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Effect of Outlet Position on Homogeneity of Two Layer Stratified Liquid

Janka Bobek*, Dóra Rippel-Pethő, Róbert Bocsi

Department of Chemical Engineering Science, University of Pannonia, 10 Egyetem str., Veszprém, 8200-Hungary
bobekj@almos.uni-pannon.hu

In industry, there are several fields where density stratification occurs. It can happen when one batch of liquid is loaded on the top of another batch in the same storage tank. This phenomenon can cause trouble in operation and it can induce decadency of product quality, as well. In this paper, homogenisation of two stratified layer liquid was investigated. The homogenisation was achieved by an external pump. The experiments were carried out in a cylinder tank with 3.043 l active volume which is the scale-down of a ~100 m^3 industrial tank. The residence time in the system was 3.48 h. The main goal of our research was to examine the effect of outlet position on mixing time. In our research, borax was used as stratified liquid. The density of the upper layer was 1.0022 g/cm^3 and the lower layer was 1.0136 g/cm^3 density. The inlet was positioned above the liquid level. Two different experiments were carried out for three outlet positions. Firstly, we examined the mean residence time of the systems. For this, experiments were carried out in a constant, continuous tank filled with 1.0022 g/cm^3 borax solution meanwhile the inlet liquid density was 1.0136 g/cm^3. Experiments were performed in the other way around, too (1.0136 g/cm^3 tank solution, 1.0022 g/cm^3 inlet). The flowrate of the outlet and the inlet was constant and identical. Secondly, mixing two-layer stratified liquid in circulated system using external pump was investigated, as well. Measuring apparatus was conductivity probe. Two probes were placed into the system. One of them was used for sampling the outlet and the other was situated in a fix position during all experiments. The data was evaluated by mean residence time where it was possible, and it was also analysed in accordance with the time request to achieve 95 % homogeneity. We examined the concentration differences between the sampling points in time.

1. Introduction

A number of geophysical (Sullivan and List, 1993) and industrial situations arise where density stratification is occurred. It can happen when one batch of liquid is loaded on the top of another batch in the same storage tank (Degawa et al., 2017). This phenomenon can cause trouble in operation and it can induce decadency of product quality, as well. Mixing of two or more miscible fluid can be achieved several ways, however problem is posed when two liquids have very different viscosity or the stirring is carried out by external pump with low volumetric flow rate (Culson and Richardson, 1999).

The average residence time (τ_{av}) can be calculated from the reactor volume filled with the solution (V) and from the volumetric flow rate (B), Eq(1) (Dankwerts, 1953).

$$\tau_{av} = \frac{V}{B} \tag{1}$$

One of the main methods to examine mixing in a continuous flow apparatus is the theory of residence time distribution (RTD). The RTD method is based on the distribution of material age at the outlet of the reactor (Liu, 2012). By examining the shape of the distribution curve mixing properties may be concluded. The residence time distribution is given by function F(t). The value of F(t) function for a specified length if time equals the fraction of the molecules which remain shorter than a time t in the system. From the definition of F(t) Eq(2) can be stated (Dankwerts, 1953).

$$\lim_{t\to\infty} F(t) = 1 \tag{2}$$

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By the compartment model the shape of the F(t) curve can be compared with the ideal piston-flow (see Figure 1a) and with the complete-mixing system (see Figure 1c). Using this model information about the behaviour of the liquid flowing through the vessel can be obtained (Levenspiel, 1999).

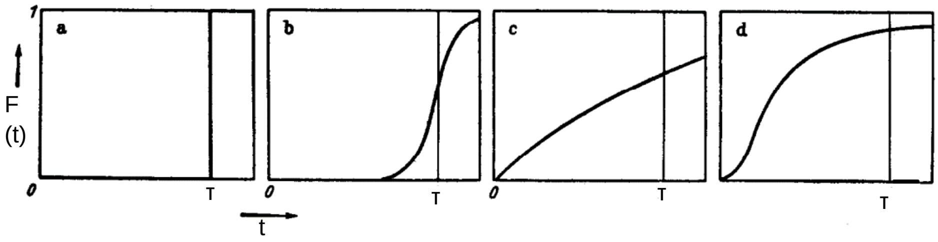


Figure 1: F (t) diagrams of piston flow (a), piston flow with some longitudinal mixing (b), complete mixing (c) and dead water (d). τ is the mean residence time (Dankwerts, 1953)

