experiment 12: Residence Time Distribution in a Series of Continuously Stirred Tank Reactors

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**Synopsis**

The experiment found that an increasing the flowrate reduces the mean residence time and the variance of the tracer in the vessels. It also found that by using a series of CSTRs, a more realistic reactor could be modelled. Aside from two of the eight experiments, the results were found to be consistent and the erroneous results were put down to human error.

**Introduction**

This experiment seeks to perform step and pulse tracer studies on a cascade of Continuously Stirred Tank Reactors (CSTRs) modelling a real reactor performing somewhere between the extreme differences in performance of CSTRs and the ideal Plug Flow Reactor (PFR). By doing so, we will increase our knowledge of reactor engineering. (Heriot Watt University School of Engineering & Physical Sciences, 2006)

**Theory**

The performance of a reactor is to a large measure determined by the residence time of the reactants of the reactor. The residence time is the time spent by molecules in a vessel. A tracer is a nonreactive substance that is easily detected by analysis in small concentrations. While performing an experiment, the tracer is injected at the inlet of the vessel under otherwise normal conditions and conductivity probes are used in the vessel to record the conductivity and hence the concentration of the tracer. This data can be converted into a residence time distribution, allowing us to see the fractions of molecules that spend a certain amount of time in the vessel. (Perry & Green, 1997) The flow paths and consequently the times spent within the vessel are dependent on the fluid mixing pattern, therefore giving an effective method to investigate the non-ideal nature of the vessel in question. (Heriot Watt University School of Engineering & Physical Sciences, 2006)

In reactor engineering, two extremes can be distinguished in reactor performance: the ideal Plug Flow Reactor (PFR) and the ideal Continuously Stirred Tank Reactor (CSTR). In the ideal PFR there is no mixing at all and any material introduced into the reactor will exit as effluent molecules having had the same residence time. Conversely, the ideal CSTR is fully mixed and all material introduced into the reactor is immediately fully dispersed and will leave the reactor over a prolonged period of time. In a CSTR an agitator is used to mix through the bulk flow of the liquid and by the motion of turbulent eddies on the microscopic scale. For solid suspension, bulk flow is the predominant mixing mechanism. (Sinnott & Towler, 2009) An ideal PFR can be modelled by an infinitely long series of CSTRs in which the outflow of each individual CSTR is the inflow of the next. In practice all reactors behave between these extreme cases, thus real reactors can be modelled by a small number of CSTRs in series. (Heriot Watt University School of Engineering & Physical Sciences, 2006) (Perry & Green, 1997)

The main methods that are used in a tracer experiment are the pulse method and the step method.

The pulse method is the injection of a significant amount of tracer material into the system over an ideally infinitely short time, but practically over a very short time period. The function that describes the residence time distribution that results from a pulse input is called the exit-age distribution function E(t):

Where:

E(t) – Exit-age distribution function (residence time distribution)

Ct – Concentration at time t

E(tr) – Normalised residence time distribution ()

– Mean residence time (s)

(Heriot Watt University School of Engineering & Physical Sciences, 2006) (Perry & Green, 1997)

The step method involves the application of a significant sudden change in concentration of the tracer in the system, which is then kept constant. The residence time distribution that results from a step input is the exit-age distribution F(t):

If the step input and inlet concentration is constant with time, C0, we can take it outside the integral as follows:

Where:

Cout – Outlet concentration

Cin – Inlet concentration

E(t’) – Exit-time distribution function

F(t) - Exit-time distribution function (age)

(Heriot Watt University School of Engineering & Physical Sciences, 2006) (Perry & Green, 1997)

The mean residence time is the average time taken for a tracer element to leave the vessel from its entry. It is given by:

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Where:

– Mean residence time (s)

C – Concentration of tracer

t – Time (s)

Ci – Conductivity at time i (μS/cm)

ti **–** Time i (s)

(Heriot Watt University School of Engineering & Physical Sciences, 2006) (Perry & Green, 1997)

Pulse results can also give the variance (second moment) of a residence time distribution, σ2:

(Heriot Watt University School of Engineering & Physical Sciences, 2006) (Perry & Green, 1997)

Deviation from plug flow is represented by the dispersion DL. The above formulae assume that an ideal dispersion of tracer occurs as with plug flow, but they can also be used for scenarios where the dispersion is a small value (<0.01). For large dispersion values, the boundary conditions for the vessel become significant, causing the initial concentration of the tracer and the injection time to have a larger effect on the trace measured by the sensor at the vessel output. Large dispersion values occur due to a gradient of concentration or temperature. The effect is represented by Fick’s Law. Dispersion can be calculated as follows:

