Experiment Instructions

WL 220 Boiling Heat Transfer Unit

Experiment Instructions

Last modification by: Dipl.-Ing. Peter Mittasch

This manual must be kept by the unit.

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

Table of Contents

1 Introduction

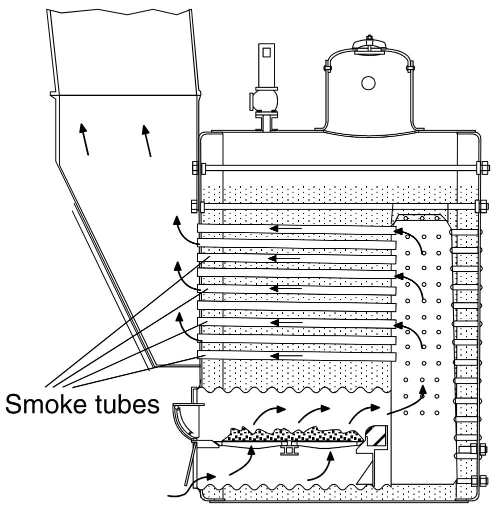


Fig. 1.1 Radiator tank boiler

Knowledge of the evaporation process is an essential requirement for the design and construction of steam generators.

The evaporation process on heated pipes as occurs, for example, in radiator tank boilers can be shown with the test rig **WL 220 Boiling Heat Transfer Unit** with PC-supported measured data acquisition. The different phases of boiling which occur on a smoke gas tube can particularly be seen here.

The various boiling forms are illustrated and the fundamentals of heat transfer can be clarified. It is also possible to experimentally investigate the influence of parameters such as temperature or pressure on the evaporation process.

The evaporation process occurs in a glass cylinder. The test rig is operated with a low-boiling, non-toxic evaporation fluid, so that the pressure and temperature levels are low and therefore not dangerous. The heating output is low due to the low evaporation heat.

2 Safety

2.1 Intended use

The unit is to be used only for teaching purposes.

2.2 Structure of safety instructions

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

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

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

Symbol	Explanation
	Electrical voltage
	Hazard (general)
	Explosive materials
	Gas canisters
	Notice

2.3 Safety instructions

⚠ WARNING

Reaching into the open control cabinet can result in electric shocks.

- Disconnect from the mains supply before opening.
- Work should only be performed by qualified electricians.
- Protect the control cabinet against moisture.

⚠ WARNING

Burns caused by escaping evaporation liquid are possible when filling / draining.

- Allow the system to cool down before filling / draining. Wear appropriate protective gloves.
- When handling evaporation liquid, wear protective goggles.
- Observe the safety recommendations for the evaporation liquid used.

⚠ WARNING

Injuries due to explosion are possible.

- No naked flames or fire are permitted in the vicinity of the evaporation liquid.

⚠ WARNING

Escaping evaporation liquid can cause shortness of breath.

- If large quantities of evaporation liquid escape in a confined room, ventilate thoroughly immediately and leave the room.

⚠ WARNING

Risk of injury.

Modification or adjustment of the safety features can make the experimentation stand unsafe. Do not make any modifications or adjustments to:

- Overheating protection (80 °C), adjustable on the large digital display
- Fuses (4 A)
- Protective covers
- Threaded fittings
- Pressure switch (1,8 bar)
- Safety valve (2 bar)

⚠ WARNING

Significant risk of injury due to defects.

Do not operate this system if there are obvious defects such as:

- Defective mains cable
- Leaks

Consult a specialist to repair the defect.

⚠ WARNING

Risk of injury from bursting parts.

Do not exceed the following limit values:

- Max. pressure in the glass cylinder: 3,2 bar abs.
- Max. surface temperature of the heater: 120 °C

NOTICE

Operate the unit only in dry closed rooms which contain no flammable or corrosive gases, vapours or dust. Drain the cooling water circuit if there is a risk of frost. During storage, keep the ventilation valve of the glass cylinder closed, otherwise liquid will be lost.

