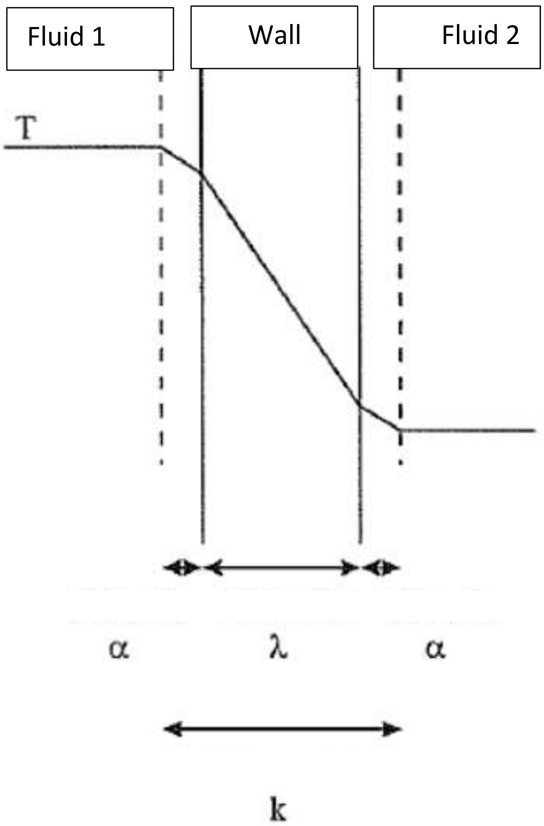
Countercurrent heat exchanger

1. Theoretical summary

The basic operating principles and the simplified calculations regarding the counter current heat exchanger were discussed in the subject Chemical Unit operations I. To be able to perform the measurement, recalling the things studied in that subject is necessary. In the notes below, we collected the most important information and calculation formulas.

1.1 Types of heat transport in a heat exchanger according to the film-model



λ	heat conductivity coefficient of the wall	$\left[\frac{W}{m \cdot K}\right]$
α	heat transfer coefficient of the fluid	$\left[\frac{W}{m^2 \cdot K}\right]$
k	overall heat transfer coefficient	$\left[\frac{W}{m^2 \cdot K}\right]$

1.2 Heat conductivity – Heat transport in solid materials

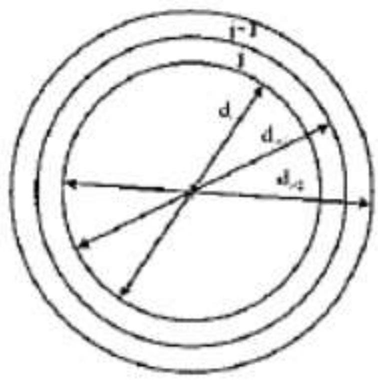
Heat conduction through a plain wall:

The heat current can be calculated with the following formula:

$$\dot{Q} = \frac{1}{\sum_j \frac{s_j}{\lambda_j}} \cdot A \cdot (T_1 - T_2)$$

s	thickness of the wall	$[m]$
j	index (number) of the wall	
A	surface area of the wall	$[m^2]$
T_1 and T_2	temperature measured at the two sides of the wall	$[°C \text{ or } K]$

Heat conduction through a cylindrical wall:



$$\dot{Q} = \frac{2 \cdot \pi \cdot L}{\sum_j \frac{1}{\lambda_j} \cdot \ln \frac{d_{j+1}}{d_j}} \cdot (T_1 - T_2)$$

L	tube length	$[m]$
d	diameter	$[m]$
T_1 and T_2	temperatures at each side of the walls	$[°C$ or K]

1.3 Heat radiation

$$\dot{Q} = \varepsilon \cdot C_0 \cdot \left[\left(\frac{T_1}{100} \right)^4 - \left(\frac{T_2}{100} \right)^4 \right]$$

ε	relative emission coefficient (grade of blackness)	
C_0	10^8 times the emission coefficient of the ideal blackbody (σ)	$\left[\frac{W}{m^2 \cdot K}\right]$
T_1 and T_2	temperatures of the wall the medium	$[K]$

(C_0 is used instead of σ in order to get numbers that are easy to handle.)

