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DYNAMIC CHARACTERIZATION OF RESIDENCE TIMES IN A NON-IDEAL PISTON FLOW REACTOR USING PULSED TRACERS AND MATLAB MONITORING

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Abstract:

Piston flow reactors (PFRs) are widely used in the chemical industry and are a fundamental pillar in the training of engineers, as they allow the hydrodynamic behavior of non-ideal systems to be studied under controlled conditions. This paper presents the design, construction, and experimental characterization of a laboratory-scale vertical piston flow reactor, complemented by an application developed in MATLAB App Designer for real-time data acquisition and analysis using flow, conductivity, and temperature sensors. Using the pulse tracer method with NaCl solutions, the distribution of residence times (DTR) was determined in a range of flow rates

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from 1 to 15 L/min and concentrations from 0.05 to 0.25 M. The results confirm that, under the conditions studied, the average residence time depends exclusively on the volumetric flow rate, being independent of the amount of tracer injected. In addition, a rational empirical model was obtained that describes with high precision the inverse relationship between flow rate and residence time, facilitating rapid estimates without the need for further testing. Beyond its technical contribution, this proposal constitutes an innovative pedagogical tool that integrates physical experimentation, low-cost automation, and computational processing, strengthening key competencies in chemical engineering students and promoting active, reproducible teaching aligned with the current challenges of higher education. This study is aligned with SDGs 4 (Quality Education), 9 (Industry, Innovation, and Infrastructure), and 12 (Responsible Consumption and Production).

Keywords: piston flow reactor, residence time distribution (RTD), pulse tracer, MATLAB app designer, engineering education, quality education, responsible production and consumption, innovation.

Sustainable Development Goal(s) (SDG) to which the research work is directed

4. QUALITY EDUCATION

Description:
Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all.
Relation to the study:
The proposal constitutes an innovative and accessible educational platform for experimental teaching in chemical engineering, integrating physical experimentation, automatic data acquisition, and real-time computational analysis. This experience strengthens technical, digital, and analytical skills in university students, promoting active, reproducible learning focused on solving real problems.

9 – INDUSTRY, INNOVATION, AND INFRASTRUCTURE

Description:
Build resilient infrastructure, promote inclusive and sustainable industrialization, and foster innovation.
Relation to the study:
A low-cost solution based on open hardware (Arduino), commercial sensors (, flow meter, conductivity meter) and software widely used in industry (MATLAB) is implemented, demonstrating how accessible technologies can modernize teaching laboratories and bring academic training closer to current industrial practices.

12 – RESPONSIBLE CONSUMPTION AND PRODUCTION

Description:
Ensure sustainable consumption and production patterns.
Relation to the study:
Experimental design optimizes the use of resources (water, reagents, energy) through accurate and repeatable measurements, minimizing waste. In addition, by fostering a critical understanding of the performance of non-ideal reactors, an efficiency- and sustainability-oriented mindset is cultivated from an early stage in future engineering professionals.

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INDEX

1. Introduction

The average residence time is the measure that quantifies the time particles remain inside a reactor. If the reactor is ideal, the spatial time and the average residence time are the same. However, when working with a real reactor, deviations from ideal conditions such as radial diffusivity, fluid turbulence, and dead zones can affect the time particles remain in the reactor (*Fogler, 2016; Levenspiel, 1999; Danckwerts, 1953*). One of the simplest methods for obtaining average residence times in real reactors is the pulse tracer method. There are other tracer techniques, such as step tracer, negative step (elusion), frequency-response methods, and methods that use feeds other than step or pulse, which are often more complex to perform than the pulse method and are not used as frequently. *(Fogler, 2016; Nechita et al., 2023; Westerterp et al., 1984).*

In a pulse feed, a quantity of tracer is injected into the feed stream in as short a time as possible. The concentration at the outlet is then measured as a function of time. The injection must be carried out over a very short period, and there must be negligible dispersion between the injection point and the inlet to the reactor system. If these conditions can be met, the technique is a simple method for determining the residence time distribution (*Fogler, 2016*).

The purpose of this research is to analyze the hydrodynamic behavior of a vertical piston flow reactor (PFR) through a detailed study of the residence time model, a key parameter for characterizing the performance of flow systems in chemical reactors. This type of practical experience, based on accessible hardware and interactive software, strengthens key competencies in engineering education *(*Alam *et al., 2020; Prabowo et al., 2024).* To achieve this objective, a reactor is designed and built that allows for the controlled injection of a tracer at the inlet and the measurement of flow rate and concentration at the outlet.

This proposal goes beyond technical analysis: it is conceived as an innovative laboratory experience aimed at training future chemical engineers. By integrating low-cost sensors, automatic data acquisition, and an interface developed in MATLAB App Designer, it promotes active learning based on experimental evidence and accessible digital tools. This teaching strategy contributes directly to Sustainable Development Goal 4 (Quality Education) by strengthening critical skills in university settings through reproducible, student-centered methodologies. It also supports SDG 9 (Industry, Innovation, and Infrastructure) by demonstrating how rapid prototyping technologies and free software can modernize teaching laboratories, and reinforces

SDG 12 (Responsible Consumption and Production) by promoting, through teaching, a culture of efficiency in chemical processes and rational use of resources.

Based on the experimental data obtained, the concentration profile of NaCl solutions over time is analyzed. In addition, a graphical interface is developed in MATLAB App Designer, which allows parameters such as the residence time distribution function (RTDF) and the average residence time to be calculated. Finally, an empirical relationship between reactor flow rate and average residence time is established based on the experimental data obtained.

Although there are numerous studies that analyze residence time in piston flow reactors using computer simulations, accurate experimental measurement remains a challenge due to the difficulty of tracking the concentration profile in real time. This study proposes an innovative experimental approach using conductivity and flow sensors connected to an Arduino system, which allows direct, real-time measurement of flow behavior.

Dey et al. (2007) investigated the behavior of a horizontal piston flow reactor (PFR) using tracers to analyze residence time distribution. In their study, they conducted a triplicate experiment using a NaCl solution and a dye, injected into the reactor, while recording the response curves of a conductivity probe and a light sensor. Subsequent studies have confirmed the usefulness of the pulse tracer, although they highlight the need for greater reproducibility and instrumental control *(Pundir, 2020).* The results showed that the curves obtained had a high correlation with each other, despite evidence of a lag between the salt and dye profiles.

However, the study by Dey et al. (2007) lacks experimentation under different flow conditions, which is essential for a more comprehensive evaluation of hydrodynamic behavior. In addition, the authors do not specify the methodology used to obtain the tracer concentrations from the conductivity meter and light sensor measurements, limiting the reproducibility of the results. Finally, vertical piston flow reactors (PFRs) are not commonly evaluated at the experimental and industrial levels. For these reasons, a new experiment is designed that not only addresses these limitations but also implements more modern tools, such as MATLAB App Designer, for data analysis and process simulation.

