdot (0{,}12\mathrm{m})^2 \cdot 1008\frac{\mathrm{J}}{\mathrm{kg} \cdot \mathrm{K}} \cdot (35{,}8°\mathrm{C} - 25{,}4°\mathrm{C})$$

$$\dot{Q} = 156{,}2\mathrm{W}$$

$$\eta = \frac{\dot{Q}}{P_{el}} = \frac{156{,}2\mathrm{W}}{180\mathrm{W}} = 0{,}87$$

12. The electric power applied is fully converted into heat. When calculating the efficiency only one of the three heat transfer mechanisms is considered. What does this mean for the efficiency?

The efficiency only takes account of the heat which is transferred by convection in the inside of the duct. Heat transfer to other places reduces this convection efficiency.

8 Appendix

8.1 Technical data

Dimensions		
Length x Width x Height	700 x 350 x 1200	mm
Weight	44	kg
Connection values		
Electric power supply:	230V / 50	Hz
Alternatives optional, see rating plate		
Air duct		
Flow cross-section:	120 x 120	mm^2
Height:	1	m
Maximum air velocity:	3,0	$\frac{m}{s}$
Maximum air volume flow:	160	$\frac{m^3}{h}$
Flow sensor	0...10	$\frac{m}{s}$
Measurement medium temperature range:	-20...85	°C
Ambient temperature range:	0...60	°C
Handheld temperature sensor display		
Thermocouple:	Type K	
Display range:	0...199	°C
Display tolerance:	± 4°C	
Pt100 Sensor		
Measuring range:	0...100	°C
Display tolerance:	± 2°C	
Maximum heater output:	170	W
Temperature limit:	120	°C

Heat exchanger surfaces

Flat plate:

$$A = 0{,}118\text{m} \cdot 0{,}118\text{m} = \underline{0{,}014\text{m}^2}$$

Pipe bundle equal to plate with 17 rods ($d = 0{,}015\text{m}; l = 0{,}105\text{m}$), layout:

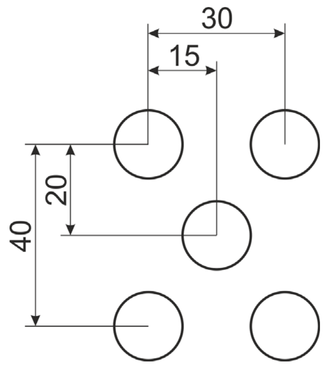


Fig. 8.1 Layout of the rods in pipe bundle

$$A = 0{,}014\text{m}^2 + 17 \cdot (\pi \cdot 0{,}015\text{m} \cdot 0{,}105\text{m}) = \underline{0{,}098\text{m}^2}$$

Fins:

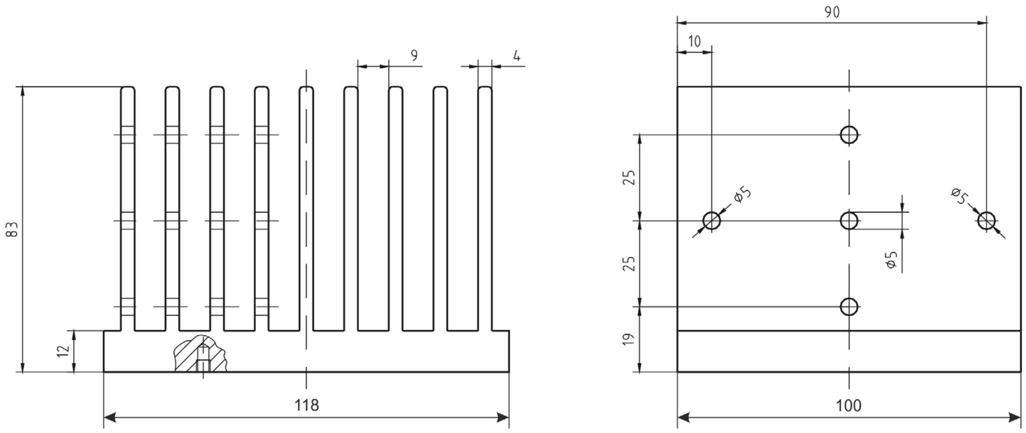


Fig. 8.2 Fin heater fins attachment

$$A = 0{,}118\text{m} \cdot 0{,}1\text{m} + 18 \cdot ((0{,}083\text{m} - 0{,}012\text{m}) \cdot 0{,}1\text{m}) = \underline{0{,}14\text{m}^2}$$

Measurement data acquisition

USB communication

Program environment: LAB-VIEW Runtime

System requirements:

- PC with Pentium IV, 1 GHz processor
- Minimum 1024 MB RAM
- Minimum 1 GB free hard disk space
- 1 x USB port
- Graphic card resolution min. 1024 x 768 pixels, True Color
- Windows XP / Windows Vista / Windows 7

8.2 List of formula symbols and units used

Instruction manual	Software	Description	Unit
$A_{\dot{m}}$		Area flowed through	m²
A_α		Heat exchanger area	m²
c_p		Specific thermal capacity	J/kg K
d		Diameter	m
l		Length	m
m		Mass	kg
$\dot{m}$	dm/dt	Mass flow	kg/s
p		Pressure	Pa
P_{el}	P1	Input power	W
Q		Thermal energy	J
$\dot{Q}$	dQ/dt	Heat flow	W
R		Specific gas constant	J/kg K
T		Temperature	°C
T_0	T0	Ambient temperature	°C
T_1	T1	Inlet temperature of air in the air duct	°C
T_2	T2	Outlet temperature of air from the air duct	°C
T_3	T3	Handheld measuring device temperature	°C
T_4	T4	Heater surface temperature	°C
v		Specific volume	m³/kg
w	w	Flow velocity	m/s
Re	Re	Reynolds number	1
Nu	Nu	Nusselt number	1
α	alpha	Heat transfer coefficient	W/m² K
η	eta	Efficiency	1
λ		Thermal conductivity	W/m K
π		Pi	1
ρ		Density	kg/m³
υ		Kinematic viscosity	m²/s
-	PHI	Relative humidity	%

8.3 Physical properties of air

T in °C	ρ in $\frac{kg}{m^3}$	c_p 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
140	0,8425	1,017	0,03466	23,19	27,53	40,5	0,68
160	0,8036	1,020	0,03607	24,01	29,88	44,0	0,68
180	0,7681	1,023	0,03749	24,91	32,43	47,7	0,68
200	0,7356	1,026	0,03891	25,70	34,94	51,6	0,68
250	0,6653	1,035	0,04243	27,40	41,18	61,6	0,67
300	0,6072	1,046	0,04591	29,20	48,09	72,3	0,67
400	0,5170	1,069	0,05257	32,55	62,95	95,1	0,66
500	0,4502	1,093	0,05848	35,50	78,86	119	0,66
600	0,3986	1,116	0,0635	38,30	96,08	143	0,67
700	0,3577	1,137	0,0678	40,87	114,3	166	0,69
800	0,3243	1,155	0,0713	43,32	133,6	190	0,70
900	0,2967	1,171	0,0743	45,65	153,9	214	0,72
1000	0,2743	1,185	0,0768	47,88	175,1	237	0,74

Tab. 8.1 Physical properties of dry air at 1 bar

8.4 Index