Experiment Instructions

WL 372   Heat Conduction Unit

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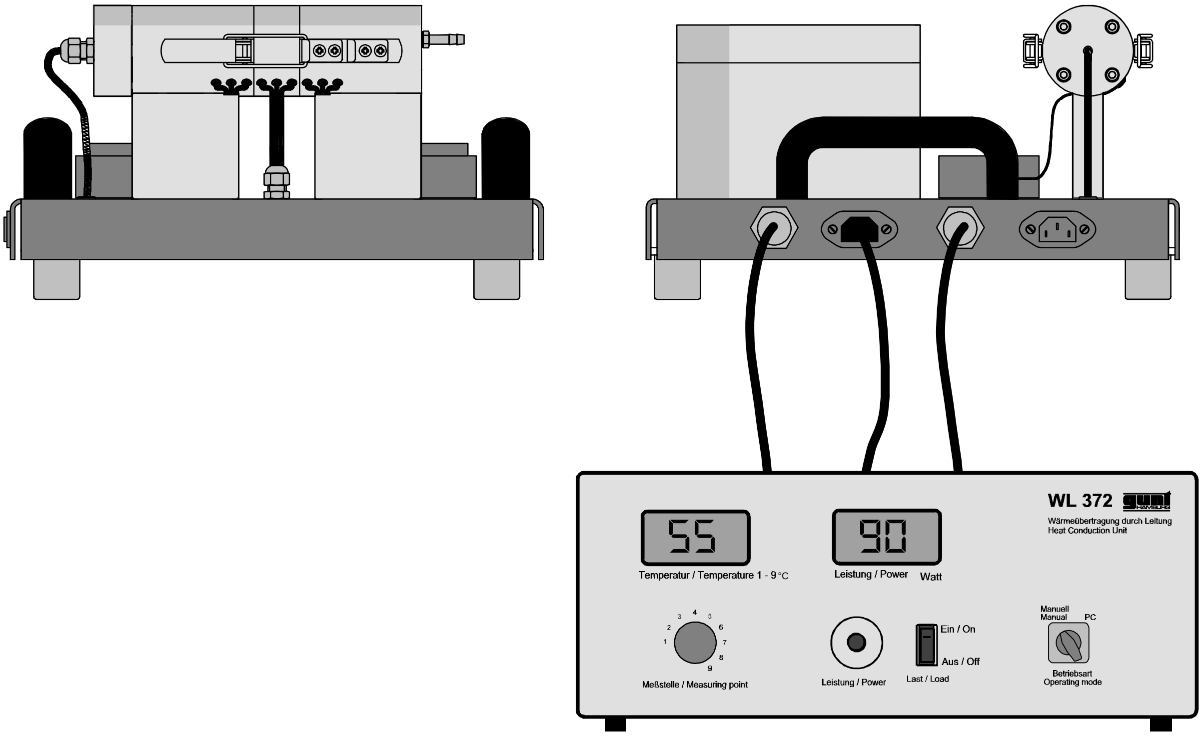

Experiment Instructions

Please read and follow the safety instructions before the first installation!

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Table of Contents

1 Introduction

In technical calculations it is important to be able to determine the amount or heat that is transferred between two mediums of different temperatures per unit time, when the two mediums are separated by a wall. The transport of heat is termed heat transfer and occurs in three main forms:

- **Thermal conduction** in a solid body, in a moving liquid body, or in a gaseous body.
- **Convection** between a solid medium and a flowing liquid or gaseous medium.
- **Thermal radiation**, occurs without a material carrier.

Heat is mostly transferred simultaneously by conduction, convection and radiation. Since the individual types of heat transfer are governed by differnet laws, they must be addressed separately.

Using the **G.U.N.T. WL 372 Heat Conduction Unit** the fundamental laws and characteristics of **thermal conduction** in solid bodies can be determined experimentally.

The tabletop **WL 372 Heat Conduction Unit** comprises two experimental arrangements, **linear conduction** and **radial conduction**.

Using the **linear conduction** arrangement, experiments can be made with different materials or diameters by installing different inserts.

2 Unit Description

2.1 Unit Construction

The **WL 372 Heat Conduction Unit** is a tabletop unit with two experimental arrangements, **linear conduction** (1) and **radial conduction** (2). The storage vessels serve as storage locations for the inlets.The control and display unit (3) is placed near the study unit. The two units are connected together via two cables, a data cable (4) and a power cable (5). A laboratory cooling water feed and return system (6,7) and mains power (8) complete the experimental setup.

