FELLES LAB
RE7: Residence time distribution (RTD)
Fall 2018

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1. Overview

Elements of fluid taking different routes through the reactor may require different lengths of time to pass through the vessel. The distribution of these different times for the stream of fluid is called residence time distribution of the fluid (RTD). The RTD is used to characterize mixing and flow inside a reactor, and to compare the behavior of a real reactor with an ideal model. This is useful for estimating yield of a given reaction, designing reactors and troubleshooting working reactors.

In this lab, you will find the RTD for a reactor. A dye and a NaCl solution are used as tracers. You can use different concentrations of NaCl and control the pumping rate. The conductivity is measured at the inlet and outlet of the reactor and you will use the conductivity data to determine RTD. In the report you shall discuss the RTD and aspects of the observed flow through the reactor, also with respect to different pump rates, tracer concentrations and compared to an ideal PFR.

2. Before the lab: Work plan

You must read the Risk Assessment for the experiment, and create a work plan before the lab. In the work plan you will:

1. State the objective of the experiment
2. Give a short explanation of the relevant theory
3. Describe your experimental procedure
4. Mention shortly the risks and measures suggested in the risk assessment

You must submit the work plan to me no later than 2 days before you lab session. You need an approval of the work plan from me before you are allowed into the lab.

3. Experimental

Our experimental setup (Figure 1) consists of a water tank, a filter (orange), a pump (green), a septum for tracer injection (purple), a reactor with conductivity sensors (CI) at the inlet and outlet. You control the pumping rate from the computer, and the same program collects the conductivity data. A dye and a NaCl solution is used as tracers and it is a pulsed input experiment.

1. Switch the pump on, and control the pumping rate from the computer program.
2. When the flow and conductivity is stable, you can start a measurement. Inject the tracer through the septum by using a syringe.
3. Do the test for 3 different NaCl concentrations at 3 pumping rates, in total 9 measurements. Depending on how you plan to analyze your data, it might be useful to record the background conductivity separately as well.
4. Use the blue dye to visually inspect the flow through the reactor.
5. Find the volume V, and the volumetric flow rate ν.

