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INVESTIGATE EFFECT OF INFLUENTIAL PARAMETERS ON RTD IN CSTRS IN SERIES

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Abstract – *This study aims to investigate the influential properties affecting Residence Time Distribution (RTD) in a series of Continuous Stirred Tank Reactors (CSTRs). The parameters under consideration include flow rate, choice of tracer material, mixing efficiency, and inlet concentration. The research is motivated by the critical role RTD plays in determining the efficiency and effectiveness of chemical reactions within reactor systems. By systematically varying these parameters, this study seeks to provide insights into how they impact the distribution of residence times, which, in turn, influences the overall performance of the reactor series. The predicted outcomes of this investigation will give a valuable insight of effect of influential factors on the resulting RTD profiles. By knowing how alterations in these parameters affect the distribution of residence times, this study helps to contribute important knowledge that can useful to improve reactor system designs and operational practices. Ultimately, this will lead to enhanced efficiency and effectiveness across a wide range of chemical processes, happening in various industries and different applications. This project employs tracer materials to monitor reactant movement within the series of Continuous Stirred Tank Reactors (CSTRs). Through careful selection, these tracers provide valuable insights into residence time distributions (RTD). Tracer concentrations will be accurately detected using a titration process, enabling the construction of detailed concentration profiles. This combined approach enhances the precision of our analysis, forming a solid foundation for drawing meaningful conclusions from the experimental data*.

Key Words: **Residence Time Distribution1, Continuous Stirred Tank Reactors2, Flow Rate, Tracer Material3, Mixing Efficiency4, inlet concentration5**

1.INTRODUCTION

In the field of chemical engineering, understanding the behavior of reactants within reactors is of importance for optimizing the industrial processes. One crucial parameter in this regard is the Residence Time Distribution (RTD), which serves as a tool in informing us about the duration each component of a mixture spends inside a reactor. This distribution is necessary in determining the efficiency and effectiveness of chemical reactions. Essentially, RTD enables us to understand how reactants travel through a reactor system, making it an vital tool in designing and refining chemical processes.[1][8][9]

Residence Time Distribution is particularly significant in the context of Continuous Stirred Tank Reactors (CSTRs). CSTR reactor is a large mixing vessel that continuously blends reactants and convert them into the products. This reactor type is widely used in industries where precise control over reactions is imperative. When multiple CSTRs are connected in series, it creates a sequential flow of reactants, where the output of one reactor becomes the input of the next. Understanding how RTD interacts with a series of CSTRs is important in determining the overall efficiency and yield of chemical reactions in complex systems. By connecting CSTRs in series, we essentially create a controlled environment for reactions to progress in stages, enabling more complex chemical transformations. This arrangement finds widespread application in industries where precise control over reaction pathways and outcomes is essential for producing high-quality products. Understanding the interplay between RTD and CSTRs in series is pivotal in optimizing reactor design and operational conditions for specific chemical processes.[6][7]

Industries such as chemical manufacturing, petrochemical refining, pharmaceuticals, environmental engineering, food and beverage production, and biotechnology utilize Residence Time Distribution (RTD) in Continuous Stirred Tank Reactors (CSTRs) in series. This configuration ensures precise control over reactions and product quality in processes like polymerization, catalytic cracking, drug synthesis, wastewater treatment, fermentation, and more. RTD analysis is particularly valuable in optimizing chemical reactions and ensuring consistent, high-quality outputs across a range of industrial sectors.[3]

1.1 Objective of project

- Investigate the impact of flow rate on RTD in a series of CSTRs.
- Evaluate the effect of mixing efficiency on RTD.
- Assess the influence of inlet concentration on RTD.

- Which parameter has maximum effect on RTD in series.