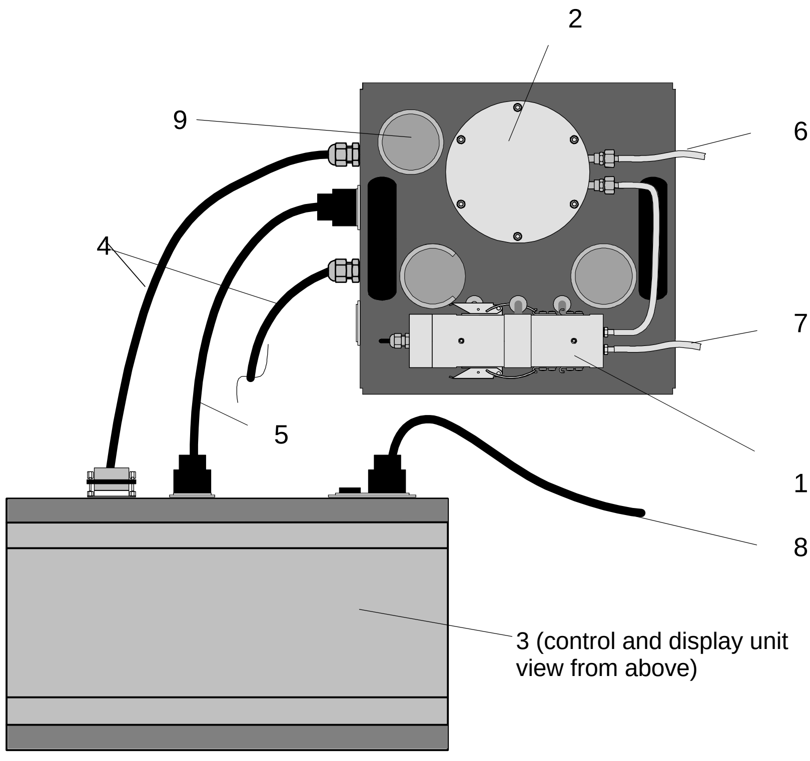


Fig. 2.1 Table-top device with control unit

2.1.1 Linear Conduction

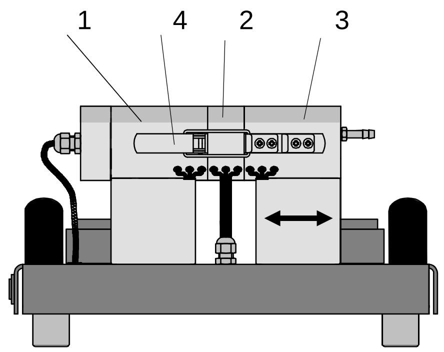


Fig. 2.4 Linear conduction

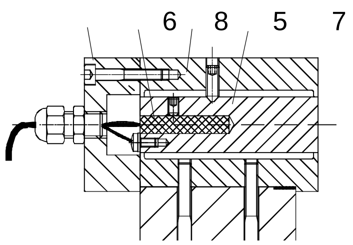


Fig. 2.2 Heater

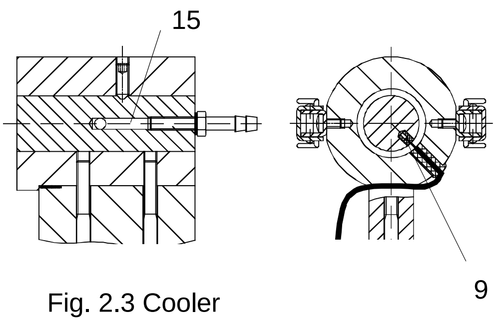


Fig. 2.3 Cooler

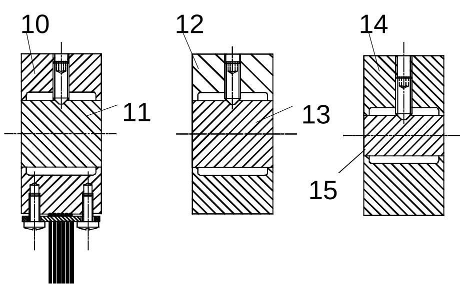


Fig. 2.5 Inserts

The setup for **linear conduction** comprises three elements:

- Fixed part with heater (1)
- Various Insertsinserts (2)
- Moveable part with cooler (3)

By opening the toggle fastener (4) and sliding back the cooler (3), the insert can be installed. By this means the heat is transferred linearly from the heater, though an insert, to the cooler.
The heater (1) comprises external insulation(5), lid (6), brass rod (7) and the electrical heater element (8). There are three temperature measuring points (9) under the insulation (5) in the brass rod (7) at 45°. Together with the insert (10) there is thus a measurement section of nine measuring points.
Insert 1 (10) has three temperature measuring points in a brass rod (11). This brass rod has the same diameter as the heater (1) and the cooler (3). When using other inserts, insert 1 can be placed on one side.
Insert 2 (12) also has the same diameter as the heater and the cooler, but is made from corrosion resistant steel (13) and does not have any tempe-rature measuring points.
Insert 3 (14) on the other hand has a smaller diameter and is again made from brass (15), it also has no temperature measuring points.
All the inserts are fitted with an insulating sleeve.
The cooler (3) comprises external insulation and a brass rod as for the heater. However this brass rod has bores (15) through which the cooling water can flow.

2.1.2 Radial Conduction

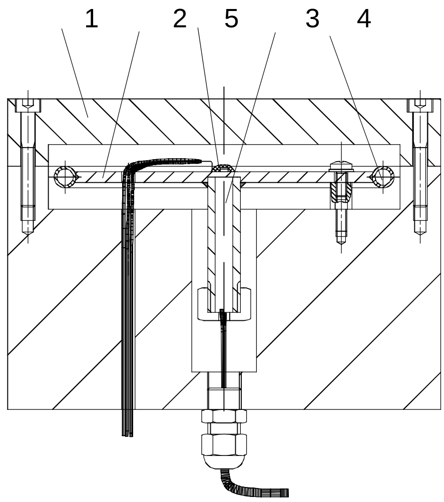


Fig. 2.6 Radial conduction

The **radial conduction** test item is a sealed unit. It comprises:

- An insulating housing (1) with lid
- A disc (2) with heater (3) and cooler (4)

The heater (3) is fixed from below in the centre of the brass disc (2). There is copper pipe (4) around the disc through which cooling water can flow. From above, six temperature measuring points (5) are fitted in a line that stretches radially from the centre to the circumference.

Using this apparatus the heat is transferred radially from the heater to the cooler.

2.1.3 Control and Display Unit

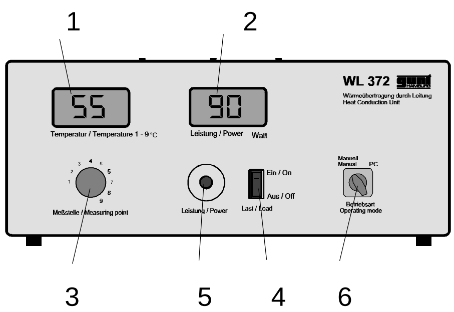


Fig. 2.7 Control and display unit

The control and display unit has a temperature display and a power display (1,2). These are both digital displays. The temperature is displayed in °C and the heater power in Watts.
The measuring point for the temperature display is selected via the rotary knob (3).
The heater power is switched with the ON / OFF switch (4) and adjusted using the potentiometer (5). Alternative, the temperature can also be provided via software; in this case the switch (6) has to be set onto operation mode “PC”.

2.2 Measuring Points and Dimensions

2.2.1 Linear Conduction

The measuring points are numbered from left to right. The distance between adjacent measuring points is 10mm.

