CHEG 3128

CSTR – 1
Reactor Mixing

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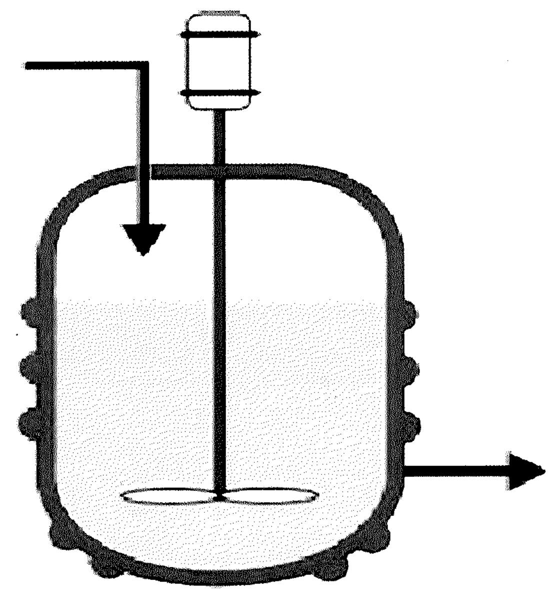
Conventional Thinking for Mixing in CSTRs

- Steady State Operation
- Instantaneous, homogeneous distribution of feed, reactant and product streams
- What do your instincts tell you about mixing?



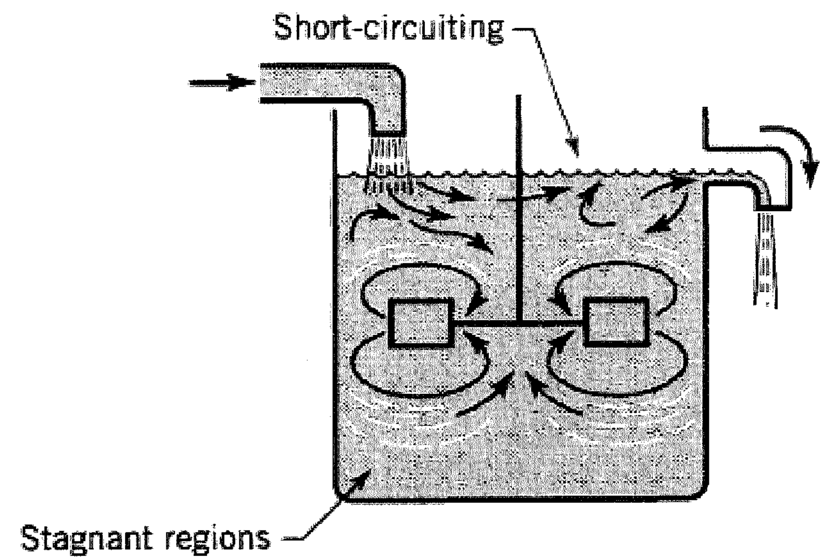
Influential Factors in CSTR Mixing

- Reactor Volume
- Reactor Aspect Ratio
- Reactor Shape
- Number of Impellers
- Impeller Size
- Impeller Speed

- Anything else….?

What Artifacts to These Create in CSTRs?

- Dead Zones
- Back Mixing
- Short-Circuit Flow



- Now, every molecule has a different residence time (distribution of residence time)

- How do these impact mixing and the equations you derive in 2103 and 3151?

Some Additional Resources

- "Mixing in Chemical Reactors" - http://jbrwww.che.wisc.edu/home/jbraw/chemreacfun/ch8/slides-mixing.pdf
- "Laminar & Turbulent "Distributions of Residence Times for Chemical Reactors" - http://umich.edu/~essen/html/byconcept/cdchap/13chap/ECRE_CD-CH13.pdf

Material Balance Equation

In - out + gen - consumption = Accumulation

In an ideal CSTR with a pulse feed,

"In" = 0

since there is no reaction
"gen" = "consumption" = 0

Therefore,

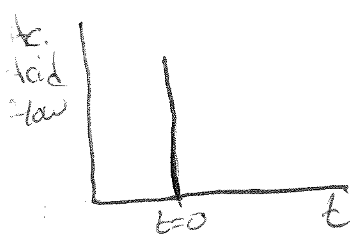
-out = accumulation

In our experiment, we will measure the pH, but we are interested in the acetic acid concentration (Note: these are NOT the same. we will discuss later)

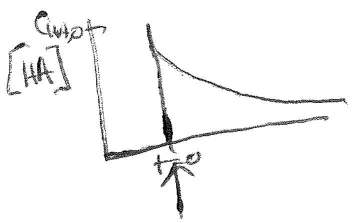
At constant Volume (V) + volumetric flow rate (v)

$$-v\,C_{HA} = V\frac{\partial C_{HA}}{dt}$$

$$-\frac{v}{V}dt = \frac{\partial C_{HA}}{C_{HA}} \qquad \tau \equiv \frac{V}{v}$$



$$-\frac{1}{\tau}dt = \frac{\partial C_{HA}}{C_{HA}}$$



$$-\frac{1}{\tau}\int_0^t dt = \ln C_{HA}\Big|_{C_{HA,0}}^{C_{HA}}$$

$C_{HA,0}$ is the ~~instantaneous~~ concentration of the acid assuming instantaneous thomogeneous mixing of the pulse

$$\boxed{C_{HA} = C_{HA,0}\exp\left[-t/\tau\right]}$$

→ this is a dilution experiment

Why can't we just measure the pH + assume that [H^+] = [Acetic Acid] ?

