11 Heat exchanger (T1)

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1 Background and overview of mathematical equations

Heat transfer is the transport of energy from a region of higher temperature to a region of lower temperature driven by the temperatures difference. An apparatus realizing heat transfer between two fluids is called heat exchanger. A most common kind of heat exchangers is that where the hot and cold streams are separated by a solid wall forming a heat transfer surface. If the heat exchanger is in the steady state and the overall heat transfer coefficient *k* is constant, then the heat flow from the hot to the cold fluid is described by equation

$$\dot{Q} = kA\Delta t_{\mathrm{ls}} \tag{11-1}$$

Here, *A* is the heat transfer surface area and Δt_{ls} is an appropriately defined temperature difference between the hot and cold streams. The formula for calculating Δt_{ls} depends on the arrangement of the flow streams in the heat exchanger. Not long ago, the majority of heat exchangers in technical practice were constructed as shell and tube exchangers, in which the heat transfer surface is formed by a cluster of parallel tubes enclosed in a shell. However, due to recent advance in the technology, more plate heat exchangers have been recently used in chemical and food industries. In plate heat exchangers, the fluids are separated by several profiled, but effectively parallel, plates. In such cases the overall heat transfer coefficient is

$$1/k = 1/\alpha_{\mathrm{A}} + \delta/\lambda_{\mathrm{w}} + 1/\alpha_{\mathrm{B}}, \tag{11-2}$$

where α is the individual convection heat transfer coefficient for each fluid, δ is the thickness of the wall separating the fluids having thermal conductivity λ_{w} , and subscripts A and B denote the hot and cold fluid, respectively.

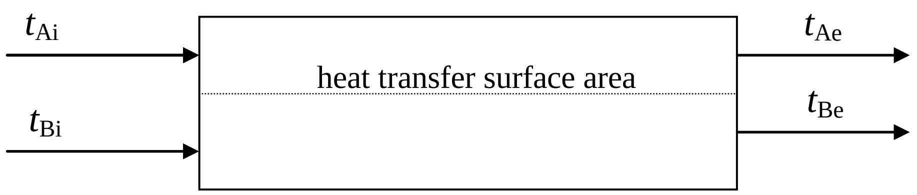

Fig. 11-1 Parallel streams arrangement

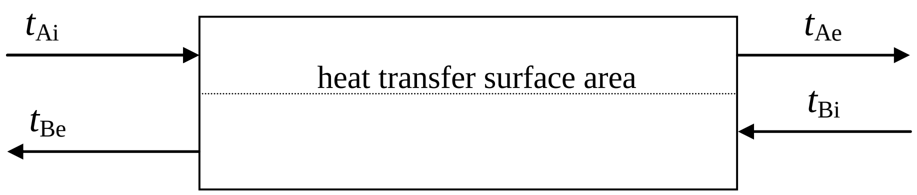

Fig. 11-2 Counter-current streams arrangement

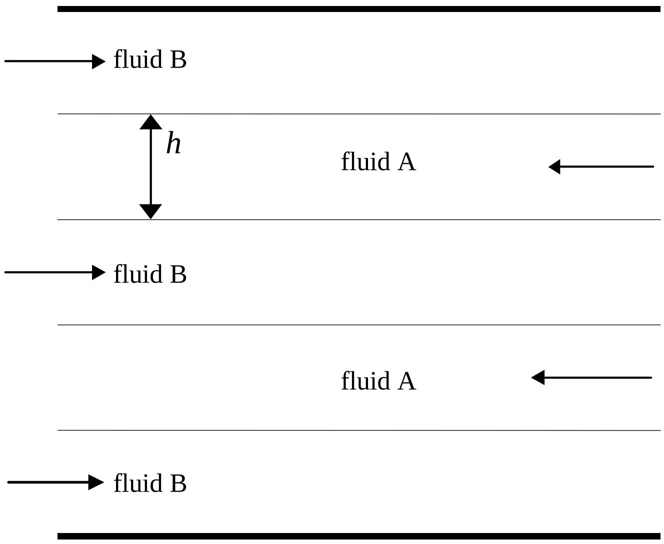

Fig. 11-3 Scheme of the plate heat exchanger

Two basic types of flow arrangement, parallel and counter-current streams, can be realized in the heat exchanger in our laboratory. These are schematically depicted in Figs. 11-1 and 11-2. The subscripts **i** and **e** denote the input and the exit, respectively. Mean temperature difference Δt_{ls} in Eq. (11-1) is the logarithmic mean temperature difference (LMTD) defined by the following equation

