ChE-203 TP-1
Heat exchanger

Instructions for use, Spring 2025

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1. Statement of purpose

The new Laboratory for Biophysical Chemistry of Macromolecules (LCBM) at ISIC, EPFL, has an adiabatic bioreactor that requires the supply of ultrapure water at exactly 37 °C at a flow rate of 1 liter per minute. Your overall objective for this TP is to design a concentric tube heat exchanger to meet this need.

2. Theoretical basis.

Heat is an energy transfer due to temperature differences. When there is a difference in temperature in one or more media, heat transfer occurs. There are three distinct modes (or processes) of heat transfer: conduction, convection, and radiation. Conduction and convection are two important processes in industrial heat exchange. Radiation heat transfer will not be accounted for in this unit.

Conduction: Heat transfer through stationary solids and fluids occurs by conduction. The physical mechanism of conduction is the diffusion of energy from interactions between molecules in a medium. At the atomic scale, an atom with more heat vibrates more strongly and can collide with other adjacent atoms, transferring energy by inelastic collision. On a macroscopic scale, the equation that quantifies the process of heat transfer by conduction is known as Fourier's Law.

$$q = -k\nabla T \qquad \textit{(Eq. 1)}$$

where q is the heat flux density [W m^{-2}], k is the thermal conductivity of the material [W m^{-1} K^{-1}], et ∇T is the temperature gradient. In the one-dimensional case and at steady state, the heat flow through a wall is given by the following expression:

$$Q = -kA\,\frac{(T_2 - T_1)}{x} \qquad \textit{(Eq. 2)}$$

where Q is the heat flow [W], x is the thickness of the material [m], T_2 is the temperature of the cold side of the material [K], T_1 is the temperature of the hot side of the material [K], and A is the area perpendicular to the direction of heat flow [m^2].

Thermal Resistance

Thermal resistance is a key concept in the evaluation of heat transfer. There is an analogy between the flow of heat and the flow of electrical charge. In the same way that electrical resistance (R_e) is associated with electrical conduction, thermal resistance (R_T) can be associated with thermal conduction. Ohm's law defines electrical resistance as:

$$R_e = \frac{(V_1 - V_2)}{I} \qquad \textit{(Eq. 3)}$$

where $(V_1 - V_2)$ is the difference of the electric potential (voltage) and I is the electric current (electron flow). In heat transfer, we can consider the thermal resistance as:

$$R_T = \frac{(T_1 - T_2)}{Q} \qquad (Eq. 4)$$

where (T_1 - T_2) is the temperature difference and Q is the heat flow. From equation 1, the heat conduction resistance can be determined according to:

$$R_{T,cond} = \frac{x}{kA} \qquad (Eq. 5)$$

Convection: The mode of heat transfer between a surface and a moving fluid, which are at different temperatures, is called convection. It is the result of the superposition of two physical phenomena: the energy transported by the random motion of the molecules (diffusion) and the energy transported by the fluid flow (macroscopic motion). Convective heat transfer can be classified as forced or natural convection. Forced convection occurs when external means (a fan, pump or atmospheric wind) cause a flow or current. Natural convection occurs when the flow is induced by buoyant forces, which are the result of density differences caused by changes in fluid temperature.

Irrespective of whether convection can be forced or natural, the convective heat flow between a surface and a fluid is given by Newton's law of cooling, which is expressed as follows:

$$Q = A\,h\,(T_s - T_\infty) \qquad (Eq. 6)$$

where, Q is the heat flow (or heat transfer rate) [W], h is the heat transfer coefficient [W m^{-2} K^{-1}], A is the surface area involved in the heat exchange [m^2], T_s is the temperature of the surface [K], T_∞ is the temperature of the fluid (far away from the surface) [K]. Therefore, we can write an expression for resistance to convection heat transfer:

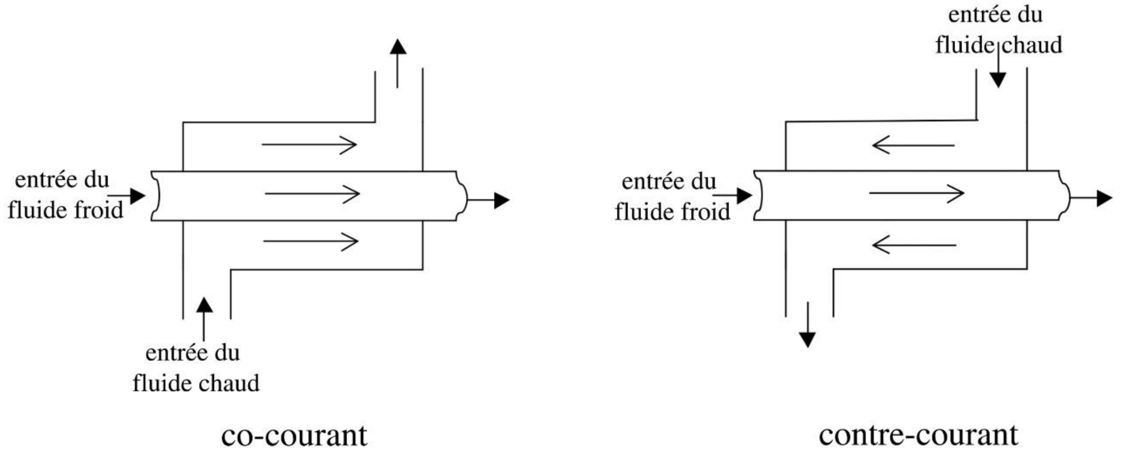
$$R_{T,conv} = \frac{1}{hA} \qquad (Eq. 7)$$

In general, the total heat flow can be calculated by adding up all the thermal resistances:

$$Q_{total} = \frac{\Delta T}{\sum R_T} \qquad (Eq. 8)$$

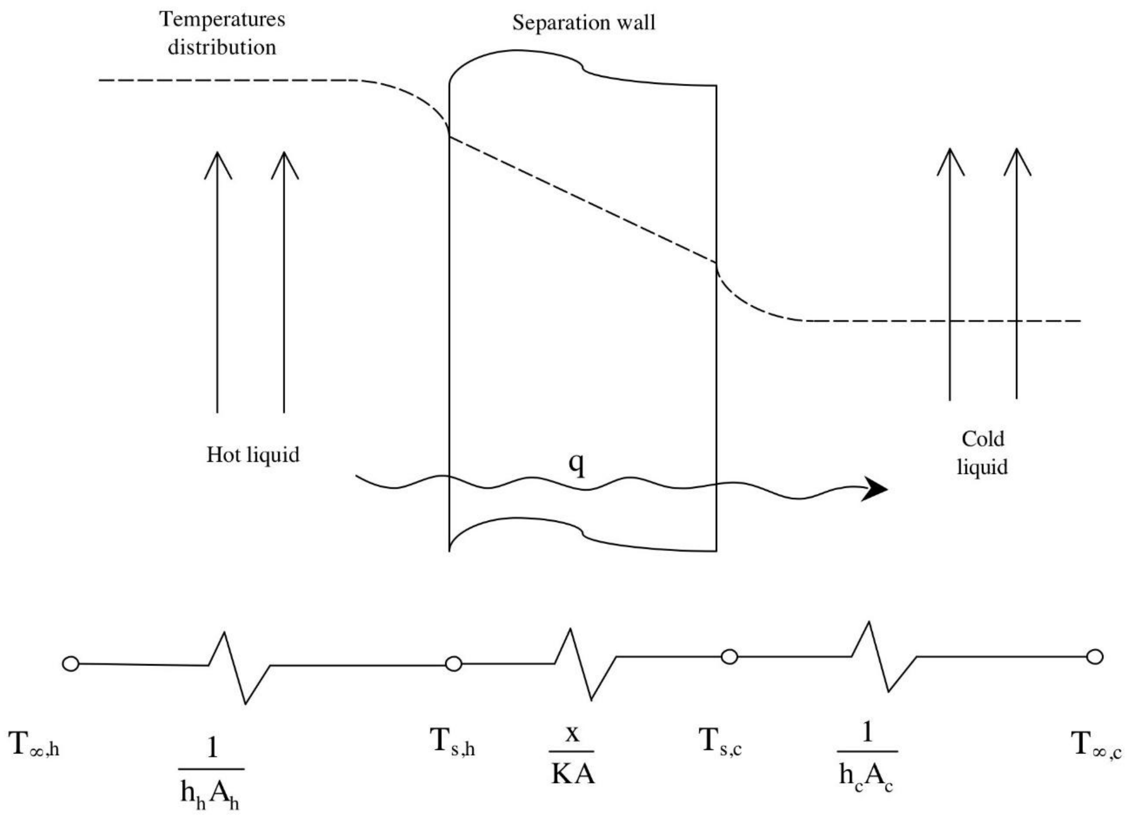
2.2 Heat transfer in heat exchangers

A heat exchanger is a device designed to allow heat transfer between two fluids at different temperatures without physically mixing the fluids because they are separated by a solid wall. Heat exchangers have multiple applications in engineering and, therefore, there are different models suitable for each application. The first-generation model is constructed using two concentric tubes, where the fluids can move in the same or opposite directions. With parallel flow (co-current), hot and cold fluids can enter and leave on the same side while flowing in the same direction. Countercurrent flows of fluids enter and exit at opposite ends, flowing in opposite directions.



2.3 Global heat transfer coefficient

In order to represent the global heat transfer phenomenon between fluids in an exchanger, we can refer to the thermal resistances that appear in each medium. The heat flow on its way between the hot and cold medium must overcome the resistances created by the boundary layer of the hot medium, the partition wall and the boundary layer of the cold medium. These three resistors, arranged in series, make up the total resistance ($\sum R_T$), which is the sum of each individual resistor.



where, A_h is the surface area in contact with the hot fluid [m^2], A_c is the surface area in contact with the cold fluid [m^2], $T_{\infty,h}$ is the average temperature of the hot fluid [K], $T_{\infty,c}$ is the average temperature of the cold fluid [K], $T_{s,h}$ is the temperature of the surface at the hot fluid/solid material interface [K], $T_{s,c}$ eis the temperature of the surface at the cold fluid solid interface [K], h_h is the heat transfer coefficient on the hot side [W m^{-2} K^{-1}], h_c is the heat transfer coefficient on the cold side [W/m^2 K], k is the thermal conductivity of the solid wall material [W m^{-1} K^{-1}], A is the average surface area for exchange [m^2], and x is the wall thickness [m].

The heat transfer is:

$$Q = \frac{(T_{\infty,h} - T_{\infty,c})}{\sum R_T} = \frac{(T_{\infty,h} - T_{\infty,c})}{\frac{1}{h_h A_h} + \frac{x}{kA} + \frac{1}{h_c A_c}} \qquad (Eq.\ 9)$$

The overall heat transfer coefficient U, is defined as the factor which, for a given geometric and hydrodynamic configuration, provides the total quality of heat transferred when multiplied by the exchange area and the total temperature difference.