Weak acids do not fully dissociate

So:

$$HA \rightleftharpoons H^+ + A^-$$

acidity is also controlled by water:

$$H_2O \rightleftharpoons H^+ + OH^-$$

∴ At relatively high pH values (low acidity) the acid is mostly dissociated. However, as the acid concentration is increased, most molecules remain in their conjugated form.

So, now we need to understand how pH + C_{HA} are related for weak acids.

2 reactions:

$$HA \underset{}{\overset{\varepsilon_1}{\rightleftharpoons}} H^+ + A^-$$

$$H_2O \underset{}{\overset{\varepsilon_2}{\rightleftharpoons}} H^+ + OH^-$$

RXN 1: $K_a = \frac{a_{H^+} a_{A^-}}{a_{HA}} \cong \frac{[H^+][A^-]}{[HA]}$ → Eqn 7

RXN 2: $K_W = \frac{a_{H^+} a_{OH^-}}{a_{H_2O}} \cong [H^+][OH^-]$ → Eqn 8

Reaction table:

Species	initial	Δ	final
HA	C_{HA}	$-\varepsilon_1$	$C_{HA} - \varepsilon_1$
H^+	0	$\varepsilon_1 + \varepsilon_2$	$\varepsilon_1 + \varepsilon_2$
A^-	0	ε_1	ε_1
OH^-	0	ε_2	ε_2
H_2O	∞	~ 0	∞

→ Eqn 9 $[HA] = C_{HA} - [A^-]$

→ Eqn 11 $[A^-] = [H^+] - [OH^-]$

Two ways to solve: 1) solve for ε's, then calculate $[H^+]$

Eqn 1: $(K_a)(C_{HA} - \varepsilon_1) - (\varepsilon_1 + \varepsilon_2)(\varepsilon_1) = 0$

Eqn 2: $K_W = (\varepsilon_1 + \varepsilon_2)(\varepsilon_2)$

Method 2) Rearrange to be explicit w/ $[H^+]$

Eqn 1 above is really:

$$(K_a)(C_{HA} - [A^-]) - [H^+][A^-] = 0$$

$$K_a(C_{HA} - ([H^+] - [OH^-])) - [H^+]([H^+] - [OH^-])$$

$$K_a\left(C_{HA} - \left([H^+] - \frac{K_W}{[H^+]}\right)\right) - [H^+]\left([H^+] - \frac{K_W}{[H^+]}\right) = 0$$ → This is Eqn. 2 above

$$K_a[H^+]\left(C_{HA} - \left([H^+] - \frac{K_W}{[H^+]}\right)\right) - [H^+]^2\left([H^+] - \frac{K_W}{[H^+]}\right) = 0$$

$$K_a C_{HA}[H^+] - K_a[H^+]^2 + K_A K_W - [H^+]^3 + K_W[H^+] = 0$$

$$\boxed{[H^+]^3 + [H^+]^2 K_a - [H^+](K_a C_{HA} + K_W) - K_A K_W = 0}$$

⇓

Now we need to find a numerical method to solve cubic equations

↓

One such method follows

A.7 Solutions to cubic equations

In order to predict phase changes in fluids, equations of state must predict a dependence on volume that is cubic, or higher. Hence, many equations of state are cubic, and methods for inverting cubic equations are helpful for studying stability. We first write our cubic equation for x in the form

$$x^3 + a_2x^2 + a_1x + a_0 = 0. \tag{A.30}$$

The equation may have 1, 2 or 3 roots; we are interested only when there exist either 1 or 3 roots.[1] We can determine the number of roots from the sign of the discriminant $q^3 + r^2$ where

$$q := \frac{3a_1 - a_2^2}{9} \tag{A.31}$$

$$r := \frac{a_2\left(9a_1 - 2a_2^2\right) - 27a_0}{54}. \tag{A.32}$$

(A.33)

When $q^3 + r^2 > 0$ there is a single real root to Eqn.(A.30)

$$x_1 = \left(r + \sqrt{q^3 + r^2}\right)^{1/3} + \left(r - \sqrt{q^3 + r^2}\right)^{1/3} - \frac{a_2}{3}. \tag{A.34}$$

When $q^3 + r^2 < 0$, then Eqn.(A.30) has three real roots

$$\begin{aligned} x_1 &= 2\sqrt{-q}\,\cos\left(\frac{\theta}{3}\right) - \frac{a_2}{3} \\ x_2 &= -2\sqrt{-q}\,\cos\left(\frac{\theta - \pi}{3}\right) - \frac{a_2}{3} \\ x_3 &= -2\sqrt{-q}\,\cos\left(\frac{\theta + \pi}{3}\right) - \frac{a_2}{3}, \end{aligned} \tag{A.35}$$

where

$$\theta := \cos^{-1}\left(\frac{r}{\sqrt{-q^3}}\right). \tag{A.36}$$

These equations are particularly useful for programming spreadsheets, for example.

