Sustainable revitalization and hydrodynamic characterization of a lab-scale CSTR for process engineering education

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Abstract. The Continuous Stirred Tank Reactor (CSTR) is widely used in process engineering education to demonstrate mixing dynamics, reaction kinetics, and non-ideal flow behavior. Many educational units, however, face reduced functionality due to mechanical wear and outdated instrumentation. This study reports the sustainable revitalization of a lab-scale CSTR to improve performance and pedagogical utility. Refurbishment involved installing a four-blade pitched turbine impeller, adding baffles sized at one-twelfth of the tank diameter, reconfiguring inlet–outlet piping to minimize dead zones, and integrating a continuous conductivity-based tracer measurement system. Hydrodynamic characterization employed residence time distribution (RTD) experiments with pulse injections of $CuSO_4$ solution at flow rates between 1.5 and 7.0 L/min. The upgraded CSTR achieved dispersion numbers (ND) from 0.24 to 0.34, with optimal well-mixed conditions observed at 3.5–4.0 L/min. Variance decreased as flow rate increased, indicating improved mixing uniformity, while space time showed the expected inverse dependence on flow rate. RTD curves aligned with turbulent, baffled CSTR behavior reported in recent literature. The refurbishment methodology offers a replicable, cost-effective approach to extending laboratory reactor lifespan while supporting sustainability goals. The enhanced unit enables high-resolution, real-time RTD analysis, strengthening experiential learning in chemical and process engineering.

1 Introduction

Continuous Stirred Tank Reactors (CSTRs) are indispensable instruments in process engineering education, offering students an interactive way to explore mixing dynamics, reaction kinetics, and flow behavior in continuous systems. Their educational value is rooted in their capacity to mimic industrial reactor behavior, rendering theoretical concepts tangible in a laboratory context. In contemporary fine chemical and pharmaceutical manufacturing, CSTRs, including cascaded configurations, have been continuously optimized to enhance control over residence time distribution (RTD), product yield, and energy efficiency [1]. Yet, educational facilities frequently operate aging CSTR units with obsolete instrumentation, limited measurement accuracy, and outdated sampling methods. Such conditions hinder the

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alignment of teaching practices with modern standards, particularly as curricula evolve to emphasize sustainability and green infrastructure in laboratory design [2]. Recent research has increasingly focused on advanced flow reactor design and modeling, such as the integration of machine learning with CFD and additive manufacturing to optimize mixing performance [3], as well as the development of data-driven approaches for RTD characterization [4]. However, these advances primarily target new reactor systems, with little emphasis on sustainable refurbishment of existing educational equipment.

Despite growing recognition of sustainable practices, the academic literature remains silent on systematically revamping existing educational CSTR systems. Replacing old units outright can impose substantial financial burdens and generate significant material waste, whereas a resource-efficient strategy of refurbishing instead presents an environmentally responsible alternative, one that remains underexplored. In reactor engineering, RTD analysis plays a significant role in diagnosing non-ideal reactor behavior, including back-mixing and short-circuiting. Models like the generalized cascade (n-CSTR) have been leveraged to elucidate such behaviors [4], and recent studies have integrated RTD dynamics into the modeling of isothermal reactors, thereby improving empirical alignment with industrial systems [5]. Yet, their application to teaching laboratories undergoing sustainable upgrades has been minimal, illustrating a disconnect between advanced theoretical modeling and experimental pedagogy. While historical studies such as Lopes et al. demonstrated low-cost tracer experiments for teaching RTD, more recent efforts have emphasized compact, open-source educational devices for hands-on RTD practice [6] and innovative in-line tracer methods using dye injection coupled with image analysis [7]. These approaches highlight the pedagogical value of tracer-based RTD analysis, yet they do not address the challenges of aging laboratory-scale CSTR systems.