1.2 Theory and Formula

In a CSTR system, by pulse input experiment, a tracer substance is introduced as a sudden concentration spike and this provides valuable information about the flow patterns, mixing, and residence time distribution in CSTR systems. Theoretical graphs are developed to describe the behavior of the tracer substance in the CSTR system. These graphs consider factors such as dispersion, mixing, and residence time distribution. This can be used to predict the expected concentration profiles and residence time distribution curves for both pulse input experiments. The results can help optimize the reactor configuration, such as the number of reactors in series, their volumes, and the flow rates. Tracer studies and the comparison of experimental results can aid in process optimization and scale-up of CSTR systems. By understanding the flow behaviour and mixing characteristics, process parameters can be adjusted to achieve desired reaction kinetics and product quality. The insights gained from tracer studies can also facilitate the scaling-up of CSTR systems to larger production capacities while maintaining efficient mixing and residence time distribution. These studies contribute to the understanding and improvement of CSTR systems for various applications, ranging from fine chemical synthesis to industrial-scale production processes. There are different formulas which are used to calculate the tracer tests and they are given as, For tracer pulse tests, the response will be a concentration profile, C(t), that has the same shape as the residence time distribution, E(t). The RTD can be calculated by normalizing the concentration profile by the area underneath the profile:

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt}$$

2. METHODOLODY

2.1 Experimental Setup

The reactor setup consists of three Continuous Stirred Tank Reactors (CSTRs) arranged in series. Each reactor is equipped with inlet and outlet ports to facilitate the continuous flow of reactants and products through the system. Within each reactor, mixing apparatus such as impellers ensures thorough agitation and homogenization of the reaction mixture. The reactors are interconnected in such a way that the outlet of one reactor feeds directly into the inlet of the next, creating a sequential flow path. This configuration allows for the observation of how reactants progress through each reactor in succession, experiencing different residence times and mixing conditions. By controlling parameters such as flow rates, mixing efficiency, and inlet concentrations helps to investigate their influence on the Residence Time Distribution (RTD) within the system. The setup is designed to provide insights into the behavior and performance of CSTRs in series, which is essential for optimizing reactor design and operation in various chemical processes.[1][3][12]

2.2 Tracer Material Selection

A tracer is chemically inactive substance which is used to track the flow of feed through a reactor. Various tracer materials will be chosen based on their compatibility with the reactants and ease of detection. Tracers have different properties such as density, ionic strength, ability to disperse in fluid. The tracer concentration provides valuable information about the residence time distribution (RTD) and mixing behavior within the reactors. KCl or NaCl used as chemical tracer for stability, solubility, feasibility readily available. Hence, monitoring the tracer concentration, it is possible to determine the mean residence time into the system. In this experiment. This tracers are commonly used tracer in residence time distribution (RTD) studies due to its high solubility, low cost, and ease of detection using a conductivity meter.[2][3][8]

2.3 Experimental Procedure:

To initiate the experiment, a Continuous Stirred-Tank Reactor (CSTR) is primed with 250 ml of deionized water to establish initial conditions, guaranteeing comprehensive mixing to achieve homogeneity. Subsequently, the CSTR is injected with a 0.05 M NaCl tracer solution at an initial flow rate of 150 ml/min. Over a total duration of 60 minutes, conductivity meter readings are meticulously recorded at 5-minute intervals to track the behavior and dispersion of the tracer within the system.[9][12]

Multiple iterations of the experiment will be executed under diverse conditions to evaluate the impacts of varying parameters on the Residence Time Distribution (RTD) curves for both NaCl and KCl tracers. Parameters under scrutiny include flow rate, mixing efficiency, and tracer concentration. Each iteration will strictly adhere to the identical procedure to uphold consistency and reliability of results. Conductivity meter readings will be taken across a spectrum of conditions, encompassing 0.01 M and 0.05 M mixtures, flow rates of 150 ml/min and 140 ml/min, and agitation speeds of 100 rpm and 200 rpm. It's noteworthy that while parameters are manipulated, all other experimental conditions remain constant throughout each iteration. After collecting the data, calculate and plot RTD curves for each set of conditions tested was carried out. Analysis of the RTD curves will involve determining key characteristic such as concentration change and mean residence time determination. By comparing RTD curves obtained under different conditions, we'll gain insights into the impact of each parameter on reactor performance.