From "Molecular Engineering Thermodynamics"
→ J. de Pablo and J. Schieber

→ Attached is a solution plot for a chemical with a pKa = 3.75 (i.e. formic acid) for you to compare to!

pKa	Ka	Kw
3.75	0.000177828	1.01E-14

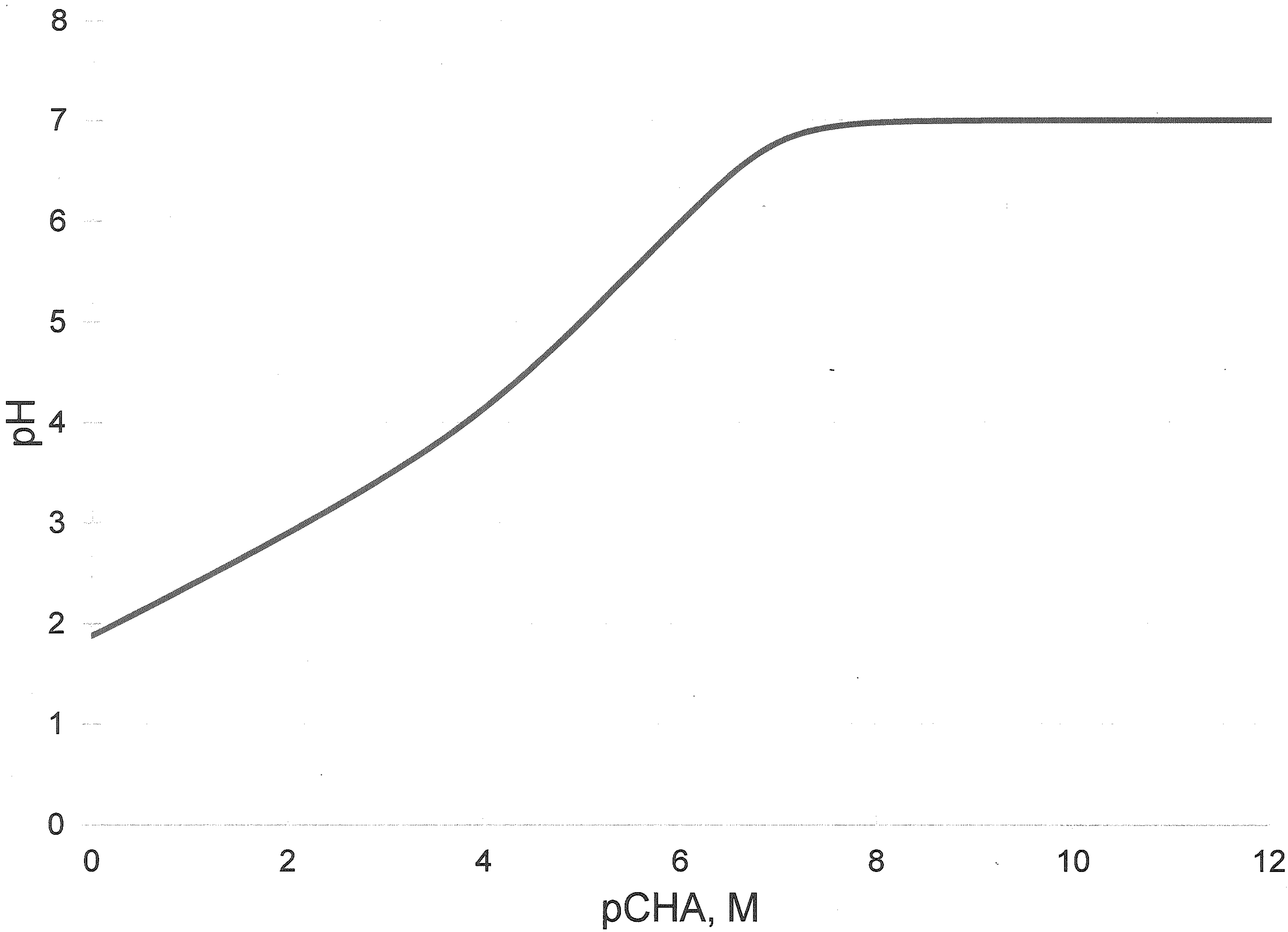
x1 is obviously the only meaningful root!