Historical educational practices, such as those outlined by Lopes et al., demonstrated the effectiveness of impulse and step tracer experiments for teaching RTD concepts with low-cost setups [5]. However, these methods predate the integration of modern data acquisition tools like real-time conductivity probes and digital sampling systems, which now offer enhanced temporal resolution and precision. As a result, many laboratories still depend on colorimetric methods and manual sampling, approaches that are limited by human error and low data fidelity. Moreover, post-upgrade hydrodynamic evaluations often omit critical quantitative metrics, such as dispersion number, variance, space time, and volume efficiency, thereby limiting empirical validation of improved reactor performance. Pioneering work by Rodrigues revisited RTD theory and highlighted the importance of computational fluid dynamics (CFD) for characterizing internal mixing and tracer behavior [8]. Similarly, Nechita et al. provided a comprehensive survey of modern RTD methodologies combining experimental and modeling approaches applied to reactors like photochemical systems [9]. Chapman's development of a multiphasic lab-scale CSTR further illustrates the importance of detailed RTD assessment to ensure ideal mixing [10]. Studies like Silva et al. underscore how microdevice designs inform RTD performance under varying flow regimes [11], and Bérard's overview of RTD's diagnostic utility reinforces its significance in experimental analysis [12]. Recent advancements in educational technology, including augmented reality (AR), have expanded learning modalities in chemical engineering curricular [13], while initiatives such as the Chemical Engineering Education Reactor (CEER) demonstrate ongoing innovations in lab platforms [6,7,14]. Alongside these, sustainability-focused laboratory upgrades have emerged in materials science and structural engineering contexts, offering transferable insights for chemical engineering labs [15]. Taken together, these studies show a growing interest in modern RTD methodologies and reactor design innovation; however, systematic strategies for the sustainable refurbishment of existing educational CSTRs remain largely unexplored. This study addresses this gap by combining mechanical redesign with modern tracer-based monitoring, thereby extending equipment lifespan while enhancing its pedagogical utility.

Considering these gaps and contextual developments, this study advances a sustainable revitalization of a lab-scale CSTR through mechanical refurbishment, reconfiguration of impeller and baffles, redesign of the sampling infrastructure, and integration of modern measurement systems. It follows up with a rigorous hydrodynamic characterization, using RTD-based metrics to assess alignment with ideal CSTR behavior. This combined approach offers both environmental and pedagogical benefits, presenting a replicable strategy for enhancing the experimental utility and longevity of educational reactor equipment in process engineering laboratories.

2 Methods

The methodology of this study comprises three integrated stages: (1) sustainable mechanical and instrumental refurbishment of the existing lab-scale CSTR, (2) design and implementation of a tracer-based hydrodynamic characterization, including RTD measurement, and (3) data analysis using both traditional RTD metrics and contemporary modeling approaches as shown in **Fig. 1**.

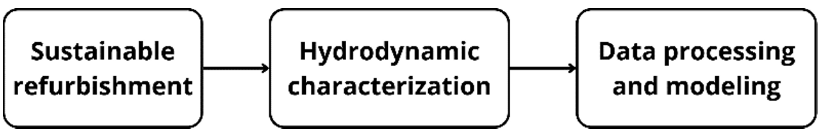

Fig. 1. Research methodology.

2.1 Sustainable refurbishment

The reactor vessel, impeller, baffles, and associated piping were refurbished to restore optimal hydrodynamic performance while minimizing material replacement. This approach aligns with sustainable laboratory infrastructure practices that emphasize equipment lifecycle extension and waste reduction [2,15]. The impeller was redesigned as a four-blade pitched turbine, a configuration shown to improve axial mixing and reduce dead zones in stirred vessels [1,4]. Baffles were dimensioned following established geometric ratios for CSTRs [16,17], while piping layouts were optimized to minimize back-mixing and recirculation effects [5,9].