$$\Delta t_{\mathrm{ls}} = \frac{\Delta t_1 - \Delta t_2}{\ln(\Delta t_1 / \Delta t_2)} \qquad (11\text{-}3)$$

where for **parallel** streams arrangement

$$\Delta t_1 = t_{\mathrm{A,i}} - t_{\mathrm{B,i}} \qquad \Delta t_1 = t_{\mathrm{A,e}} - t_{\mathrm{B,e}} \qquad (11\text{-}4)$$

and for **counter-current** streams arrangement

$$\Delta t_1 = t_{\mathrm{A,i}} - t_{\mathrm{B,e}} \qquad \Delta t_2 = t_{\mathrm{A,e}} - t_{\mathrm{B,i}} \qquad (11\text{-}5)$$

In plate heat exchangers, the cross-section flow for both fluids is divided into channels of rectangular shape. As can be seen in Fig. 11-3, there are more channels for stream B than those for stream A, i.e. the number of channels for a particular stream can differ by one. The quantity denoted as *h* in Fig. 11-3 is the mean distance between the plates and is referred to as the channel depth. Plates drawn as thick lines at the outside of the heat exchanger are not part of the heat transfer area. Plates drawn as thin lines count as the heat transfer area, and their dimension perpendicular to the plane of the figure is the channel width and will be denoted as *b* (not visible in Fig. 11-3). In wielded or soldered plate heat exchangers, the division into channels is realized by built-in supports. Whereas sealing pieces are arranged appropriately to separate the streams in an assembled heat exchanger. It can be seen on sample plates which are placed next to the station.

The individual heat transfer coefficients α_A and α_B in Eq. (11-2) can be calculated from the approximate empirical relations

$$\mathrm{Nu} = C\ \mathrm{Re}^m\ \mathrm{Pr}^n \quad (11\text{-}6)$$

$$\mathrm{Nu} = \alpha d_\mathrm{eq}/\lambda, \quad (11\text{-}7)$$

where d_eq is the channel equivalent diameter defined as

$$d_\mathrm{eq} = 2h, \quad (11\text{-}8)$$

λ is the thermal conductivity of the fluid, Pr is the Prandtl number and *n* is

$$n = 0.33\exp[3.4/(\mathrm{Pr}+30)]. \quad (11\text{-}9)$$

Equation (11-6) is valid for Re > 800 and Pr > 1 and the error for calculated heat transfer coefficient is below 10%. For fluid B (cooling water) in counter-current flow arrangement the empirical constants *C* and *m* have values *C* = 0.19 and *m* = 0.76. In all other cases (i.e. fluid A or fluid B in parallel flow arrangement) *C* = 0.17 and *m* = 0.74. The values for parallel and counter-current flow differ because the plates in the heat exchanger are equipped with arrow headed turbulators; and the cooling water flows along arrows direction at parallel and against arrows direction at counter-current flow arrangement. Fundamental equations for heat and hydraulic design of the heat exchanger are not provided by its designer, because they are considered to be classified information.

Reynolds number in Eq. (11-6) is calculated as

$$\mathrm{Re} = \frac{v d_\mathrm{eq} \rho}{\eta} \quad (11\text{-}10)$$

where v is the fluid flow velocity inside channel, ρ and η are the fluid density and the dynamic viscosity, respectively. Fluid flow velocity v can be calculated using equation

$$v = \frac{\dot{V}_\mathrm{C}}{n_\mathrm{C} h b} \quad (11\text{-}11)$$

where $\dot{V}_\mathrm{C}$ is the volumetric flow rate, and the subscript C denote either A or B, depending on the fluid whose velocity is calculated, and n_C is the number of channels for the respective fluid.