NOTICE

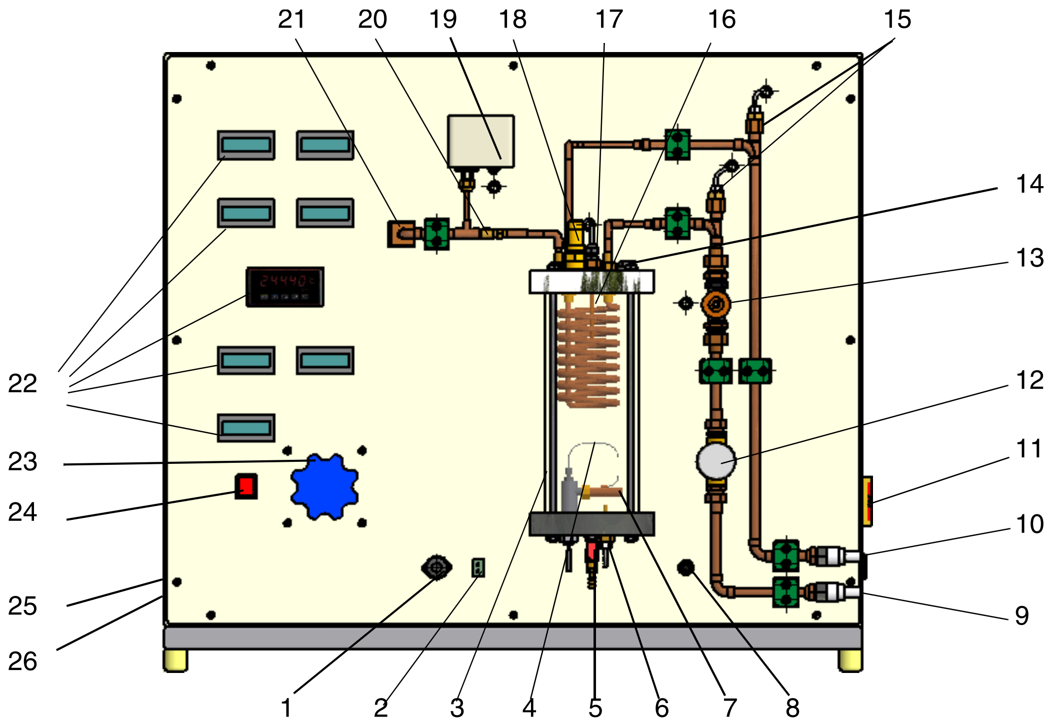
- Never switch on the heater if it is not surrounded by evaporation liquid. Otherwise, the surface load will be too great and the heater will be destroyed.

NOTICE

- When the connecting the cooling water, ensure that the intake and outlet are not mixed up. If the flow rate sensor is flowed through in the wrong direction, incorrect measurement results are obtained.
- The indicators have been designed for operation up to 120 ltr/h.

3 Description

3.1 Unit Layout

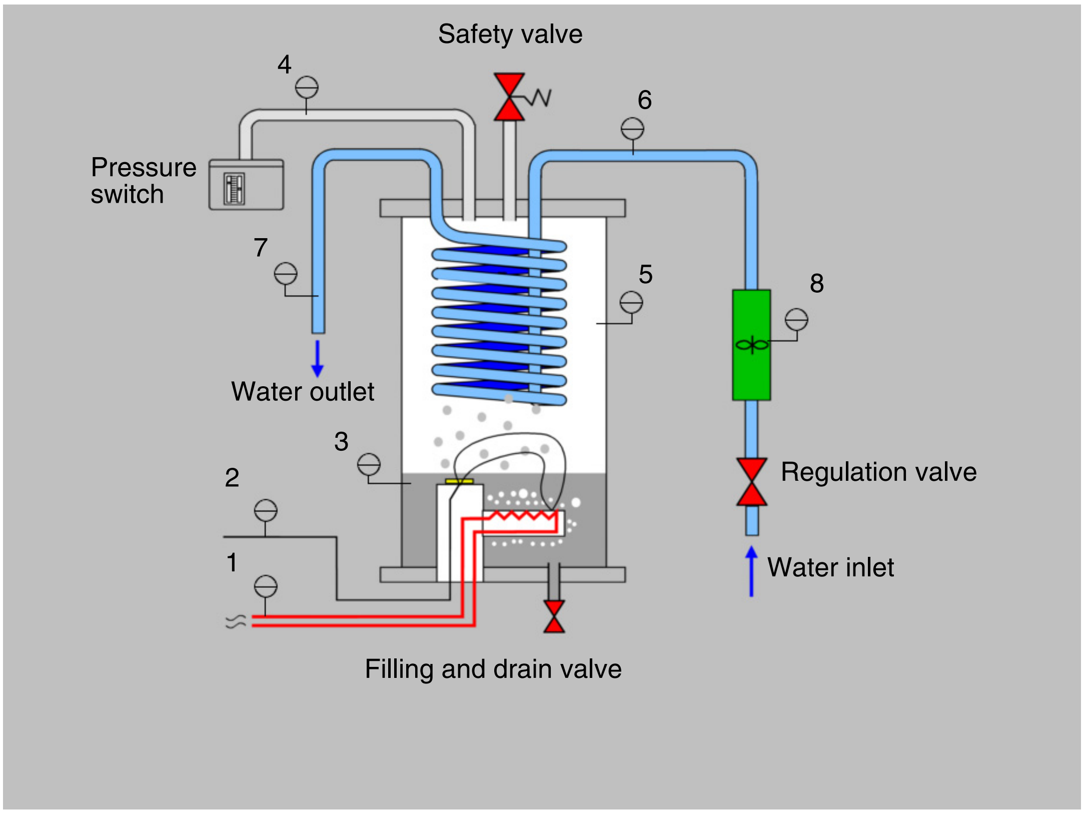


1	Electrical Connection Heater	14	Refilling screw
2	Connection temperature sensor heater surface	15	Temperature sensor
3	Glass cylinder	16	Water condenser
4	Thermocouple	17	Temperature sensor
5	Drain valve	18	Safety valve
6	Temperature sensor	19	Pressure switch
7	Heater	20	Air bleed valve
8	Connection Temperature sensor	21	Pressure transmitter (not visible)
9	Water inlet	22	Digital displays
10	Water outlet	23	Heater power adjuster
11	Main switch	24	On/Off switch heater
12	Regulating valve	25	USB port (edgewise)
13	Volumetric flow sensor (water)	26	Power supply port (edgewise)