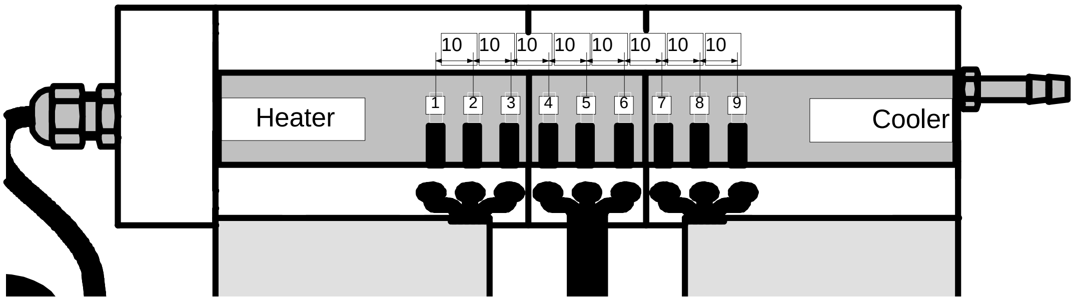


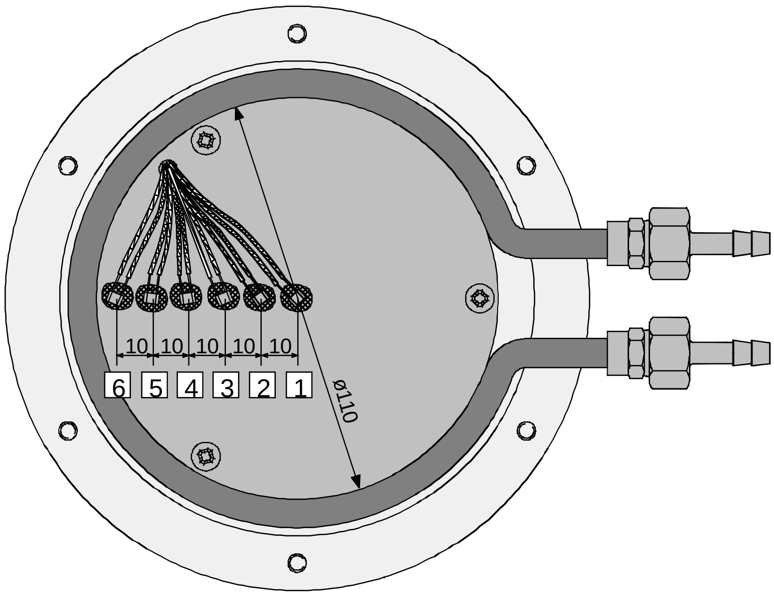
Fig. 2.8 Measuring Points Linear Conduction

The diameter of the heater, cooler, insert 1 and insert 2 is 25mm. Insert 3 has a diameter of 15mm.

If insert 1 is not used in the experiments, the temperatures displayed for measuring points 4, 5, and 6 should be ignored.

2.2.2 Radial Conduction

The measuring points are numbered from the centre outwards. The distance between adjacent measuring points is 10mm.



'Fig. 2.9 Measuring Points Radial Conduction

The diameter of the disc is 110mm; it is 4mm thick.

The heater is in the centre of the disk on the underside and has a diameter of 12mm.

The temperatures for measuring points 7, 8 and 9 should be ignored during the experiments.

2.3 Commissioning

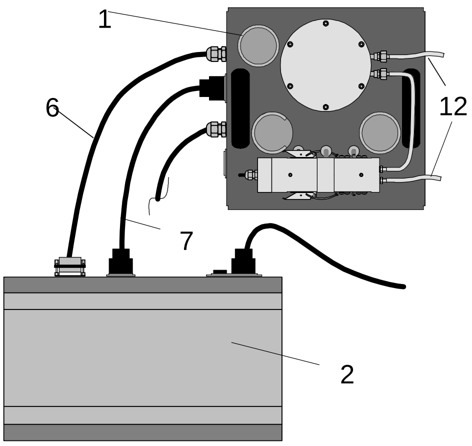


Fig. 2.10 Unit

The experiment instructions are to be carefully read prior to commissioning and each participant in the experiments shown how to use the unit correctly.

- Place the test unit (1) and the control and display unit (2) on a table and ensure that they are securely located.
- Provide electrical power:
  On the rear of the control and display unit (2) there is a mains connector (3) with a series fuse (4) and the main switch (5) via which the control and display unit is supplied.
- Connect the test unit to the control and display unit with the data cable (6) and the mains cable (7). The sockets for the heater load (8) and data acquisition (9) are on the rear.
  The data cable and socket on the left of the test unit are used for experiments on **radial conduction** (10), those on the right for **linear conduction** (11).
- Make the connections for the cooling water feed and return (12) using a 6mm hose.

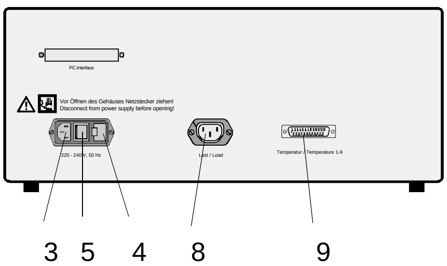


Fig. 2.12 Back view of control unit

Important!

Never connect the heater directly to the mains. The connection must always be made via the control and display unit.

Before changing over the connections, always switch off the control and display unit first.

Never operate without cooling water.

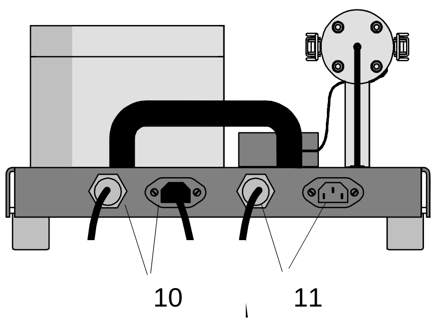
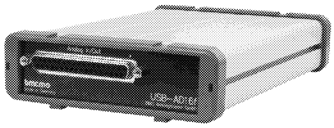


Fig. 2.11 Connection side o

2.4 Data Acquisition

2.4.1 Installation of the Hardware



- Connect the USB-Box to the PC
- Connect the Control Unit to the USB-Box
- Switch on the PC, if not already done so

Fig. 2.14 USB-Box

2.4.2 Installation of the Software

The software is installed on the PC with the aid of the user. The installation is to be performed by taking the following steps:

- Switch on the PC, if not already done so
- Place the CD in the CD/DVD-Drive.
- Select the drive (e.g. D)
  Execute the file D:\installer\Setup.exe
- Follow the installation dialog
- Start the Program

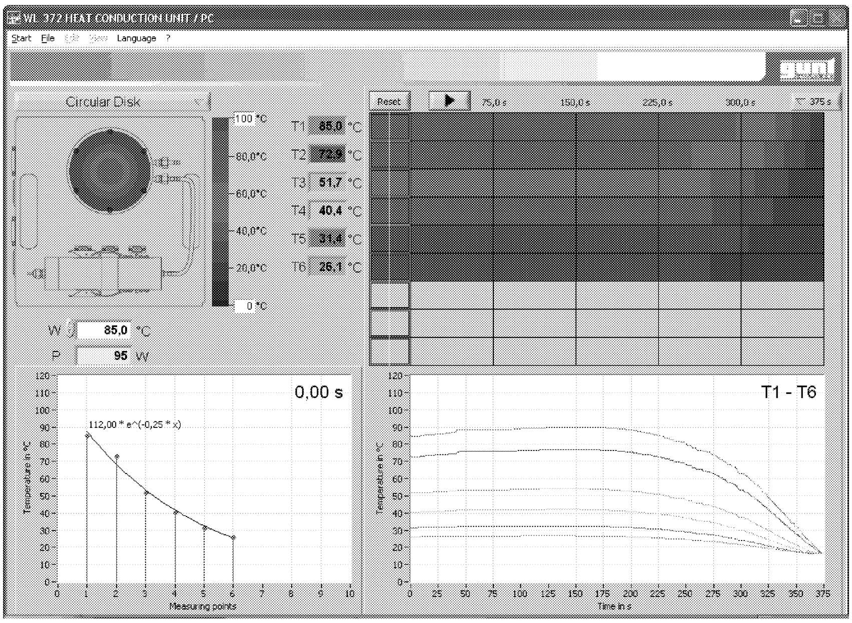
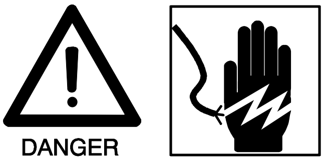