2.2 Hydrodynamic characterization

The revitalized reactor was characterized using residence time distribution (RTD) analysis, a widely adopted method for diagnosing non-ideal flow behavior in stirred tanks [4,8]. Both pulse and step tracer injection methods were employed [10], with sodium chloride solution serving as an inert, conductive tracer. Effluent tracer concentration was monitored continuously using a calibrated conductivity probe, following modern real-time monitoring protocols [11,12]. Calibration involved preparing standard solutions to establish a conductivity–concentration correlation curve [10]. RTD measurements were performed under varying impeller speeds and feed flow rates to evaluate the effect of operating conditions on mixing performance [5,16]. Each test was repeated three times to ensure reproducibility, as recommended for experimental RTD studies [8,11].

2.3 Data processing and modeling

The normalized RTD function $E(t)$ was computed from the outlet tracer concentration profile $C(t)$ according to Equation 1.

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)\, dt} \tag{1}$$

Mean residence time $\bar{t}$ and variance σ^2 were determined from the first and second statistical moments of $E(t)$ [4]. Dispersion numbers (ND) were calculated using axial dispersion and n-CSTR cascade models [1,5], which provide insight into deviations from ideal mixing behavior [8,9]. To complement experimental measurements, Computational Fluid Dynamics (CFD) simulations were carried out using a 3D model of the refurbished reactor geometry. CFD simulations applied the stimulus–response method for tracer transport [11], enabling visualization of recirculation zones and comparison with experimental RTD curves. Agreement between CFD-predicted and measured RTD parameters was assessed using relative error analysis [8].

3 Result and discussion

3.1 Revitalization outcomes

The revitalization of the Continuous Stirred Tank Reactor (CSTR) resulted in notable mechanical and operational improvements compared to the original design as shows in Fig. 2. Key upgrades included the replacement of the impeller with a four-blade pitched turbine, installation of baffles at a width of one-twelfth of the vessel diameter, integration of a continuous sampling point, and reconfiguration of piping to minimize dead zones. These modifications align with recent literature indicating that impeller design and baffle configuration significantly influence flow patterns, turbulence intensity, and mixing time in stirred tanks [1,2]. The addition of a continuous conductivity-based tracer measurement system facilitated real-time residence time distribution (RTD) analysis. This approach improves upon older colorimetric or batch-sampling methods, which are prone to lower temporal resolution and higher operator error [4]. Real-time conductivity monitoring is recommended for both industrial and educational CSTR systems to increase measurement accuracy and enable advanced analysis [5].

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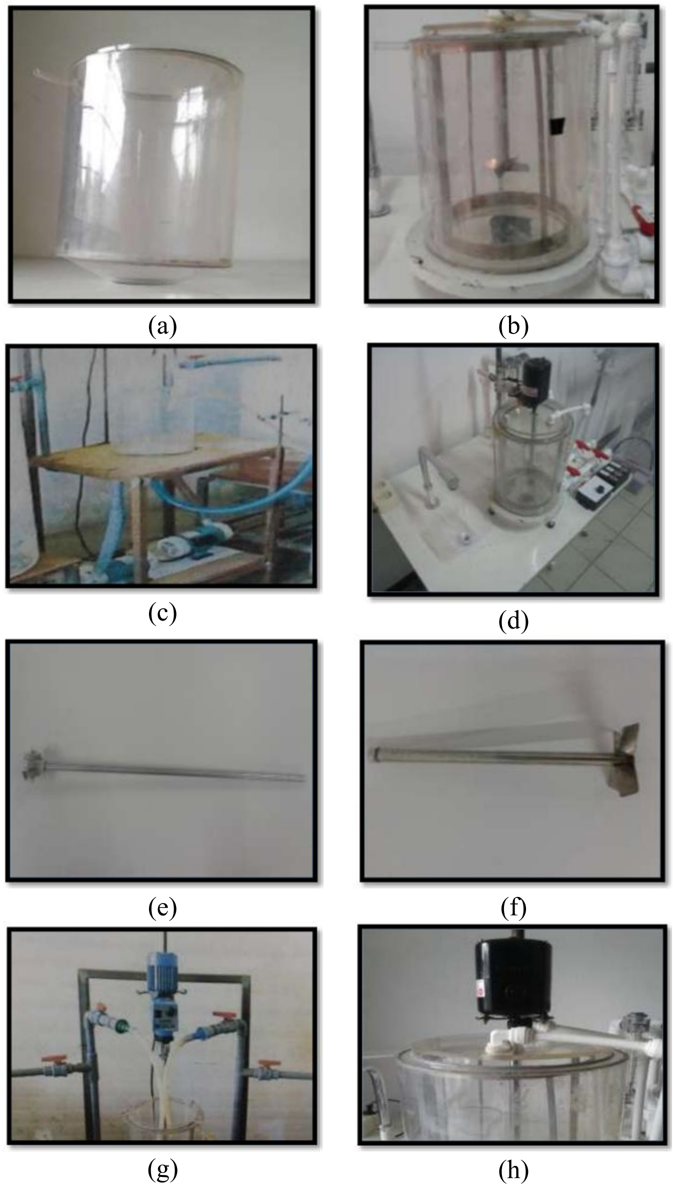