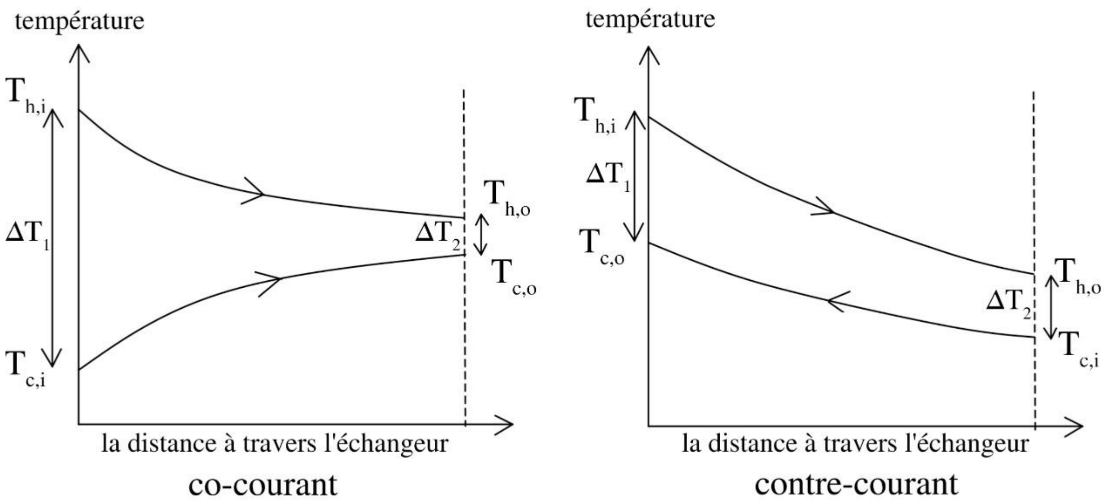
$$Q = UA(T_{\infty,h} - T_{\infty,c}) \qquad (Eq.\ 10)$$

where by comparing with equation 9, we get:

$$\frac{1}{U\,A} = \sum R_T = \frac{1}{h_h A_h} + \frac{x}{kA} + \frac{1}{h_c A_c} \qquad (Eq.\ 11)$$

2.4 Temperature distribution in heat exchangers

The temperature distribution of a simple concentric tube heat exchanger with parallel and counter-current flow is shown in the following figures:



$T_{h,i}$ is the temperature of the hot fluid at the inlet of the exchanger

$T_{h,o}$ is the temperature of the hot fluid at the outlet of the heat exchanger.
$T_{c,i}$ is the temperature of the cold fluid at the inlet of the exchanger.
$T_{c,o}$ is the temperature of the cold fluid at the outlet of the exchanger.

In the parallel flow exchanger, the hottest zone of the hot fluid exchanges heat with the coldest zone of the cold fluid, in the inlet region. Initially, the rate of heat transfer is greatest because the temperature difference is at its maximum, but the difference decreases rapidly along the exchanger, asymptotically towards zero. It should also be pointed out that for this type of exchanger, the temperature at the outlet of the cold fluid does not exceed the outlet temperature of the hot fluid.

In countercurrent, the hottest zone of the hot fluid exchanges heat with the hottest zone of the cold fluid and the coldest zone of the hot fluid with the coldest zone of the cold fluid. This configuration provides optimal heat transfer along the entire heat exchanger. This configuration also maintains a constant temperature difference, resulting in consistent heat transfer rates. In addition, the outlet temperature of the cold medium may exceed the outlet temperature of the hot medium.

2.5 Logarithmic mean of temperature differences

As seen previously, the temperature differences between the fluids vary along the exchanger so the definition of an average value is essential. This average is represented by ΔT_m, and is used to calculate the total heat transfer:

$$Q = UA\Delta T_m \qquad (Eq.\ 12)$$

From the analysis developed in most textbooks dealing with heat transfer, we can see that the average temperature difference is a logarithmic average of the temperature differences, ΔT_{lm}:

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)} \qquad (Eq.\ 13)$$

with $\Delta T_1 = T_{h,i} - T_{c,i}$ and $\Delta T_2 = T_{h,o} - T_{c,o}$ for co- current
$\Delta T_1 = T_{h,i} - T_{c,o}$ and $\Delta T_2 = T_{h,o} - T_{c,i}$ for counter- current

The precise reason for using ΔT_{lm} will not be discussed here (but you should see this in the course), but we can see that at equal input and output temperatures, ΔT_{lm} is greater for the countercurrent than for the parallel current. Thus, the area required for a specific heat transfer rate *Q,* is smaller for countercurrents than for parallel currents, assuming an identical *U.*

2.6 Estimating the overall heat transfer coefficient from the heat flow

Two important relationships for the analysis of a heat exchanger are the overall energy balances for hot and cold fluids. By ignoring the potential and kinetic energy changes along the exchanger, we obtain:

General heat flow from the hot fluid:

$$Q_h = m_h C_{p,h}\left(T_{h,o} - T_{h,i}\right) \qquad (\textit{Eq. 14})$$

General heat flow into the cold fluid:

$$Q_c = m_c C_{p,c}\left(T_{c,o} - T_{c,i}\right) \qquad (\textit{Eq. 15})$$

where m_h and m_c are the mass flow rates [kg s^{-1}], and $C_{p,h}$ and $C_{p,c}$ are the specific heats of the hot and cold fluids [J kg^{-1}K^{-1}].

Note: By convention, since the hot fluid is losing heat, $Q_h < 0$, and since the cold fluid gains heat, $Q_c < 0$. Theoretically, $|Q_h|$ should be equal to $|Q_c|$ but due to energy losses (Q_l) and also errors in measurement and instrumental observations, they are not always equal. Earlier we obtained another important expression for heat transfer from Newton's cooling law, using U instead of h:

$$Q = UA\Delta T_{lm} \qquad (\textit{Eq. 16})$$

If we get Q from equation 14 or 15 (Equation 14 can be used because the effect of the loss of the hot fluid to the environment is smaller. The hot fluid is surrounded by the cold fluid, while the latter is in contact with the surrounding atmosphere) the overall heat transfer coefficient multiplied by the transfer area results:

$$U\,A = \frac{-Q_h}{\Delta T_{lm}} = \frac{-Q_h}{\frac{\Delta T_1 - \Delta T_2}{ln\left(\frac{\Delta T_1}{\Delta T_2}\right)}} \qquad (\textit{Eq. 17})$$

Note: U can thus be calculated by averaging the heat transfer area.

3. Practical Laboratory Exercises

3.1 Objectives

Determine the heat transferred by the hot fluid (Q_h) to the cold fluid (Q_c) in both co-current and counter-current heat exchangers.

Determine the overall heat transfer coefficient (U)

Determine the influence of different variables on U and the efficiency of the exchanger.

Calculate the area required for a heat exchanger for the LCBM.

3.2 Warnings, main instructions and precautions

- Avoid contact with the heating tank as temperatures above 70°C can be reached.
- Do not open the heating tank drain valve when it is full.
- Fill the tank above the level switch.
- Do not remove the tank cover while doing this work.
- Check the position of the valves before the start of each work (use only the concentric tube heat exchanger, TITC, in this practice, make sure that the valves of the other two exchangers are closed).
- Check that the computer is connected to the interface and the sensors are connected to the interface.

3.3 Performing the practical work

1. Check that the correct temperature sensors are connected to the interface module.
2. When you start the software, choose the TITC module.
3. Check that the heating tank is filled with water to above the level.
4. Heat the water in the tank to 40°C (ST16).
5. Open the valves to circulate the water in a co-current configuration.
6. Open the cold water inlet valve and switch on the hot water pump.
7. Set the hot water flow rate to approximately 2 L min^{-1} (SC1) and set a cold water flow rate (SC2).
8. Allow temperatures to stabilize and record temperature and flow rate measurements.

Repeat operations 7 and 8 at different parameters.

For each condition calculate:

- heat transfer through hot water (Q_h)
- the heat absorbed by the cold water (Q_c)
- heat losses (Q_l)
- the overall heat transfer coefficient (U)

Choose parameters to respond to the following points :

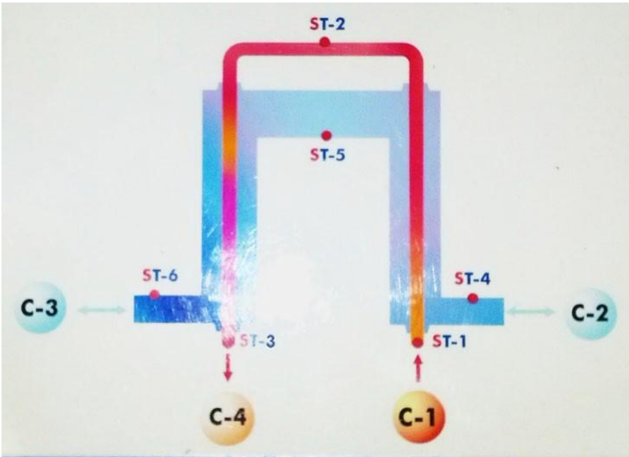
What is the effect of the different parameters on U and heat exchange?

