ChE-309 TP-01
Continuous chemical reactions

instructions for use, spring 2025

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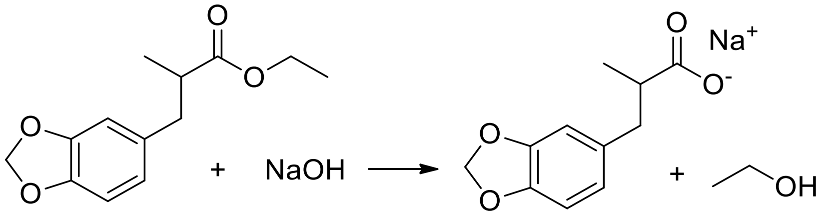
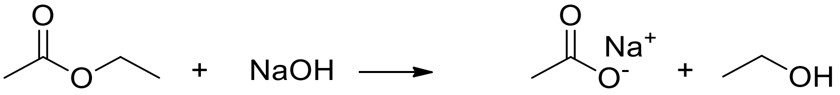
1. Statement of the objective

The pharmaceutical company you work for, Accropharm, is looking to expand production of its new anti-anxiety drug, Contiguflex-AC. The final step to produce the drug is the basic saponification of the precursor (the ethyl ester) as follows:



Contiguflex-AC

Accropharm is interested in exploring the possibility of using a continuous reactor to produce Contiguflex-CA at a rate of 1 mole per hour (24/365). However, this reaction must be carried out using water as a solvent due to the environmental regulations of the chemical plant and a diluted concentration due to the relatively low solubility of the reagent and the products. Fortunately, the Accropharm chemists have already determined that the kinetics of the desired reaction is essentially identical to the model reaction:



Where ethyl acetate is converted to sodium acetate and ethanol from sodium hydroxide. Your objective will be to design a continuous reactor system that produces the product at the desired speed at the lowest cost, using the model reaction as a reference.

2. Theoretical basis

In general, the discipline of chemical engineering focuses on the need to carry out chemical reactions on a large scale and at the lowest possible cost. This is usually achieved with a system that continuously produces products from an uninterrupted flow of reactants that are introduced into a reactor. There are many different types of real reactors, and for this exercise we will only look at our reaction in two reactors: a series of continuous stirred tank reactors (CSTRs) and a plug flow reactor (PFR) (see schemes in Figure 1).

2.1 Perfectly mixed reactors

To begin to understand how a stirred reactor works as a continuous reactor, we can write a material balance on the number of moles of one of the components, *i*:

$$\{\boldsymbol{accumulation}\} = \{\boldsymbol{in}\} - \{\boldsymbol{out}\} + \{\boldsymbol{production}\}$$

$$\frac{dN_i}{dt} = F_{i0} - F_i + V\nu_i r \qquad \text{(eq. 1)}$$

where Ni is the number of moles of component i in the reactor, F_{i0} and F_i are the flows [mol s^{-1}] into and out of the reactors, V is the reactor volume [L], ν_i is the stoichiometric coefficient, and r is the reaction rate [mol L^{-1} s^{-1}].

