Experiment Instructions

WL 230 Condensation Unit

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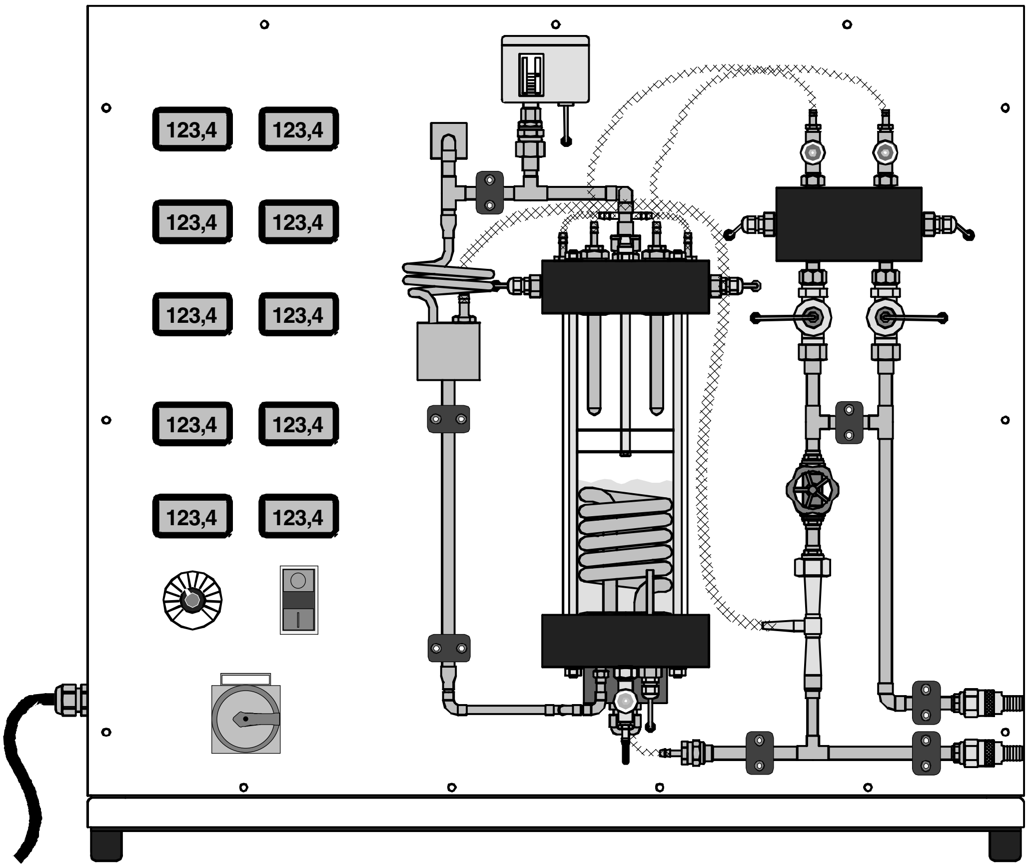

Experiment Instructions

Please read and follow the safety instructions before the first installation

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1 Introduction

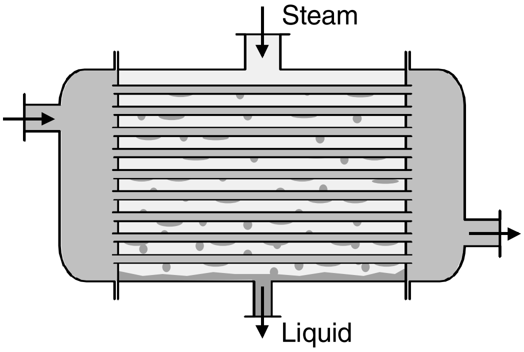


Fig. 1.1 Construction of a Condenser

Knowledge of the process of condensation is an important prerequisite for the design and construction of **Condensers** in power plants and processing plants.

With the **WL230 Condensation Process with PC-based Data Acquisition** test stand, the process of condensation on cooled pipes can be made visible. In particular, the different forms of condensation, that is **drop and film condensation,** can be demonstrated.

Furthermore, the **influence** on the condensation process of the **pressure, temperature and air content** of the steam can be investigated experimentally.

The condensation process takes place in a glass cylinder so that the action of condensation is clearly visible.

The test stand is operated with **distilled water** in a vacuum. This enables the temperature to be kept under 100°C and the results to be easily related to practice. Furthermore, there are no storage or disposal problems as is the case with special low boiling point liquids.

The test stand is intended for use in the **educational and experimental sectors**.