Using heat transfer as an analogy, a radiation heat transfer coefficient can be defined:

$$\dot{Q} = \alpha_{rad} \cdot A \cdot (T_1 - T_2)$$

α_{rad}	radiation heat transfer coefficient	$\left[\frac{W}{m^2 \cdot K}\right]$

1.4 Convective heat transfer

$\dot{Q} = \alpha \cdot A \cdot (T_1 - T_2)$

α	heat transfer coefficient	$\left[\frac{W}{m^2 \cdot K}\right]$
A	surface area of heat transfer	$[m^2]$
T_1 and T_2	temperature of the wall and the fluid	$[°C \text{ or } K]$

When the flow in a pipe is turbulent, Reynolds-number is over 7000, the Sieder-Tate equation can be used. It also gives a fair estimation in the transition flow.

$Nu = C \cdot Re^a \cdot Pr^b \cdot Vis^c$

$Nu = \frac{D \cdot \alpha}{\lambda}$	Nusselt-number	
D	specific size	$[m]$
C	proportionality factor	
$Re = \frac{D \cdot v \cdot \rho}{\eta}$	Reynolds-number	
ρ	density	$\left[\frac{kg}{m^3}\right]$
η	dynamic viscosity	$[Pa \cdot s]$
$Pr = \frac{c_p \cdot \eta}{\lambda}$	Prandtl-number	
c_p	specific heat capacity	$\left[\frac{J}{kg \cdot K}\right]$
$Vis = \frac{\eta_{bulk}}{\eta_{wall}}$	viscosity index	

Having a turbulent flow $C = 0.023; a = 0.8; b = \frac{1}{3}; c = 0.14$, and in the case of liquids with a low viscosity $Vis = 1$. The properties of the materials have to be calculated for the average temperature.

In the case of water, watery solutions or any liquids that have a negligible change in viscosity with temperature $Vis = 1$.

$Pr = 3 - 6$	water
$Pr > 3 - 6$	other liquids
$Pr = 1$	gas

If it is possible, the transition flow needs to be evaded. If heat transfer has to be done in transition flow (of the fluids) (for example) the Gnielinski-equation can be used for the calculations:

$$Nu = \frac{\left(\frac{f_F}{2}\right) \cdot (Re - 1000) \cdot Pr}{1 + 1.27 \cdot \left(\frac{f_F}{2}\right)^{\frac{1}{2}} \cdot \left(Pr^{\frac{2}{3}} - 1\right)} \cdot \left[1 + \frac{D}{L}\right]^{\frac{2}{3}} \cdot Vis^{0.14}$$

$$f_F = (3.64 \cdot \lg Re - 3.28)^{-2}$$

1.5 Heat transfer

$$\dot{Q} = k \cdot A \cdot \Delta T_{avg}$$

k	overall heat transfer coefficient	$\left[\frac{W}{m^2 \cdot K}\right]$
A	surface area of heat transfer	$[m^2]$
ΔT_{avg}	average logarithmic temperature difference	$[°C \text{ or } K]$

The thermal resistance of the layers add up:

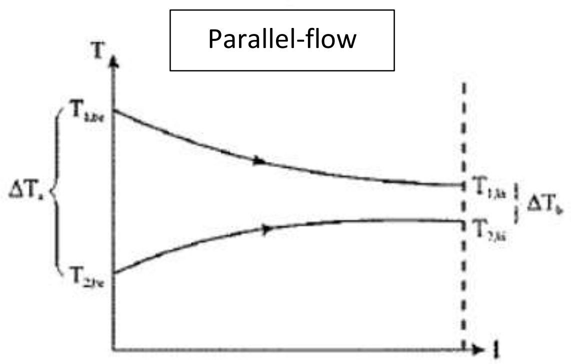
$$k = \frac{1}{\sum_i R_i}$$

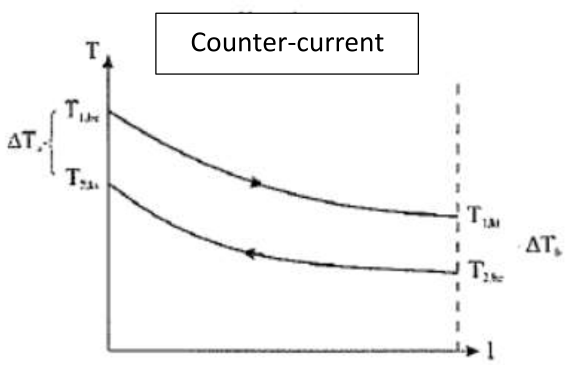
If there is a solid (plain) wall between two forced fluid flows:

$$k = \frac{1}{\frac{1}{\alpha_1} + \sum_{j=1}^{n} \frac{s_j}{\lambda_j} + \frac{1}{\alpha_2}}$$

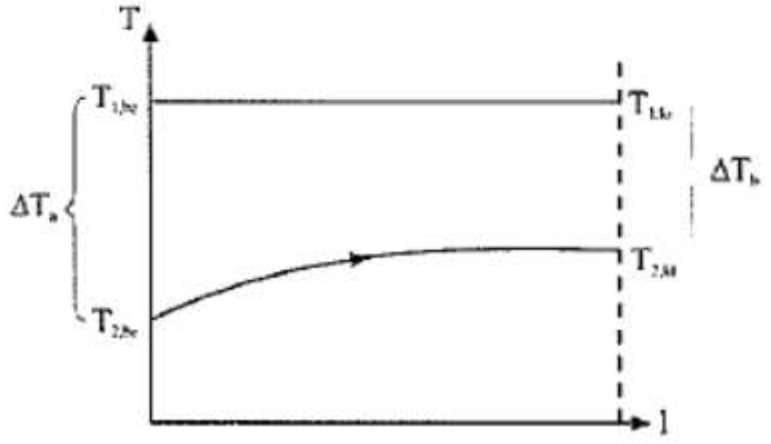
1.6 The average logarithmic temperature difference

Temperature profiles in simple heat exchangers, where l is the length of the heat exchanger.





Temperature profile when one of the streams undergoes phase transition during the heat transfer (for example the condensation of a heating steam):



In this case, it makes no sense to talk about parallel flow or counter flow.

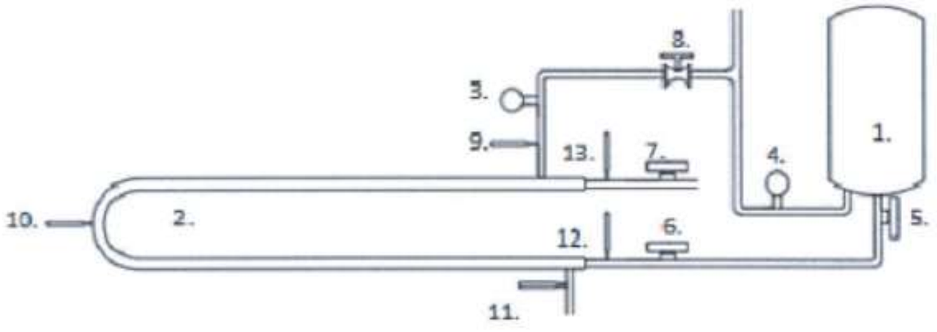
The average logarithmic temperature difference:

$$\Delta T_{avg} = \frac{\Delta T_{left} - \Delta T_{right}}{\ln \frac{\Delta T_{left}}{\Delta T_{right}}}$$

2. Aim of the measurement

The aim of the measurement is to study the double tube heat exchanger and its properties and to calculate the Reynolds numbers and heat transfer coefficients, and to give and estimation for the thermal resistance caused by contamination of the surface.

3. Description of the equipment



1.	Boiler
2.	Heat exchanger
3. and 4.	Water meter
5.-7.	Taps
8.	Valve
9.-13.	Thermometers

The equipment depicted above is a double tube heat exchanger operated with cold and warm water. The flow of the warm water can be measured by water meter nr. 4., temperatures $T_{in;warm}$ and $T_{out;warm}$ can be measured by thermometers number 12. and 13- respectively. The flow of the cold water stream can be measured by water meter number 3. while $T_{in;cold}$, $T_{mid;cold}$ and $T_{out;cold}$ are measured by the thermometers number 9., 10. and 11. respectively. The flow of warm water can be set using tap number 5. while the flowrate of the cold water can be regulated using the valve number 8.. Warm water is produced by the boiler number 1..