Fig. 3.1 The illustration shows the layout of the components seen from the front

3.2 System Diagram

The arrangement of the sensors in the system can most easily be illustrated using a schematic diagram of the system



1	Heater power transmitter
2	Heater surface temperature sensor
3	Evaporation fluid temperature sensor
4	Evaporation tank pressure sensor
5	Vapour chamber temperature sensor
6	Water inlet temperature sensor
7	Water outlet temperature sensor
8	Volumetric flow sensor (water)

Fig. 3.2 Schematic diagram

3.3 Features of the Unit

The **WL 220 Evaporation Process** experimental stand is a laboratory unit for the investigation of evaporation processes.

An external water connection is fitted for condensation. The system has the following features:

- Clear arrangement of all components on a table support.
- A transparent tank allows the evaporation to be observed.
- Various sensors allow analysis of the heat transfer process.
- Measured values are shown on digital displays.
- Measured value display and analysis on a PC.
- Calculation of energy balances and key figures for heat transfer.

3.4 Commissioning

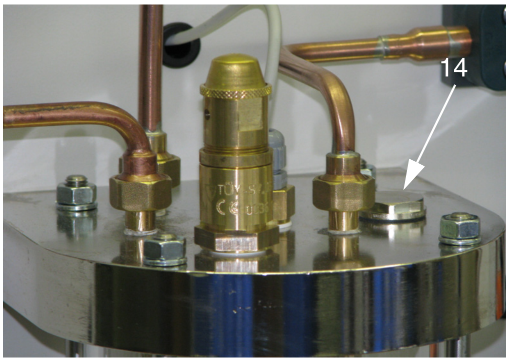


Fig. 3.3 Upper flange

To fill the glass cylinder with the evaporation fluid (SES 36) or compensate for any losses, proceed as follows:

- Unscrew refilling screw (14) at the upper flange of the glass cylinder.
- Gradually fill funnel with the evaporation fluid (cp. Fig. 3.4)

Fig. 3.4 Filling the glass cylinder

NOTICE

- Do not pour fluid onto the hands; at a body temperature of 36-37 °C, the fluid will evaporate immediately.

- Stop filling the tank when the fluid level is approx. 2-3 cm above the heater.
- Close refilling opening with refilling screw (14).

To start up the experimental stand, the system must be connected to a mains socket outlet (e.g. 230 V/ 50 Hz).

When the master switch is pressed, only the displays initially light up. The heater is started up using a separate switch. The power is set to the desired level using a potentiometer.