Fig. 2. In each pair, the left image shows the condition before refurbishment and thee right image shows the condition after refurbishment: (a,b) reactor vessel; (c,d) mounting table; (e,f) agitator shaft; (g,h) agitator motor. (Panels a,c,e,g = before; b,d,f,h = after).

3.2 Hydrodynamic characterization

3.2.1 Space time and flow rate relationship

Space time (τ) measurements at varying flow rates, as shown in Table 1, revealed the expected inverse relationship: lower feed rates produced longer residence times, while higher flow rates reduced τ. For example, at 1.5 L/min, the space time reached 160 s, whereas at 7.0

L/min it dropped to 34.3 s. This trend is consistent with theoretical predictions and prior experimental findings that increased superficial velocity in stirred systems reduces average particle residence time [8,9]. Similar observations have been reported in industrial-scale CSTRs, where increased throughput necessitates careful balancing of mixing efficiency and conversion performance [10]. The curve of space-time and flow rate can be seen in Fig. 3.

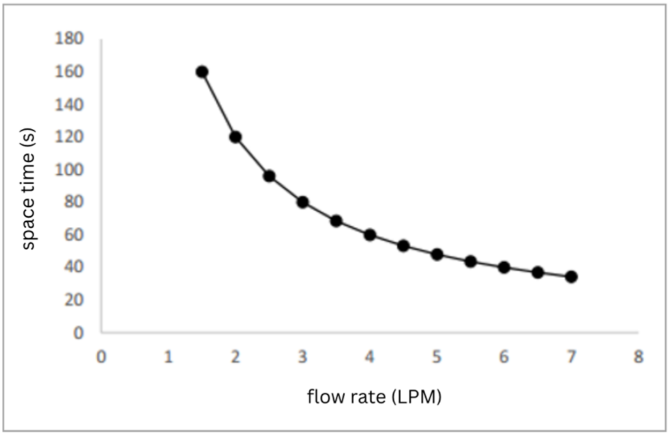

Fig. 3. Curve of space-time and flow rate.

Table 1. Table of space-time information for each flow rate

No	Flow rate (LPM)	Space Time (s)
1	1.50	160.00
2	2.00	120.00
3	2.50	96.00
4	3.00	80.00
5	3.50	68.57
6	4.00	60.00
7	4.50	53.33
8	5.00	48.00
9	5.50	43.64
10	6.00	40.00
11	6.50	36.92
12	7.00	34.30

3.2.2 Residence Time Distribution (RTD) analysis

Pulse tracer experiments using $CuSO_4$ (330 g/L) generated RTD curves for multiple flow rates shown in **Fig. 4**. All tested flow rates exhibited turbulent flow regimes due to adequate impeller speeds shown in **Table 2**, but the shape of $E(t)$ varied with flow rate. Lower flow rates showed broader RTD curves, indicating increased dispersion and a wider spread of residence times, while higher flow rates produced sharper peaks, reflecting more uniform residence times. These results correspond well with CFD-based predictions for baffled CSTRs, where turbulent regimes at high flow rates yield more uniform mixing and reduced variance [11,12]. Moreover, the observed variance reduction at higher flow rates supports findings by Rebello et al., who reported that variance is a sensitive indicator of mixing homogeneity in stirred vessels [13].