By differencing the F(t) function, the residence time frequency function is given in Eq(3) (Zwietering, 1958).

$$E(t) = \frac{dF(t)}{dt} \tag{3}$$

The distribution of material is caused by different pathways of molecules. Some elements of fluid spend more time, other less time in the system. From E(t) function the mean residence time (τ) (see Eq4) can be calculated where t is the current time (Zwietering, 1958).

$$\tau = \int_0^\infty t * E(t)dt \tag{4}$$

The deviation from piston-flow can be measured by the hold-back (H), Eq(5). The value of H is varied from 0 to 1. H is equal to 1for a vessel most of whose most of volume is occupied by dead water. H is equal 0 for piston flow. For a completely mixed system the value of H is equal to exp(-1)=0.37.

$$H = \frac{1}{\tau_{av}} \int_{t=0}^{\tau_{av}} F(t)dt \tag{5}$$

General idea is given about the system by the magnitude of hold-back (Dankwerts, 1953). The methods above are useful to get a general information about the behaviour of our examined system.

For measuring the mixing time several techniques developed in the last years. To detect the changes in the system, firstly the disturbance of the detection system need to be examined. The measuring system may not be act as a baffle. For a system wherein the rate of flow is very low, intrusive techniques can be used. Conductometry is an easy way to trace changes in the system. Conductivity values can be converted into concentration data. Conductivity has temperature dependence, for this reason the temperature compensation is an essential step to get correct values (Ascanio, 2015).

2. Experiment

The investigated system was a cylinder where considerable changes of the construction, like impeller or baffle built in was not accomplishable. Therefore, the effect of vertical position of the outlet was researched on mixing capability. According to increment of homogeneity energy consumption can be reduced by less operation time of the pump. The diameter of the tank was 194 mm. The volume of the vessel occupied by the fluid was 3.043 l. The model liquid was two-layer stratified borax solution. The residence time was constant 3.48 h during all measurements. The volumetric flowrate of the inflow and the outflow was 0.874 l/h = 14.6 ml/min. The inlet was 17 mm above the liquid level. The angle between the inlet and outlet was 110° in all cases. The diameter of inlet and outlet was 4 mm. Three outlet positions were examined. Position_0 was 8 mm, Position_1 was 26 mm and Position_2 was 77 mm above the tank bottom. Density changes were traced by conductivity measurements. Two probes (graphite-two cells/probe) were placed into the system. The conductivity measurements were automatically compensated with temperature. One of probes was always sampling the outlet (CH2) and the other (CH1) was in a fix position during all experiments (see Table1). The values of conductivity were being sampled in every 30 seconds. The stratified liquid was borax with density 1.0022 g/cm^3 and 1.0136 g/cm^3. Two different methods were used to investigate the effect of three outlet position on mixing.

In the first case, to determine the residence time distribution, the experiments were implemented (see Figure 3a) in a tank filled with 1.0022 g/cm^{3}solution, meanwhile the inlet liquid density was 1.0136 g/cm^3 solution. The volumetric flowrate of inlet and outlet was constant 14.6 ml/min. Experiments were carried out the other way around, as well (1.0136 g/cm^3 tank solution, 1.0022 g/cm^3 inlet). The uniformity of inlet flow into the experimental tank (1.) was ensured by gravity flow from a puffer tank (4.). The liquid level in the puffer tank (100 ml) was constant achieved by an overflow outlet and continuous feed through a peristaltic pump (3.) from the solvent storage tank (2.). To generate constant outlet flowrate another tank (5.) was built into the system. The inlet of the 5. tank was at the same height as the liquid level in the experimental tank (1.). The outlet and the inlet flowrate were set and checked before all experiments.