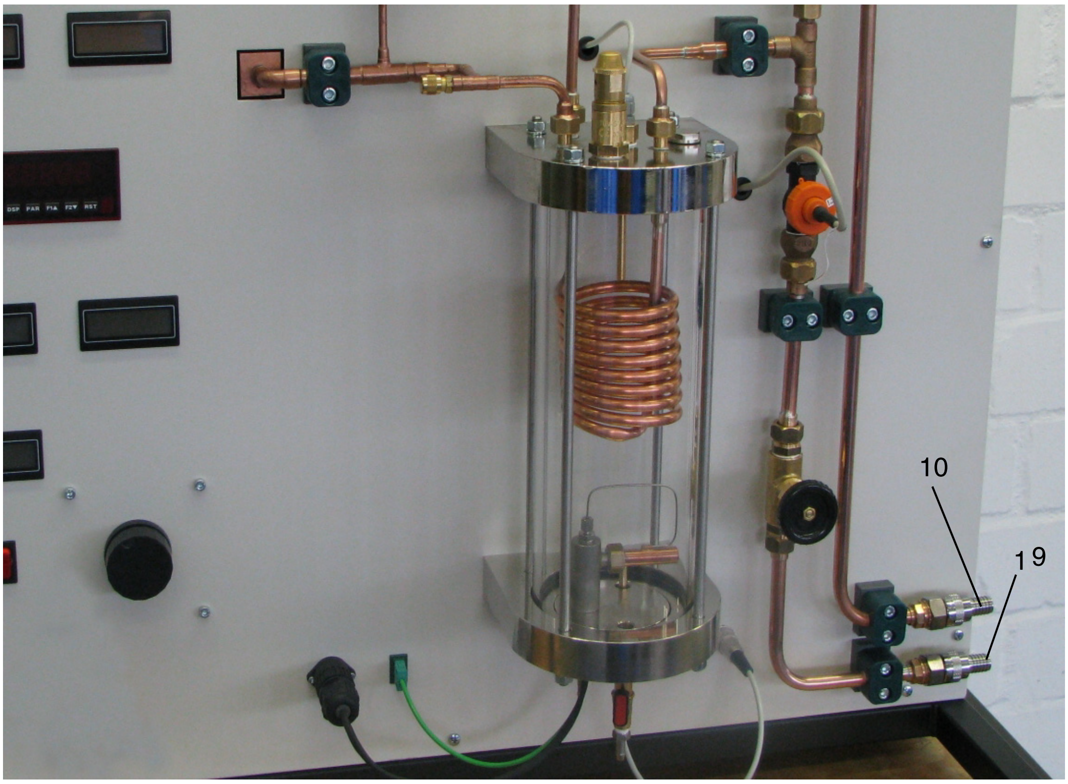


Fig. 3.5 Water connection for condenser

To condense the evaporated fluid again, the condenser must be connected to an external cold water network. To do this, the inlet (9) is connected to a water tap using a hose. The outlet (10) should also be connected to a drain using a hose.

3.5 Software

The software permits investigation of the processes occurring in heat transfer on a PC. It includes options for saving data and printing out clear diagrams and curves. This helps the user to understand the processes taking place as well as the theoretical background.

3.5.1 System requirements

- PC with Pentium IV, 1 GHz
- min. 1 GB HDD space
- 1024 MB RAM
- CD-ROM drive
- Graphics resolution 1024 x 768, TrueColor
- USB port 1.1
- Operating system Windows XP / 2000 / Vista

3.5.2 Software installation

The following is needed for the installation:

– A fully operational PC, laptop or notebook with a USB port.

– G.U.N.T. CD-ROM

NOTICE

- All components necessary to install and run the program are contained on the CD-ROM shipped by G.U.N.T. along with the **WL 220**.

After starting, the installation runs automatically. During the course of the installation, various program components are loaded onto the PC:

- LabVIEW® - runtime program for PC data acquisition
- Driver routines for the “LabJack®” USB converter

NOTICE

- The WL220 must not yet be connected to the PC’s USB port while the program is being installed. Only after the software has been installed may the USB hardware be connected.

- Boot the PC
- Load the G.U.N.T. WL220 CD-ROM

Start the “**Setup.exe**” installation program from the “**Installer**” folder.

- Follow the installation procedure on-screen.
- Reboot the PC after the installation is finished.

Once the software has been installed, the program can be called up by selecting

“Start / All Programs / G.U.N.T. / WL220”.

The first time the program is started, a dialogue box opens to specify the language.

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

4 Basic Principles

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

4.1 Evaporation

The liquid which has been heated up to boiling temperature in a heated vessel with a low heating surface load moves upwards due to upwelling and evaporates mainly at the surface. Hardly any vapour bubbles form at the heating surface. At the same time, heat transfer coefficients occur, as in **free convection.** The heat transfer coefficient α increases with the heating surface load which in turn increases with the temperature gradient between the heating surface and the liquid.

In the case of a marked heating surface load, more vapour bubbles occur directly at the heating surface and these rise upwards, significantly improving the heat transfer coefficient as a result of an agitation effect. This type of evaporation is also known as **nucleate boiling.**

From a critical heating surface load onwards, the heat transfer coefficients become smaller, because a film of vapour forms between the heating surface and the liquid and acts as an additional thermal resistor. α is reduced very noticeably in the area of unstable **film boiling** as the temperature gradient between the surface and liquid increases, and again reaches approximately the value it was at during free convection.

After the film boiling stabilizes, α continues to increase only insignificantly as the temperature gradient increases. The heating surface load falls in the area of unstable film evaporation as the temperature gradient increases, and rises again when the stable film boiling is reached.

The individual areas are shown in the diagram below, using the example of water.