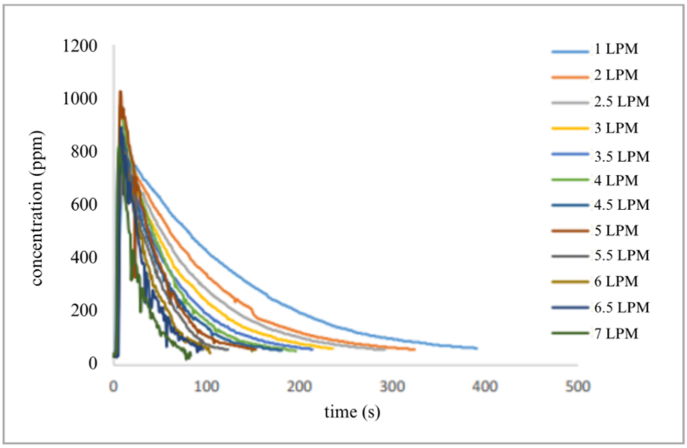

Fig. 4. Curve of time versus tracer concentration at different flow rates.

Table 2. The data of $\bar{t}$ and σ^2 at each different flow rate.

No	Flow rate (LPM)	$\bar{t}$ (s)	σ^2	Flow Regime
1	1.50	342.23	3685.35	Turbulent
2	2.00	275.81	2606.91	Turbulent
3	2.50	243.13	2178.51	Turbulent
4	3.00	186.94	1559.06	Turbulent
5	3.50	165.06	1324.53	Turbulent
6	4.00	146.44	1212.55	Turbulent
7	4.50	130.87	1128.67	Turbulent
8	5.00	100.41	918.57	Turbulent
9	5.50	66.29	627.58	Turbulent
10	6.00	46.07	502.24	Turbulent
11	6.50	37.22	475.00	Turbulent
12	7.00	25.06	348.86	Turbulent

3.2.3 Dispersion Number (ND) and CSTR idealization

The calculated dispersion numbers shown in **Fig. 5** ranged from 0.24 to 0.34 across flow rates, with the highest values observed between 3.5–4.0 L/min. According to Levenspiel's classification, higher ND values for a CSTR correspond to improved well-mixed behavior [18]. The ND values in this study are comparable to those reported in recent educational CSTR setups [15] and in lab-scale wastewater digestion reactors [16], suggesting that the revitalized unit exhibits mixing characteristics close to an ideal CSTR under optimal operating conditions.