2 Unit Description

2.1 Unit Construction

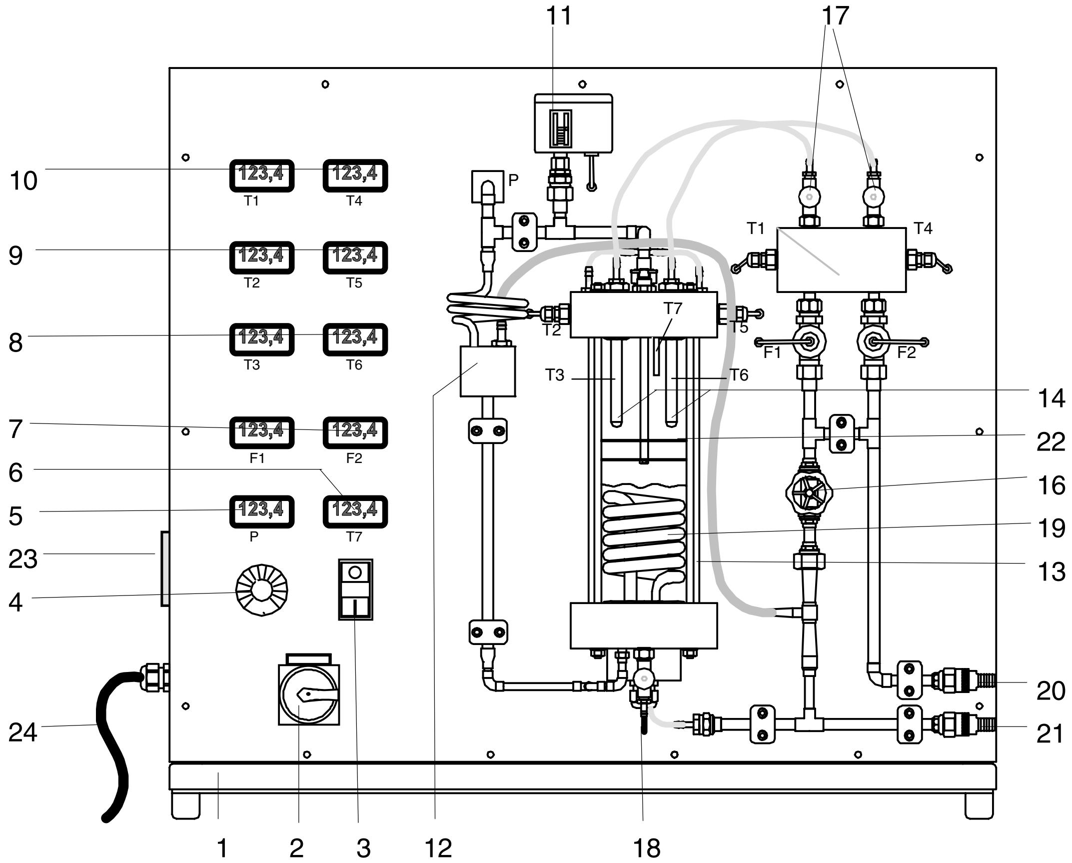


Abb. 2.1 View of the Test Stand

1 Table Top Stand
2 Main Switch
3 Heater Switch
4 Heater Power Adjuster
5 Vessel Pressure Display
6 Vessel Temperature Display T7
7 Cooling Water Flow Rate Displays F1, F2
8 Temperature Displays Condenser Surface T3, T6
9 Temperature Displays Cooling Water Outlet T2, T5
10 Temperature Displays Cooling Water Inlet T1, T4
11 Pressure Switch
12 Condensate Separator
13 Vessel
14 Condenser Pipes
15 Vacuum Pump (inside the cabinet)
16 Vacuum Pump Adjustment Valve
17 Cooling Water Control Valve
18 Vessel Fill and Drain Valve
19 Heater
20 Cooling Water Feed
21 Cooling Water Return
22 Drop Collector
23 Socket for PC Interface
24 Mains Connection

The test stand is designed as a **table top unit**. All components, controls and displays are arranged in a clear manner on a panel. A **schematic diagram** makes the function of the unit easier to understand.

All parameters are **measured electronically** and displayed digitally.

In addition, the measured parameters are fed to a multi-way connector on the side of the housing as 0-5 V signals. Using a ribbon cable, the test stand can be connected from here to a **Data Acquisition Card**.

The entire electrical circuitry is protected behind the panel.

2.2 System Schematic Diagram

The **function of the system** is explained with the aid of the system schematic diagram.