By analyzing the concentration-time data, and RTD-time curve, the RTD of the reactor can be determined. The RTD provides information about the distribution of residence times of fluid elements within the reactor.[3][12]

2.4 EXPERIMENTAL RESULTS:

Table -1: Concentration at different conditions for NaCl tracer

Time (mins)	Conc (0.05)	Conc (0.10)	Flowrate (140ml/ min)	Flowrate (150ml/ min)	Mixing (100 rpm)	Mixing (200 rpm)
0	0	0	0	0	0	0
10	0.0036	0.0050	0.0042	0.0060	0.0048	0.0066
20	0.0025	0.0046	0.0012	0.0020	0.0037	0.0059
30	0.0010	0.00269	0.00085	0.00096	0.0015	0.0018
40	0.000481	0.00066	0.0039	0.00045	0.00042	0.00084
50	0.00023	0.00043	0.00021	0.00023	0.00022	0.00041
60	0.000084	0.00017	0.000076	0.00008	0.00015	0.00026

Table 2: Concentration at different conditions for KCl tracer

Time (mins)	Conc (0.05)	Conc (0.10)	Flowrate (140ml/ min)	Flowrate (150ml/ min)	Mixing (100 rpm)	Mixing (200 rpm)
0	0	0	0	0	0	0
10	0.0025	0.0032	0.0024	0.0027	0.0031	0.005
20	0.0011	0.0024	0.00133	0.0025	0.0017	0.0026
30	0.0007	0.0014	0.00065	0.00065	0.0007	0.0019
40	0.0002	0.00066	0.0028	0.00028	0.0003	0.00069
50	0.00010	0.00020	0.00019	0.00019	0.00022	0.00034
60	0.00008	0.0009	0.000073	0.00009	0.000095	0.00008

3. Resultant Graph and Analysis

3.1 NaCl TRACER:

3.1.1 INITIAL CONCENTRATION:

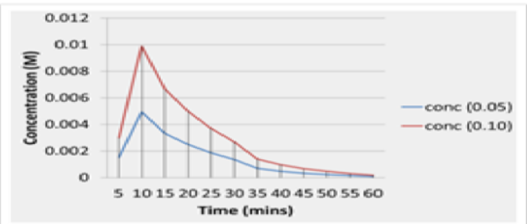

Chart -1: Concentration vs Time graph for initial concentration parameter of NaCl tracer

The RTD curve for NaCl displays sharper peaks and a shorter tail due to its status as a strong electrolyte. In water, NaCl readily dissociates into sodium (Na^+) and chloride (Cl^-) ions, enhancing its ionic strength. This characteristic enables NaCl to rapidly mix and disperse throughout the solvent. The sharp peaks signify uniform residence times within the reactor, indicating efficient mixing and dispersion of NaCl. Overall, NaCl's strong electrolytic properties facilitate rapid and thorough mixing, underscoring its effectiveness as a tracer material for studying reactor dynamics.[2][4][5]