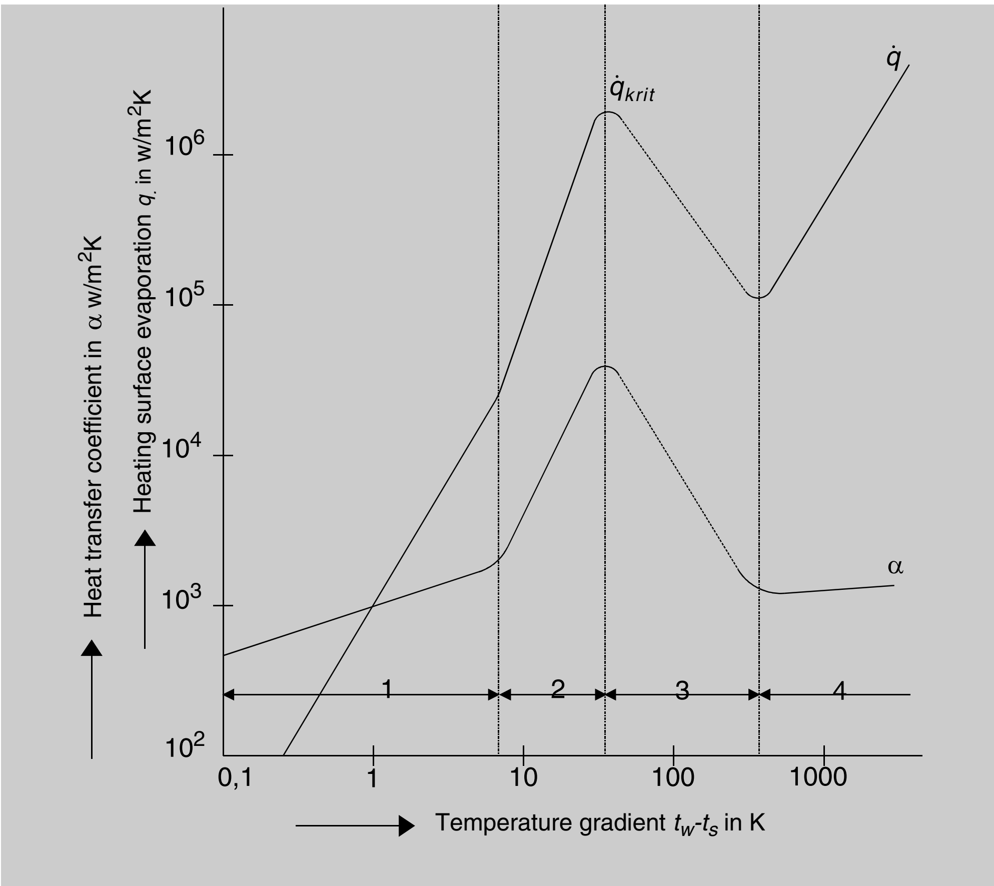


Fig. 4.1

Boiling phases:

1. Free convection
2. Nucleate boiling
3. Unstable film boiling
4. Stable film boiling

4.2 Condensation

At wall temperatures t_W below the saturation temperature t_S of a vapour in contact with the wall, the vapour begins to condense, even if the mean vapour temperature is still above the saturation temperature. The condensation can run down the wall as a liquid film or in drops.

4.3 Steam Pressure as a Function of the Temperature

The relationship between pressure and temperature is expressed by the Clapeyron-Clausius formula in the boundary changeover from liquid to gas:

$$r = h'' - h' = T \cdot (s'' - s') = T \cdot (v'' - v') \cdot \frac{dp}{dT} \quad (4.1)$$

If the gas is regarded as approximately ideal, the following is obtained if the volume v' of the liquid phase is ignored and with the gas equation

$$v'' \approx \frac{R \cdot T}{p} \quad (4.2)$$

$$r = h'' - h' \approx \frac{R \cdot T^2}{dT} \cdot \frac{dp}{p} \quad (4.3)$$

Transformed:

$$\frac{r}{R \cdot T^2} \cdot dT = \frac{1}{p} \cdot dp \quad (4.4)$$

Integrated:

$$\int \frac{r}{R \cdot T^2} \cdot dT = \int \frac{1}{p} \cdot dp \tag{4.5}$$

Result:

$$p = e^{-\frac{r}{R \cdot T}} \tag{4.6}$$

Since the relationship between the temperature and pressure is only identifiable with difficulty from this equation. The following diagram shows the steam pressure over the temperature.

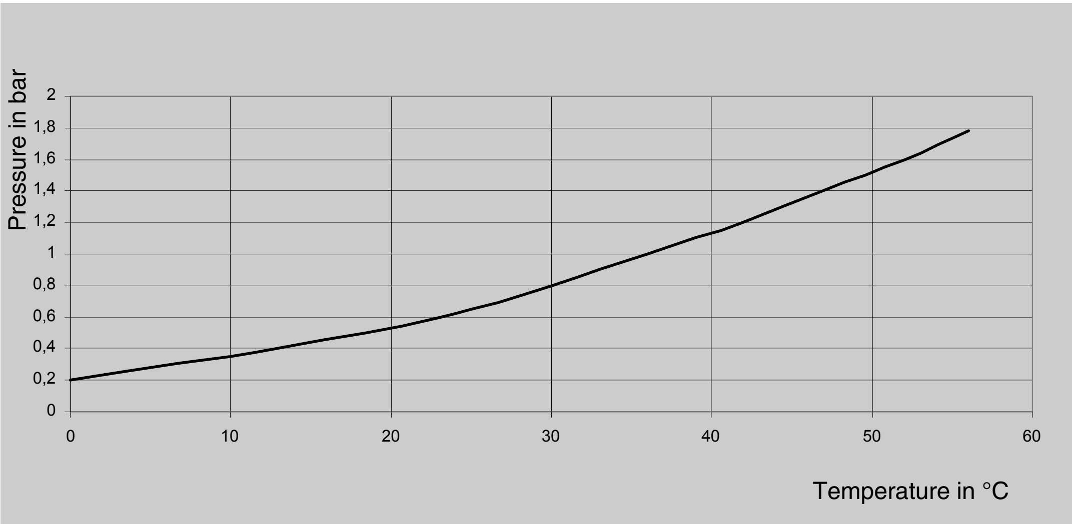


Fig. 4.2 Steam pressure over temperature (SES 36)