Analogical measurements and calculations as those performed during this assignment are used in technical practice to assess the state of operated heat exchangers. Solid deposits with low thermal conductivity present in media flowing through the heat exchanger usually accumulate on its surface and this result in the increase of the overall heat transfer resistance and in the decrease of heat exchanger efficiency. Since the thickness of the deposits layer cannot be determined during operation and its thermal conductivity is unknown, these effects are expressed by an additional resistance term *R*

$$1/k_\mathrm{exp} = 1/\alpha_\mathrm{A} + \delta/\lambda_\mathrm{W} + 1/\alpha_\mathrm{B} + R \quad (11\text{-}12)$$

If overall heat transfer coefficient *k* calculated from Eq. (11-2) is valid for a clean heat exchanger, the additional thermal resistance is estimated as

$$R = 1/k_{\mathrm{exp}} - 1/k. \qquad (11\text{-}13)$$

Heat transfer coefficients α in Eq. (11-2) are obtained from Eqs. (11-6)–(11-11). The experimental overall heat transfer coefficient k_{exp} is calculated from measured data using the procedure described in section VI. If the ratio of the additional heat transfer resistance (*R*) to the overall heat transfer resistance ($1/k_{\mathrm{exp}}$) exceeds a certain limit provided by the manufacturer or by economic considerations, it is necessary to clean the heat exchanger or to install a new one if cleaning is not possible.

II List of work objectives

1. Determine experimental values of the overall heat transfer coefficient k_{exp} using the procedure in section VI for the two given sets of operational parameters.
2. Calculate the overall heat transfer coefficient for the clean heat exchanger using Eqs. (11-6)-(11-11) and (11-2).
3. Calculate the additional thermal resistance using Eq. (11-13)

III Equipment description

The "Heat Exchanger (T1)" station layout is illustrated in Fig. 11-4. Distilled water, hereinafter referred to as "pumped water" (PW), is pumped by the centrifugal pump **2** from a tank **1** through plate heat exchanger **3**. Steam is used to heat PW in the heat exchanger to the prescribed temperature. Steam entering the heat exchanger is opened and closed by black coloured valve **7A** and its flow is controlled by red coloured valve **7B**. Hot PW leaving heat exchanger **3** is cooled down in another plate heat exchanger **6** by cooling water (CW) from water main. Heat exchange coefficient k_{exp} is measured for heat exchanger **6**. Steam condensate is drained from heat exchanger **3** through steam trap **10** and collected in tanks **11** equipped by level gauge. Condensate is directed into one of the tanks using pair of two-port valves **11A**. Opening another pair of valves **11B** at the bottom empties the tanks. Dimensions and other parameters of the heat exchanger **6** required for all the calculations are listed in the Table 11-1.

Tab. 11-1 List of selected parameters of the assembled heat exchanger

Parameter	Symbol	Value
Total heat exchange area	A	0,58 m^2
Channel depth	h	2,4 mm
Channel width	b	100 mm
Plate thickness	δ	0,5 mm

Thermal conductivity of the plate material (stainless steel AISI 316)	λ_w	14,65 $Wm^{-1}K^{-1}$
Number of channels at the side of cooling water (B)	$n_{\cdot B}$	9
Number of channels at the side of pumped water (A)	n_A	10

Temperatures needed to obtain the overall heat transfer coefficient are measured by thermometers **13A, 13B, 18A** and **18B**, the steam temperature by thermometer **9A** and the condensate temperature by thermometer **9B**. The volumetric flow of pumped water (PW) is measured by flow meter **12** and the flow of cooling water (CW) by flow meter **16**. All measured values are displayed on display panel **5**.

Translation of labels on display panel 5:

průtok chladicí vody	cooling water (CW) flow rate
průtok čerpané kapaliny	pumped water (PW) flow rate
vstupní (s), výstupní (p) teplota chladicí vody	input (p), output (c-c) CW temperature
vstupní teplota čerpané kapaliny	input PW temperature
vstupní (p), výstupní (s) teplota chladicí vody	input (c-c), output (p) CW temperature
výstupní teplota čerpané kapaliny	output PW temperature
teplota páry	stream temperature
teplota kondenzátu	condensate temperature
zapnuto / vypnuto	on / off

CZ (s): souproud	EN (p): parallel flow arrangement
CZ (p): protiproud	EN (c-c): counter-current flow arrangement