3.1.2 FLOWRATE:

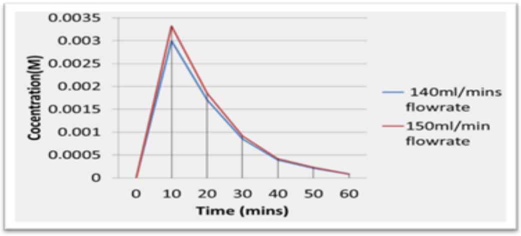

Chart-2: Concentration vs Time graph for flow rate parameter of NaCl tracer

At a higher flow rate of 150 ml/min, NaCl experiences shorter residence times within the Continuous Stirred Tank Reactors (CSTRs), leading to accelerated mixing and dispersion throughout the system. The increased flow rate facilitates a more rapid turnover of reactants within the reactor, reducing the time they spend inside. Consequently, there's less time for reactants to remain in stagnant zones, promoting more vigorous mixing and dispersion of NaCl throughout the reactor volume. This results in a more homogeneous distribution of NaCl, contributing to efficient process performance. Conversely, at a lower flow rate of 140 ml/min, NaCl encounters longer residence times within the CSTRs, leading to slower mixing and dispersion. With reduced flow rates, the reactants spend more time within the reactor, allowing for greater interaction and mixing.. This can result in slower dispersion of NaCl and less uniform reaction conditions, potentially impacting process efficiency and product quality. Therefore, the flow rate plays a crucial role in determining the residence time and mixing dynamics within the CSTR, influencing the overall performance of the system.[5][10][11]

3.1.3 MIXING EFFICIENCY:

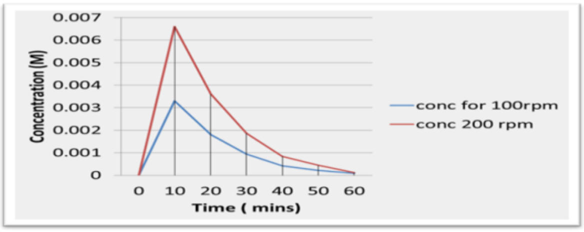

Chart -3: Concentration vs Time graph for mixing efficiency parameter of NaCl tracer

At a higher mixing efficiency of 200 rpm, NaCl undergoes more vigorous mixing within the Continuous Stirred Tank Reactors (CSTRs), resulting in shorter residence times and enhanced dispersion throughout the system as increased agitation facilitates faster and more homogenization of the tracer thoroughout solvent, promoting rapid dispersion of tracer material. Consequently, tracer experience shorter residence times within the reactor, leading to efficient reaction kinetics and improved process performance. Conversely, at a lower mixing efficiency of 100 rpm, NaCl encounters less vigorous mixing, leading to longer residence times and slower dispersion. The reduced agitation results in less effective mixing of NaCl within the reactor, leading to uneven distribution and slower dispersion throughout the system, potentially affecting reaction efficiency and product quality. Therefore, mixing efficiency plays a critical role in determining the residence time and dispersion dynamics within the CSTR, influencing the overall performance of the system.[1][4][6]

3.2 KCl TRACER:

3.2.1 INITIAL CONCENTRATION:

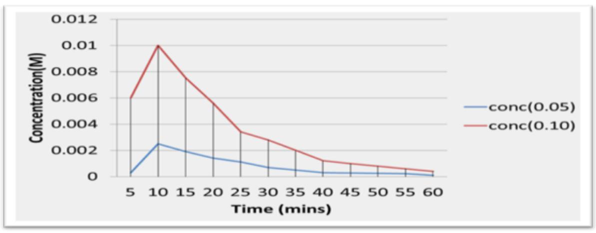

Chart-4: Concentration vs Time graph for initial concentration parameter of KCl tracer

The RTD (Residence Time Distribution) curve for KCl demonstrates broader peaks and a longer tail compared to NaCl. This characteristic can be attributed to the properties of KCl as a slightly weaker electrolyte with lower ionic strength. Unlike NaCl, which readily dissociates into sodium and chloride ions, KCl exhibits slower dissolution kinetics due to its weaker electrolytic nature. As a result, KCl ions disperse more slowly within the solvent, leading to less efficient mixing and dispersion throughout the system. The broader peaks in the RTD curve indicate less uniform residence times within the reactor, suggesting uneven distribution of KCl. Additionally, the longer tail signifies prolonged residence times or delayed dispersion of KCl, potentially due to its slower dissolution kinetics. Overall, the weaker electrolytic properties of KCl result in slower mixing and dispersion dynamics within the CSTR, influencing the shape of the RTD curve and potentially impacting process efficiency and performance.[2][7][11]