Determining the residence time distribution (RTD) in a reactor provides information on how long the various elements of the fluid have been in the reactor. However, TRD does not address reaction kinetics, and a model is needed to handle TRD data, which are determining factors in predicting conversion in chemical reactors (*Fogler, 2016; Nauman, 2008*).

Once the reactor has been characterized by knowing its DTR, it is possible to integrate this data with experimental h r information on reaction kinetics and DTR fitting models, which allow the performance of the actual reactor to be predicted for different reactions. However, the purpose of this research is not to define DTR fitting models or delve into reaction kinetics, but rather to provide an initial characterization of the reactor based on the DTR. This characterization is an essential preliminary step in understanding the residence time of the fluid elements in the reactor and, subsequently, complementing this analysis with additional information that allows for a comprehensive evaluation of the reactor's performance.

2 Materials and methods

2.1 Materials

For the construction of the reactor, a transparent acrylic tube with an internal diameter of 7 cm, a thickness of 3 mm, and a length of 81 cm is used, which is connected to two adjustable rubber heads: one at the top and one at the bottom. The lower head has two connections, the first for the fluid inlet, which has a valve to regulate the flow, and the second for the introduction of the tracer. The upper head is designed to allow the fluid to exit, thus ensuring continuous flow within the reactor. Water is introduced as the working fluid through a piping system connected to the lower head, which is constructed by thermofusing polyethylene pipes and fittings, with an external diameter of 2.54 cm and an internal diameter of 2 cm.

The reactor is equipped with multiple sensors, located both in the pipe and around it, to measure various parameters: flow rate, conductivity, and temperature. The flow rate is measured using a rotameter-type flow meter, model YF-S201, which has a ½-inch connection and a flow measurement range of 1 to 30 L/min. This sensor incorporates a rotor with magnetic paddles inside an isolated chamber and an external Hall effect sensor that detects changes in the magnetic field produced by the movement of the rotor. The Hall effect sensor generates electrical pulses that are converted to flow by an Arduino Uno, thus allowing the quantification of the rotor's movement. This accessible instrumentation approach has proven effective in engineering teaching laboratories *(Visco et al., 2023; Perry & Green, 2008).* The operating voltage range of the flow meter used is between 3.5 and 12 volts. The flow meter is located more than 60 mm from the fluid outlet, the minimum distance required for its installation, in order to avoid high reading fluctuations due to turbulence at the pipe intersection.

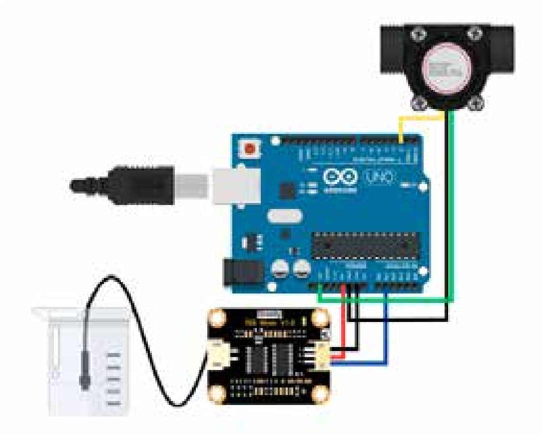
On the other hand, conductivity is measured with a conductivity meter or TDS conductivity sensor, which determines the amount of total dissolved solids (TDS) in the water, i.e., it indicates how many milligrams of soluble solids are dissolved in one liter of water (ppm). This sensor is installed in the upper head, at the same height as the fluid outlet. A conductivity sensor with an XH2.54-3P module interface and XH2.54-2P electrode is used, with a TDS measurement range of 0 to 1000 ppm and a margin of error of ± 0.1 ppm at 25°C. This sensor is connected to the same Arduino Uno board as the flow meter. The operating voltage range of the conductivity meter used is 3.3 to 5.5 volts. Finally, a type K thermocouple or thermocouple is used to record the operating temperature.

2.2. Sensor configuration

Figure 1 shows the connection diagram for the flow meter and conductivity meter on the Arduino Uno board. The flow meter connections are represented by the following colors: yellow (voltage connection), black (ground connection), and green (electrical pulse connection). The voltage connection was made in the *Power* section, on the 5V port. The ground connection was made in the *Power* section, on the GND port. The electrical pulse connection was made in the *Digital PWM* section, on port 2.

The conductivity meter connections are represented by the following colors: red (voltage connection), black (ground connection), and blue (TDS connection). The voltage connection was made in the *Power* section, at the 5V port. The ground connection was made in the *Power* section, at the GND port. The TDS connection was made in the *Analog In* section, at port A1.

Figure 1. *Arduino connections.*



The flow meter was calibrated in a range of 3 to 15 L/min, through volume measurement tests in a 2000-milliliter graduated cylinder in a given time. This procedure determined the actual flow values to obtain the calibration factor, which was 1/0.43 (ratio between the flow given by the flow meter and the actual flow).

On the other hand, the conductivity meter was calibrated using a series of sodium chloride (NaCl) solutions at different molar concentrations with known parts per million values in a range of 200 to 900 ppm. The molar concentrations used were 0.0033 M, 0.005 M, 0.0067 M, 0.0083 M, 0.01 M, 0.012 M, 0.013 M, and 0.015 M. The conductometer results were corrected by applying a calibration factor of 1/0.91 (ratio between the concentrations in ppm measured by the conductometer and the theoretical values).

2.3. Methodology used

The nature of the research is exploratory and descriptive. In this case, it covers the investigation of a little-explored topic, such as the design of reactors for calculating residence times. It is also descriptive, as it seeks to describe the behavior of a tracer throughout the volume of the reactor to estimate its actual residence time.

The nature of the research is quantitative, as it consists of measuring different parameters for subsequent analysis. Thus, numerical values are assigned to each study variable, such as time, concentration, and flow rate.

2.4. Measurement technique

In order to collect the data necessary for the construction of the simulation curve, five sodium chloride solutions at different molar concentrations were used: 0.05 M, 0.10 M, 0.15 M, 0.20 M, and 0.25 M. These solutions were evaluated in a flow rate range from 1 to 15 L/min. For each combination of flow rate and concentration, particle measurements per million (ppm) were taken in triplicate as a function of time.

To do this, the flow rate was measured first. The programming carried out for the Arduino allows 1 reading per second to be obtained. These flow rate data were transferred to MATLAB for real-time graphical representation, which allowed the lower inlet valve to be manipulated until the desired value was reached. The working flow rate was estimated using the numerical average of 10 readings obtained.