		Coefficients from Notes							roots			
pCHA	Acid Concentration [CHA,M]	a2	a1	a0	q	r	q^3+r^2	theta	x1	x2	x3	pH
0	1	0.000178	-0.00018	-1.8E-18	-5.92795E-05	-5.2707E-09	-2.0828E-13	1.582345	0.013247	-0.01342	-1.00981E-14	1.877896
0.1	0.794328235	0.000178	-0.00014	-1.8E-18	-4.70881E-05	-4.1867E-09	-1.0439E-13	1.583754	0.011796	-0.01197	-1.27175E-14	1.928249
0.2	0.630957344	0.000178	-0.00011	-1.8E-18	-3.74041E-05	-3.3256E-09	-5.232E-14	1.585335	0.010504	-0.01068	-1.60088E-14	1.978645
0.3	0.501187234	0.000178	-8.9E-05	-1.8E-18	-2.97119E-05	-2.6417E-09	-2.6223E-14	1.587108	0.009352	-0.00953	-2.01528E-14	2.02909
0.4	0.398107171	0.000178	-7.1E-05	-1.8E-18	-2.36017E-05	-2.0984E-09	-1.3143E-14	1.589098	0.008326	-0.0085	-2.53715E-14	2.079589
0.5	0.316227766	0.000178	-5.6E-05	-1.8E-18	-1.87482E-05	-1.6669E-09	-6.5871E-15	1.591331	0.007411	-0.00759	-3.19391E-14	2.130149
0.6	0.251188643	0.000178	-4.5E-05	-1.8E-18	-1.4893E-05	-1.3241E-09	-3.3015E-15	1.593836	0.006595	-0.00677	-4.0208E-14	2.180778
0.7	0.199526231	0.000178	-3.5E-05	-1.8E-18	-1.18306E-05	-1.0518E-09	-1.6548E-15	1.596647	0.005868	-0.00605	-5.06202E-14	2.231482
0.8	0.158489319	0.000178	-2.8E-05	-1.8E-18	-9.39812E-06	-8.3552E-10	-8.2939E-16	1.5998	0.005221	-0.0054	-6.37261E-14	2.282273
0.9	0.125892541	0.000178	-2.2E-05	-1.8E-18	-7.46592E-06	-6.6372E-10	-4.1571E-16	1.603338	0.004643	-0.00482	-8.02284E-14	2.333161
1	0.1	0.000178	-1.8E-05	-1.8E-18	-5.93111E-06	-5.2725E-10	-2.0837E-16	1.607306	0.004129	-0.00431	-1.00999E-13	2.384156
1.1	0.079432823	0.000178	-1.4E-05	-1.8E-18	-4.71197E-06	-4.1886E-10	-1.0444E-16	1.611758	0.003671	-0.00385	-1.27152E-13	2.435273
1.2	0.063095734	0.000178	-1.1E-05	-1.8E-18	-3.74358E-06	-3.3275E-10	-5.2353E-17	1.616752	0.003262	-0.00344	-1.60075E-13	2.486527
1.3	0.050118723	0.000178	-8.9E-06	-1.8E-18	-2.97435E-06	-2.6436E-10	-2.6243E-17	1.622354	0.002898	-0.00308	-2.01523E-13	2.537933
1.4	0.039810717	0.000178	-7.1E-06	-1.8E-18	-2.36333E-06	-2.1003E-10	-1.3156E-17	1.628637	0.002573	-0.00275	-2.53701E-13	2.58951
1.5	0.031622777	0.000178	-5.6E-06	-1.8E-18	-1.87798E-06	-1.6687E-10	-6.5955E-18	1.635683	0.002284	-0.00246	-3.1939E-13	2.64128
1.6	0.025118864	0.000178	-4.5E-06	-1.8E-18	-1.49246E-06	-1.326E-10	-3.3068E-18	1.643585	0.002026	-0.0022	-4.02088E-13	2.693265
1.7	0.019952623	0.000178	-3.5E-06	-1.8E-18	-1.18622E-06	-1.0537E-10	-1.6581E-18	1.652443	0.001797	-0.00197	-5.06199E-13	2.745492
1.8	0.015848932	0.000178	-2.8E-06	-1.8E-18	-9.42975E-07	-8.3739E-11	-8.3148E-19	1.662374	0.001592	-0.00177	-6.37267E-13	2.797991
1.9	0.012589254	0.000178	-2.2E-06	-1.8E-18	-7.49754E-07	-6.6559E-11	-4.1703E-19	1.673502	0.00141	-0.00159	-8.02272E-13	2.850793
2	0.01	0.000178	-1.8E-06	-1.8E-18	-5.96273E-07	-5.2913E-11	-2.092E-19	1.68597	0.001248	-0.00143	-1.01E-12	2.903936
2.1	0.007943282	0.000178	-1.4E-06	-1.8E-18	-4.74359E-07	-4.2073E-11	-1.0497E-19	1.699933	0.001103	-0.00128	-1.27151E-12	2.95746
2.2	0.006309573	0.000178	-1.1E-06	-1.8E-18	-3.7752E-07	-3.3463E-11	-5.2685E-20	1.715563	0.000974	-0.00115	-1.60074E-12	3.011412
2.3	0.005011872	0.000178	-8.9E-07	-1.8E-18	-3.00597E-07	-2.6623E-11	-2.6453E-20	1.733048	0.000859	-0.00104	-2.01521E-12	3.065843
2.4	0.003981072	0.000178	-7.1E-07	-1.8E-18	-2.39496E-07	-2.119E-11	-1.3288E-20	1.752593	0.000757	-0.00093	-2.53701E-12	3.120809
2.5	0.003162278	0.000178	-5.6E-07	-1.8E-18	-1.90961E-07	-1.6875E-11	-6.6788E-21	1.774421	0.000666	-0.00084	-3.1939E-12	3.176374
2.6	0.002511886	0.000178	-4.5E-07	-1.8E-18	-1.52408E-07	-1.3447E-11	-3.3594E-21	1.79877	0.000585	-0.00076	-4.02088E-12	3.232608
2.7	0.001995262	0.000178	-3.5E-07	-1.8E-18	-1.21785E-07	-1.0724E-11	-1.6912E-21	1.825888	0.000513	-0.00069	-5.06199E-12	3.289588
2.8	0.001584893	0.000178	-2.8E-07	-1.8E-18	-9.74597E-08	-8.5614E-12	-8.5241E-22	1.856037	0.000449	-0.00063	-6.37267E-12	3.347401
2.9	0.001258925	0.000178	-2.2E-07	-1.8E-18	-7.81377E-08	-6.8434E-12	-4.3024E-22	1.889478	0.000393	-0.00057	-8.02271E-12	3.406139
3	0.001	0.000178	-1.8E-07	-1.8E-18	-6.27896E-08	-5.4787E-12	-2.1753E-22	1.926464	0.000342	-0.00052	-1.01E-11	3.465905
3.1	0.000794328	0.000178	-1.4E-07	-1.8E-18	-5.05982E-08	-4.3948E-12	-1.1023E-22	1.967227	0.000297	-0.00048	-1.27151E-11	3.526808
3.2	0.000630957	0.000178	-1.1E-07	-1.8E-18	-4.09143E-08	-3.5337E-12	-5.6002E-23	2.011959	0.000258	-0.00044	-1.60074E-11	3.588967
3.3	0.000501187	0.000178	-8.9E-08	-1.8E-18	-3.3222E-08	-2.8498E-12	-2.8546E-23	2.060789	0.000223	-0.0004	-2.01521E-11	3.652507
3.4	0.000398107	0.000178	-7.1E-08	-1.8E-18	-2.71118E-08	-2.3065E-12	-1.4609E-23	2.113751	0.000192	-0.00037	-2.537E-11	3.717555
3.5	0.000316228	0.000178	-5.6E-08	-1.8E-18	-2.22584E-08	-1.8749E-12	-7.5122E-24	2.170756	0.000164	-0.00034	-3.1939E-11	3.784245