4.4 Heat Transfer

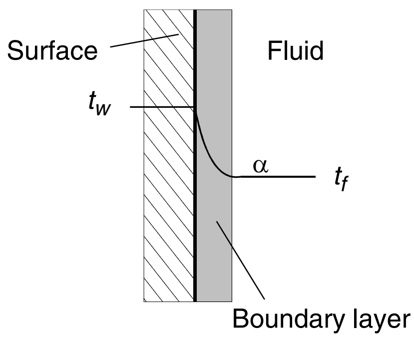


Fig. 4.3

Heat transfer is defined as the heat transmission between moving liquids or gases and a stationary wall. The heat flow absorbed by a fluid with the mean temperature t_f at a wall surface A with a surface temperature of t_w is determined on the basis of a relationship defined by Newton:

$$\dot{Q} = \alpha \cdot A \cdot (t_w - t_f) \qquad (4.7)$$

The proportionality factor α is designated the heat transfer coefficient. Its unit is $\frac{W}{m^2 K}$.

α depends in a complex way on very different influencing variables which are determined by the physical properties and the flow state of the fluid and by the geometric shape of the heating surfaces.

A further measurement for the heat transfer from a heated body to a fluid is the heat transfer resistance:

$$R_{ü} = \frac{t_w - t_f}{\dot{Q}} = \frac{1}{\alpha A} \qquad (4.8)$$

5 Experiments

In the following chapter, examples of a few procedures for experiments are described which can be carried out with this unit. The choice of experiments does not claim to be complete. Rather, it is intended to give you ideas for your own series of experiments.

The listed measurement results must not be regarded as guideline or calibration values to be adhered to under all circumstances. Depending on the design of the individual components and experimental skill, as well as the evaporation liquid used, greater or lesser deviations can occur in your experiments.

NOTICE

- During the experiments always operate the condenser.
- When starting up the condenser, the formation of steam bubbles is normal.

5.1 Experiment Preparation

The glass cylinder should be ventilated before the experiment.

After filling, evaporation liquid is at the bottom of the container, with air at the top. To remove the air, first set the heating capacity to 250W.

In this case the water condenser is not running.

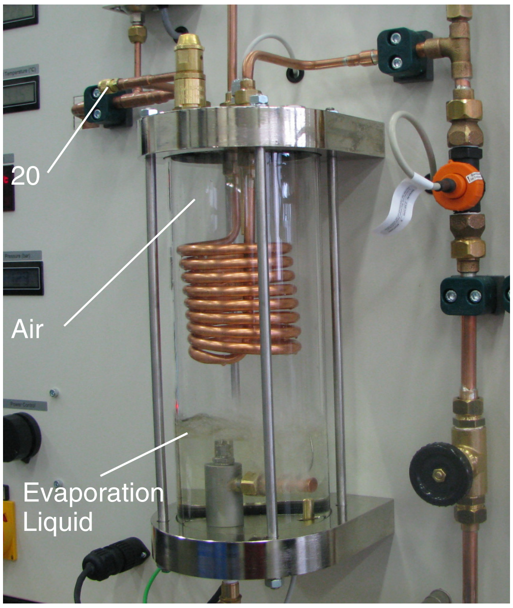


Fig. 5.1 Evaporation vessel

NOTICE

- Never switch on the heater if it is not surrounded by evaporation liquid. Otherwise, the surface load will be too great and the heater will be destroyed.

The liquid evaporates at the heater surface (nucleate boiling). The pressure in the cylinder rises.

At a pressure of approx. 1,2 bar abs., unscrew the protection cap of the air bleed valve (cp. Fig. 5.1, Page 21, 20). Open the air bleed valve with a prick by pushing the inner piston.

Keep the valve open until a liquid film runs down on the glass cylinder (liquid condensing).

Then close the air bleed valve and screw on the protection cap.

⚠ WARNING

Burns caused by escaping evaporation liquid are possible when filling / draining.

- Allow the system to cool down before filling / draining. Wear appropriate protective gloves.
- When handling evaporation liquid, wear protective goggles.
- Observe the safety recommendations for the evaporation liquid used.

There is now only liquid and vapour in the container. After switching off the heater and letting the container cool down for a while, the internal pressure drops to approx. 0,6 bar abs.

If this is not the case, repeat the venting procedure.

5.2 Evaporation

A heating capacity of 10 W is set at the start of the experiment. If the pressure in the container before the start of the experiment was 0,58 bar abs., this now rises slowly. No bubbles form on the surface of the heater. However, the pressure rise indicates evaporation. If you carefully observe the surface of the liquid, the formation of small bubbles can be seen. This is free convection. The surface temperature of the heater rises to approx. 31,4 °C.