Abb. 2.13 Screenshot, the Software ist to be used intuitive

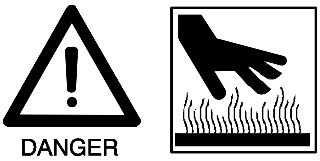
3 Safety Instructions

3.1 Hazards for Life and Limb

The following points are to be noted in respect of **health and safety** when using the **WL 372 Heat Conduction Unit:**



- **DANGER! Take care when opening the control and display unit and when reaching into all other electrical circuits.**
  There is a risk of electric shock.Always unplug first.
  Work is only to be performed by specialist personnel.
- Only use protection devices (fuses) of the stipulated value.



- **DANGER! Do not touch hot surfaces and covers!**
  There is a risk of burns.
  Always leave the unit to cool down first.
  When operated at high power, the insulation will also become hot. The screws on the toggle fasteners can also reach high temperatures. It should then only be undone using gloves or a cloth.

3.2 Hazards for the Unit and Its Function

ATTENTION

- There is a risk of overheating.
  Do not operate the study unit above 120°C.
  The plastic parts may disintegrate.

ATTENTION

- Never operate the study unit without cooling water. The unit may be overheated.

ATTENTION

- Do not connect the heater directly to the mains. Heaters that are heated in this manner will overheat and burn out.

ATTENTION

- Always switch off the control and display unit prior to changing the power supply and data cables. The temperature sensors and measurement converter may be damaged.

4 Theoretical Principles

4.1 Steady-State Thermal Conduction

Thermal conduction is the molecular transfer of heat in solid, liquid and gaseous media under the influence of a temperature difference. The maintenance of the transfer of heat by the continuous supply of heat is the commonest form of **steady-state thermal conduction**, e.g. in heat exchangers.

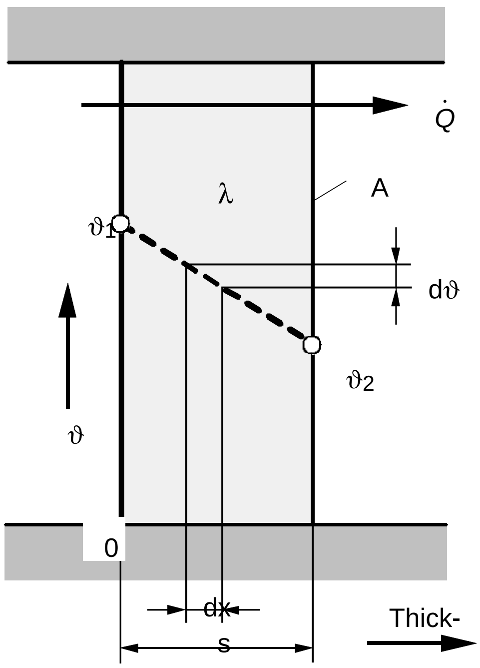


Fig. 4.1 Conduction of Heat Through a Wall

The quantity of heat Q flows through the cross-section of the solid body, Fig. 4.1, over time t in a steady-state in accordance with Fourier's law. The cross-sectional area is considerably larger than the peripheral area.

The **flow of heat** $\dot{Q}$ due to the conduction of heat is described by the following equation:

$$Q = -\lambda \cdot A \cdot t \cdot \frac{d\vartheta}{dx} \qquad (4.1)$$

Here λ is the **coefficent of thermal conductivity** of the material through which the heat flows, ϑ the **temperature**, A the isothermic **area** and $d\vartheta / dx$ the **temperature drop** in the direction of the heat flow.

The **heat flow** $\dot{Q}$ is equal to the quotient of the amount of heat per unit time.

$$\dot{Q} = \frac{Q}{t} = -\lambda \cdot A \cdot \frac{d\vartheta}{dx} \qquad (4.2)$$

It is a prerequisite for the calculation that a temperature difference is only present in one direction; the temperature in the layers perpendicular to this temperature difference is constant.

The flow of heat per unit area is termed the **density of the heat flow** $\dot{q}$:

$$\dot{q} = \frac{\dot{Q}}{A} \tag{4.3}$$

If one defines a material with a temperature dependent coefficient of thermal conductivity $\lambda = f(\vartheta)$, and sets this coefficient of thermal conductivity λ to an average coefficient of thermal conductivity $\lambda_{1,2}$ over the range between the temperatures ϑ_1 and ϑ_2, then one obtains for the **density of the heat flow** $\dot{q}$:

$$\dot{q} = \frac{\lambda}{s} \cdot (\vartheta_1 - \vartheta_2) \tag{4.4}$$

4.2 Thermal Conductivity

Thermal conductivity is a molecular process that comprises an exchange of kinetic energy from one molecule to another.

In addition to molecular vibration, thermal conduction in metals occurs due the flow of electrons that increases the conduction properties. In such materials electrons are not bound to a fixed position but move around in a lattice (like the molecules in a gas). This is the reason why electrical conductors have considerably higher thermal conductivity than electrical insulators. The coefficient of thermal conductivity at 20°C is approximately:

$$\lambda_{20°C} \approx \frac{2.45 \cdot \chi_e \cdot T}{10^8} \quad in \quad \frac{W}{m \cdot K} \tag{4.5}$$

with χ_e = electrical conductivity $(1/(\Omega \cdot m))$
T = absolute temperature (K)

4.3 Linear Conduction

4.3.1 Heat Conduction Through a Wall

From equation 4.1 the heat flow through a wall is:

$$Q = -\lambda \cdot A \cdot t \cdot \frac{d\vartheta}{dx} \quad .$$

For a constant cross-section A and $dx = s$ one obtains:

$$\dot{Q} = \frac{\lambda}{s} \cdot A \cdot (\vartheta_1 - \vartheta_2) \tag{4.6}$$