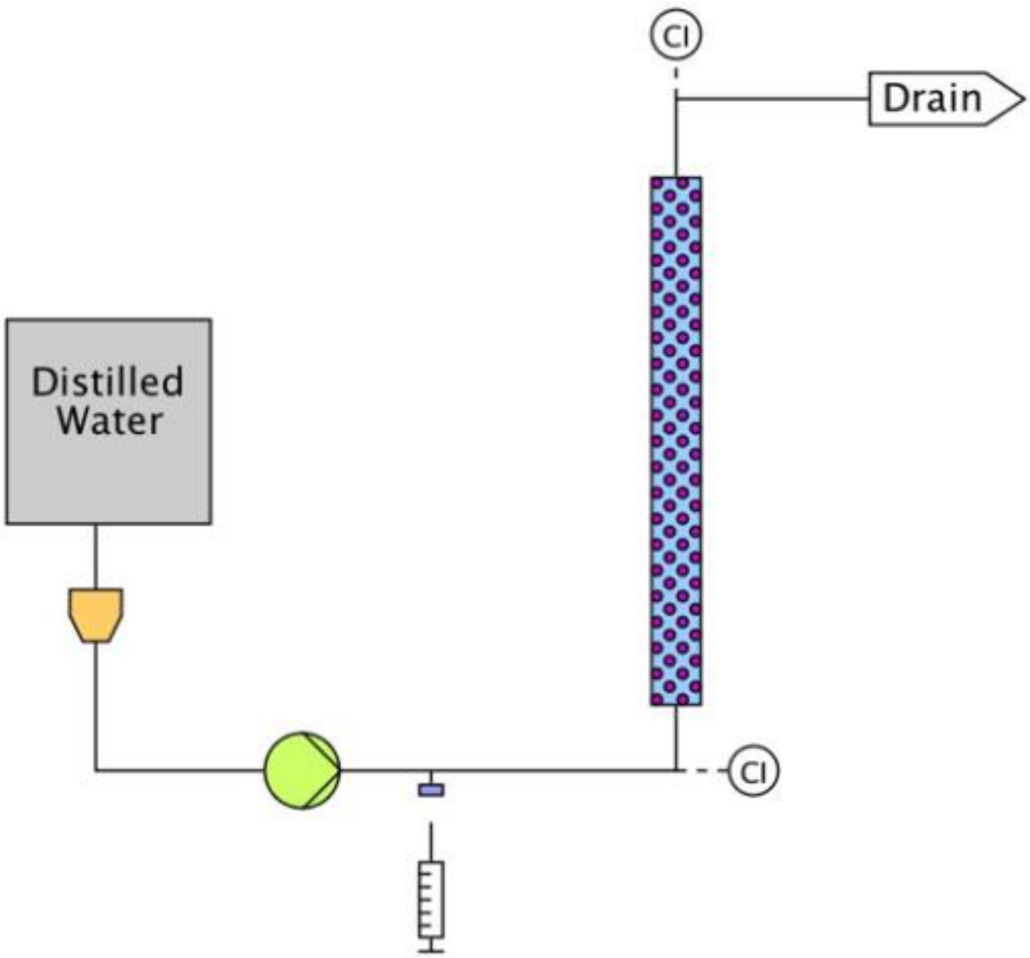

Figure 1 Experimental setup

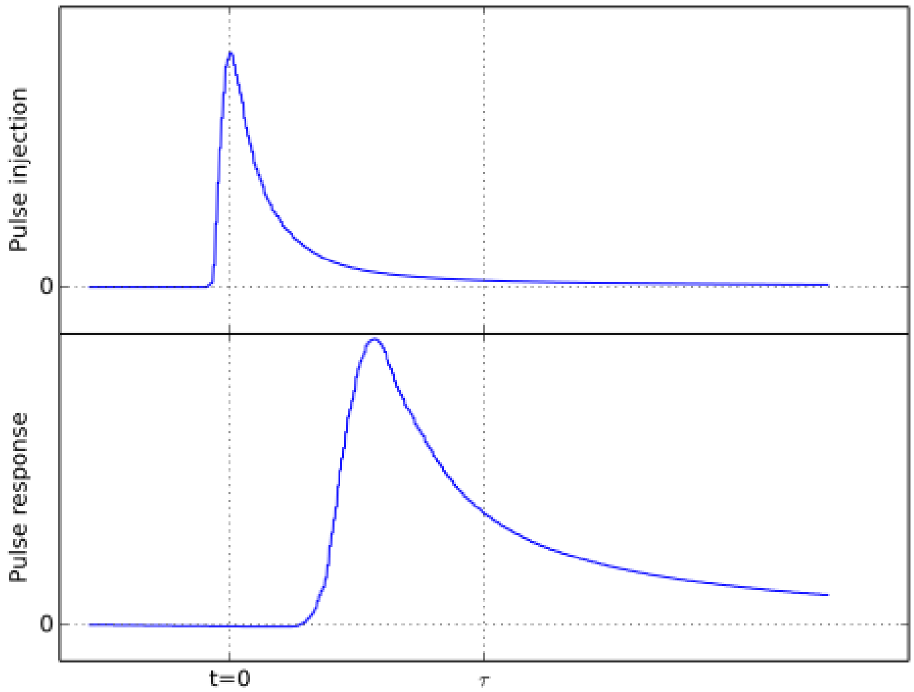

Figure 2 Possible response curve after background subtraction and centering

4. Theory

The theory is described in the attached pdf-file, Scott Fogler's *Elements of Chemical Reaction Engineering*, chapter 13, and in the following links on Youtube: 1, 2, 3 and 4. The students are also encouraged to search in the literature for theory on their own. The following theory is not a substitute for the other sources, and does not fully cover the curriculum, but it is meant as a refresher:

Elements of fluid taking different routes through the reactor may require different lengths of time to pass through the vessel. The distribution of these different times for the stream of fluid is called the exit age (E) distribution or residence time distribution of the fluid (RTD). E for an element of the exit stream refers to the time spent by that element in the vessel.