Once the working flow rate was established, the tracer sample to be used was taken. To do this, a 60-milliliter Grossmed syringe was used to extract a 60-milliliter sample of NaCl solution, which would be injected by pulse into the reactor in the lower head pipe.

Prior to injecting the tracer, the reading of particles per million began at a rate of 10 measurements per second. The data was transferred to MATLAB for real-time graphical representation. After 1 minute, the tracer was injected into the reactor and the necessary time was allowed to elapse to ensure that the tracer had passed completely through the reactor. This was estimated by observing that the curve, once it had reached its maximum reading, returned to its initial value and remained constant.

The collected data was transferred to an Excel file to generate the simulation curve in the application design.

2.5. Application design

The application design focuses on real-time data collection and analysis using sensors connected to an Arduino system. The use of MATLAB App Designer for educational interfaces has gained relevance due to its ability to integrate theory, simulation, and real-time experimentation *(Gupta & Yadav, 2020; MathWorks, 2024).* Readings are taken at a frequency of approximately 10 measurements per second, where one measurement corresponds to the flow meter and the rest to the conductivity meter. Specific MATLAB functions are used to record the time elapsed since the start of the experiment.

The application includes an interface that allows the user to select a port to connect the Arduino device. Once the connection is established, it remains registered in the application. In the event of a connection problem, the user must manually reconnect to the Arduino.

The application allows the flow rate to be measured for an indefinite period of time, displaying the flow rate value on the screen along with a real-time graph. To measure the flow rate, the application operates for a 15-second interval, calculating the simple arithmetic mean of the values measured during that time, and this flow rate is presented to the user at the end of the measurement. As for concentration measurement (ppm), the user starts data logging with a button, and the readings of both variables are recorded simultaneously. If the value is less than 50, it is classified as data provided by the flow meter, while higher values are considered to come from the conductivity meter.

During the injection of the tracer, a sudden increase in flow is observed, and when this increase exceeds 2 L/min, that moment is recorded as time zero for the calculation of the average residence time. When the graph corresponding to Conductivity (ppm) as a function of time stabilizes, the user must instruct the application to stop recording data.

In relation to the concentration data, the application discards empty points and readings prior to injection, and then calculates the average residence time. Although this data is not used in the calculation, it is stored in the application as conductivity and steady-state time.

The average residence time is calculated using the constant volume of the reactor and the average flow rate, which allows the theoretical spatial time to be determined, a reference value for comparisons. All post-injection time data is subtracted from the injection time, thus establishing a new zero time. From the steady-state data, the average value of the feed water conductivity is calculated to adjust the post-injection readings by subtracting this average in order to obtain the actual concentration of the solution used.

Subsequently, a numerical integration is performed using the trapezoidal method from time zero to the final time, which allows the residence time distribution function to be calculated. Once this process is complete, the application presents the user with the theoretical spatial time, the experimental average residence time, and the graph of E(t) as a function of time, providing an effective tool for analyzing the data obtained.

Additionally, a simulation tab independent of the real-time data is presented for calculating the average residence time. For this, with the experimental data obtained, a curve of average residence time as a function of flow rate was constructed, using a rational fit to model the relationship between these variables. This interface allows the user to enter a flow rate within the range of 1 to 15 L/min and obtain an estimate of the corresponding average residence time through the adjustment function generated from the experimental data.

3. Results and discussion

3.1 Concentration as a function of time, residence time distribution function, and cumulative distribution function

The tracer method allows the average residence time to be calculated using a flow rate and a known amount of tracer. To determine this, a series of ordered pairs of time and concentration must be obtained in order to generate a curve that reflects the behavior of the tracer concentration in the reactor as a function of time (*Fogler, 2016; Levenspiel, 1999*). Ideally, these curves can be fitted to known functions such as Gaussian, log-normal, and Weibull. However, when experimenting and adjusting the data, it is observed that the aforementioned curves do not fit any function adequately, which is consistent with previous findings in non-ideal systems with axial dispersion (*Mikkola et al., 2019; Alasino et al., 2015).* If a data series achieves a relatively good fit, this does not imply that other similar curves will reproduce this result.

Figure 2. *Tracer concentration in the reactor as a function of time.*

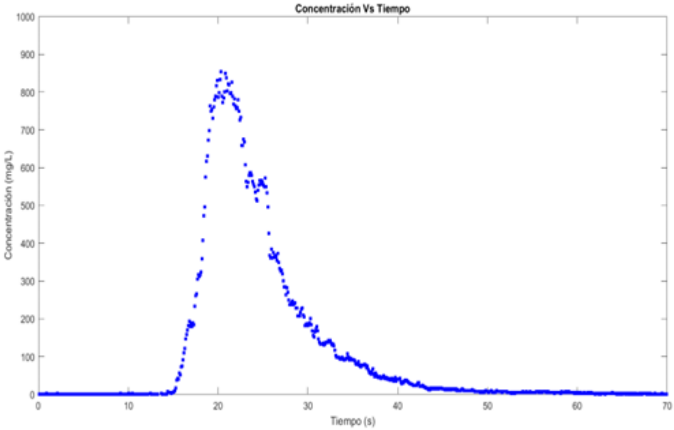


Figure 2 shows the experimental data obtained for the tracer concentration (mg/L) as a function of time (seconds) in one of the tests performed. The graph shows behavior characteristic of a piston flow system (PFS), where an initial increase in concentration is observed until a maximum peak is reached, followed by a progressive decrease. This behavior reflects the temporal distribution of the tracer molecules as they enter, pass through, and exit the reactor (*Fogler, 2016; Levenspiel, 1999*).

In addition to knowing the concentration curve as a function of time, it is important to determine the residence time distribution function, also known as E(t), from the experimental data. According to Fogler and Levenspiel, this function can be expressed as:

$$E(t) = \frac{C(t)}{\int_0^\infty C(t)dt} = \frac{C(t) \cdot vo}{No} \qquad [1]$$

where No is the number of moles injected and vo is the reactor inlet flow rate, which in this case is the same as the outlet flow rate because there is no chemical reaction, pressure drops and temperature variations are negligible. As can be seen in this equation, the distribution of average residence times is a function of the concentration curve as a function of time, the initial flow rate, and the number of moles entering.