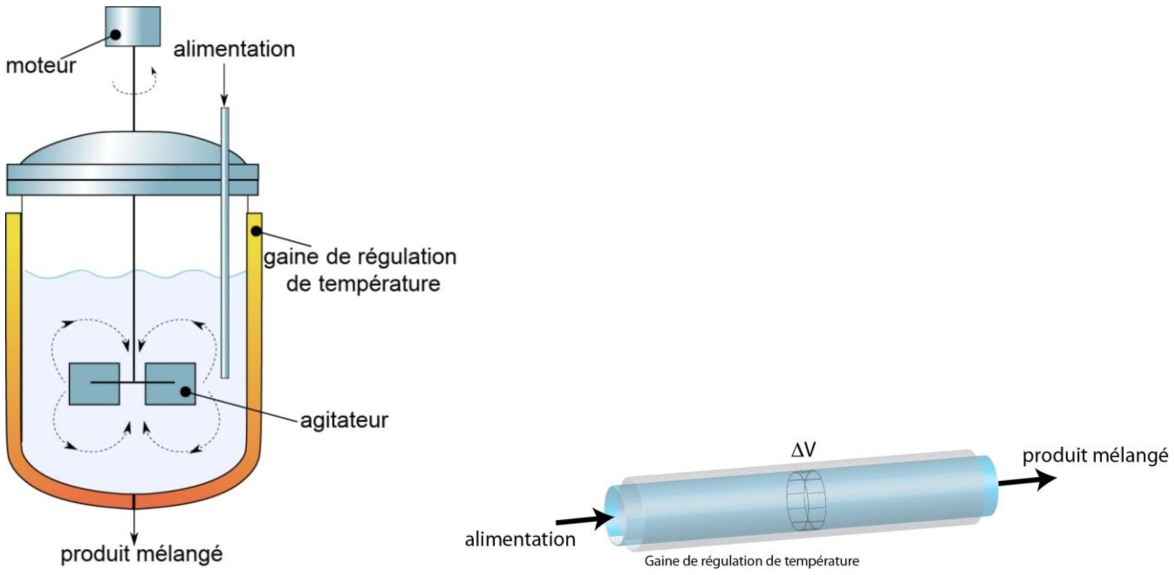


Figure 1. A stirred vessel reactor and a plug flow reactor (PFR).

This equation is correct if the reactor is perfectly mixed (i.e., there is no spatial variation in the concentrations in the reactor) and if there is only one reaction that occurs in the reactor. If we further assume that the reactor volume is constant and that the density does not change with composition, the mass balance is simplified into:

$$V\frac{dC_i}{dt} = \dot{V}_0(C_{i0} - C_i) + V\nu_i r \qquad \text{(eq. 2)}$$

where $\dot{V}_0$ is the volumetric flow [L s^{-1}] into and out of the reactor. We can define a characteristic time, the passage time, of the reactor, τ:

$$\tau = \frac{V}{\dot{V}_0}$$

The passage time is a very important concept in reactor engineering and can also be considered as the average passage time of a (non-reactive) molecule through the reactor. It also helps to simplify the reactor equation:

$$\tau\frac{dC_i}{dt} = (C_{i0} - C_i) + \tau\nu_i r \qquad \text{(eq. 3)}$$

and at a steady state:

$$C_{i0} - C_i = -\tau\nu_i r \qquad \text{(eq. 4)}$$

2.2 Plug flow tubular reactors

For a tubular reactor, it is first assumed that the tube has a constant diameter, D, and also that the density does not vary with position in the reactor (no change in the number of moles or temperature). In this case, flows through the tube with a linear velocity, *u*, equal to the volumetric flow velocity, $\dot{V}_0$ divided by the cross-sectional area, A_t. For a cylindrical tube with a diameter D:

$$u = \frac{\dot{V}_0}{A_t} = \frac{4\dot{V}_0}{\pi D^2} \quad \text{(eq. 5)}$$

also assuming steady-state operation of the tubular reactor, a balance on the *i*-th component of the element of length *dz* between *z* and *z* + *dz* gives:

$$0 = F_i(z) - F_i(z + dz) + A_t dz\, \nu_i r \quad \text{(eq. 6)}$$

The molar flow of species *i* is related to these quantities by the relation:

$$F_i = A_t u C_i \quad \text{(eq. 7)}$$

Therefore, our mass balance becomes:

$$0 = A_t u\big(C_i(z) - C_i(z + dz)\big) + A_t dz\, \nu_i r \quad \text{(eq. 8)}$$

Finally, we set dz →0 to get the final form of the mass balance.

$$u \frac{dC_i}{dz} = \nu_i r \quad \text{(eq. 9)}$$

Note that this equation assumes: 1) plug flow, 2) steady state, 3) constant density, 4) constant tube diameter, and 5) a single reaction.

2.3 Reaction kinetics

The reaction rate, *r*, used in the above equations is the one generally used in reaction kinetics. For our reaction model of ethyl acetate (EA) and sodium hydroxide (SH) we have:

$$r = \frac{dC_{SA}}{dt} = kC_{EA}C_{SH} \quad \text{(eq. 10)}$$

where C_{SA} is the concentration of the product (sodium acetate), *k* is the rate constant and the order of reactions is known to be one for both EA and SH concentrations. This equation can be applied to the mass balance for the stirred vessel reactor or in the tubular reactor.