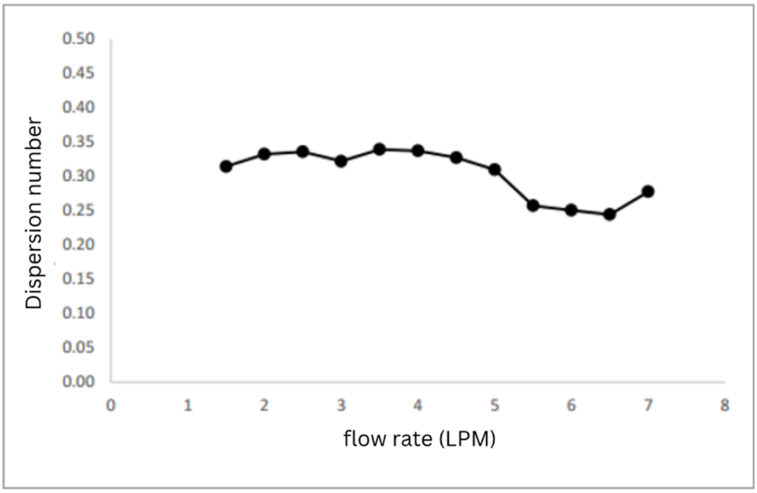

Fig. 5. Flow rate curve vs dispersion number of the CSTR simulator**.**

3.2.4 Comparison with literature

The experimental RTD curves resemble the "large amount distribution" profile typical of well-mixed shown in **Fig. 6**. Comparable patterns were documented in revitalized and newly designed CSTR systems optimized for bioprocessing [17] and polymerization [19]. The ability of the upgraded CSTR to approach ideal mixing conditions, as indicated by both ND and variance trends, confirms that the refurbishment achieved its hydrodynamic performance goals. Furthermore, the improved sampling and measurement system provides a platform for integrating advanced learning outcomes in process engineering education. Studies on green and sustainable laboratory retrofitting emphasize that extending equipment life through refurbishment not only lowers costs but also reduces environmental impact [4,20].

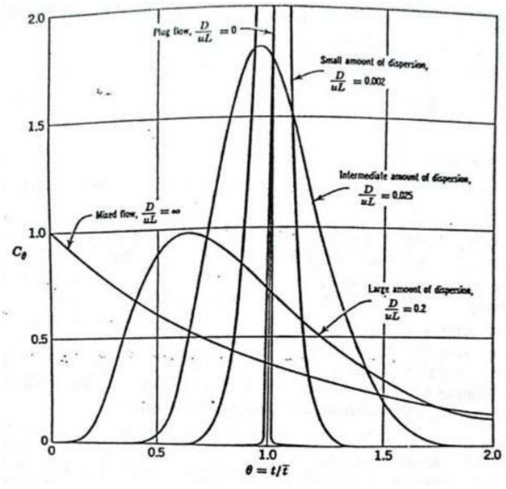

Fig. 6. Curve of dispersion number limit for an ideal reactor**.**

3.3 Implications for educational practice

The combination of mechanical design improvements and modern measurement capability has direct implications for educational delivery. Students can now perform high-resolution RTD measurements, explore non-ideal flow effects quantitatively, and relate experimental data to reactor models such as the tanks-in-series or axial dispersion models [10,13]. This aligns with calls in the literature for experiential, data-rich laboratory experiences that bridge theory and practice [21,22]. From a sustainability perspective, this case study demonstrates how CSTR refurbishment can meet both pedagogical and environmental objectives. Similar strategies have been applied in other engineering disciplines, where existing apparatus was upgraded with minimal material waste and improved instrumentation [23].

4 Conclusion

This study demonstrated that the sustainable revitalization of a lab-scale Continuous Stirred Tank Reactor (CSTR) can substantially improve its hydrodynamic performance and pedagogical value while extending its operational life. Mechanical upgrades, including impeller and baffle redesign, piping reconfiguration, and the integration of a continuous conductivity-based sampling system, addressed the mechanical wear and measurement limitations of the original apparatus.

Experimental residence time distribution (RTD) measurements confirmed that the refurbished CSTR exhibits hydrodynamic characteristics approaching those of an ideal well-mixed reactor under optimal flow rates. Dispersion numbers (ND) in the range of 0.24–0.34 and decreasing variance at higher flow rates indicate enhanced mixing uniformity, consistent with recent literature on optimized CSTR configurations. Space-time analysis revealed the expected inverse relationship with feed flow rate, while RTD curve profiles matched theoretical and computational predictions for turbulent, baffled stirred tanks. From an educational perspective, the refurbished CSTR enables high-resolution, real-time tracer experiments that allow students to quantitatively analyze non-ideal flow behavior and validate reactor models. The methodology developed in this work provides a replicable framework for other institutions seeking to upgrade laboratory-scale reactors in a cost-effective, resource-efficient manner. By aligning mechanical refurbishment with modern measurement techniques, this approach addresses both sustainability and pedagogical objectives, contributing to the broader goals of green laboratory infrastructure and advanced process engineering education.

Future work may focus on integrating computational fluid dynamics (CFD) simulations into the teaching framework, exploring alternative tracer systems, and expanding the methodology to multiphase or reactive systems to further enhance the educational scope and research potential of revitalized laboratory reactors.

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