Figure 3. *Distribution function of residence times.*

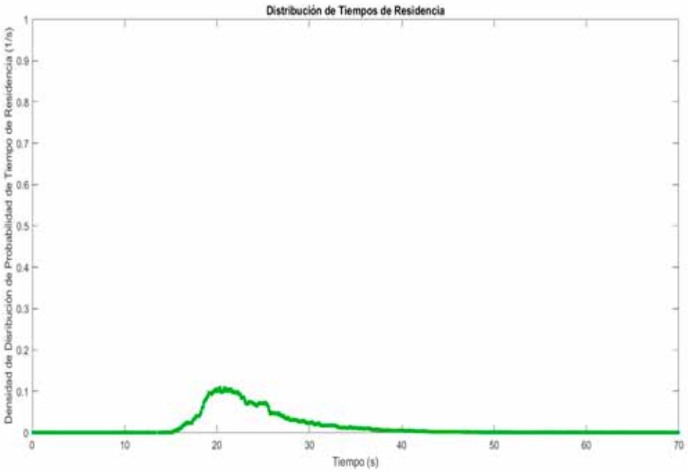
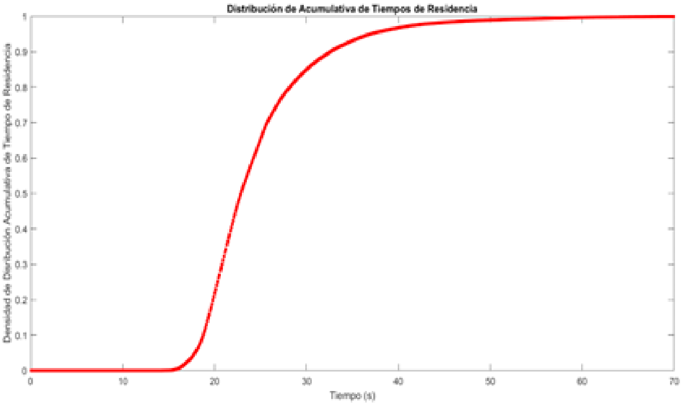


Figure 3 shows the distribution of experimental residence times, represented as a probability density as a function of time (s). The distribution of residence times varies from 0 to 1 because it is a probability. This statistical analysis allows us to identify the probability that particles will remain in the reactor for a specific time interval.

Similarly, another important concept to consider in this type of non-ideal reactor is the cumulative residence time distribution function, which can be expressed as:

$$F(t) = \int_0^t E(t)\,dt \qquad [2]$$

Figure 4. *Cumulative residence time distribution function.*



The cumulative function obtained is monotonically non-decreasing, which is an intrinsic property of cumulative distribution functions. This means that as time increases, F(t) never decreases. This can be seen in Figure 4, where the curve always rises until it becomes asymptotic at probability 1 (Fogler, 2008; Levenspiel, 1999).

In the initial region, corresponding to the time interval between 0 and 20 seconds, a low slope is observed in the curve, indicating a slow growth of the cumulative probability. This suggests that most of the particles are in the reactor. Between 20 and 50 seconds, the curve experiences a more pronounced increase, which characterizes the transition region. Most of the residence times are concentrated in this zone, showing that this interval is the most representative of the system. Finally, for times greater than 50 seconds, the curve asymptotically approaches the maximum cumulative probability value. This indicates that, in this interval, all the cumulative probability has been reached, implying that there are no tracer particles left inside the reactor.

3.2 Determination of residence times.

To calculate the residence time of the tracer in the reactor, theoretically, it is recommended to fit the concentration curve to a known function; however, for the purposes of this work, the trapezoidal method was used, a function known in MATLAB as "cumtrapz." It was decided to apply this calculation method because the graphs have a pronounced upward trend with peaks that make it difficult to fit any of the existing models. Therefore, through numerical integration, the average residence time was calculated using the following equation:

$$DTMR = \int_0^\infty tE(t)dt \quad [3]$$

Figure 5. *Concentration as a function of time with Weibull function adjustment.*

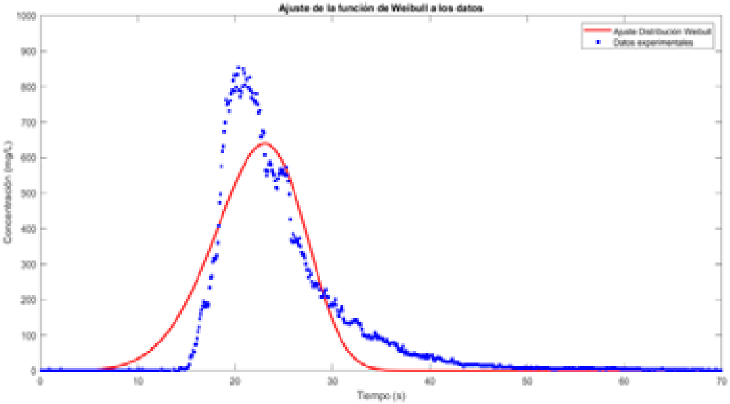


Figure 6. *Concentration as a function of time with lognormal function adjustment.*

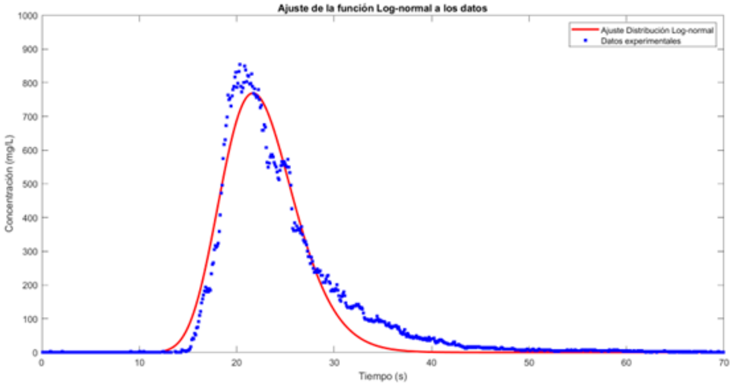
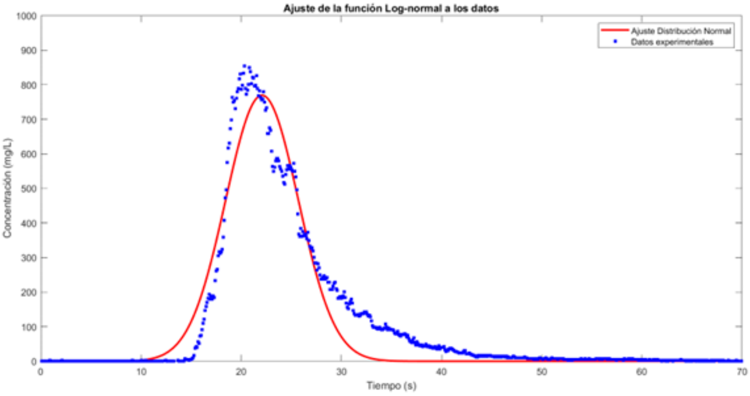


Figure 7. *Concentration as a function of time with Normal function adjustment.*



In Figures 5, 6, and 7, adjustments were implemented using the Weibull, normal, and lognormal distributions, respectively, in order to evaluate their ability to represent the experimental concentration data as a function of time. In Figure 5, the Weibull function fit explicitly shows that, although this distribution can model certain asymmetric behaviors, it fails to adequately capture the peak and dispersion of the experimental data as a whole. This result indicates that the Weibull function is not optimal for describing this specific data set.