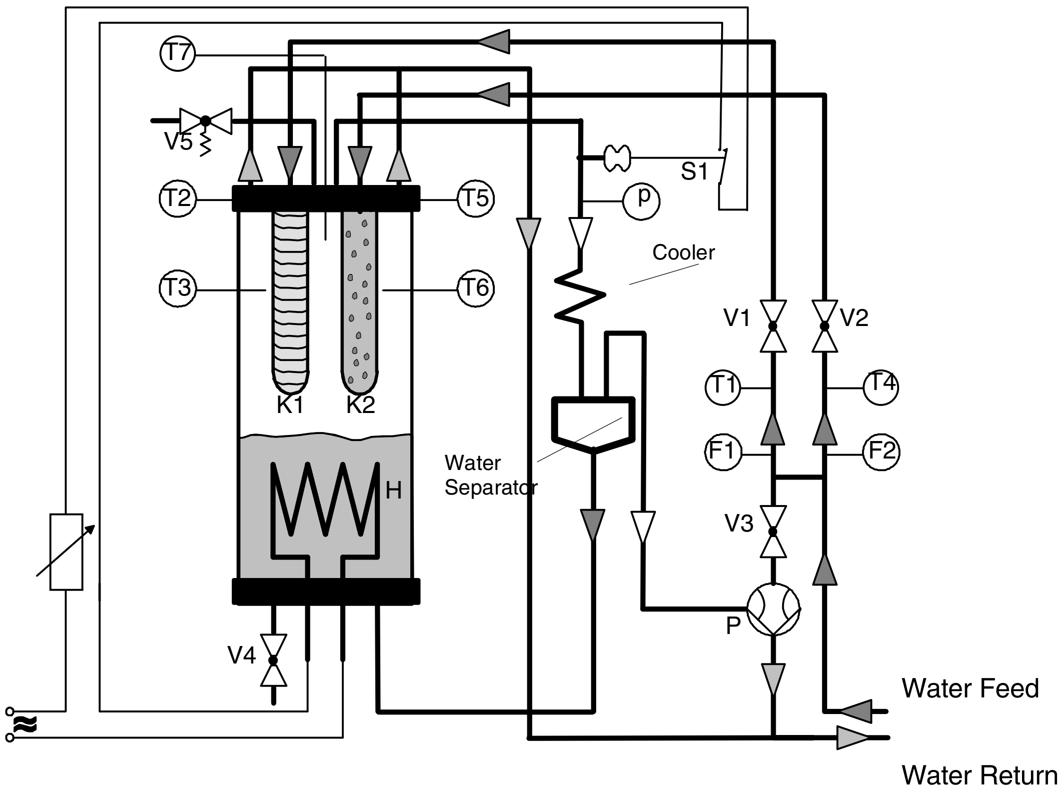


Abb. 2.2 System Schematic Diagram

The two **condenser pipes** K1, K2 are fitted in the upper part of the vessel. Cooling water flows through the inside of the pipes in immersion tubes. The heat given off by the steam at the condensation pipes can be determined from the measurement of the feed and return temperatures (T1, T2 and T4, T5) and the mass flow rate (F1 and F2). The cooling water flow rate is adjusted via the control valves V1 and V2.

The **heater** H is in the lower part of the vessel; the output power of the heater is adjustable. The temperature of the vapour is measured via T7, and the absolute pressure in the vessel via p. A safety valve V5 prevents the build up of excessive over pressure. The pressure switch S1 switches off the heater in the event of excessive overpressure.

The vessel can be evacuated using the **water jet pump** P. For this purpose water is fed to the pump via the control valve V3. A non return valve built into the water jet pump prevent water flowing back into the vessel. In order to prevent the escape of steam and thus the loss of water, the suction pipe is fitted with cooling system and a water separator. The water drawn off is fed back into the vessel.

The vessel can be filled with distilled water and drained via the valve V4.

2.3 Condenser Construction

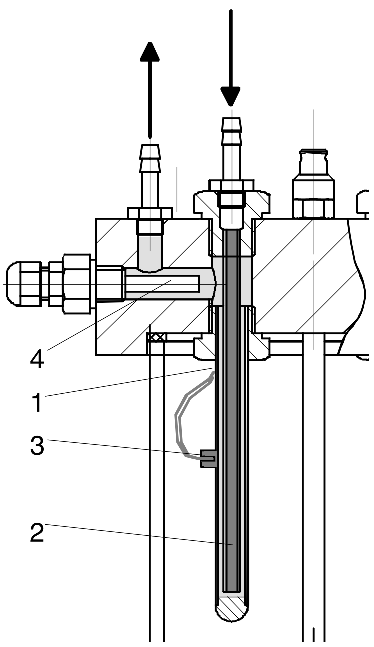


Abb. 2.3 Condenser Pipe

The two condenser pipes (1) are mounted in the lid of the vessel.

Cooling water flows through them lengthways. On entry, the cooling water is fed through an immersion tube (2) to the lower end of the condenser pipe and then rises up the inner wall. This type of construction ensures even cooling over the entire length of the condenser pipe. The copper material used improves the evenness of the temperature distribution due to its high thermal conductivity.