3.6	0.000251189	0.000178	-4.5E-08	-1.8E-18	-1.84031E-08	-1.5322E-12	-3.8852E-24	2.231553	0.00014	-0.00032	-4.02088E-11	3.852706
3.7	0.000199526	0.000178	-3.5E-08	-1.8E-18	-1.53408E-08	-1.2599E-12	-2.023E-24	2.295701	0.000119	-0.0003	-5.06199E-11	3.923062
3.8	0.000158489	0.000178	-2.8E-08	-1.8E-18	-1.29083E-08	-1.0436E-12	-1.0617E-24	2.362548	0.000101	-0.00028	-6.37266E-11	3.995427
3.9	0.000125893	0.000178	-2.2E-08	-1.8E-18	-1.0976E-08	-8.7179E-13	-5.6231E-25	2.431229	8.51E-05	-0.00026	-8.02271E-11	4.069893
4	0.0001	0.000178	-1.8E-08	-1.8E-18	-9.44124E-09	-7.3532E-13	-3.0087E-25	2.500686	7.14E-05	-0.00025	-1.01E-10	4.14653
4.1	7.94328E-05	0.000178	-1.4E-08	-1.8E-18	-8.2221E-09	-6.2692E-13	-1.6281E-25	2.569721	5.95E-05	-0.00024	-1.27151E-10	4.225375
4.2	6.30957E-05	0.000178	-1.1E-08	-1.8E-18	-7.25371E-09	-5.4082E-13	-8.9179E-26	2.637077	4.94E-05	-0.00023	-1.60074E-10	4.306427
4.3	5.01187E-05	0.000178	-8.9E-09	-1.8E-18	-6.48448E-09	-4.7242E-13	-4.9479E-26	2.701537	4.08E-05	-0.00022	-2.0152E-10	4.389646
4.4	3.98107E-05	0.000178	-7.1E-09	-1.8E-18	-5.87346E-09	-4.1809E-13	-2.7817E-26	2.762022	3.35E-05	-0.00021	-2.53699E-10	4.474953
4.5	3.16228E-05	0.000178	-5.6E-09	-1.8E-18	-5.38812E-09	-3.7494E-13	-1.5846E-26	2.81768	2.74E-05	-0.00021	-3.19386E-10	4.562233
4.6	2.51189E-05	0.000178	-4.5E-09	-1.8E-18	-5.00259E-09	-3.4066E-13	-9.1438E-27	2.867937	2.23E-05	-0.0002	-4.02081E-10	4.651339
4.7	1.99526E-05	0.000178	-3.5E-09	-1.8E-18	-4.69636E-09	-3.1343E-13	-5.3412E-27	2.912516	1.81E-05	-0.0002	-5.06185E-10	4.742103
4.8	1.58489E-05	0.000178	-2.8E-09	-1.8E-18	-4.45311E-09	-2.9181E-13	-3.1555E-27	2.951414	1.46E-05	-0.00019	-6.37239E-10	4.834346
4.9	1.25893E-05	0.000178	-2.2E-09	-1.8E-18	-4.25989E-09	-2.7463E-13	-1.8836E-27	2.984855	1.18E-05	-0.00019	-8.02217E-10	4.927885
5	0.00001	0.000178	-1.8E-09	-1.8E-18	-4.10641E-09	-2.6098E-13	-1.1347E-27	3.01323	9.49E-06	-0.00019	-1.00989E-09	5.022541
5.1	7.94328E-06	0.000178	-1.4E-09	-1.8E-18	-3.98449E-09	-2.5014E-13	-6.8906E-28	3.037033	7.62E-06	-0.00019	-1.2713E-09	5.118142
5.2	6.30957E-06	0.000178	-1.1E-09	-1.8E-18	-3.88765E-09	-2.4153E-13	-4.2138E-28	3.056807	6.1E-06	-0.00018	-1.60032E-09	5.214534
5.3	5.01187E-06	0.000178	-8.9E-10	-1.8E-18	-3.81073E-09	-2.3469E-13	-2.5923E-28	3.073096	4.88E-06	-0.00018	-2.01438E-09	5.311573
5.4	3.98107E-06	0.000178	-7.1E-10	-1.8E-18	-3.74963E-09	-2.2926E-13	-1.6031E-28	3.086421	3.9E-06	-0.00018	-2.53535E-09	5.409129
5.5	3.16228E-06	0.000178	-5.6E-10	-1.8E-18	-3.70109E-09	-2.2494E-13	-9.9587E-29	3.097258	3.11E-06	-0.00018	-3.19062E-09	5.507079
5.6	2.51189E-06	0.000178	-4.5E-10	-1.8E-18	-3.66254E-09	-2.2151E-13	-6.2124E-29	3.106026	2.48E-06	-0.00018	-4.01438E-09	5.605305