Figure 6 shows the log-normal distribution fit, which performs significantly better than the Weibull distribution in terms of approximating the experimental data. This model captures the asymmetry characteristic of the distribution of concentrations over time, adequately representing both the rise and fall of the curve around the main peak. However, discrepancies are also evident in the tails of the distribution, especially in the region of lower concentration.

Figure 7 shows the fit of the experimental data using a normal distribution. At first glance, it can be seen that the symmetrical nature of the normal function considerably limits its ability to adequately represent the experimental data, which exhibit asymmetric behavior. Therefore, for subsequent calculations, it was decided to use the trapezoidal rule numerical integration method, due to the number of experimental numbers involved.

3.3 Variance, standard deviation, and their physical interpretation.

Variance is a key measure for analyzing the dispersion of residence times in a system, indicating how far these values are from the average time. Mathematically, it is defined as:

$$\sigma^2 = \int_0^\infty (t - trm)^2 \cdot E(t)\, dt$$

where $E(t)$ is the probability density function of the residence time distribution (Fogler, 2008). In physical terms, a high variance suggests greater heterogeneity in the flow, which could be due to phenomena such as recirculation or significant dispersion, while a low variance reflects greater uniformity, characteristic of systems closer to ideal behavior. On the other hand, standard deviation is defined as the square root of variance (Fogler, 2008; Levenspiel, 1999).

A high standard deviation suggests greater variability in residence times, which may be associated with non-ideal flows, while a low value indicates residence times more concentrated around the average, reflecting a more uniform flow (Fogler, 2008; Levenspiel, 1999). In research such as that of Alasino et al. (2015), this parameter is used to adjust hydrodynamic models of parallel piston flow reactors (PFRs) with dispersion, allowing the actual flow conditions in complex systems, far from ideal behavior, to be characterized.

Figure 8. *Standard deviation of the mean residence time.*

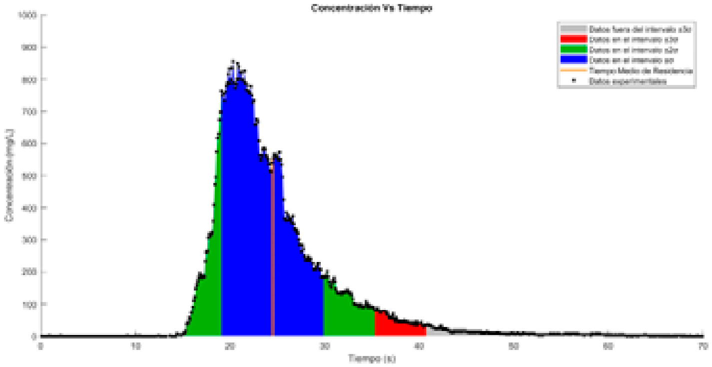


Figure 8 shows the distribution of tracer concentration (mg/L) as a function of time (s), highlighting the confidence intervals (±σ, ±2σ, ±3σ) and experimental points. Most of the data falls within the ±σ interval (blue), indicating a high density of data around the central core of the distribution, reflecting the consistency of the measurements in this region. The mean residence time, represented by the orange band, does not coincide with the peak concentration, indicating the presence of asymmetry in the distribution. This asymmetry, characterized by a long tail to the right, suggests the existence of delayed events that shift the mean time toward higher values. Values outside ±3σ (gray) are considered extreme, possibly attributable to experimental anomalies or noise in the measurements. In general, the distribution exhibits moderately asymmetric behavior, indicating inherent variability in the system that must be considered when interpreting the results and modeling reactor behavior.

3.4 Effect of turbulence and diffusivity on the calculation of average residence times.

Turbulence and diffusivity directly influence the dispersion and transport of particles within flow systems. Turbulence introduces chaotic fluctuations that promote intense mixing, redistributing kinetic energy and facilitating advective transport in the medium. This behavior generates greater dispersion in residence times and can lead to phenomena such as recirculation and stagnation zones, which alter the ideal flow and affect the uniformity of transport *(Andrade, 2021; Incropera et al., 2013).*

On the other hand, diffusivity regulates particle transport by smoothing concentration gradients, which favors greater spatial homogeneity. This process complements the action of turbulence, being particularly important in areas where advection is limited. Its influence is manifested in the redistribution of tracers within the system, affecting the shape and extent of the residence time distribution curve (Andrade, 2021).

The interaction between turbulence and diffusivity highlights the inherent complexity of real flow systems, where both phenomena contribute to the heterogeneity of residence times. Ignoring these factors in the analysis could lead to an underestimation of the hydrodynamic complexity and the deviations observed from ideal behavior.

3.5 Surface and experimental grid

As mentioned above, according to equation [1], the average residence times depend on the flow rate entering the reactor and the moles in the tracer (Fogler, 2008; Levenspiel, 1999). Consequently, for the first phase of experimentation, the flow rate was varied from 3 L/min to 10 L/min while maintaining a constant tracer concentration; then a range of concentrations from 0.05 M to 0.25 M was used while the flow rate remained fixed. In this way, an experimental grid was established.

Figure 9. *Residence times as a function of flow rate and initial moles injected.*