Table 1: Position of inlet, outlets and sampling points

	Inlet	Outlet		CH1	CH2	
Position_0	x=97 mm	x=-17 mm	y_0=8 mm	x=64 mm	x=-17 mm	y_0=3 mm
Position_1	y=120 mm		y_1=26 mm	y=67 mm		y_1=15 mm
Position_2	z=0 mm	z=-45 mm	y_2=77 mm	z=64 mm	z=-30 mm	y_2=60 mm

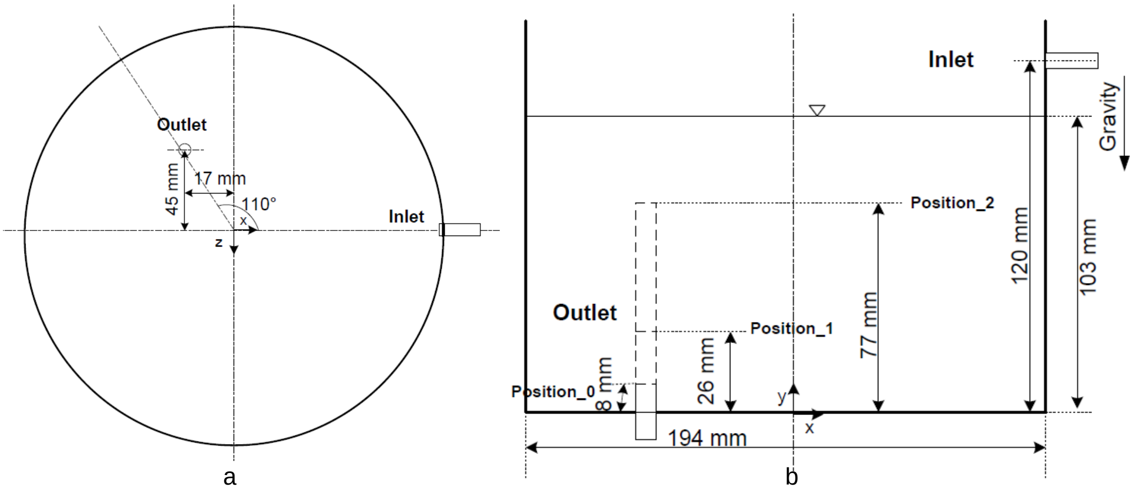


Figure 2: Schematic of positions of inlet and outlet (a) top view (b) front view

The second experiment was carried out in circulated system (Figure 3b) and the effect of outlet positions were examined. The original content of the tank was stratified two layer liquid. 1.521 l 1.0136 g/cm^3 solution was stratified under 1.521 l 1.0022 g/cm^3 liquid. The outlet of experimental tank (1.) was pumped into the puffer tank (4.) by a peristaltic pump. The inlet flowrate was ensured by gravity flow. Before these experiments the position of puffer tank was set and the inlet flow rate was checked. The overflow outlet of the puffer tank (4.) was also built into the system however the fluid level was constant so overflow was not noticed in the 5. storage tank.After all experiments the tank content was stirred manually to check the final value of density. It was necessary to convince that inhomogeneous fluid elements were not existed in the system.