After the heating capacity is increased to 60 W, the surface temperature initially rises to approx. 40 °C. Small bubbles then form on the heater surface. At the same time, the surface temperature falls to 36,4 °C due to improved circulation. This temperature corresponds to a steam pressure of approx. 0,72 bar abs.

When the heating capacity is increased to 100 W, the following operating values are set after a period of more pronounced bubble formation:

Absolute pressure:	p = 0,93 bar abs.
Surface temperature:	t_W = 43,7 °C
Liquid temperature:	t_f = 33,9 °C
Steam temperature:	t_D = 35,8 °C

The following heating surface load is obtained from the heating capacity used and the surface of the heater:

$$\dot{q} = \frac{\dot{Q}}{A} \tag{5.1}$$

$$\dot{q} = \frac{100\text{W}}{0,001875\text{m}^2} = 53{,}33 \cdot \frac{\text{kW}}{\text{m}^2} \tag{5.2}$$

The heat transfer coefficient α is calculated with the following formula:

$$\alpha = \frac{\dot{Q}}{A \cdot (t_w - t_f)} \tag{5.3}$$

$$\alpha = \frac{100\text{W}}{0,001875\text{m}^2 \cdot (43,7°\text{C} - 33{,}9°\text{C})} = 5442{,}2 \cdot \frac{\text{W}}{\text{m}^2\text{K}} \tag{5.4}$$

The value below is obtained for the heat transfer resistance $R_ü$:

$$R_ü = \frac{t_w - t_f}{\dot{Q}} = \frac{1}{\alpha A} \tag{5.5}$$

$$R_ü = \frac{43{,}7°\text{C} - 33{,}9°\text{C}}{100\text{W}} = 0{,}098 \cdot \frac{\text{K}}{\text{W}} \tag{5.6}$$

$$R_ü = \frac{1}{5442{,}2 \cdot \frac{\text{W}}{\text{m}^2\text{K}} \cdot 0,001875\text{m}^2} = 0{,}098 \cdot \frac{\text{K}}{\text{W}} \tag{5.7}$$

5.3 Condensing

If the cooler is put into operation at a heating capacity of 107 W and if it is flowed through with a constant volumetric flow of 41 l/h (set with the regulating valve), the following operating values can be read off:

Absolute pressure:	$p =$	0,61 bar abs.
Surface temperature:	$t_W =$	34,6°C
Liquid temperature:	$t_f =$	24,2°C
Steam temperature:	$t_D =$	22,4°C
Water intake temperature:	$t_1 =$	20,2°C
Water outlet temperature:	$t_2 =$	21,9°C

These values give a Cooling capacity of:

$$\dot{Q}_K = \dot{m}_w \cdot c_{p_w} \cdot (t_2 - t_1) \tag{5.8}$$

$$\dot{Q}_K = 41 \cdot \frac{\mathrm{dm}^3}{\mathrm{h}} \cdot 1 \cdot \frac{\mathrm{kg}}{\mathrm{dm}^3} \cdot 4{,}198 \cdot \frac{\mathrm{kJ}}{\mathrm{kgK}} \cdot (21{,}9°\mathrm{C} - 20{,}2°\mathrm{C}) = 81\,\mathrm{W} \tag{5.9}$$

with a mean water temperature of:

$$\overline{t}_w = t_1 + \frac{t_2 - t_1}{2} \tag{5.10}$$

$$\overline{t}_w = 20{,}2\,°C + \frac{21{,}9\,°C - 20{,}2\,°C}{2} = 21\,°C \tag{5.11}$$

With the given cooler surface A_K, we then obtain a heat throughput coefficient of:

$$k = \frac{\dot{Q}_K}{A_K \cdot (t_D - \overline{t}_w)} \tag{5.12}$$

$$k = \frac{81\,W}{0{,}0578\,m^2 \cdot (22{,}4\,°C - 21\,°C)} = 1000{,}1 \cdot \frac{W}{m^2K} \tag{5.13}$$

Between the steam chamber and the water, there also results a mean logarithmic temperature difference of:

$$\Delta T_m = \frac{t_2 - t_1}{ln \cdot \frac{(t_D - t_1)}{(t_D - t_2)}} \tag{5.14}$$

$$\Delta T_m = \frac{21{,}9\,°C - 20{,}2\,°C}{ln \cdot \frac{(22{,}4\,°C - 20{,}2\,°C)}{(22{,}4\,°C - 21{,}9\,°C)}} = 1{,}15\,K \tag{5.15}$$

5.4 Film boiling

To illustrate film boiling, a heating power of 250 Watt is set. Initially, no change is apparent on the heater. However, after a few seconds small clusters of bubbles appear. Shortly afterwards, the entire heater is covered with small and large bubbles. The surface temperature only rises slowly. At a value of around 50 °C, film boiling begins around the heating element. The bubbles disappear and a gas covering is formed around the outside of the heater, preventing it from giving off its heat to the surrounding liquid. The gas covering extends to the tip of the heater, where the thermocouple that measures the surface temperature is located. When the entire heater is surrounded by the gas (or vapour) film, the surface temperature rises very rapidly. At a value of 80 °C, the heater is automatically shut down. This is done to prevent it being destroyed by a lack of cooling. Despite the heater being shut down, the surface temperature continues to rise, to a value of around 90 °C. Film boiling can be seen for several minutes more.