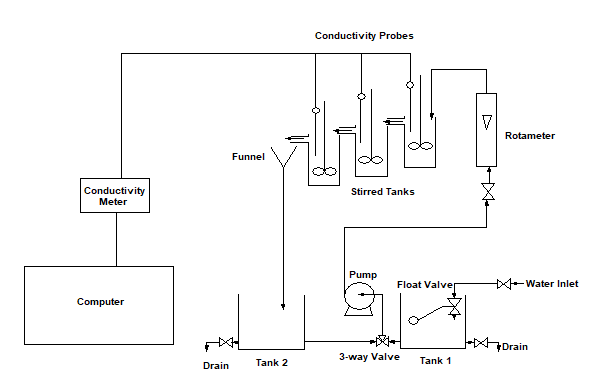
(Heriot Watt University School of Engineering & Physical Sciences, 2006) (Perry & Green, 1997)

**Experimental Technique**

Equipment

* Closed tanks x2
* Water source
* Ball valves x4
* Float valve
* 3-way valve
* Pump
* Rotameter
* Open tanks x3
* Stirrers x3
* Conductivity probes x3
* Funnel
* Assorted piping
* Conductivity meter
* Computer
* 500ml beaker
* NaCl
* Scales
* Spatula

Diagram



Methodology

Initial Setup

1. The equipment was assembled as illustrated above.
2. A 1M NaCl solution was created by thoroughly dissolving 5.844g of NaCl in 100ml of water.
3. All three stirrers were set to a speed of 300rpm.
4. The rotameter valve was initially set to an arbitrary high value.

Pulse (Single Stirrer)

1. The valves on the pump inlet were set so that the pump drew water from Tank 1 (the tank being fed continuously with fresh water via the float valve). The drain on Tank 2 was opened and the drain on Tank 1 was closed. The pump was then turned on.
2. Water was allowed to flow through the system until it was deemed that the system would not overflow or otherwise have any issues.
3. Stirrer 1 (for the stirred tank on the right) was then turned on at 300rpm, the other two stirrers remained off.
4. Conductivity probe 1 (for the stirred tank on the right) was turned on.
5. The rotameter valve was adjusted such that a flowrate of 0.5 litres/minute (l/min) was achieved.
6. The logger software on the computer was activated and the base conductivity was noted.
7. 5cm3 of the NaCl solution was injected into the inlet stream of the first (right hand) tank.
8. The time and conductivity were recorded once or twice per second for the time period taken for the tank to return to the base conductivity. The logger software was then stopped, and the collected data was copied to a spreadsheet.
9. The flowrate was then adjusted to three further different values and steps 7 and 8 were repeated until four sets of data had been collected.

Pulse (Multi Stirrer)

1. Steps 1 and 2 from the Pulse (Single Stirrer) were carried out.
2. All three stirrers were turned on, all at 300rpm.
3. The rotameter valve was adjusted such that a flowrate of 0.5 litres/minute (l/min) was achieved.
4. All three conductivity probes were turned on.
5. The logger software on the computer was activated and the base conductivity was noted for each probe.
6. 5cm3 of the NaCl solution was injected into the inlet stream of the first (right hand) tank.
7. The time and conductivity were recorded twice per second for the time period taken for the tank to return to the base conductivity. The logger software was then stopped, and the collected data was copied to a spreadsheet.
8. The flowrate was then adjusted to three further different values and steps 6 and 7 were repeated until four sets of data had been collected.

Step

1. The setup from the Pulse experiments was used as a base.
2. The rotameter valve was adjusted so that a flowrate of 0.7l/min was achieved.
3. The drain valve in Tank 2 was closed and the tank was allowed to fill above the line of the outlet pipe.
4. The three-way valve was adjusted such that the pump drew water from Tank 2 only, so that the system would run in a closed circuit.
5. Stirrer 1 (for the stirred tank on the right) was then turned on at 300rpm, the other two stirrers remained off.
6. Conductivity probe 1 (for the stirred tank on the right) was turned on.
7. The logger software on the computer was activated and NaCl solution was added and left to circulate until a high conductivity trace became steady.
8. The drain valve on Tank 2 was opened. At the same time, the three-way valve was adjusted so that fresh water was drawn into the system from Tank 1.
9. The time and conductivity were recorded twice per second for the time period taken for the tank to return to the base conductivity. The logger software was then stopped, and the collected data was copied to a spreadsheet.
10. The flowrate was adjusted, and steps 3-9 were repeated.

**Results**

For ease of reading and due to limited space, only the graphical results, the mean residence time, variance and dispersion for each experiment has been included in this section.