2.4 Residence time distribution concept for non-ideal reactors

The above theory is based on the assumption that the reactor is perfectly mixed, but of course this is not the case in reality. Chemical engineers use a concept called residence time distribution (RTD) to characterize mixing and flow in reactors and compare the behavior of actual reactors to their ideal models. This is useful, not only for troubleshooting existing reactors, but also for estimating the performance of a given reaction and the design of future reactors. For a stirred reactor the RTD is most conveniently represented by an exit age distribution, *E*(*t*), which has units of time^{-1} and is defined as:

$$\int_0^{\infty} E(t)dt = 1 \quad \text{(eq. 11)}$$

Assuming that some material is injected into the reactor at the time *t* = 0, the fraction of the material that has exited the reactor at a time t_1 is

$$\int_0^{t_1} E(t)dt.$$

The average residence time is given by the first moment of the exit age distribution:

$$\bar{t} = \int_0^{\infty} t\, E(t)dt \qquad \text{(eq. 12)}$$

$E(t)$ for a reasonably well-mixed vessel reactor is shown in Figure 2 below with the value of $\bar{t}$ indicated.

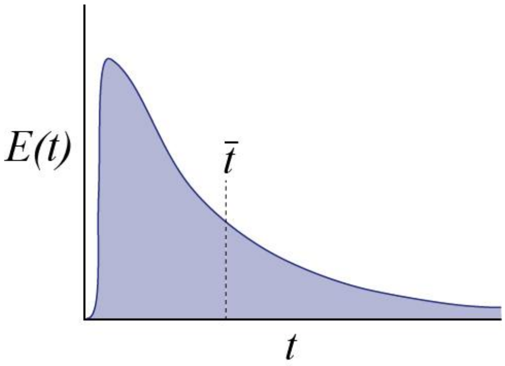


Figure 2. Typical RTD for a real stirred tank reactor.

If there are no dead, or stagnant areas inside the reactor, then $\bar{t}$ will be equal to τ. The $E(t)$ can be determined experimentally by introducing a non-reactive tracer into the system at the inlet. The tracer concentration is introduced as a known function of time and the response is obtained by measuring the tracer concentration at the output, $C(t)$. For example, the introduction of a very small volume of concentrated tracer at the reactor inlet, so that it is close to the distribution of Dirac can be used. This "pulse experiment" gives the RTD per:

$$E(t) = \frac{C(t)}{\int_0^{\infty} C(t)dt} \qquad \text{(eq. 13)}$$

Once $E(t)$ is known for a particular reactor, the product concentration can be predicted using a combination of a mixing reactor model and reaction kinetic data. There are many models of varying complexity, and they will not be discussed here. The simplest model, the segregation model, assumes that infinitesimally small segments, or globules, pass through the reactor and do not mix, rather they react as if they were separate reactors that spend an amount of time in the reactor as determined by $E(t)$. In the case of our reaction, the concentration of the product in each globule, $C_{AS}(t)$, will increase over time as governed by equation 10, and it can then be predicted that the average concentration of the output segments is:

$$\overline{C_{SA}} = \int_0^{\infty} C_{SA}(t)\, E(t)dt \qquad \text{(eq. 14)}$$

3. Practical laboratory exercises

3.1 Objectives

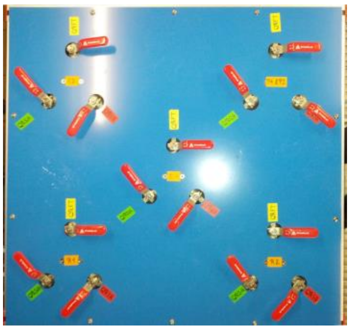
3.1.1 Determine the yield of the saponification reaction at 40 °C and compare the yield obtained from the plug flow reactor (QRFT) and a series of three stirred tanks in a cascade reactor (QRSA)[11].

3.1.2 Determine the RTD characteristics for both reactor systems.

3.1.3 Design a reactor to produce the product at the desired rate.

3.2 Experimental equipment

The system consists of a basic unit, which feeds the reactors with reagents, heating water and receives the product. A system of valves on the top of the unit allows the active reactor to be selected. Here is a picture of the valve system with all but one valve closed (can you find it?).



In this experiment, you will work with two different reactor systems: QRSA (three stirred tanks reactors in series) and QRFT (one plug flow reactor).

3.2 Experimental preparation

Turn on the computer and electronic panel. Start the appropriate control program. The three continuous stirred reactors (CSTRs) correspond to the QRSA and the plug flow reactor (PFR) corresponds to the QRFT. You start with the QRFT.

To work with a certain reactor, **open all valves** for that reactor and close all other valves. In addition, when changing the reactor, **move the conductivity meter** while *wearing gloves* as the pipes may leak. The conductivity meter (red colored probe) is screwed into the Teflon block on the reactor system panel (Ask the assistant to help you move the position). Finally, before starting your experiment (and when changing reactors), **make sure to connect the appropriate sensors and actuators (thermocouples and stirrers)** to the electronic panel.