Not all the elements spend the same time in a reactor, and the probability for an element to reside the time t in the reactor is E(t). Since E(t) is a probability distribution function,

$$\int_0^\infty E(t)\,dt = 1$$

The average residence time t_m will be:

$$t_m = \int_0^\infty t\, E(t)\, dt$$

If there are no dead zones or stagnant zones in the reactor, t_m will be equal to the space time, τ the volume, V divided by the volumetric flow rate, ν:

$$\tau = V / \nu$$

The variance of E(t) describes the spread of the residence times. Since we want to characterize the extent of a nonideal flow by means of the exit age distribution function, E(t), it is important to know how to evaluate it for any flow. For experimental evaluation of E(t), we can use stimulus-response techniques. They enable us to see the system response as a result of disturbing the system with a stimulus.

A tracer is used as stimulus, and any type of input signal can be used such as a random signal, a periodic signal or a pulse signal. Tracer must be inert in the reactor, ideally, should not adsorb on surfaces in the reactor, have similar physical properties to the reaction mixture and be easy to detect. The flow of the tracer through the reactor should reflect the flow of the reaction mixture.

When we impose an instantaneous pulse of tracer on the stream entering the vessel with no initially present tracer, it is called a pulse input or impulse. For a pulse input experiment, E(t) is related to the outlet concentration C(t) of the tracer as follows:

The amount of tracer material ΔN leaving the reactor between time t and t + Δt is

$$\Delta N = C(t)\nu\Delta t$$

$$\frac{\Delta N}{N_0} = \frac{C(t)\nu}{N_0}\Delta t = E(t)\Delta t$$

By dividing with N_0 (total amount of material), we obtain the material fraction, which we can relate to E(t). If N_0 is unknown, it can be found from C and ν

$$dN = C(t)\nu dt$$

$$N_0 = \int_0^\infty \nu C(t)\,dt$$

And from there we can to find E(t) as a function of C(t).

Some drawbacks or challenges with the pulse input experiment: The pulse should be short compared to the reactor residence time, and the dispersion between the point of injection and the reactor entrance should be negligible. Another challenge is in cases where the concentration-time curve has a large tail, which may lead to large inaccuracies; this is described in the book.

Finally, some assumptions behind general RTD theory should be noted: 1) the reactor is in steady state. 2) The transport mechanism at the inlet and outlet is by advection only. 3) The fluid is incompressible (volumetric flow rate is ν constant).

5. Data Analysis

The conductivity measurements are saved in a .txt file, with comma separated values:

```
194.6,10,116.29,0,0.20009398460388184
194.6,10,116.29,0,0.40010905265808105
194.6,10,115.81,0,0.6000900268554688
194.6,10,115.81,0,0.8000919818878174
194.6,10,115.81,0,1.0000860691070557
```

Column 1: Conductivity at the inlet
Column 2: Pump Rate
Column 3: Conductivity at the outlet
Column 5: Time

You can treat and analyze the data with for example Matlab, Python or Excel. Keep in mind that you should subtract the background conductivity, and center the maximum of the inlet signal at t = 0.

6. Report

In the report, you should explain what you have done, describe (briefly) the theory you have used in the evaluation of your data, and discuss/show the followings:

- Show an example of the reactor inlet and reactor outlet signals, using one of your tests.
- Find the RTD for all the 9 NaCl tests.
- Compare the RTD's for different pump speeds at equal concentrations.
- Compare the RTD's for equal pump speeds at different concentrations.

- Compare t_m and τ
- Compare the RTD's you found with an ideal PFR. Is your reactor ideal? If not, what can be the sources of non-ideality? Remember the dye tracer experiment.
- For a 2nd order A → B reaction in the reactor, the feed concentration C_{AO} = 2.5 mol/L, and the reaction rate constant k = 0.2 L/mol*s. You can assume a segregated flow, and calculate the average concentration of A, C_A, leaving our reactor. How is C_A affected by different pump speeds?

Show your data in a way that makes them easy to compare and evaluate. i.e. plot several E(t)'s in the same plot. You should add an appendix in which you include calculations and program code. Also include references.

7. Submission deadlines

The work plan must be submitted electronically within two days before the lab takes place. You should send a first draft to me within 7 days after the lab, such that I can give you feedback on how to improve your report. The final report must be submitted within 7 days after receiving comments from me for your first draft report.

2 days before the experiment day: Work plan
7 days after the experiment day: Draft report
7 days after receiving feedback of the draft report: Final report