3.2.2 FLOWRATE:

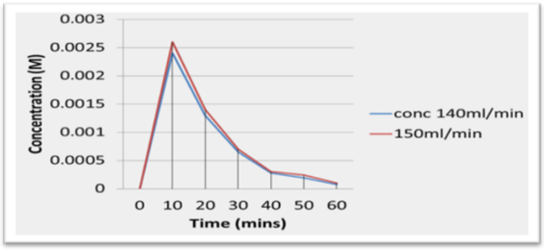

Chart-5: Concentration vs Time graph for flow rate parameter of KCl tracer

3.2.3 MIXING EFFICIENCY:

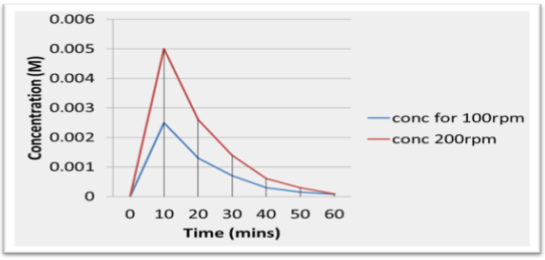

Chart -6: Concentration vs Time graph for mixing efficiency parameter of KCl tracer

Despite sharing the same mixing rates as NaCl (100 rpm and 200 rpm), KCl is anticipated to exhibit a slower decrease in concentration over time due to its weaker properties. The weaker electrolytic nature of KCl results in slower dissolution and dispersion kinetics within the system, leading to a slower rate of uniform distribution throughout the CSTRs. As a consequence, KCl takes longer to reach a homogeneous distribution within the reactor system, resulting in prolonged residence times and reduced overall process efficiency. This delayed and less uniform distribution of KCl underscores the importance of considering the electrolytic properties of tracers in CSTR systems and highlights the need for tailored approaches to optimize mixing dynamics and enhance process performance.[10][11][12]

3.3 RTD GRAPHS:

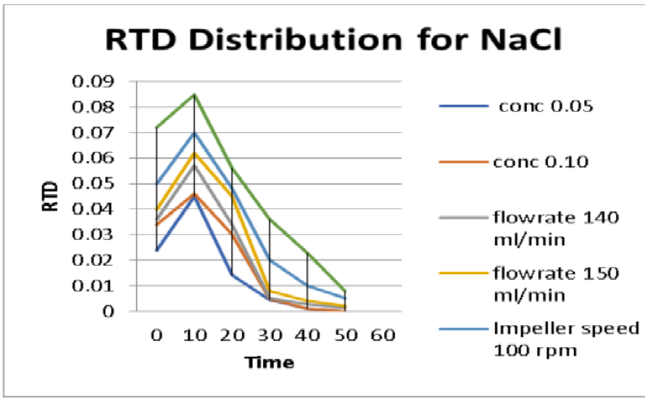

Chart-7: RTD graph for all the variants of all the parameters for NaCl tracer

The combined RTD graph illustrates how different parameters impact the distribution of residence times and mixing efficiency within the reactor system using NaCl as a tracer. When comparing mixing efficiencies of 200 rpm and 100 rpm, the RTD curve at 200 rpm exhibits a narrower and taller peak, indicating more effective mixing and faster material turnover. In contrast, the RTD curve at 100 rpm shows a broader and shorter peak, suggesting less efficient mixing and longer residence times. Similarly, varying flow rates of 150 ml/min and 140 ml/min result in distinct RTD curves. The higher flow rate (150 ml/min) leads to a broader and shorter peak, indicating faster material turnover and shorter residence times, while the lower flow rate (140 ml/min) shows a narrower peak, suggesting slower flow and potentially longer residence times. Additionally, differences in initial concentrations of 0.1 M and 0.05 M influence the shape of the RTD curve. The higher initial concentration (0.1 M) results in a steeper and taller peak, reflecting faster dispersion and reaction rates, whereas the lower initial concentration (0.05 M) exhibits a gentler slope and lower peak height, indicating slower dispersion and reaction kinetics.[2][3][5][6]