The surface temperature is measured via a type K thermocouple (3). The right hand condenser is polished and gold plated so as to achieve drop condensation. The surface of the left hand condenser is made of copper and has a matt finish. Film condensation will occur here.

The outlet temperature of the cooling water is measured with a PT100 (4) in the lid.

Dimensions of the Condenser Pipe

Outer Diameter:	12 mm
Cooled Length:	96 mm
Surface Area Cooled:	36.18 cm^2

2.4 Commissioning

- Place the unit on a table.
- Make the water feed and return connections using 1/2" hose. Suitable quick action couplings are supplied.

  Water Pressure Required

At Least	1 bar

  Flow Rate Required

Continuous:	400 l/h
Peak:	1200 l/h

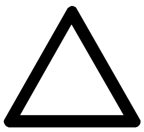
- Connect up to the electrical supply and switch on at the main switch.

2.4.1 Filling the Vessel

- Connect a hose to the drain valve and submerge the end in distilled water.
- Close drain valve V4.
- Start the water jet pump via V3 and evacuate the vessel to 0.3 bar.
- Open drain valve V4. The distilled water is drawn into the vessel. Fill the vessel to the mark (approx. 1- 2 cm above the heater element).

ATTENTION

IMPORTANT! Only use clean distilled water. Impure water will cause deposits on the condenser. These will prevent the formation of drop condensation.



ATTENTION

IMPORTANT! **The water level in the vessel must be at least 1cm above the heater element, otherwise the heater will overheat**.

There is a risk that the heater will burn out.

Add more water before the level in the vessel drops too far.

2.4.2 Removing the Air

- Evacuate the cold vessel down to 0.3 bar using the water jet pump .
- Switch on the heater and heat up to around 80°C (T7) at half power (50%).
- Restart the water jet pump. As the pressure drops the water starts to boil vigorously.
- Adjust the jet power using V3 such that the water does not boil excessively and no water is drawn into the water jet pump. The cooling system must be hot, i.e. steam is being given off from the vessel.
- The remainder of the air is removed after around 3 min. Switch off the heater and the water jet pump.

2.4.3 Adjusting the Cooling

The flow of cooling water through the condensers is adjusted via valves V1 and V2.

The flow rate can be read off on indicators F1 and F2 in l/h.

Reference of condensers and values		
Type of Condensation	Film condensation	Drop condensation
Surface	Copper	Gold
Flow adjusting valve	V1	V2
Display of flow rate	F1	F2
Inlet temperature	T1	T4
Outlet temperature	T2	T5
Surface temperature	T3	T6

2.5 PC Measurement Data Acquisition

2.5.1 Installation of the software

The following is needed for the installation:

- A fully operational PC with USB port (for minimum requirements see appendix).
- G.U.N.T. CD-ROM.
  All components necessary to install and run the program are contained on the CD-ROM delivered by G.U.N.T.

Installation Routine

NOTICE

The trainer must not be connected to the PC's USB port during the installation of the program. Only after the software has been installed can the trainer be connected.

- Boot the PC.
- Load the G.U.N.T. CD-ROM.
- From the "Installer" folder, launch the "**Setup.exe**" installation program.
- Follow the installation procedure onscreen.
- After starting, the installation runs automatically. During the course of the installation, various program components are loaded onto the PC:
  - Program for PC-data acquisition
  - Driver routines for the „LabJack®" USB converter
- Reboot the PC after installation is finished.

2.5.2 Operating the Software

- Select and start the program by choosing: **Start / All Programs / G.U.N.T. / WL 230**
- When the software is run for the first time after installation, the language to be used for the program is requested.
- The language selected can subsequently be changed at any time on the “Language” menu.
- Various pull-down menus are provided for additional functions.
- For detailed instructions on use of the program refer to its Help function. This Help function is accessed by opening the pull-down menu „?” and choosing „Help”.

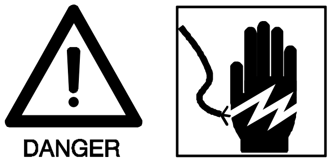
The generated files can be easily imported by EXCEL$_{TM}$ for further processing.

3 Safety Instructions

The experimental instructions, in particular the safety instructions, are to be read prior to commissioning the system.

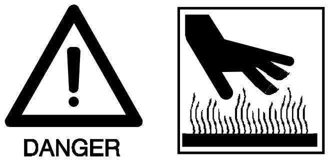
Those taking part in the experiments are to be instructed in the safety aspects and correct use of the system.

3.1 Hazards to Life and Limb



DANGER, Electric Shock Hazard!

- The back panel is only to be opened by suitably qualified personnel.
- Unplug before opening the back panel and working on the electrics.
- Protect the electrical system from water and moisture.