3.3 Experimental procedure

Experiments 3.3.1 and 3.3.2 are carried out in both systems.

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1. The reactor names are abbreviations according to the manufacturer.

3.3.1 Saponification reaction at 40°C:

- Start the appropriate control program for the reactor
- Set the valves for the chosen reactor
- Connect all thermocouples and stirrers, move conductivity meter accordingly
- Set the bath temperature to 40°C and circulate the water
- Start data acquisition (1 point every 2 seconds is sufficient)
- Fill the reactor with the 0.01 M NaOH and 0.02 M EtOAc solutions as follows:
    - Check liquid level in the tanks – refill if needed
    - Turn the valves for the tanks to the flow direction "réservoir"
    - Switch on both pumps (NaOH: 6 L/h and EtOAc: 3 L/h)
    - Turn the flow control valves to "réacteur"
- For the PFR set the temperature of the pre-heater to 40 °C
- For three CSTRs, start the agitator when the mixture level is sufficient
- Allow the reaction to unfold and wait for the conductivity to stabilize
- **Refill the tanks whenever needed – make sure to always have 5 L in stock**

Explain the evolution of conductivity. What does it correspond to? What conductivity value do you obtain in the steady state?

Determine the yield of the reaction at 40°C. Compare the results of the two systems. What's the better one? Why?

3.3.2 Determining the residence time distribution of the reactors:

- Prepare a tracer solution: Rhodamine B in 0.2 M NaOH (The exact amount of Rhodamine B is not important, but the tracer solution should be intense pink in color).
- With the reactor in a steady state, introduce this tracer solution into the reactor at once (use the "luer-lock" syringe valves). **Note the time** *t* of your measurement.
- Wait for stabilization (removal of the "tracer" and return to steady state).

Determine $E(t)$ and the average residence time.

Are the reactors well mixed? Compare the real cases with an ideal reactor? (Hint: What is the ideal RTD for three CSTRs in series and the QRFT?)

Based on the results of this experiment for both reactors, which one has a better mixing?

3.4 Other questions for consideration

What would be the volume of three CSTRs required to produce the desired product at the required rate (1 mole / hour) at 40°C? What for a PFR? Use the RTDs you found for your design.

3.5 Important advice

The laboratory equipment is designed to carry out the saponification reaction and to detect the progress of the reaction using a conductivity meter. Because both the NaOH reagent and the NaOAc product are conductive, **it is necessary to feed the products in stoichiometric proportions.**

Throughout the experiments, make sure you have enough NaOH and EtOAc solution ready to feed into the reactor. Prepare new batch of solution if necessary.

To facilitate the calculations, note the important times and those where there have been changes (stabilization, agitator stop/start, temperature change, etc.) so you can find back these points in your data.

3.6 Conductivity calculation

$$\kappa = \kappa_0 + \kappa_1 C + \kappa_2 T$$

$$\kappa \,[\mu\mathrm{S\ cm^{-1}}]$$

$$\mathrm{C}\,[\mathrm{M}]$$

$$\mathrm{T}\,[^\circ\mathrm{C}]$$

$$\begin{array}{lll} \text{NaOH} & \kappa_0 = 30.73 & \mu\mathrm{S\ cm^{-1}} \\ & \kappa_1 = 2.806 \cdot 10^5 & \mu\mathrm{S\ cm^{-1}} M^{-1} \\ & \kappa_2 = -1.235 & \mu\mathrm{S\ cm^{-1}} {}^\circ C^{-1} \\ \text{NaOAc} & \kappa_0 = -54.09 & \mu\mathrm{S\ cm^{-1}} \\ & \kappa_1 = 1.011 \cdot 10^5 & \mu\mathrm{S\ cm^{-1}} M^{-1} \\ & \kappa_2 = 1.455 & \mu\mathrm{S\ cm^{-1}} {}^\circ C^{-1} \end{array}$$

EtOH and EtOAc are not electrically conductive.

3.7 Pre-lab questions

The following questions will be asked before starting the experiment. Failing to answer these questions will result in the deduction of lab participation marks.

3.7.1 Which amount of 2 M NaOH (in mL) and EtOAc (in g) will you need to mix 5 L of each solution with the appropriate concentrations (NaOH: 0.01 M, EtOAc: 0.02 M)?

3.7.2 Five liters of NaOH and EtOAc have been prepared for you. Will this amount last the entire experiment? If not, which reactant will run out first and how long will you have before 5 L of it run out?