5.7	1.99526E-06	0.000178	-3.5E-10	-1.8E-18	-3.63192E-09	-2.1879E-13	-3.8911E-29	3.113089	1.98E-06	-0.00018	-5.04907E-09	5.703683
5.8	1.58489E-06	0.000178	-2.8E-10	-1.8E-18	-3.60759E-09	-2.1663E-13	-2.4478E-29	3.118758	1.58E-06	-0.00018	-6.34702E-09	5.802069
5.9	1.25893E-06	0.000178	-2.2E-10	-1.8E-18	-3.58827E-09	-2.1491E-13	-1.5478E-29	3.123288	1.26E-06	-0.00018	-7.97188E-09	5.900282
6	0.000001	0.000178	-1.8E-10	-1.8E-18	-3.57292E-09	-2.1354E-13	-9.8522E-30	3.126895	1E-06	-0.00018	-9.99945E-09	5.998077
6.1	7.94328E-07	0.000178	-1.4E-10	-1.8E-18	-3.56073E-09	-2.1246E-13	-6.329E-30	3.129752	8.03E-07	-0.00018	-1.2517E-08	6.095107
6.2	6.30957E-07	0.000178	-1.1E-10	-1.8E-18	-3.55105E-09	-2.116E-13	-4.1192E-30	3.132001	6.44E-07	-0.00018	-1.56194E-08	6.190875
6.3	5.01187E-07	0.000178	-8.9E-11	-1.8E-18	-3.54335E-09	-2.1092E-13	-2.7314E-30	3.133757	5.19E-07	-0.00018	-1.93992E-08	6.28468
6.4	3.98107E-07	0.000178	-7.1E-11	-1.8E-18	-3.53724E-09	-2.1037E-13	-1.8589E-30	3.135112	4.21E-07	-0.00018	-2.39286E-08	6.375565
6.5	3.16228E-07	0.000178	-5.6E-11	-1.8E-18	-3.53239E-09	-2.0994E-13	-1.3099E-30	3.136141	3.45E-07	-0.00018	-2.9232E-08	6.462307
6.6	2.51189E-07	0.000178	-4.5E-11	-1.8E-18	-3.52853E-09	-2.096E-13	-9.6424E-31	3.136908	2.86E-07	-0.00018	-3.5254E-08	6.543499
6.7	1.99526E-07	0.000178	-3.5E-11	-1.8E-18	-3.52547E-09	-2.0933E-13	-7.4645E-31	3.137465	2.41E-07	-0.00018	-4.18374E-08	6.61773
6.8	1.58489E-07	0.000178	-2.8E-11	-1.8E-18	-3.52304E-09	-2.0911E-13	-6.0915E-31	3.13786	2.07E-07	-0.00018	-4.87303E-08	6.683865
6.9	1.25893E-07	0.000178	-2.2E-11	-1.8E-18	-3.52111E-09	-2.0894E-13	-5.2256E-31	3.138133	1.81E-07	-0.00018	-5.56288E-08	6.741285
7	0.0000001	0.000178	-1.8E-11	-1.8E-18	-3.51957E-09	-2.088E-13	-4.6793E-31	3.138317	1.62E-07	-0.00018	-6.224E-08	6.789992
7.1	7.94328E-08	0.000178	-1.4E-11	-1.8E-18	-3.51835E-09	-2.0869E-13	-4.3344E-31	3.138438	1.48E-07	-0.00018	-6.83359E-08	6.830522
7.2	6.30957E-08	0.000178	-1.1E-11	-1.8E-18	-3.51739E-09	-2.0861E-13	-4.1165E-31	3.138517	1.37E-07	-0.00018	-7.3777E-08	6.863754
7.3	5.01187E-08	0.000178	-8.9E-12	-1.8E-18	-3.51662E-09	-2.0854E-13	-3.9789E-31	3.138568	1.29E-07	-0.00018	-7.85082E-08	6.890716
7.4	3.98107E-08	0.000178	-7.1E-12	-1.8E-18	-3.51601E-09	-2.0848E-13	-3.8918E-31	3.1386	1.22E-07	-0.00018	-8.25383E-08	6.912431
7.5	3.16228E-08	0.000178	-5.6E-12	-1.8E-18	-3.51552E-09	-2.0844E-13	-3.8367E-31	3.138621	1.18E-07	-0.00018	-8.59171E-08	6.929835
7.6	2.51189E-08	0.000178	-4.5E-12	-1.8E-18	-3.51513E-09	-2.0841E-13	-3.8018E-31	3.138634	1.14E-07	-0.00018	-8.87156E-08	6.94374