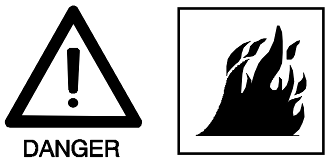


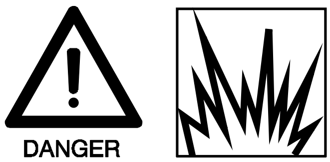
DANGER, Risk of Burns and Scolding!

- The vessel, cooling system and water separator can reach temperatures of up to 100°C.
- Take care when opening the drain valve. Hot water may escape.

DANGER!

- Do not remove or change the settings of safety devices such as safety valves and pressure switches.





RISK OF FIRE AND EXPLOSION!

- Do not fill the unit with inflammable liquids. There is a risk of fire and explosion if the heater overheats and inflammable liquids (acetone, ether, alcohol, etc.) are used. Serious damage and injuries may result.

3.2 Hazards to the Unit and its Function

ATTENTION

IMPORTANT, Risk of Overheating

- **Only switch on the heater when the tank has been filled. Check the water level.**
- **Do not let the heater element boil dry. There is a risk that the heater will burn out**.

ATTENTION

IMPORTANT!

- Only fill the tank with clean distilled water.
- Tap water or impure water will cause the build up of deposits on the condensers and lead to a reduction in the transfer of heat.
- Never fill the tank with any other liquids. The heater, seals and materials are designed for use with water. Failure to observe this instruction can lead to serious damage.

ATTENTION

IMPORTANT!

- Do not leave the unit in operation unsupervised.
- Keep a continuous check on the water level in the unit.

ATTENTION

IMPORTANT!

- The system is only to be operated in dry, closed rooms, in which there are no caustic gases, steam or dust.

4 Theoretical Principles

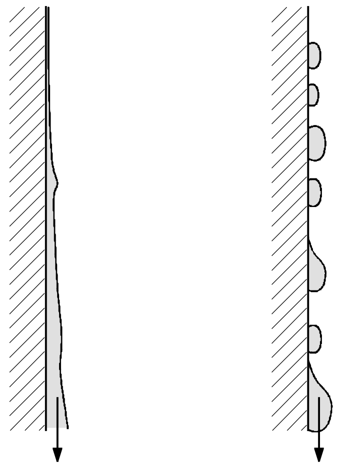


Fig. 4.1 Condensation on a Vertical Wall

Condensation occurs when steam comes into contact with a wall that has a temperature lower than the saturation temperature of the steam, the steam precipitates as liquid.

The condensate can take the form of a continuous film or individual drops of liquid on the wall. Hence the terms film and drop condensation.

In practice film condensation usually occurs. Drop condensation only occurs on very smooth surfaces that cannot be wet. The transfer of heat is much higher in the case of drop condensation than for film condensation since there is no continuous liquid film to isolate the steam from the wall.

Since smooth surfaces that cannot be wet are not realisable in practice over the long term, the poorer, but more certain values of film condensation are usually assumed.

One of the condensers on the test stand is polished and gold plated to provide a durable surface that cannot be wet. In addition the surface must be perfectly clean. It is for this reason that only pure distilled water may be used.

4.1 Steam Pressure as a Function of Temperature

The relationship between temperature and pressure in the boundary region from the gaseous to liquid state is expressed by the *Clapeyron-Clausius* formula:

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

If the gas is considered as close to ideal, then if the volume of the liquid phase v' is ignored and the gas equation is applied

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

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

The solution of this differential equation yields the relationship between pressure *p*, temperature *T* and evaporation enthalpy *r*:

$$p = e^{-\frac{r}{R \cdot T}} \qquad (4.4)$$

Since the relationship between temperature and pressure is very difficult to extract from this equation, a diagram is given below in which steam pressure is plotted against temperature.

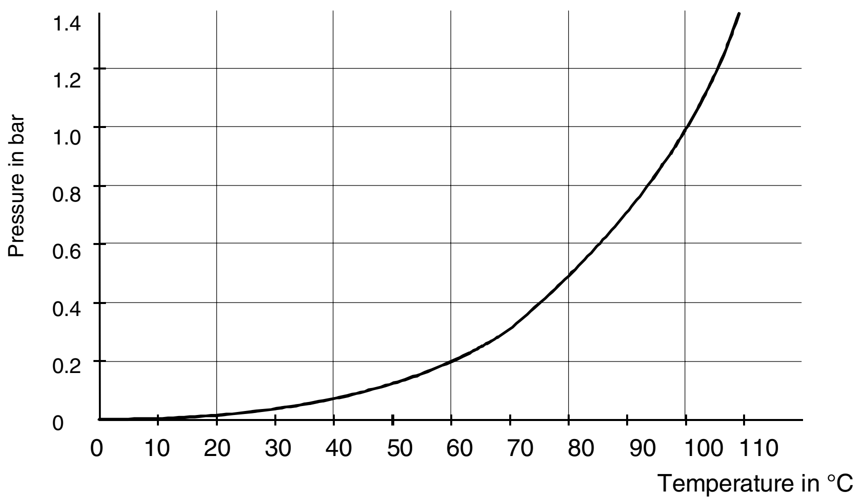


Diagramm.: 4.2 Steam Pressure Against Temperature (Water)