Experiment I: Pulse, single tank, Q=0.5l/min

Mean Residence Time = 233.75s

Variance = 31136.4

Dispersion = 0.285

Experiment II: Pulse, single tank, Q=0.55l/min

Mean Residence Time = 67.75s

Variance = 2278.2

Dispersion = 0.248

Experiment III: Pulse, single tank, Q=0.6l/min

Mean Residence Time = 121.03s

Variance = 8262.36

Dispersion = 0.282

Experiment IV: Pulse, single tank, Q=0.7l/min

Mean Residence Time = 101.24s

Variance = 5576.90

Dispersion = 0.272

Experiment V: Pulse, multi tank, Q=0.5l/min

Mean Residence Time = 427.47s

Variance = 82187.96

Dispersion = 0.225

Experiment VI: Pulse, multi tank, Q=0.55l/min

Mean Residence Time = 272.47s

Variance = 33123.67

Dispersion = 0.223

Experiment VII: Pulse, multi tank, Q=0.6l/min

Mean Residence Time = 203.30s

Variance = 18345.98

Dispersion = 0.222

Experiment VIII: Pulse, multi tank, Q=0.7l/min

Mean Residence Time = 158.75s

Variance = 10882.55

Dispersion = 0.216

Experiment IX: Step, single tank, Q=0.7l/min

Mean Residence Time = 69.25s

Variance = 4726.27

Dispersion = 0.493

Experiment X: Step, single tank, Q=0.6l/min

Mean Residence Time = 91.37

Variance = 4450.96

Dispersion = 0.267

**Discussion of Results**

For the single tank pulse experiments, the maximum conductivity was fairly consistent at around 220-230 μS/cm, except for experiment II, which shall be discussed shortly. The distributions are visually very similar, all showing the same trend. The distributions also clearly show that an increased flowrate will reduce the residence time in the reactor – the conductivity decreases at a faster rate with an increased flowrate. The strange results observed in Experiment II are thought to have been caused by the NaCl solution being injected into the inlet at an angle, causing the solution to bypass the tank and sensor, causing the mean residence time to be anomalously low.

For the multi tank pulse experiments, the maximum conductivity was consistent at around 120 μS/cm. Again, the distributions are all visually very similar showing the same general trend. Again, the distributions also clearly show that an increased flowrate will reduce the residence time in the reactor – the conductivity decreases at a faster rate with an increased flowrate. Compared to the single tank pulse experiments, the mean residence times and variances for the respective flowrates are greatly increased. This is consistent with the expected results for a realistic reactor, where the vessel is more thoroughly mixed, and the tracer exits over a long time period.

For the step experiments, we first achieved a consistent baseline of around 210 μS/cm. Again, the distributions are all visually very similar showing the same general trend. Again, the distributions also clearly show that an increased flowrate will reduce the residence time in the reactor – the conductivity decreases at a faster rate with an increased flowrate.

Aside from experiment II, all experiments were found to give consistent results and are therefore assumed to be within reasonable accuracy. Small sources of error include the parallax error involved with injecting the solution into the vessel each time as it is impossible to inject the solution into the solution at a consistent speed or position between experiments. Although care was taken to ensure that the solution returned to the baseline value each time, small amounts of solution may have remained in the tank causing the following experiments results to be affected, however, it can be assumed that this effect would largely be negligible.

The dispersion value was found to largely be consistent across all experiments, implying that all of the experiments have deviated from plug flow by a similar amount. The exception to this was experiment IX, where the variance was found to be smaller than expected, the reason for which is not known, but is likely due to have been caused by human error when performing the valve switch part of the experiment.

**Conclusions**

In conclusion, the experiment found that an increasing the flowrate reduces the mean residence time and the variance of the tracer in the vessels. It also found that by using a series of CSTRs, a more realistic reactor could be modelled. Aside from two of the eight experiments, the results were found to be consistent and the erroneous results were put down to human error.

**Appendix I**

Example Calculations

Citi: 233.5 x 2 = 467

t2: 22=4

Citi2: 233.5 x 4 =934

Mean Residence Time:

Variance:

Dispersion:

# **References**

Heriot Watt University School of Engineering & Physical Sciences, 2006. *Residence Time Distribution in a Series of Continuously Stirred Tank Reactors..* 1st ed. Edinburgh: Heriot Watt University.

Perry, R. H. & Green, D. W., 1997. 23-15 Residence Time Distribution (RTD) and Reactor Efficiency. In: *Perry's Chemical Engineers' Handbook (Seventh Edition).* New York: McGraw-Hill, pp. 2315-2325.

Sinnott, R. & Towler, G., 2009. 10.11.2. Liquid Mixing. In: *Chemical Engineering Design (Fifth Edition).* Oxford: Elsevier, pp. 648-649.