4.3.2 Heat Conduction Through a Wall Made Up of Several Layers

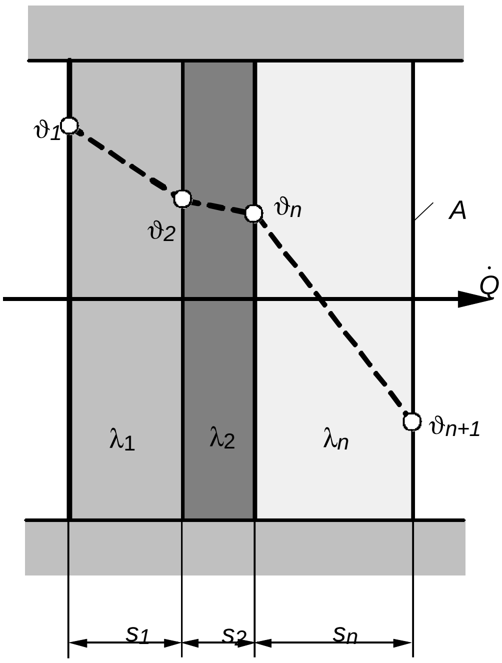


Fig. 4.2 Conduction of Heat Through a Wall Made Up of Several

For every layer in the wall the heat flow is the same. The following applies:

1st Layer : $$\dot{Q} = \frac{\lambda_1}{s_1} \cdot A \cdot (\vartheta_1 - \vartheta_2)$$

2nd Layer : $$\dot{Q} = \frac{\lambda_2}{s_2} \cdot A \cdot (\vartheta_2 - \vartheta_n)$$

nth Layer : $$\dot{Q} = \frac{\lambda_n}{s_n} \cdot A \cdot (\vartheta_n - \vartheta_{n+1})$$

By reorganising and adding equations for the individual layers together, the heat flow from the overall temperature difference is found to be as follows:

$$\dot{Q} = \frac{A \cdot (\vartheta_1 - \vartheta_{n+1})}{\frac{s_1}{\lambda_1} + \frac{s_2}{\lambda_2} + \frac{s_n}{\lambda_n}} \tag{4.7}$$

4.4 Radial Conduction

Radial conduction corresponds to the conduction of heat through a hollow cylinder. Whilst for a wall the cross-sectional area of the heat flow remains constant, the area through which the heat flows changes in the case of radial heat transfer, $A = f\,(r)$. However, the flow of heat remains constant, and at any point on the cylinder one obtains:

$$\dot{Q} = -\lambda \cdot A \cdot \frac{d\vartheta}{d\,r}\,. \qquad (4.8)$$

With $A = 2 \cdot r \cdot \pi \cdot L$ L = length of the cylinder

This yields:

$$\dot{Q} = -\lambda \cdot 2 \cdot r \cdot \pi \cdot L \cdot \frac{d\vartheta}{d\,r}\,.$$

By reorganising and integrating over the limits r_i to r_a one obtains the flow of heat through a hollow cylinder:

$$\dot{Q} = \lambda \cdot \frac{2 \cdot \pi \cdot L}{\ln\frac{r_a}{r_i}} \cdot (\vartheta_1 - \vartheta_2) \qquad (4.9)$$

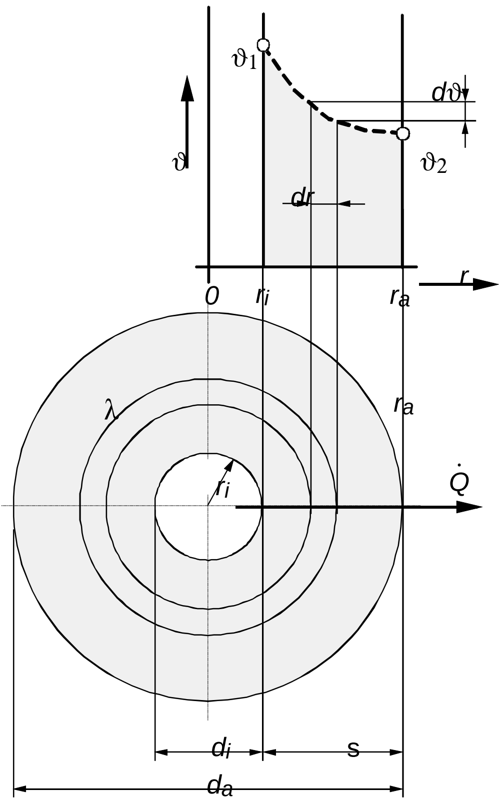


Fig. 4.3 Radial Conduction

5 Experiments

In this section example experiments that can be performed using this unit are described.

The measurements results should not be taken as being correct under all conditions. Depending on experimental skill, the ambient temperature and the temperature of the cooling water, the results may vary.

The section is divided into experiments on **linear** and **radial conduction**.

The objective of the experiments is to graphically depict the temperature changes for the linear and radial conduction cases, in addition the coefficient of thermal conductivity λ can be determined.

5.1 Linear Conduction with Insert 1

- Set up the unit as per sect. 2.3, install insert 1 and adjust the cooling water flow rate (only a very low cooling water flow rate of approx. 1l/h is required to dissipate a heater power of 90 Watts at a temperature difference of 90°C).
- Switch on the unit and adjust the desired temperature drop via the power setting on the control and display unit.
- When the thermal conduction process has reached a steady state condition, i.e. the temperatures at the individual measuring points are stable and no longer changing, note the measurement results at the individual measuring points and the electrical power supplied to the heater.

Insert 1 with 3 Temperature Measuring Points	Measurement Section: Brass / Brass / Brass Diameter: 25mm 25mm 25mm Coefficient of Thermal Conduction*: 113 113 113 $W/(m \cdot K)$ Power: 82 Watt * at 20°C			
Measuring Point	Distance s in mm	Temperature ϑ in°C	Temperature Difference $\Delta\vartheta$ in K	Coefficient of Thermal Conduction λ in $\frac{W}{m \cdot K}$
1	-	120.8	-	-
2	10	112.6	8.2	203.7
3	20	103.5	9.1	183.6
4	30	89.2	14.3	116.8
5	40	78.1	11.1	150.5
6	50	67.6	10.5	159.1
7	60	52.3	15.3	109.2
8	70	41.5	10.8	154.7

Tab. 5.1 Measured Value Insert 1

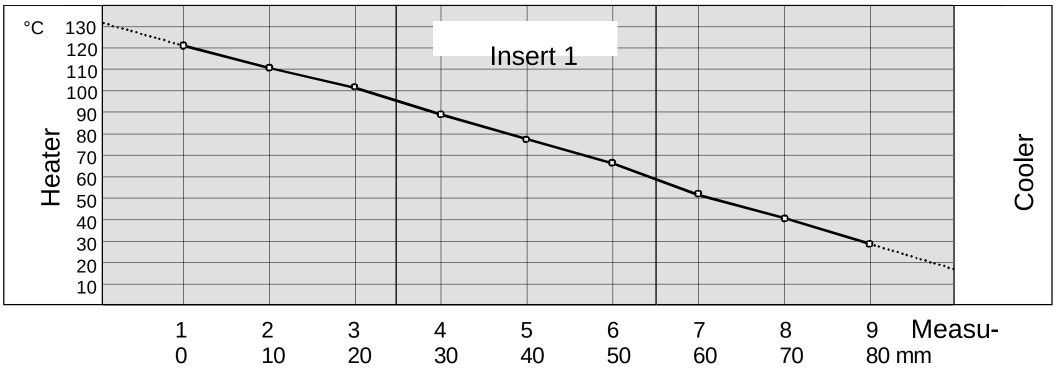


Fig. 5.1 Temperature Graph for Insert 1

5.1.1 Evaluation of the Test Results

The higher value for λ, compared to the values generally given in the literature $\lambda_{Brass} = 113\ W/(m \cdot K)$, results on the one hand from the loss of heat through the insulation, and on the other from increased thermal conduction at higher temperatures.