4.2 Coefficient of Heat Transfer

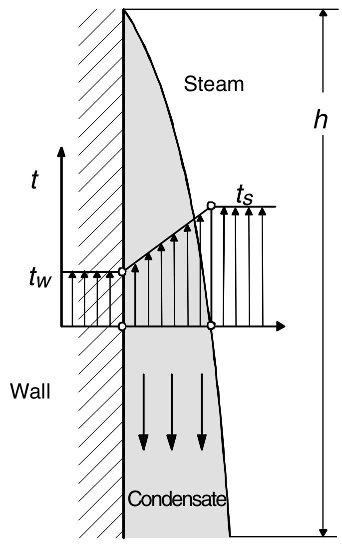


Fig. 4.3 Temperature Curve for Film Condensation

Theoretical calculations of film condensation have been made for laminar and turbulent condensation processes. In the case of the small dimensions of the condenser in the test stand, a laminar condensation process occurs. The following relationship for the coefficient of heat transfer ($\rho_{fl} >> \rho_g$) applies to the condensation of moving saturated steam on vertical surfaces at low pressures:

$$\alpha_m = 0.943 \sqrt[4]{\frac{\lambda^3 \rho g r}{\nu h (T_s - T_w)}} \tag{4.5}$$

In this equation λ is the thermal conductivity , ρ the density and ν the viscosity of the liquid film, h is the height of the wall, t_S - t_W the difference between the temperature of the saturated steam and the wall and r is the evaporation enthalpy of the liquid. In the case of water at 81°C and 0.5baris r = 2305 kJ/kg. Conductivity, density and viscosity at the mean temperature are used.

$$T_{fm} = \frac{T_s + T_w}{2} \tag{4.6}$$

In the case of film condensation, values for the coefficient of heat transfer between 4 and 12 kW/m^{2}K can be assumed. In the case of drop condensation, this value can increase to 45 kW/m^{2}K.

To determine the coefficient of heat transfer experimentally, the amount of heat energy transferred $\dot{Q}$ is established and inserted in the formula along with the transfer surface area A and the temperature difference t_S - t_W.

$$\alpha = \frac{\dot{Q}}{A(T_s - T_w)} \tag{4.7}$$

The energy transferred is determined from the cooling water flow rate.

$$\dot{Q} = \dot{m}\, c_p\, (T_{out} - T_{in}) = \rho\, \dot{V}\, c_p\, (T_{out} - T_{in}) \quad (4.8)$$

In this equation $\dot{V}$ is the cooling water flow rate, t_{out} the return temperature and t_{in} the feed temperature of the cooling water. The heat capacity c_p and the density ρ at the mean coolant temperature are used.

$$T_{km} = \frac{T_{in} + T_{out}}{2} \quad (4.9)$$

4.3 Heat Flow Density and Coefficient of Heat Transmission

Further important parameters for assessing the performance of a condenser are the heat flow density $\dot{q}$ and the coefficient of heat transmission k. The heat flow density provides an indication of the loading of the condenser surface area.

$$\dot{q} = \frac{\dot{Q}}{A} \quad (4.10)$$

The coefficient of heat transmission *k* refers to the flow of heat due to the difference between the mean temperatures of the steam and the cooling water.

$$k = \frac{\dot{Q}}{A\,(T_s - T_{km})} \quad (4.11)$$

5 Performing the Experiments

In the following sections, examples of experimental test procedures that can be performed with this unit are described. No claim is made that the procedures given cover all the possible experiments that can be performed with the unit, instead it is the intention to provide inspiration for the definition of own experiments.

The measured values given should not be considered as reference or calibration values. Variations in the values may occur to a smaller or large degree during your experiments depending on experimental conditions such as pressure, cooling water and ambient temperature, and the way in which the test is performed.

5.1 Preparing for the Experiments

Prior to the performance of the actual experiments, the air must be removed from the glass cylinder. In the cold state at atmospheric pressure the vessel contains liquid and air. The air will considerably hinder the transfer of heat to the condenser.