In the event that m_h, m_c $T_{c,i}$, et $T_{h,i}$ are constant, compare the heat transfer in co- and counter-current along the exchanger. For this, consider that the length of the exchange is 1.0 m and that we have three measuring points:

Hot water: ST1 at x=0, ST2 at x= 0.5 m and ST3 at x=1.0 m

Cold water: ST4 at x=0 (or 1.0 m), ST5 at x= 0.5 m and ST6 at x=1.0 m (or 0 m)

see figure below :



In addition, for your report, answer the following points:

How can this installation be improved to maximize heat transfer?

In the best case (highest value for U found), what is the area required (m^2) to supply water at the conditions specified for the LCBM (37 °C at a flow rate of 1 litre per minute) assuming that hot water is available at 60 °C at a flow rate of 0.5 litres per minute, and ultrapure water is initially at 17 °C?

What is the surface area required if steam is used on the hot side at a rate of 0.1 kg per minute? Assume $T_{h,i} = T_{h,o} = 100°C$, only liquid water comes out of the heat exchanger, and use the following empirical equations to estimate reasonable values for h_h and h_c (justify your choices).

- *Internal flow*
  - $Nu = 3.66$ *(Re < 2300)*
  - $Nu = 0.0243\, Re^{0.8}\, Pr^{0.4}$ *(Re > 2300)*

$$Where\ Nu = \frac{h\, D_H}{k};\ Re = \frac{\rho\, D_H\, V}{\mu} = \frac{D_H\, V}{\nu};\ \mathrm{Pr} = \frac{\nu}{\alpha} = \frac{\mu\, C_p}{k};$$

$$D_H = \frac{4*(cross\ section\ area)}{Perimiter\ through\ which\ heat\ transfer\ is\ occured} = \frac{4\,A_c}{P} = \frac{4\,[\frac{\pi}{4}(D_2^2 - D_1^2)]}{D_1} = \frac{\pi\,(D_2^2 - D_1^2)}{D_1}$$

- *Condensation in horizontal tubes*

$$Nu_D = \frac{h_D\,D}{k_l} = 0.555\left[\frac{\rho_l\,g\,(\rho_l - \rho_v)\,h'_{fg}\,D^3}{\mu_l\,k_l\,(T_{sat} - T_s)}\right]^{0.25}$$

Where $h'_{fg} = h_{fg} + 0.375\,C_{P,l}\,(T_{sat} - T_s)$; *$h_{fg}$ is the enthalpy of evaporation at T_{sat}; ρ_l, $C_{p,l}$, μl, and k_l are the density, heat capacity, viscosity, and conductivity of the condensate, respectively; ρ_v is the density of the vapor phase, T_{sat} is the temperature of either the saturated vapor or saturated liquid which in this case is equal to 373 °K; T_s is the temperature of the surface on which condensation is occurred and in this case since the surface temperature varies between 290 to 310 °K, an average temperature can be considered as T_s which is 300 °K.*

4. The physical properties of the heat exchanger

- Consists of two concentric *copper* tubes with hot water flowing through the inner tube and cold water flowing through the ring-shaped area.
- Exchange length L=2x0.5=1m.

- Inner Tube
  Inner diameter $D_{int} = 16 \cdot 10^{-3}$ m
  External diameter $D_{ext} = 18 \cdot 10^{-3}$ m
  Thickness 10^{-3} m
- External Tube
  Inner diameter $D_{int} = 26 \cdot 10^{-3}$ m
  External diameter $D_{ext} = 28 \cdot 10^{-3}$ m
  thickness 10^{-3} m