If the losses were = 0, the amount of heat required would be less and λ smaller. The magnitude of the loss depends on the size of the temperature difference to the ambient environment.

It can be seen in Table 5.1 that the coefficient of thermal conductivity λ falls with decreasing temperature.

It is therefore not possible to clearly identify how large the components are that lead to the increase in the coefficient of thermal conductivity λ.

Changes in the temperature line can be clearly seen in Fig. 5.1 at the contact points on the insert. The higher temperature differences $\Delta\vartheta$ and the lower coefficient of thermal conduction λ between measuring points 3-4 and 6-7 also result from this imperfect contact.

5.2 Linear Conduction With Insert 2

- Install insert 2 and adjust the cooling water flow rate.
- Switch on the unit and adjust the desired temperature drop via the power setting on the control and display unit.
- When the thermal conduction process has reached a steady state, note the measurement results at the individual measuring points and the electrical power supplied to the heater.

Insert 2 No Temperature Measuring Points	Measurement Section: Brass / Stainless Steel / Brass Diameter: 25mm 25mm 25mm Coefficient of Thermal Conduction*: 113 15 113 $W/(m \cdot K)$ Power: 20 Watt * at 20°C			
Measuring Point	Distance s in mm	Temperature ϑ in°C	Temperature Difference $\Delta\vartheta$ in K	Coefficient of Thermal Conduction λ in $\frac{W}{m \cdot K}$
1	-	99.3	-	-
2	10	98.9	-	-
3	20	97.6	-	-
Contact Point 1	25	~94	5.3	192.2
Contact Point 2	55	~29	65	18.8
7	60	28.4	-	-
8	70	25.8	-	-

Tab. 5.2 Measured Values Insert 2

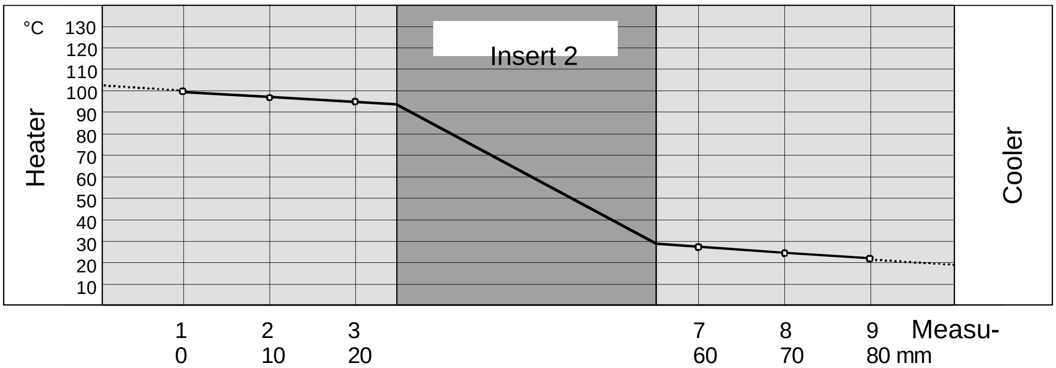


Fig. 5.2 Temperature Graph for Insert 2

5.2.1 Evaluation of the Test Results

The temperatures at contact points 1 + 2 have been removed from Fig. 5.2.
A value close to those generally quoted in the literature $\lambda_{Brass} = 113\ W/(m \cdot K)$ and $\lambda_{VA-Steel} = 15\ W/(m \cdot K)$ can also be seen here. The values are again slightly high, see sect. 5.1.1.
Since these measurements are performed in a sensitive region, the values for λ can only be determined over a longer section. Temperature inaccuracies due to sensor variations and displays then cause, with small deviations, relatively large errors that can no longer be interpreted. This can be seen by attempting to establish a value for λ between the initial measuring points.

5.3 Linear Conduction With Insert 3

- Install insert 3 and adjust the cooling water flow rate
- Switch on the unit and adjust the desired temperature drop via the power setting on the control and display unit.
- When the thermal conduction process has reached a steady state, note the measurement results at the individual measuring points and the electrical power supplied to the heater.

Insert 3 No Temperature Measuring Points	Measurement Section: Brass / Brass / Brass Diameter: 25mm 15mm 25mm Coefficient of Thermal Conduction*: 113 113 113 $W/(m \cdot K)$ Power: 23 Watt * at 20°C			
Measuring Point	Distance s in mm	Temperature ϑ in°C	Temperature Difference $\Delta\vartheta$ in K	Coefficient of Thermal Conduction λ in $\frac{W}{m \cdot K}$
1	-	99.8	-	-
2	10	98.4	-	-
3	20	96.1	-	-
Contact Point 1	25	~94	5.8	201.9
Contact Point 2	55	~35	59	66.2
7	60	31.2	-	-
8	70	28.4	-	-

Tab. 5.3 Measured Values for Insert 3

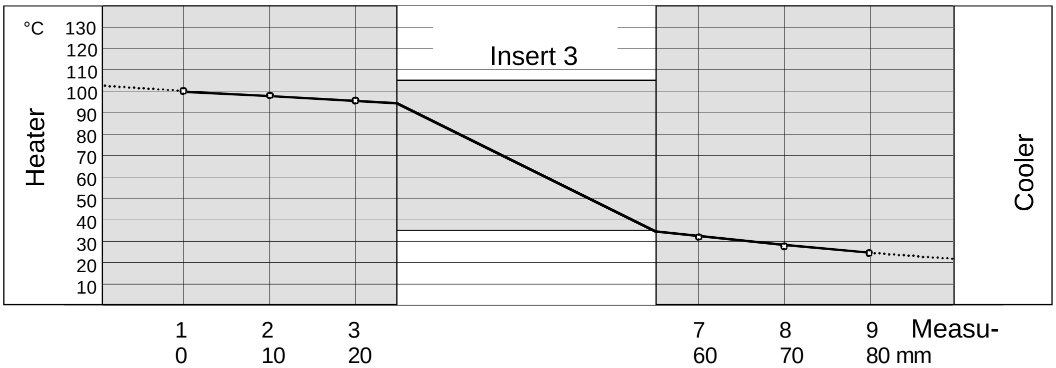


Fig. 5.3 Temperature Graph Insert 3

5.3.1 Evaluation of the Test Results

The temperatures at contact points 1 + 2 have been removed from Fig. 5.3.