Information about the heat exchanger

outer diameter of the jacket	$0.050\ m$
inner diameter of the jacket (estimation)	$0.046\ m$
inner diameter of the inner tube	$0.026\ m$
outer diameter of the inner tube	$0.030\ m$
heat conductivity coefficient of the tube (stainless steel)	$16\frac{W}{m^2 \cdot K}$
length of the heat exchanger	$4\ m$

4. Measurement process

First, the main tap needs to be opened at the wall (it is not depicted in the figure), then taps number 6. and 7. are opened all the way. Set the volumetric flowrate of warm water to roughly $0.36\frac{m^3}{h}$ using tap number 5.. It is measured by the water meter number 4..Switch on the boiler set it up to $50\ °C$. After the thermometers 12. and 13. show a constant value, approximately $50\ °C$, valve number 8. can be opened slightly and at the same time the stopwatch can be started. For 10 minutes or until a steady state is reached, the value shown by every thermometer has to be noted. The flowrate of the cold water needs to be followed using water meter number 3.. In a steady state, temperature values need to be noted every 2 minutes together with the flowrates (5-5 datapoints). Calculate the Reynolds-number (for both the cold and the warm sides).

After that, set up a turbulent flow on both sides (If it is not possible, explain its reason in the report thoroughly, and do the calculation with the fitting equation.) and measure the temperatures every minute until reaching a steady state. After reaching the steady state, collect the necessary data every 2 minutes. Then make a change in the volumetric flowrates. Measure at at least 3 steady states.

After completing the measurement, switch off the boiler and wait for the equipment to cool down. Finally close all the taps and valves carefully.

5. Evaluation

Look up the needed properties of water according to the average temperature calculated by the measured temperature data.

In every steady state

1. the Reynolds-numbers at the warm and at the cold side,

2. the transferred heat flow and the estimated heat loss,

3. the overall heat transfer coefficient,

4. in the case of a turbulent or a transition flow the heat transfer coefficients (α) at the cold and the warm sides using the fitting $Re - Nu$ relation,

5. in the case of a turbulent or transition flow, the sum of the thermal resistances

need to be calculated.

Compare the difference between the results using the equations for the plain wall and the cylindrical wall when calculating the heat conduction.

These notes were written by Dr. Edit Székely using earlier work of the working combine and was controlled by Dr. Péter Mizsey. (Translation was made by Márton Kőrösi.)

Group:	**Counter current heat exchanger**	Supervisor:

Time $[min]$	$T_{in;warm}$ $[°C]$	$T_{out;warm}$ $[°C]$	$T_{in;cold}$ $[°C]$	$T_{out;cold}$ $[°C]$	$T_{mid;cold}$ $[°C]$	WM warm $[m^3]$	Wm cold $[m^3]$

Summarizing table

	1		2		3	
	warm	cold	warm	cold	warm	cold
T_{in} $[°C]$						
T_{out} $[°C]$						
T_{mid} $[°C]$	-		-		-	
$\dot{Q}$ $[W]$						
$\dot{Q}_{loss}$ $[W]$						
T_{avg} $[°C]$						
c_p $\left[\frac{kJ}{kg \cdot K}\right]$						
ρ $\left[\frac{kg}{m^3}\right]$						
η $[mPa \cdot s]$						
λ $\left[\frac{W}{m^2 \cdot K}\right]$						
$\dot{V}$ $\left[\frac{m^3}{h}\right]$						
Re						
Pr						
Nu						
α $\left[\frac{W}{m^2 \cdot K}\right]$						
k $\left[\frac{W}{m^2 \cdot K}\right]$						
ΔT_{avg} $[°C]$						
R_{cont}						

$\dot{Q}_{plain}\ [W]$			
$\dot{Q}_{cyl}\ [W]$			
$Difference\ [\%]$			