- Evacuate the cold vessel to 0.3 bar using the water jet pump.
- Switch on the heater and heat up to around 80°C (T7) at half power (50%). The pressure will rise again.
- Start the water jet pump again. As the pressure drops the water starts to boil vigorously.
- Adjust the jet power using V3 such that the water does not boil excessively and water is not drawn into the water jet pump. The cooling system must become hot, i.e. steam is being given off from the vessel.

The remaining air is removed after around 3 min. and the water jet pump switched off.

5.2 Determining the Coefficients of Heat Transfer

When PC based data acquisition is used, the coefficient of heat transfer for both condensers is continuously displayed in the calculations module. The procedure for operation without data acquisition is briefly described here.

- Good results can be expected in the temperature range between 90°C and 100°C.
- Heat the vessel up to 90-100°C.
- Adjust the cooling water flow rate for both condensers to achieve the desired difference between the temperatures of the surfaces (T3, T6) and the temperature of the steam (T7).
- Adjust the heater power so that the steam temperature remains constant.
- If necessary readjust the cooling water flow rate to keep the difference between the temperatures (T7 - T3 and T7 - T6 respectively) constant.
- The process of condensation on the condensation pipes can be clearly observed.
- Read off all temperatures and flow rates and record.

For example, the following results were taken for film condensation:

Cooling Water Inlet Temp.	T1:	15.6°C
Cooling Water Outlet Temp.	T2:	39.3°C
Surface Temperature	T3:	62.9°C
Steam Temperature	T7:	72.4°C
Cooling Water Flow Rate	F2:	12.0 l/h

The mean temperature of the cooling water is calculated first so that the values for the materials can be determined.

$$T_{cm} = \frac{T_1 + T_2}{2} = \frac{15.6+39.3}{2} = 27.5°C\,. \qquad (5.1)$$

The material table yields for water

$$\rho = 996.3\ kg/m^3\ ,$$

$$c_p = 4.179\ kJ/kgK\ .$$

The cooling water flow rate is

$$\dot{V} = 12.0\ l/h = 3.3\ 10^{-6}\ m^3/s\ .$$

This a yields a heat flow of

$$\dot{Q} = \rho\ \dot{V}\ c_p\ (T_2 - T_1) = 996.3 \cdot 3.3\ 10^{-6} \cdot 4.179\ (39.3 - 15.6)$$

$$\dot{Q} = 0.325 kJ/s\ . \qquad (5.2)$$

Taking the surface area of the condenser

$$A = 0.003618\ m^2$$

yields a heat flow density of

$$\dot{q} = \frac{\dot{Q}}{A} = \frac{0.325}{0.003618} = 89.82\ kW/m^2\ . \qquad (5.3)$$

The coefficient of heat transfer is then

$$\alpha = \frac{\dot{Q}}{A\ (\ T_7 - T_3\ )} = \frac{0.325}{0.003618 \cdot (72.4 - 62.9)}$$

$$\alpha = 9.45 kW/Km^2\ . \qquad (5.4)$$

According to the theory, at this operating point the value is approx. 10 kW/Km^2. The result is thus in close agreement.

5.3 Further Experiments

5.3.1 The Influence of Non-Condensing Gases

If gases that do not condense are present, the coefficient of heat transfer is considerably reduced. This effect can be shown by adding air.

- Generate a vacuum using the water jet pump (approx. 0.5 bar).
- Open drain valve V4 and allow air to enter.
- Close the drain valve again when the pressure is 0.9 bar.

Then determine the coefficients of heat transfer as in Section 5.2. These will now be considerably lower.

5.3.2 The Influence of Pressure

Perform a series of measurements at low temperatures and pressures. At a pressure of e.g. 0.5 bar, the temperature should be approx. 81 °C. The coefficient of heat transfer reduces.

5.3.3 The Influence of the Difference Between the Temperature of the Condenser Surface and the Steam

At low differences between the condenser surface and steam temperatures, the coefficient of heat transfer increases. This is due to the reducing insulation effect of the liquid film.

6 Appendix

6.1 Technical Data

Dimensions

L x B x H	900 x 455 x 820	mm
Weight:	65	kg

Supplies

Electrical 230 V/50 Hz, 1ph, 16 A
Alternatives optional, see type plate

Cold Water Requirements:		
continuous:	400	ltr/h
peak:	1200	ltr/h
Cold Water Pressure, minimum:	1	bar

Process Vessel

Volume:	3.8	ltr
Evaporating Liquid:	H_2O, distilled water	
Capacity:	approx. 1.1	ltr
Pressure Range, abs.:	0.1 - 1.0	bar, abs
Safety Devices		
Pressostat	1.2	bar, abs
Safety Valve	2	bar, abs

Water Jet Pump

Water Flow Rate:	240 - 720	ltr/h
Final Vacuum at 0.5 bar Water Pressure and 14°C Water Temperature:	16	mbar