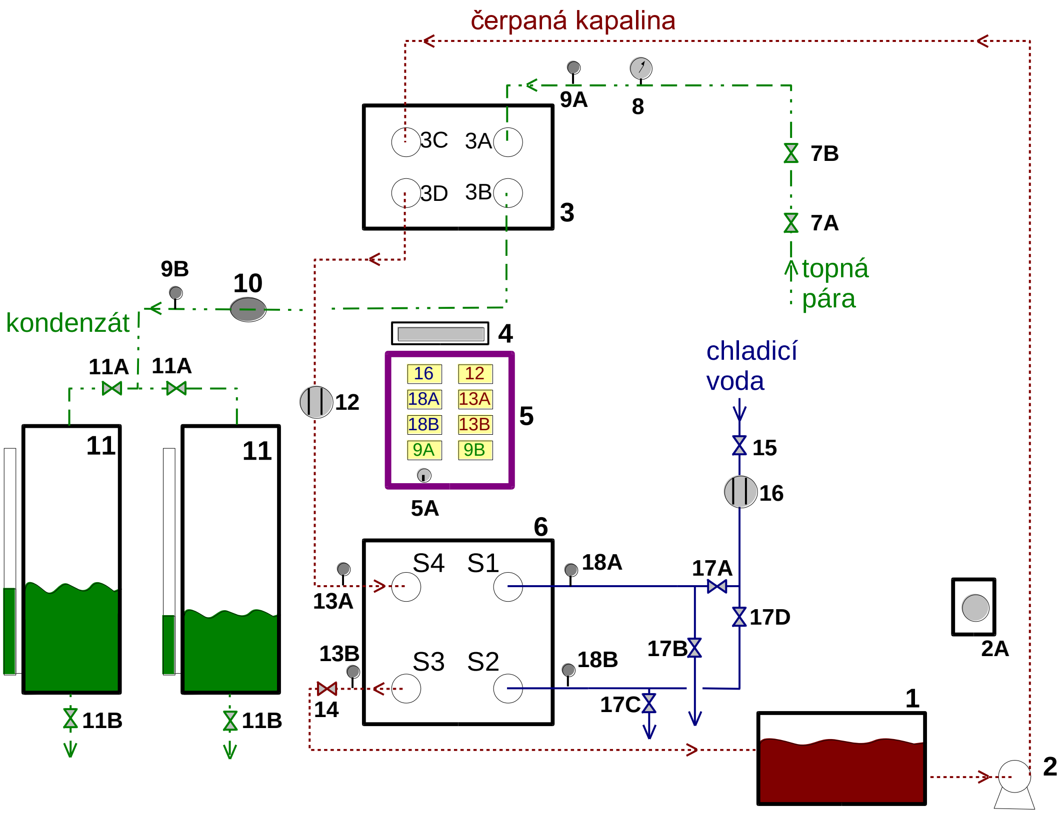

Fig. 11-4 Heat exchanger station T1 layout.

1 – tank with pumped water

2 – pump

2A – pump on/off switch

3 – heat exchanger

3A – steam input

3B – condensate output

3C – pumped water input

3D – pumped water output

4 – stopwatch

5 – measurement display panel

5A – display panel main switch

6 – heat exchanger whose overall heat transfer coefficient is measured

7A – steam cut-off valve (black)

7B – steam control valve (red)

8 – steam manometer

9A – steam temperature sensor

9B – condensate temperature sensor

10 – steam trap

11 – tanks with level gauge

11A – input valves

11B – tank drain-off valves

12 – pumped water flow meter

13A – pumped water input temperature sensor

13B – pumped water output temperature sensor

14 – valve for controlling pumped water flow rate

15 – valve for controlling cooling water flow rate

16 – cooling water flow meter

17A – valve open/parallel or closed/counter-current arrangement

17B – valve closed/parallel or open/counter-current arrangement

17C – valve open/parallel or closed/counter-current arrangement

17D – valve closed/parallel or opened/counter-current arrangement

18 – cooling water temperature sensors

IV Work instructions

IV.1 Station start-up

- Turn on display panel **5** using switch **5A**.
- Manipulate valves **18** routing the cooling water to set parallel or counter-current flow arrangement. **Please do not use excessive force to tighten the valves** (they could be damaged). Also for opened valves, it is not necessary to leave them turned completely toward their counter-clockwise limit (you can turn them back clockwise about quarter of revolution). The valve configuration is as follows:

	Parallel flow	**Counter-current flow**
17A	open	closed
17B	closed	open
17C	open	closed
17D	closed	open
18A (S1)	cooling water input	cooling water output
18B (S2)	cooling water output	cooling water input