A value close to those generally quoted in the literature $\lambda_{Brass} = 113\ W/(m \cdot K)$ can also be seen here for the large diameter D=25mm. The values are again slightly high, see sect. 5.1.1. The value of λ for the insert cannot be reached. The reason for this is the large discontinuity in the cross-section with imperfect contacts that significantly impair the flow of heat.

The measurements are also very sensitive in this case, the value for λ can therefore only be established over a longer section. Temperature inaccuracies due to sensor variations and displays then cause, with small deviations, relatively large errors that can no longer be interpreted. This can be seen by attempting to establish a value for λ between the initial measuring points.

5.4 Radial Conduction

- Set up the unit as per sect. 2.3 and adjust the cooling water flow rate (a cooling water flow rate of approx. 1l/h is required to dissipate a heater power of 90 Watts at a temperature difference of 90°C).
- Connect up the power and data cables appropriately.
- Switch on the unit and adjust the desired temperature drop via the power setting on the control and display unit.
- When the thermal conduction process has reached a steady state condition, i.e. the temperatures at the individual measuring points are stable and no longer changing, note the measurement results at the individual measuring points and the electrical power supplied to the heater.

Circular Disc as Hollow Cylinder	Measurement Section: Brass Diameter: 12 / 55mm Coefficient of Thermal Conductivity*: 113 $W / (m \cdot K)$ Power: 90 Watt * at 20°C			
Measuring Point	Distance r_a in mm	Temperature ϑ in°C	Temperature Difference $\Delta\vartheta$ in K	Coefficient of Thermal Conductivity λ in $\frac{W}{m \cdot K}$
1	-	84.9	-	-
2	10	71.9	13	not possible to calculate
3	20	55.2	16.7	148.6
4	30	44.4	10.8	134.4

Tab. 5.4 Measured Values for Radial Conduction

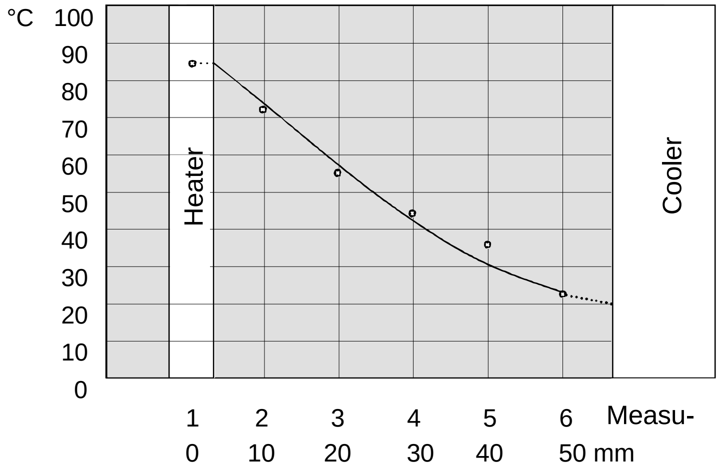


Fig. 5.4 Temperature Graph for Radial Conduction

5.4.1 Evaluation of the Test Results

A value close to those generally quoted in the literature $\lambda_{Brass} = 113\ W/(m \cdot K)$ can also be seen here. The values are again slightly high, see sect. 5.1.1.

5.5 Further Experiments

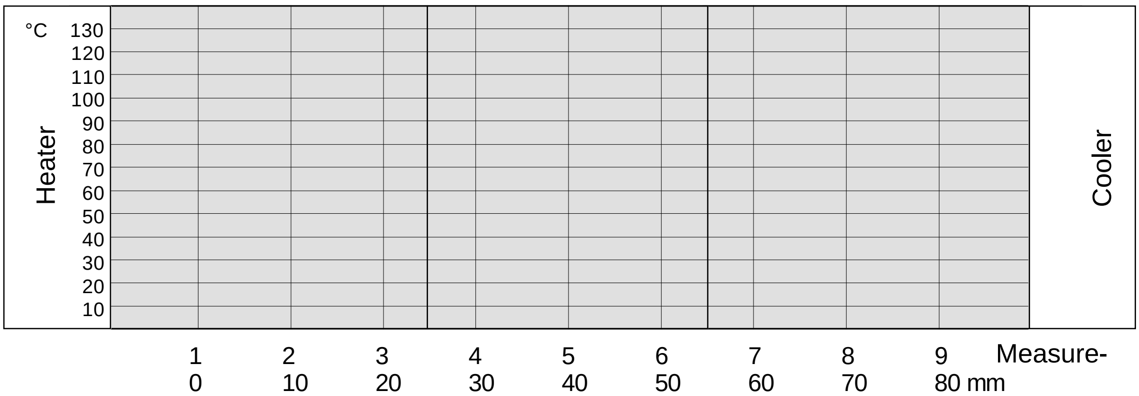
It is possible to perform further experiments by clamping paper, cork or thin metal sheet in place of the inserts. These intermediate pieces may make a poor contact, they should not be thicker than 1mm.

6 Appendix

6.1 Working Sheets

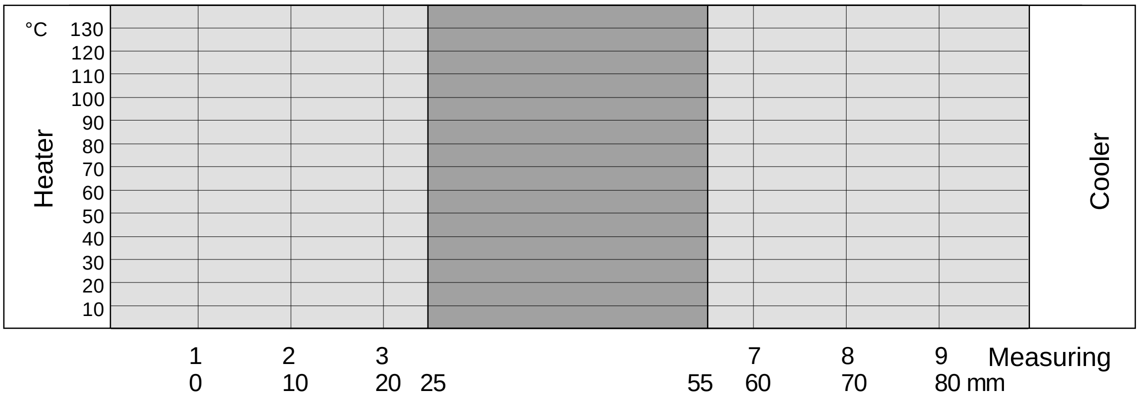
Linear Conduction with Insert 1

Insert 1 with 3 Temperature Measuring Points	Measurement Section: Brass / Brass / Brass Diameter: 25mm 25mm 25mm Coefficient of Thermal Conduction*: 113 113 113 $W / (m \cdot K)$ Power: Watt * at 20°C			
Measuring Point	Distance s in mm	Temperature ϑ in°C	Temperature Difference $\Delta\vartheta$ in K	Coefficient of Thermal Conduction λ in $\frac{W}{m \cdot K}$
1	-			
2	10			
3	20			
4	30			
5	40			
6	50			
7	60			
8	70			