Condenser

Diameter:	12	mm
Length:	96	mm
Surface Area:	36.18	cm^2
Surface Finish:		
Drop Condensation:	Gold, polished	
Film Condensation:	Copper, matt	
Cooling Water Flow Rate: each	0-200	ltr/h

Heater

Heater Power, adjustable	0 - 3000	W

Measured Parameters and Displays

Temperature

Cooling Water Inlet and Outlet
PT100 Sensor with Transmitter

Measurement Range: 0 - 100 °C

Steam Temperature:
PT100 Sensor with Transmitter

Measurement Range: 0 - 200 °C

Condenser Surface

K Type Thermocouple with Transmitter

Measurement Range: 0 - 200 °C

Flow Rate

Measurement Impeller with Transmitter

Measurement Range: 0 - 200 ltr/h

Pressure

Pressure Sensor

Measurement Range 0 - 4 bar, abs

Displays

LCD Display 3 1/2 digit

Data acquisition

USB communication
Program environment: LAB-VIEW Runtime
System requirements:

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

6.2 Steam Table of Water

p	t	v'	v''	ρ''	h'	h''	r	s'	s''
bar	°C	m³/kg	m³/kg	kg/m³	kJ/kg	kJ/kg	kJ/kg	kJ/kg K	kJ/kg K
0,006112	0,01	0,0010002	206,2	0,004851	0,00	2501,6	2501,6	0,0000	9,1575
0,010	6,9828	0,0010001	129,20	0,007739	29,34	2514,4	2485,0	0,1060	8,9767
0,015	13,036	0,0010006	87,98	0,01137	54,71	2525,5	2470,7	0,1957	8,8288
0,020	17,513	0,0010012	67,01	0,01492	73,46	2533,6	2460,2	0,2607	8,7246
0,030	24,100	0,0010027	45,67	0,02190	101,00	2545,6	2444,6	0,3544	8,5785
0,040	28,983	0,0010040	34,80	0,02873	121,41	2554,5	2433,1	0,4225	8,4755
0,050	32,898	0,0010052	28,19	0,03547	137,77	2561,6	2423,8	0,4763	8,3960
0,060	36,183	0,0010064	23,74	0,04212	151,50	2567,5	2416,0	0,5209	8,3312
0,080	41,534	0,0010084	18,10	0,05523	173,86	2577,1	2403,2	0,5925	8,2296
0,10	45,833	0,0010102	14,67	0,06814	191,83	2584,8	2392,9	0,6493	8,1511
0,15	53,997	0,0010140	10,02	0,09977	225,97	2599,2	2373,2	0,7549	8,0093
0,20	60,086	0,0010172	7,650	0,1307	251,45	2609,9	2358,4	0,8321	7,9094
0,30	69,124	0,0010223	5,229	0,1912	289,30	2625,4	2336,1	0,9441	7,7695
0,40	75,886	0,0010265	3,993	0,2504	317,65	2636,9	2319,2	1,0261	7,6709
0,50	81,345	0,0010301	3,240	0,3086	340,56	2646,0	2305,4	1,0912	7,5947
0,60	85,954	0,0010333	2,732	0,3661	359,93	2653,6	2293,6	1,1454	7,5327
0,80	93,512	0,0010387	2,087	0,4792	391,72	2665,8	2274,0	1,2330	7,4352
1,0	99,632	0,0010434	1,694	0,5904	417,51	2675,4	2257,9	1,3027	7,3598
1,0133	100	0,0010437	1,673	0,5977	419,06	2676,0	2256,9	1,3069	7,3554
1,5	111,37	0,0010530	1,159	0,8628	467,13	2693,4	2226,2	1,4336	7,2234
2,0	120,23	0,0010608	0,8854	1,129	504,70	2706,3	2201,6	1,5301	7,1268

6.3 Symbols and Units

A	Condenser Surface Area	m^2
c_p	Specific Heat Capacity	kJ/kgK
g	Gravity	m/s^2
h	Specific Enthalpy	kJ/kg
h	Height of the condenser	m
k	Coefficient of Heat Transmission	W/m^2K
$\dot{m}$	Mass Flow Rate	kg/s
p	Pressure	bar, N/m^2
$\dot{q}$	Heat Flow Density	J/m^2s
		W/m^2
$\dot{Q}$	Heat Flow Rate	J/s
		W
r	Evaporation Enthalpy	kJ/kg
R	Gen. Gas Constant	kJ/molK
s	Entropy	kJ/kgK
T	Temperature	°C,K
$\dot{V}$	Volume Flow Rate	m^3/s
α	Coefficient of Heat Transfer	kJ/m^2K
λ	Thermal Conductivity	W/m^2K
ν	Viscosity	m^2/s
ρ	Density	kg/m^3

6.4 Index