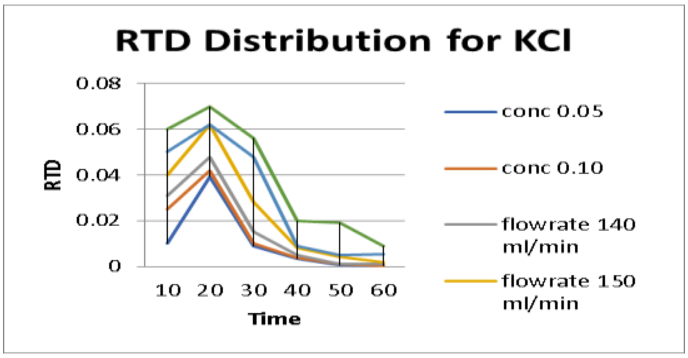

Chart-7: RTD graph for all the variants of all the parameters for KCl tracer

After conducting experiments with KCl as a tracer and varying mixing efficiency, flow rate, and initial concentration, the combined RTD graph reveals insightful patterns. Comparing mixing efficiencies of 200 rpm and 100 rpm, the RTD curve at 200 rpm tends to exhibit a narrower and taller peak, indicating more effective mixing and faster material turnover within the reactor system. Conversely, the RTD curve at 100 rpm typically shows a broader and shorter peak, suggesting reduced mixing efficiency and potentially longer residence times for KCl tracer. Similarly, variations in flow rates of 150 ml/min and 140 ml/min result in distinct shapes of the RTD curve. The higher flow rate (150 ml/min) leads to a broader and shorter peak, reflecting faster material turnover and shorter residence times, whereas the lower flow rate (140 ml/min) results in a narrower peak, indicating slower flow and potentially longer residence times for KCl dispersion. Additionally, differences in initial concentrations of 0.1 M and 0.05 M influence the RTD curve's characteristics. A higher initial concentration (0.1 M) typically results in a steeper and taller peak, representing faster dispersion and reaction rates, while a lower initial concentration (0.05 M) shows a gentler slope and lower peak height, suggesting slower dispersion and reaction kinetics for KCl tracer. [3][8]

While the general trends in RTD curves were similar for KCl and NaCl tracers under varying experimental parameters, subtle differences arose due to specific properties of each tracer. KCl, being a slightly weaker electrolyte compared to NaCl, exhibited differences in dissolution rates and dispersion behavior within the reactor system. These differences highlight the importance of considering tracerspecific characteristics when analyzing RTD behavior and optimizing reactor performance in chemical engineering applications. [3][9][12]

3. CONCLUSIONS

In conclusion, our project underscores the critical importance of mixing efficiency as the most influential parameter impacting Residence Time Distribution (RTD) within a Continuous Stirred Tank Reactor (CSTR) system. The findings reveal that variations in mixing efficiency exerted the most substantial effect on RTD compared to flow rate and initial concentration adjustments. Manipulating mixing efficiency allows for precise control over residence times and material dispersion within the reactor, leading to optimized reaction kinetics and product quality.

Following mixing efficiency, the project highlighted the significant impact of flow rate on RTD characteristics. Changes in flow rate influenced material turnover rates and residence times within the reactor, affecting overall process efficiency.

While initial concentration variations also influenced RTD, their impact was comparatively less pronounced than mixing efficiency and flow rate as the effect of initial concentration of feed vanishes as the mixing begins. So by strategically manipulating mixing efficiency, flow rate, and initial concentration, operators can achieve precise control over process dynamics and reactor performance. Optimizing these parameters enhances process efficiency, reduces production costs, and improves product quality by ensuring uniform mixing, controlled residence times, and efficient utilization of reactants.

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