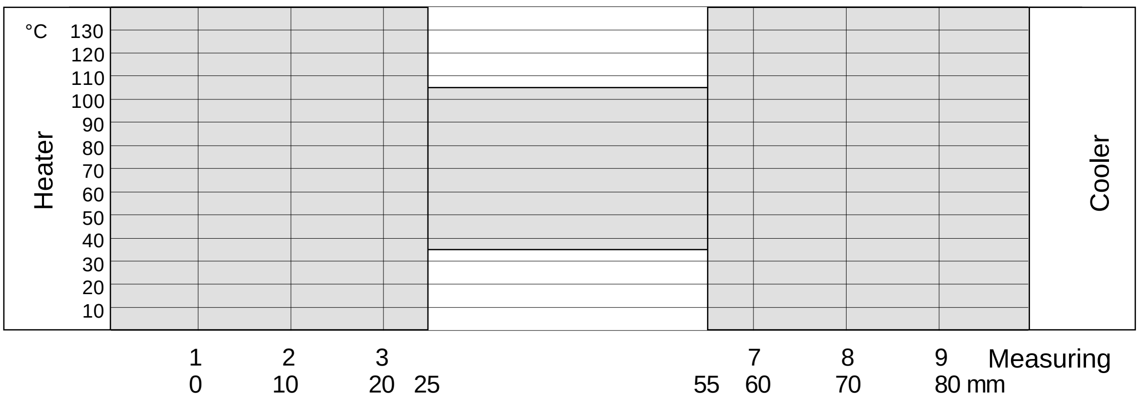
Linear Conduction with Insert 2

Insert 2 No Temperature Measuring Points	Measurement Section: Brass / Stainless Steel / Brass Diameter: 25mm 25mm 25mm Coefficient of Thermal Conduction*: 113 15 113 $W / (m \cdot K)$ Power: Watt * at 20°C			
Measuring Point	Distance s in mm	Temperature ϑ in°C	Temperature Difference $\Delta\vartheta$ in K	Coefficient of Thermal Conduction λ in $\frac{W}{m \cdot K}$
1	-			
2	10			
3	20			
Contact Point 1	25			
Contact Point 2	55			
7	60			
8	70			
9	80			



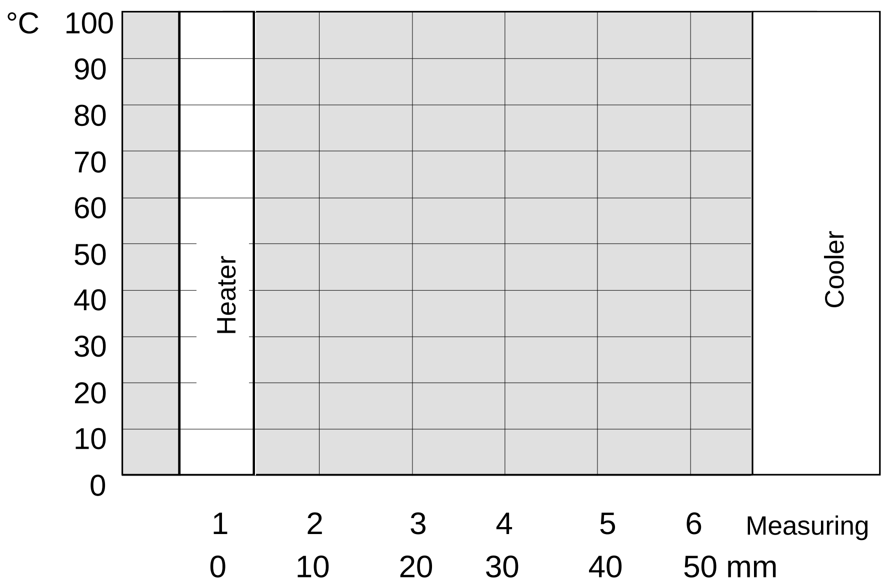
Linear Conduction with Insert 3

Insert 3 No Temperature Measuring Points	Measurement Section: Brass / Brass / Brass Diameter: 25mm 15mm 25mm Coefficient of Thermal Conduction*: 113 113 113 $W/(m \cdot K)$ Power: Watt * at 20°C			
Measuring Point	Distance s in mm	Temperature ϑ in°C	Temperature Difference $\Delta\vartheta$ in K	Coefficient of Thermal Conduction λ in $\frac{W}{m \cdot K}$
1	-			
2	10			
3	20			
Contact Point 1	25			
Contact Point 2	55			
7	60			
8	70			
9	80			



Radial Thermal Conduction

Circular Disk as Hollow Cylinder	Measurement Section: Brass Diameter: 12 / 25mm Coefficient of Thermal Conduction*: 113 $W/(m \cdot K)$ Power: Watt * at 20°C			
Measuring Point	Distance r_a in mm	Temperature ϑ in°C	Temperature Difference $\Delta\vartheta$ in K	Coefficient of Thermal Conduction λ in $\frac{W}{m \cdot K}$
1	-			
2	10			
3	20			
4	30			
5	40			
6	50			



6.2 Technical Data

Dimensions of the Study Unit:

Weight:	8	kg	
Height:		200	mm
Width:		350	mm
Length:		350	mm

Dimensions of the Control and Display Unit:

Weight:	4	kg	
Height:		195	mm
Width:		460	mm
Length:		345	mm

Mains Power:
Supply: 230V / 50Hz
Alternatives optional, see type plate
Fuse in the Control and
Display Unit: 4 A

Heater:

Power (radial):	125	Watt
Power (linear):	140	Watt

Temperature Sensors:

Type :	Pt100
Measurement Range:	0 to 100 °C

Insert 1:

Material:		Brass
Diameter:	25	mm
Length:	30	mm

Insert 2:

Material:	Stainless Steel 1.4305	
Diameter:	25	mm
Length:	30	mm

Insert 3:		
Material:		Brass
Diameter:	15	mm
Length:	30	mm

6.3 Bibliography

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