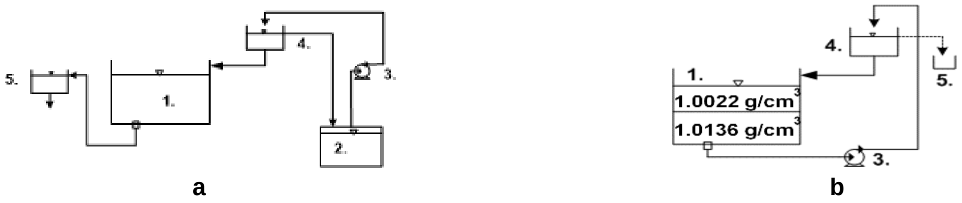
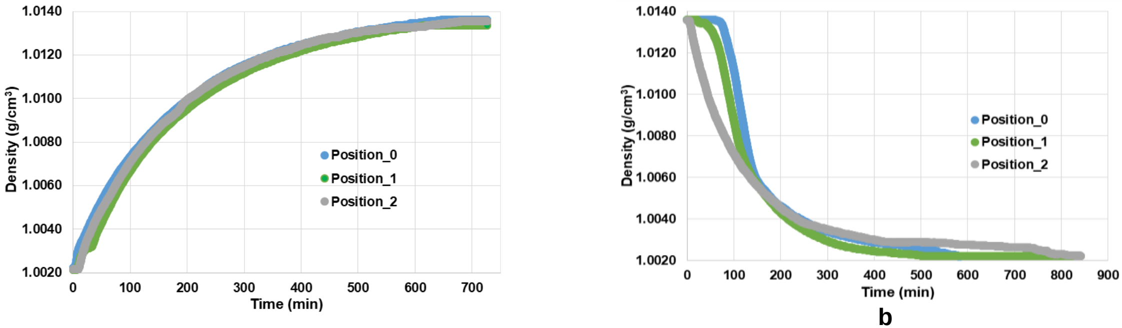


Figure 3: (a) Schematic of experimental setup for RTD measurements. (b) Schematic of experimental setup for circulated measurements

3. Results and discussion

3.1 RTD measurements

During the RTD measurements when the inlet density was 1.0136 g/cm^3, the operation time was 12.5 h and at beginning the tank was filled with 1.0022 g/cm^3 solution. Three density curves given in Figure 4a are run together. After the operation time, density differences were not shown. After 12.5 h homogeneous 1.0136 g/cm^3 solution was in the tank for all outlet position.

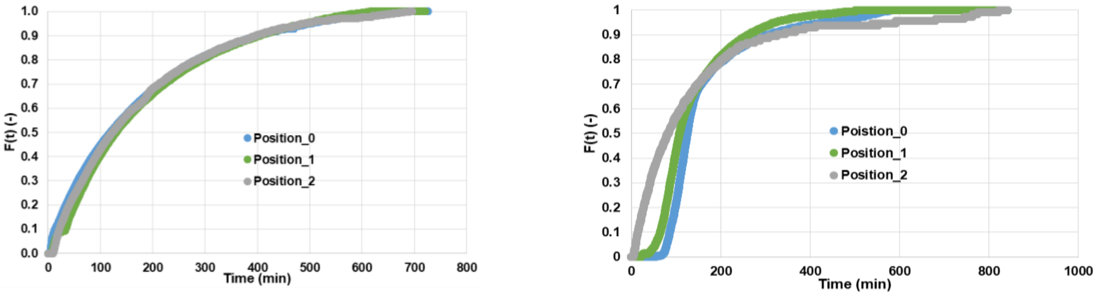


a

b

Figure 4: (a) Values of density at sampling point CH2 versus time at different outlet position with 1.0136 g/cm^3 inlet. (b) Values of density at sampling point CH2 versus time at different outlet position with 1.0022 g/cm^3 inlet

In Figure 4b the density curves are seen when the inlet was 1.0022 g/cm^3 and the initial liquid density in the tank was 1.0136 g/cm^3. The three curves are not run together as much as with the opposite setting. Examining the curves, a constant segment can be realized at the beginning of operation time. The constant part is existed at position_0 until 63 min, at Position_1 until 21.5 min and at Position_2 until 2 min. This phenomenon may be caused by specific gravity. The thinner inlet was floated above the heavy layer. The outlet position at Position_2 was the closest to the liquid level that is why this constant segment is the shortest. At Position_0 the outlet was placed the longest distance from the liquid level which provided the longest constant segment in our curve. At measurement Position_0 density difference was not observed after stirring the content of the tank. At measurement Position_1 after mixing the fluid content of the tank the final density was 1.0033 g/cm^3 which was 0.0011 g/cm^3 greater than last measured density in the tank (1.0022 g/cm^3) during the experiment. Due to residual stratification assumed in the system at measurement Position 2_0, before mixing the liquid in the tank, further samples were taken vertically. Density differences were discovered between vertical sampling points. Above 55 mm from the tank bottom density difference cannot be realized. At 25 mm above the tank bottom 1.0042 g/cm^3 density was measured. At 3 mm above the bottom of the tank the density was 1.0061 g/cm^3 which was 0.0039 g/cm^{3}greater than expected. After mixing the fluid in the tank the final density was 1.0029 g/cm^3.During these measurements density stratified phenomenon was existed however at sampling point CH2 the expected values were measured. In agreement with buoyancy force, the thinner layer floated above the more concentrated layer. The volume of liquid determined by the vertical position of outlet is not able to leave system, as the thinner layer moving up and the heavier layer sinking down in the system.