7.7	1.99526E-08	0.000178	-3.6E-12	-1.8E-18	-3.51483E-09	-2.0838E-13	-3.7797E-31	3.138642	1.11E-07	-0.00018	-9.10118E-08	6.954825
7.8	1.58489E-08	0.000178	-2.8E-12	-1.8E-18	-3.51458E-09	-2.0836E-13	-3.7657E-31	3.138647	1.09E-07	-0.00018	-9.28824E-08	6.963651
7.9	1.25893E-08	0.000178	-2.2E-12	-1.8E-18	-3.51439E-09	-2.0834E-13	-3.7567E-31	3.138651	1.07E-07	-0.00018	-9.43979E-08	6.970672
8	0.00000001	0.000178	-1.8E-12	-1.8E-18	-3.51424E-09	-2.0833E-13	-3.7511E-31	3.138653	1.06E-07	-0.00018	-9.56205E-08	6.976254
8.1	7.94328E-09	0.000178	-1.4E-12	-1.8E-18	-3.51412E-09	-2.0832E-13	-3.7474E-31	3.138654	1.05E-07	-0.00018	-9.66035E-08	6.980691
8.2	6.30957E-09	0.000178	-1.1E-12	-1.8E-18	-3.51402E-09	-2.0831E-13	-3.7451E-31	3.138655	1.04E-07	-0.00018	-9.73918E-08	6.984216
8.3	5.01187E-09	0.000178	-9E-13	-1.8E-18	-3.51394E-09	-2.083E-13	-3.7436E-31	3.138655	1.03E-07	-0.00018	-9.80227E-08	6.987018
8.4	3.98107E-09	0.000178	-7.2E-13	-1.8E-18	-3.51388E-09	-2.0829E-13	-3.7426E-31	3.138656	1.03E-07	-0.00018	-9.85268E-08	6.989243
8.5	3.16228E-09	0.000178	-5.7E-13	-1.8E-18	-3.51383E-09	-2.0829E-13	-3.742E-31	3.138656	1.02E-07	-0.00018	-9.89292E-08	6.991011
8.6	2.51189E-09	0.000178	-4.6E-13	-1.8E-18	-3.51379E-09	-2.0829E-13	-3.7416E-31	3.138656	1.02E-07	-0.00018	-9.925E-08	6.992415
8.7	1.99526E-09	0.000178	-3.6E-13	-1.8E-18	-3.51376E-09	-2.0828E-13	-3.7413E-31	3.138656	1.02E-07	-0.00018	-9.95055E-08	6.993531
8.8	1.58489E-09	0.000178	-2.9E-13	-1.8E-18	-3.51374E-09	-2.0828E-13	-3.7411E-31	3.138656	1.01E-07	-0.00018	-9.9709E-08	6.994417
8.9	1.25893E-09	0.000178	-2.3E-13	-1.8E-18	-3.51372E-09	-2.0828E-13	-3.741E-31	3.138656	1.01E-07	-0.00018	-9.98709E-08	6.995121
9	0.000000001	0.000178	-1.9E-13	-1.8E-18	-3.5137E-09	-2.0828E-13	-3.7409E-31	3.138656	1.01E-07	-0.00018	-9.99997E-08	6.99568
9.1	7.94328E-10	0.000178	-1.5E-13	-1.8E-18	-3.51369E-09	-2.0828E-13	-3.7409E-31	3.138656	1.01E-07	-0.00018	-1.00102E-07	6.996124
9.2	6.30957E-10	0.000178	-1.2E-13	-1.8E-18	-3.51368E-09	-2.0828E-13	-3.7408E-31	3.138656	1.01E-07	-0.00018	-1.00184E-07	6.996477
9.3	5.01187E-10	0.000178	-9.9E-14	-1.8E-18	-3.51367E-09	-2.0828E-13	-3.7408E-31	3.138656	1.01E-07	-0.00018	-1.00248E-07	6.996757
9.4	3.98107E-10	0.000178	-8.1E-14	-1.8E-18	-3.51367E-09	-2.0828E-13	-3.7408E-31	3.138656	1.01E-07	-0.00018	-1.003E-07	6.99698
9.5	3.16228E-10	0.000178	-6.6E-14	-1.8E-18	-3.51366E-09	-2.0828E-13	-3.7408E-31	3.138656	1.01E-07	-0.00018	-1.00341E-07	6.997156
9.6	2.51189E-10	0.000178	-5.5E-14	-1.8E-18	-3.51366E-09	-2.0828E-13	-3.7408E-31	3.138656	1.01E-07	-0.00018	-1.00373E-07	6.997297
9.7	1.99526E-10	0.000178	-4.6E-14	-1.8E-18	-3.51366E-09	-2.0828E-13	-3.7408E-31	3.138656	1.01E-07	-0.00018	-1.00399E-07	6.997408
9.8	1.58489E-10	0.000178	-3.8E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7408E-31	3.138656	1.01E-07	-0.00018	-1.00419E-07	6.997497
9.9	1.25893E-10	0.000178	-3.2E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7408E-31	3.138656	1.01E-07	-0.00018	-1.00436E-07	6.997567
10	1E-10	0.000178	-2.8E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00449E-07	6.997623
10.1	7.94328E-11	0.000178	-2.4E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00459E-07	6.997668
10.2	6.30957E-11	0.000178	-2.1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00467E-07	6.997703
10.3	5.01187E-11	0.000178	-1.9E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00474E-07	6.997731
10.4	3.98107E-11	0.000178	-1.7E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00479E-07	6.997753
10.5	3.16228E-11	0.000178	-1.6E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00483E-07	6.997771
10.6	2.51189E-11	0.000178	-1.5E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00486E-07	6.997785
10.7	1.99526E-11	0.000178	-1.4E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00489E-07	6.997796
10.8	1.58489E-11	0.000178	-1.3E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00491E-07	6.997805
10.9	1.25893E-11	0.000178	-1.2E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00492E-07	6.997812
11	1E-11	0.000178	-1.2E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00494E-07	6.997818
11.1	7.94328E-12	0.000178	-1.2E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00495E-07	6.997822
11.2	6.30957E-12	0.000178	-1.1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00496E-07	6.997826
11.3	5.01187E-12	0.000178	-1.1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00496E-07	6.997828
11.4	3.98107E-12	0.000178	-1.1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00497E-07	6.997831
11.5	3.16228E-12	0.000178	-1.1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00497E-07	6.997832
11.6	2.51189E-12	0.000178	-1.1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1.01E-07	-0.00018	-1.00497E-07	6.997834
11.7	1.99526E-12	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00498E-07	6.997835