NOTICE

- To speed up cooling, water can be fed through the condenser. After the heater has been automatically shut down, the ON/OFF switch for the heater should be set to the OFF position so that the heater will not be switched back on, allowing the cooling process to be observed in detail.

6 Appendix

6.1 Technical data

Main dimensions:

Width:	900 mm
Depth:	450 mm
Height:	895 mm
Weight:	65 kg

Supply: 230 V / 50 Hz, 4 A

Optional alternatives, see rating plate

Heater

Rating: continuously adjustable	250 W
Surface area:	0,001875 m^2

Water cooler

Number of coils:	9
Coil diameter:	80 mm
Surface area:	approx. 0,0578 m^2

Pressure transmitter

Measuring range:	0 ... 4 bar abs.
Output signal:	0 ... 10 V DC
Supply:	24 V DC

Power transmitter

Measuring range:	0 ... 300 W
Output signal:	0 ... 10 V DC
Supply:	+/- 15 V DC

Flow sensor with transmitter (water)

Measuring range:	3 ... 108 ltr/h
Output signal:	0 ... 5 V DC
Supply:	24 V DC

Thermocouple with display and transmitter

Measuring range:	0 ... 200 °C
Output signal:	0 ... 10 V DC
Supply:	230 V AC

Temperature sensors with transmitter

Measuring range:	0 ... 100 °C
Output signal:	0 ... 10 V DC
Supply:	24 V DC
Digital displays	
Measuring range:	0 ... 200 mV DC
Supply:	5 V DC

Evaporation fluid

Name:	Pentafluorobutane / Perfluoropolyether	
Trade name:	Solkatherm SES 36	
Molecular weight:	184,5	kg/kmol
Boiling point at po= 1013 mbar:	36,7	°C
Critical temperature:	177,4	°C
Critical pressure:	28,4	bar
Density Liquid (saturated) at 25°C	1363	kg/m^3
Density Vapour (saturated) at 25°C	5,8	kg/m^3
Heat of Vaporisation at 25°C	117,8	kJ/kg
Specific Heat Capacity (Liquid) at 25°C	1,25	kJ/kgK

For further information please refer to Safety Data Sheet.

6.2 Symbols and units

α	Coeffizient of heat transfer	W/m^2K
A	Surface	m^2
cp	Specific heat capacity	kJ/kgK
h	Specific enthalpy	kJ/kg
$\dot{m}_w$	Water mass flow rate	kg/s
p	Pressure	bar
$\dot{Q}$	Heating capacity	W
$\dot{Q}_K$	Cooling capacity	W
$\dot{q}$	Surface power density	W/m^2
R	Gas constant	kJ/kgK
$Rü$	Heat transfer resistance	K/W
r	Evaporation heat	kJ/kgK
s	Entropy	kJ/kgK
T	Absolute temperature	K
t	Temperature	°C
$\bar{t}_w$	Average water temperature	°C
ΔTm	Average logarithmic temperature difference	K
v	Specific volume	m^3/kg
$\dot{V}_w$	Water volumetric flow rate	ltr/h

6.3 Formulas used in software

Temperature difference, heating surface - fluid:

$dT_{5\text{-}4} = T5 - T4$ in K

Cooling water temperature difference:

$dTwater = T2 - T1$ in K

Heating capacity:

$\dot{Q} = P$ in W

Surface power density:

$\dot{q} = \frac{\dot{Q}}{A}$ in kW/m^2 (*dq* in software)

with $\dot{Q}$ in kW

A in m^2

Heater coefficient of heat transfer:

$\alpha = \frac{\dot{Q}}{A \cdot (T5 - T4)}$ in W/(m^2 K)

with $\dot{Q}$ in W

A in m^2

T in K

Cooling capacity:

$$Q_k = \dot{V} \cdot \rho \cdot c_{pw} \cdot (T2 - T1) \cdot \frac{1000}{3600} \text{ in W}$$

where

$\dot{V}$ in ltr/h

ρ in kg/dm^3

$c_{pw} = 4{,}182$

T in K

Average logarithmic temperature difference:

$$\Delta T_M = \frac{t_2 - t_1}{\ln\frac{t_D - t_1}{t_D - t_2}} \text{ in K } (dTm \text{ in software})$$

with t_1, t_2, t_3 in C

$t_D = t_3$ = Vapour temperature

Outward heat transfer coefficient:

$$k = \frac{\dot{Q}_K}{A_K \cdot (t_D - \overline{t}_w)} \text{ in W/(m}^2\text{ K)}$$

where

$t_D = t_3$ = Vapour temperature

$\overline{t}_w$ = Average water temperature

A = 0,0578 m^2 total surface area

6.4 Index

O

P

R

S

U

V

W