a

b

Figure 5: (a) F(t) diagrams of measurements with 1.0136 g/cm^3 at different outlet position. (b) F(t) diagrams of measurements with 1.0022 g/cm^3 at different outlet position

Analyzing the F(t) curves with inlet 1.0136 g/cm^3 (Figure 5a) the shape of well mixed reactor (Figure 1c) can be realized. However, the mean residence time results (Table 2) are lower than the average residence time. According to this, it can be stated, that a part of tank volume was out of convection, these parts were dead water. The shortest mean residence time was calculated at measurement Poistion_0 which was 35 minutes lower than the average residence time. The hold-back value of this measurement was the greatest among the experiments with 1.0136 g/cm^3 inlet. On this basis, the biggest dead water volume was existed when the outlet was 8 mm above the tank bottom. The results of measurement Position_1 is the closest to the ideal well-mixed case. At measurement Position_2 the mean residence time was 6 min shorter than it was at Position_1. The hold –back value of this measurement (0.41 1/min) is a mean value among these experiments.

At the beginning of F(t) curves of measurements with 1.0022 g/cm^{3}inlet a constant segment can be realized. The constant segment is a proper of real piston flow (Figure 1b). Position_0 had the longest constant zone, which means, this set-up acts the closest to plug-flow among these measurements. The H value of this measurement was found to be the lowest.

The largest value of hold-back was measured at Position_2 with inlet 1.0022 g/cm^3. That means, this set up had the greatest dead volume among the measurements. The mean residence time was decreasing with height of outlet. Comparing the residence time results according to the inlet density the 1.0136 g/cm^3 inlet measurements have longer residence time (Table 2).

Table 2: Results of Mean residence time and hold back

Density of inlet	Outlet position	τ_{av} (min)	τ (min)	H (1/min)
1.0022 g/cm^3	Position_0	209	165	0.34
	Position_1	209	154	0.41
	Position_2	209	152	0.52
1.0136 g/cm^3	Position_0	209	174	0.43
	Position_1	209	190	0.39
	Position_2	209	184	0.41

3.2 Circulated measurements

In our circulated experiments, the tank initially contained two-layer stratified liquid. These measurements data were evaluated by density differences between two sampling points. In the case of density difference is below 0.00046 g/cm^3 the experiment was considered to be done.

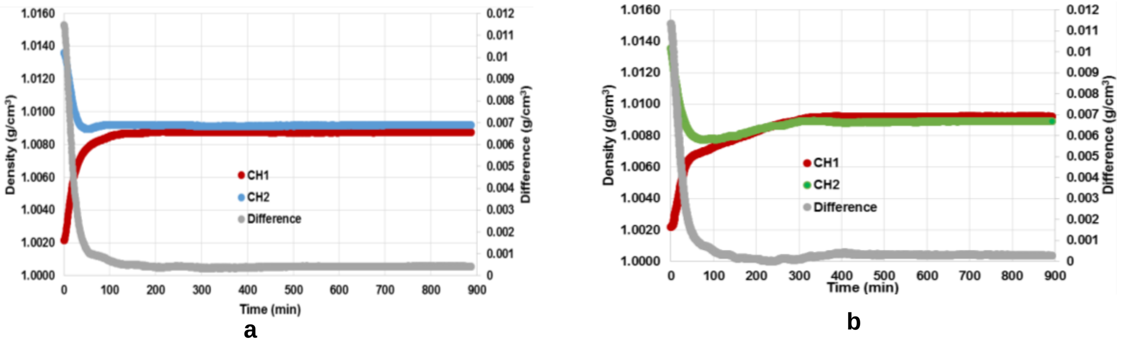


Figure 6: Density results of sampling points at measurement Position_0 (a), Density results of sampling points at measurement Position_1(b)