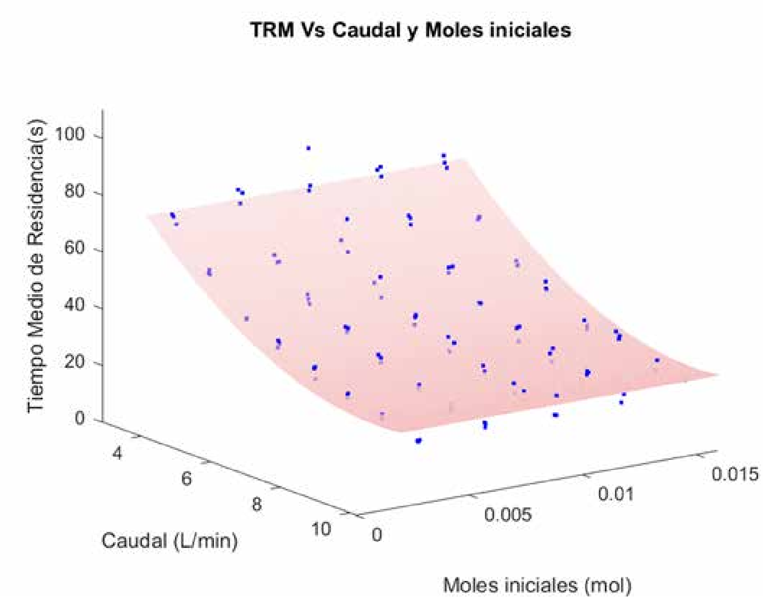


Figure 9 shows that the general trend of the surface area is decreasing with respect to flow rate and linear with respect to the number of moles. The data were fitted in MATLAB with a 2-1 degree polynomial equation, whose equation is:

$$trm\ (s) = 117{,}4 - 19{,}51 \cdot vo + 161{,}1 \cdot No$$
$$+ 1{,}006 \cdot vo^2 + 4{,}074 \cdot vo \cdot No \qquad [4]$$

Where vo is the flow rate in (L/min) and No is the number of moles injected (mol).

3.6 Effect of flow rate on residence time.

As a result of the trend observed on the surface, the average residence times were plotted as a function of flow rate, keeping the moles of the tracer constant. The trend of the curves in Figures 10 and 11 is decreasing. Using MATLAB, a rational fit was applied where the numerator is a zero-degree polynomial, constant, and the denominator is a first-degree polynomial.

Figure 10. *Average residence times as a function of flow rate, keeping No = 3 mmol constant.*

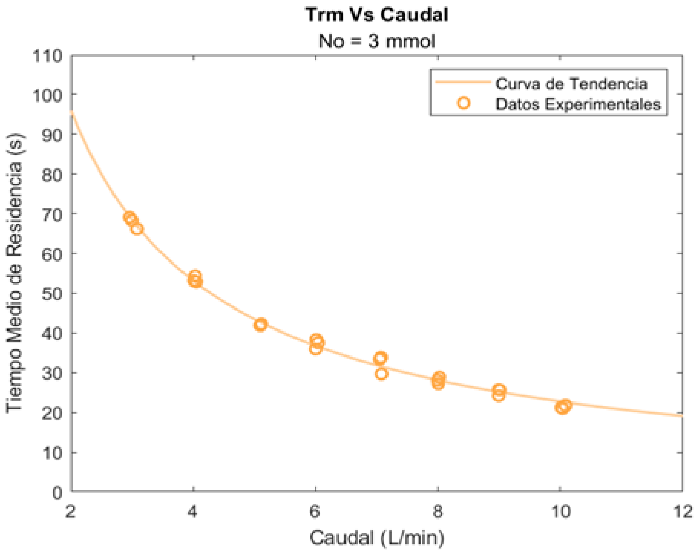
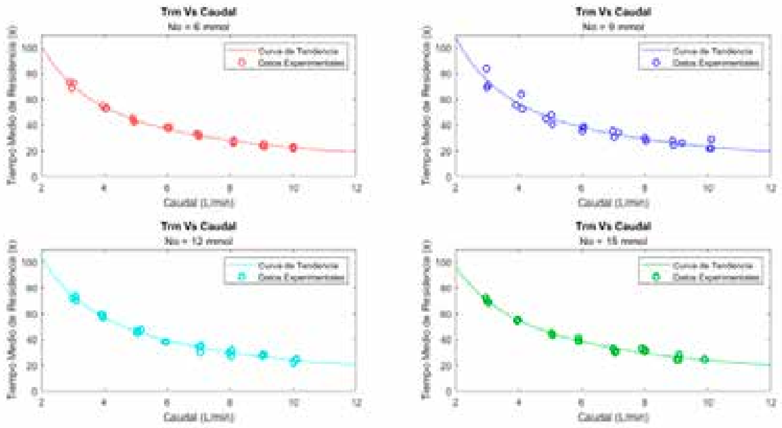


Figure 11. *Average residence times as a function of flow rate, keeping No constant for each graph.*

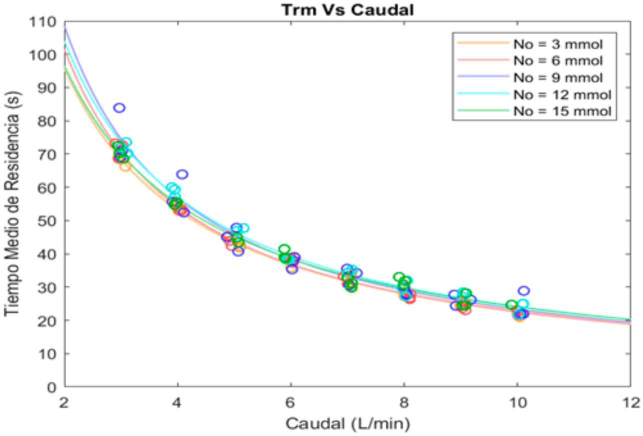


The graphs shown in Figure 11 corroborate the behavior observed during the experiment, in which, at higher flow rates, the time of sodium chloride in the reactor is shorter. When graphing and superimposing the curves, as shown in Figure 12, a similar behavior is evident in all of them; the deviations observed are due to experimental errors. The equation for all functions is of the form:

$$y = \frac{p1}{x + q1} \qquad [5]$$

where, in this case, ‘y’ represents the average residence time, ‘x’ represents the flow rate, and p1 and p2 are constants.

Figure 12. *Average residence times as a function of flow rate, keeping No constant.*



3.7 Effect of tracer moles on residence time

In turn, by keeping the flow rate constant and plotting the average residence times as a function of the moles injected, a constant trend can be observed in both Figure 13 and Figure 14. This means that the residence times are independent of the moles injected for the working range.