11.8	1.58489E-12	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00498E-07	6.997836
11.9	1.25893E-12	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00498E-07	6.997837
12	1E-12	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00498E-07	6.997837
12.1	7.94328E-13	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00498E-07	6.997838
12.2	6.30957E-13	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00498E-07	6.997838
12.3	5.01187E-13	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997838
12.4	3.98107E-13	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997838
12.5	3.16228E-13	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
12.6	2.51189E-13	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
12.7	1.99526E-13	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
12.8	1.58489E-13	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
12.9	1.25893E-13	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
13	1E-13	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
13.1	7.94328E-14	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
13.2	6.30957E-14	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
13.3	5.01187E-14	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
13.4	3.98107E-14	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
13.5	3.16228E-14	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
13.6	2.51189E-14	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
13.7	1.99526E-14	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
13.8	1.58489E-14	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
13.9	1.25893E-14	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839
14	1E-14	0.000178	-1E-14	-1.8E-18	-3.51365E-09	-2.0827E-13	-3.7407E-31	3.138656	1E-07	-0.00018	-1.00499E-07	6.997839


pH
8
7
6
5
4
3
2
1
0
0
2
4
6
8
10
12
pCHA, M

Mixing Discussion

- → Laminar flow demo
  - → low rotation rates or
  - → high viscosity

- → Analogy to 1-D shear → From CHEG 3123
  - → rotating cylinder
  - → poor mixing

- → what should you do?
  - → most just stir faster
    - → what does that do?

↓

Let's turn on the CSTRs and find out

↓

Is this "ideal" or "perfect" instantaneous, homogeneous mixing?

→ That's what this lab is all about!