- Open cooling water valve **15** and set the required flow rate.
- Open pumped water valve **14** by turning it about one half of revolution (from completely closed position) and turn on the pump using switch **2A** located on the wall right of the station. Then open valve **14** more to set the required pumped water flow rate. (Turning on the pump when the valve **14** is completely open causes undesirable hydrodynamic shocks inside pipes.)
- Check that the condensate will be collected right in one of the tanks **11**, i.e., one from the pair of valves **11A** is open and the other is closed. Also close drain-off valve **11B**. (Please note valves **11B** are safeguarded against accidental opening: it is necessary to pull away from the axis of revolution while turning them to the required position).
- Open steam cut-off valve **7A (black)** and regulate the steam input by valve **7B (red)** until the pumped water input temperature reaches the required temperature (maximum difference ±1°C). Please take into account that there is a significant delay of the order of minutes between the change of a valve setting and the response seen on the temperature panel.
- **The pumped water temperature at the entry to heat exchanger 6 must not exceed 70°C, the flow-meter and the pump could be damaged.** If there is an alarm wailing: immediately turn off the steam by closing black valve 7A and completely open cooling water valve 15.
- **Red valve 7B is not meant for closing the steam - do not close it!** There is a cut sealing with plug which **could be damaged if the valve is tightened too strongly**.

- After the station has been started up, keep pumping and cooling water flow rates at the required value within **0.2 l/min** margin and check that the pumping water temperature keeps at the required value within 1°C margin until other temperatures do not change by more than **0.5°C within 5 minutes**. This can take as long as half an hour as all the water in the tank must be heated. Please note that the pressure in water main can change, therefore cooling water flow rate has to be closely monitored and corrected if necessary. As soon as the required stability of measured temperatures is attained, you can assume that the apparatus is in the steady-state and begin your measurements.
- Finally: Before starting the measurements check that the level of condensate in tank **11** is above 10 cm. Also, in case the level of condensate is above 25-30 cm, part of the condensate can be discharged by temporarily opening valve **11B**.

IV.2 The actual measurement

- Measurement can begin after steady-state is reached and if there is the appropriate amount of condensate in tank **11** (the level between 10 and 30 cm).
- Start the stopwatch and write down the level of condensate in tank **11**. Also read off and write down all temperatures and flow rates displayed on panel **5**.
- Repeat readings and write down the values in five-minute intervals.
- Monitor the flow rates and modify valve settings if they differ from required values by more than **0.2 l/min**.
- You have to obtain 8-10 readings at the steady state.
- When finishing measurement, write down the time and the level of condensate in tank **11**.
- After measurement is finished for Set #1, change the operating parameters to values required by Set #2. Wait until steady-state is reached again and repeat measurement for Set #2 as well. It possible to switch condensate tanks **11** using valves **11A**.

IV.3 Shutting-down the station

When all required data are obtained:

- Shut down the steam by closing black valve **7A**.
- Wait until pumped water input temperature drops to 35°C.
- Close the pumped water valve **14** first and then turn off the pump by switch **2A** (exactly in this order).
- Close cooling water valve **15**.
- Empty condensate from both tanks by opening valves **11B**.
- Turn off measurement panel **5** by switch **5A**.

V Safety precautions

1. Check that the flow arrangement is set correctly before turning on the pump and opening the cooling water valve.

2. Check that both the pumped and cooling water are really flowing inside pipes before opening the steam valve.

3. Pumped water temperature at the entry **S4** (**13A**) to the heat exchanger must not exceed 70°C.

4. All valves must be closed and opened carefully and slowly (to avoid hydraulic shocks), do not use excessive force to tighten the valves (to avoid seal damage); do not close red steam regulating valve at all.

5. Check that the route for the condensate from the heat exchanger into tanks **11** is not blocked, i.e., that one of the valves **11A** is open.

VI Processing of measured data

First calculate the arithmetic mean of all measured values for the same set of conditions at the steady state and write them down on the row "average" in the form. In further calculations, you will use these average values. To evaluate the overall heat transfer coefficient, the heat flux across heat transfer surface must be obtained. There are three ways to do this:

$$\dot{Q}_{\mathrm{B}} = \dot{V}_{\mathrm{B}} \rho_{\mathrm{B}} c_{p\mathrm{B}} (t_{\mathrm{B,e}} - t_{\mathrm{B,i}}) \tag{11-14}$$

$$\dot{Q}_{\mathrm{A}} = \dot{V}_{\mathrm{A}} \rho_{\mathrm{A}} c_{p\mathrm{A}} (t_{\mathrm{A,i}} - t_{\mathrm{A,e}}) \tag{11-15}$$

$$\dot{Q}_{\mathrm{p}} = \dot{m}_{\mathrm{p}} (h_{\mathrm{p}} - h_{\mathrm{k}}) \tag{11-16}$$