Figure 13. *Average residence times as a function of the initial moles introduced into the reactor, maintaining a constant flow rate in the range of 3 L/min to 6 L/min.*

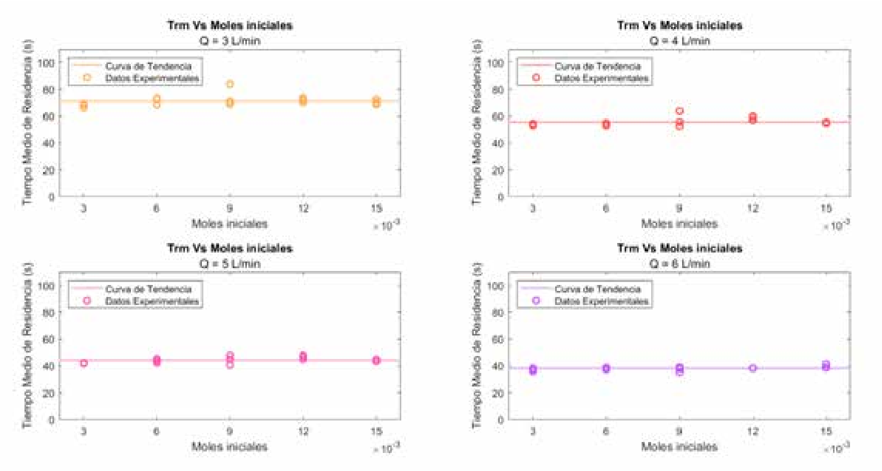
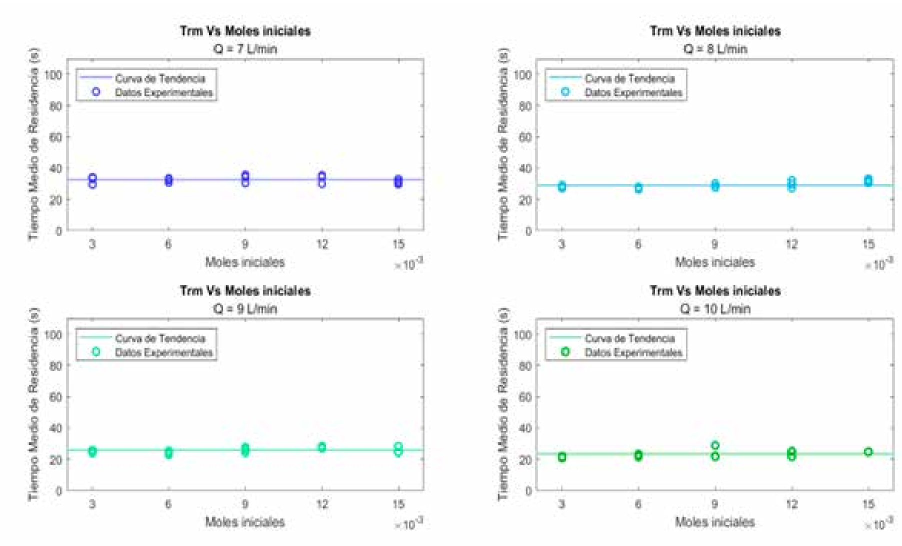
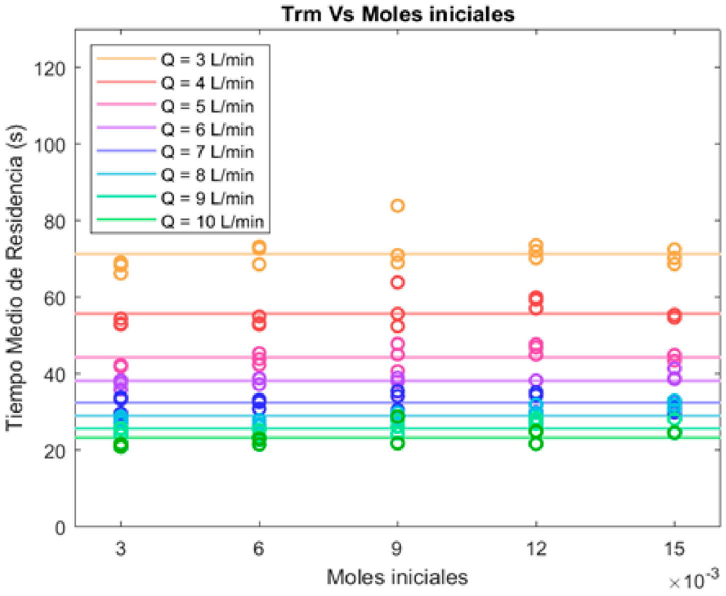


Figure 14. *Average residence times as a function of the initial moles introduced into the reactor, maintaining a constant flow rate in the range of 7 L/min to 10 L/min.*



In an ideal reactor, the space time is equal to the average residence time, which is defined as the reactor volume divided by the volumetric flow rate. Space time is a theoretical value and does not depend on the moles entering the reactor (Fogler, 2008; Levenspiel, 1999). Therefore, although the mean residence time distribution E(t) depends on the moles injected, and a priori, the moles appear to be a variable that affects the mean residence time, it can be stated that, in the working range, the number of moles does not influence the mean time value, as corroborated by Figure 15.

Figure 15. *Average residence times as a function of the initial moles introduced into the reactor at constant flow rate.*



3.8 Curve of average residence times as a function of flow rate

Previously, the effect of molar variation on average residence times was ruled out. Taking this factor into account, a second phase of experimentation was carried out, extending the flow rates to the range 1 L/min to 15 L/min, injecting 60 mL of saline solution at a concentration of 0.15 M.

Figure 16. *Average residence times as a function of flow rate, keeping No constant.*

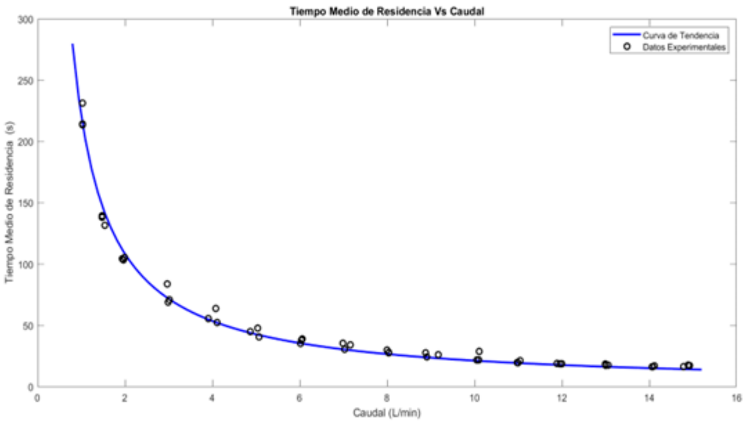


Figure 16 shows the curve that will be used to perform the simulations in the MATLAB application. This curve has a rational 0-1 fit, where the numerator is a constant and the denominator is a first-degree polynomial. The average residence time fit obtained was:

$$Trm\ (Q) = \frac{221{,}5\ L.s/min}{Q\ -\ 0{,}047\ L/min} \qquad [5]$$

where Q is the flow rate in liters per minute. The numerator has a constant (221.5) whose units are liters per second per minute, while the constant in the denominator (0.047) has units of liters per minute. The structure of Equation [5] is very similar to the spatial time equation:

$$\tau = \frac{V}{Q} \qquad [6]$$

where V is the reactor volume, which is equivalent to 3.32 ± 0.02 liters (*Fogler, 2016; Levenspiel, 1999*, *Nauman, 2008*). Thus, for the constructed reactor, the spatial time as a function of flow rate would be defined by the following equation:

$$\tau = \frac{3{,}32\ L}{Q\ (\frac{L}{min})}\ (min) \qquad [7]$$

If the numerator of the adjustment is converted to liters:

$$Trm(Q) = \frac{V_{eff} .60\ s/min}{Q - Q_o} \qquad [8]$$

Where:

$V_{eff} = 3{,}692$ is the apparent effective volume deduced from the adjustment

$Q_0 = 0{,}047\ L/min$ is a threshold flow rate (possibly related to losses or instrumental error),

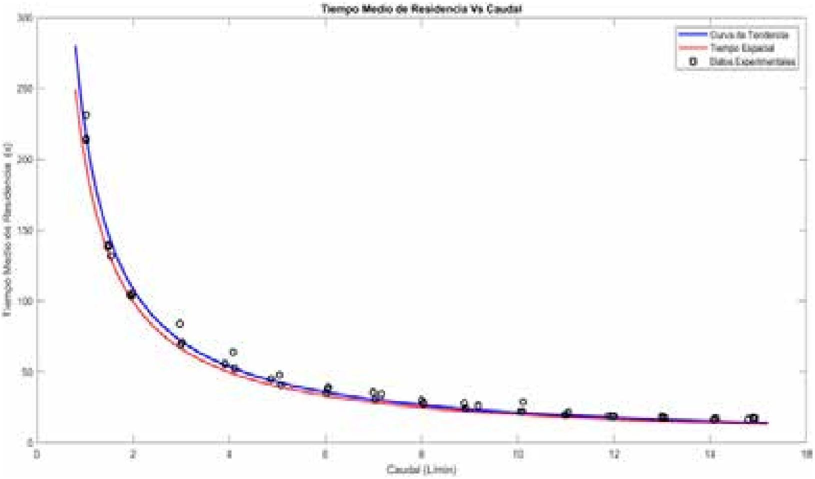
The factor 60 s/min converts the final result to seconds.

$$Trm\ (Q) = \frac{3{,}692\ L.60\ s/min}{Q - 0{,}047\ L/min} \qquad [9]$$

Equation [9] shows a conversion factor from minutes to seconds (60 s/min) and an effective reactor volume obtained from the empirical adjustment of the experimental curve, $V_{eff} = 3{,}692$ L. This value is slightly higher than the actual geometric volume of the reactor ($V = 3{,}32$ L), which results in experimental average residence times greater than the theoretical spatial time ($\tau = V/Q$).

This discrepancy is consistent with the typical behavior of real reactors and suggests the presence of stagnation zones or partial short-circuiting, phenomena common in non-ideal systems. However, as shown in Figure 17, this difference is insignificant at high flow rates (> 2 L/min), where the reactor exhibits behavior close to that of ideal piston flow.

Figure 17. *Average residence times as a function of flow rate, keeping No constant.*



The deviation between the experimental average residence time and the theoretical spatial time increases significantly when the flow rate decreases below 2 L/min. This effect can be attributed, at least in part, to the greater relative error of the flow meter at low flow ranges, which introduces uncertainty in the measurements. Additionally, at low flow rates, factors such as residual turbulence, molecular diffusivity, and axial dispersion can have a more significant influence on the flow profile.

Taken together, these findings confirm that the reactor design promotes a highly plug-flow profile, minimizing axial dispersion under typical operating conditions (especially at flow rates above 2 L/min). This characteristic validates the use of the empirical model represented by Equation [5] (and its equivalent in terms of volume, Equation [9]) for simulations in MATLAB in the range of practical interest.

4. Conclusions

In this work, a comprehensive laboratory experiment was developed for the hydrodynamic characterization of a non-ideal vertical piston flow reactor, combining physical experimentation, low-cost sensors (flow meter and conductivity meter), automatic data acquisition using Arduino, and an interactive application designed in MATLAB App Designer. This proposal not only allows real-time measurement of the average residence time using the pulse tracer method, but also constitutes an innovative pedagogical tool for teaching chemical engineering in university settings.

The experimental results confirm that, within the range studied (1–15 L/min and NaCl concentrations between 0.05 M and 0.25 M), the average residence time depends exclusively on the volumetric flow rate, being independent of the amount of tracer injected. This finding reinforces the validity of the theoretical model of spatial time ($\tau = V/Q$) and demonstrates the robustness of the experimental method implemented. In addition, a rational empirical model was obtained that accurately describes the inverse relationship between flow rate and residence time, facilitating rapid estimates without the need for repeated trials.

Beyond its technical contribution, this experience strengthens key skills in students: experimental design, instrumentation management, signal processing, numerical analysis, and data visualization. By integrating accessible hardware and software widely used in industry and academia, it promotes active, contextualized learning aligned with the current challenges of engineering education. In this sense, the work responds to the demands for modernization of teaching laboratories and contributes to a more dynamic and inclusive engineering education that is connected to professional practice and the principles of sustainability in higher education *(UNESCO, 2017; Luján et al., 2024).*

5. Recommendations

Based on the findings of this study, the following recommendations are proposed, aimed at both the technical development of the reactor and its potential use in educational settings:

- Explore alternative reactor configurations (e.g., horizontal or packed) to compare residence time distributions, as has been done in previous studies of non-vertical tubular reactors *(Li et al., 2015),* and enrich the laboratory experience. These variations would allow students to analyze how geometry and packing affect hydrodynamic behavior, strengthening their understanding of the concepts of ideality and non-ideality in reactors.
- Integrate real kinetic data with the obtained residence time distribution to predict reactor conversion, following methodologies established in the literature *(Ramachandran & Chaudhury, 2012; Chapra, 2017).* This step would be a natural extension of the current work and would offer an advanced project for upper-level reactor courses, where hydrodynamics, kinetics, and process design are articulated.
- Incorporate this experience into the chemical engineering laboratory curriculum as a practical module in subjects such as Chemical Reactors or Unit Operations.

The combination of low-cost sensors, Arduino, and MATLAB App Designer offers a replicable, scalable, and highly motivating model for students by linking theory, experimentation, and programming.

- Develop improved versions of the interface in MATLAB, with additional functionalities such as automatic adjustment of axial dispersion models, simulation of multiple reactors in series or parallel, or integration with virtual learning platforms (such as Moodle or Google Classroom), facilitating its use in hybrid or remote modalities.
- Encourage spin-off student projects, such as evaluating the impact of instrumental error on estimating average residence time, comparing different tracers (dyes vs. electrolytes), or implementing automatic flow control through real-time feedback. These activities promote critical thinking, autonomy, and innovation from the early stages of training.

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