The operation time of Position_0 experiment was 15 h. The density values at sampling points are given in Figure 6a. Density values at CH2 decreased rapidly at the beginning of the experiment. The rate of decline is decelerated after 60 min running time. At sampling point CH1 the values were increased roughly with the same rate as those are decreased at sampling point CH2. At sampling point CH2 the average density value was achieved in 80 min and at CH1 point it was realized at 192.5 min. The density difference between the two sampling points was under 0.00046 g/cm^3 after 171.5 min. At the end of the test the liquid in the tank was mixed, density difference was not detected.

At measurement Position_1 the density curves (Figure 6b) are a little bit different from the measurement Position_0. At sampling point CH2 the density values were decreased fast. The final density 1.0089g/cm^{3}was reached in 32 min but it is diminished further. In 62 min the minimum, 1.0078 g/cm^3 at this sampling point was reached. For 60 min the value of density was constant and in the 122 min it was began to grow. Analysing the curve of CH1 the same effect was observed. After 103.5 min the density difference between the two sampling points was under 0.00046 g/cm^3. At the two sampling points the average density value is reached in 300 min. After mixing the tank content, difference in the value of density was not observed.

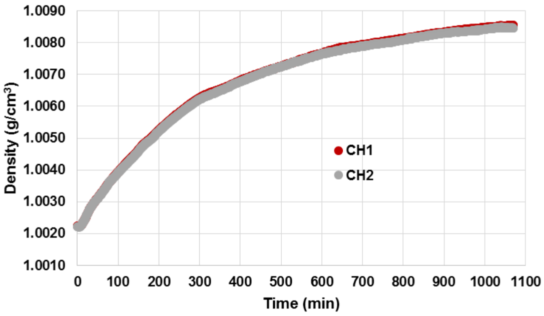


Figure 7: Density results of sampling points at measurement Position_2

At measurement Position_2 the run time of the experiment was 18 h. The curves of sampling point CH1 and sampling point CH2 run together from the beginning. The density differences between the two sampling points are under 0.0001 g/cm^3 during the whole operation time. At the end of the measurement the liquid contained by the tank was mixed manually. The final density was become 1.0090 g/cm^3 which is 0.0004 g/cm^3 higher than the last measured value in the tank during the run time. Existence of stratified layers may be concluded. After 18 h run time, that is more than 5 times longer than the theoretical residence time of the system, inhomogeneous fluid elements are remained behind in the apparatus. Due to low inlet flow rate, the flow velocity in the tank was low, as well. Conceivable horizontal shear force was not generated therefore the vertical movements of fluid elements indicated by the buoyancy force were dominated in the cylinder.

4. Conclusion

The goal of our research was to investigate the effect of vertical position of the outlet of a cylinder stirred by an external pump. To get general information RTD measurements were done. These results were evaluated by mean residence time and value of hold-back. The mean residence time of all measurements are shorter than the theoretical residence time, 209 min without the reference of the inlet density. At 1.0136 g/cm^3 inlet the outlet position had effect on values of residence time. However, at 1.0022 g/cm^3 inlet the effect of outlet position was more expressed. By increasing the height of the outlet position the mean residence time decreasing. The values of hold-back denote dead water elements in the system. After four-five times greater running time than the theoretical residence time inhomogeneous fluid elements were still found in the system. After general information was generated about the flow in the apparatus, circulated measurements were carried out with three different outlet positions. The mixing time was the longest at measurement Position_2 and it was the shortest at measurement Position_0. Effect of outlet positions on mixing two-layer stratified liquid are shown in the results. The results proved the importance of the position of sampling points, as well. In spite of the difference between the values measured at different sampling points was under a limit value, the fluid content was not necessarily homogenous.

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