The density ρ and the specific heat capacity c_p should be read from tables at the temperature equal to the average obtained from temperatures at both ends of a particular stream, the specific enthalpy of steam h_{p} at the measured steam temperature t_{p} and the enthalpy of the condensate at the measured condensate temperature t_{k}. The overall heat transfer coefficient should be evaluated by using a $\dot{Q}_{\mathrm{B}}$ value as it is usually the most accurate one. The average mass flow of steam $\dot{m}_{\mathrm{p}}$ is calculated by dividing the mass of condensate collected during measurement by the time interval.

The logarithmic mean temperature difference Δt_{ls} is calculated from Eq. (11-3) and either from Eq. (11-4) or (11-5), depending on the flow arrangement. Finally, k_{exp} is determined from Eq. (11-12).

In the next step, determine the theoretical value of heat transfer coefficients for streams A and B (the physical properties of fluid media can be established at temperature equal to the arithmetic mean of their end temperatures) and use Eq. (11-2) to determine the overall heat transfer coefficient for a clean heat exchanger *k*. Then, using Eq. (11-13), the additional resistance *R* can be determined. Although the heat exchanger was installed in December 1999, it is still relativelly clean. Therefore it is possible to obtain the negative value of additional resistance *R* due to experimental errors and imprecisions of the empirical equation (11-6). As soon as the negative value of R does not exceed 10% of the total resistance to the heat transfer, i.e. the value of $1/k_{exp}$, the result can be regarded acceptable.

VII List of symbols

A	heat transfer area	$\mathrm{m^2}$
b	channel width	m
c_p	the specific heat capacity	$\mathrm{J\,kg^{-1}K^{-1}}$
d_{eq}	the equivalent channel diameter	m
h	channel depth	m
h_{k}	the specific enthalpy of condensate	$\mathrm{J\,kg^{-1}}$
h_{p}	the specific enthalpy of steam	$\mathrm{J\,kg^{-1}}$
k	the overall heat transfer coefficient	$\mathrm{W\,m^{-2}K^{-1}}$
n_{C}	the number of channels for fluid C	-
Nu	Nusselt number	-
Pr	Prandtl number	-
$\dot{Q}$	the heat flow across the heat transfer area	W
Re	Reynolds number	-
v	fluid velocity in the channel	$\mathrm{m\,s^{-1}}$
α	heat transfer coefficient	$\mathrm{W\,m^{-1}K^{-1}}$
δ	heat exchanger plate thickness	m
λ	the thermal conductivity	$\mathrm{W\,m^{-1}K^{-1}}$

Subscripts

A	the pumped water (hot fluid)
B	the cooling water (cold fluid)
C	either fluid A or B
exp	measured value
k	condensate
ls	logarithmic mean
p	steam
s	average
w	property of the material forming the plate

VIII Review these questions before starting work

1. Specify main objectives of this assignment. Which properties will be set and which properties will be measured?

2. Show the steam route from the main pipe through the closing and regulating valves to the heat exchanger, where it condenses. Also show the condensate route and where it ends.
3. Explain the procedure of obtaining the average mass flow of the condensate.
4. Explain how the steam trap works and its purpose.
5. Describe how the temperature is regulated by changing the steam flow rate. Explain the difference between the red and the black steam valves.
6. Show the pumped water route from the tank through the pump, the heat exchanger, where it is heated up, the other heat exchanger, where it is cooled down, and back to the tank.
7. Show the cooling water route from the main pipe through the heat exchanger, where it is heated up, to the drain.
8. Show which valves should be closed or opened in order to set the route for the parallel and the counter-current flow arrangement.
9. Show temperature sensors and where their temperatures are displayed.
10. Show flow rate sensors and where their values are displayed.
11. Which physical properties one has to know in order to be able to calculate the heat exchanged during heating or cooling the medium in a heat exchanger?
12. Review SI units for the following quantities: heat, energy, heat flux, power output, specific heat capacity, enthalpy of condensation, heat conductivity, heat transfer coefficient and overall heat transfer coefficient.