The University of Jordan

School of Engineering

Department of Chemical Engineering

Chemical Engineering Laboratory (4) (0905562)

Section Number: (1)

Experiment Number: (8)

Experiment Title: 'Empirical Dynamic Models'

Report Type: Full Report

Date of Performance: 22nd October 2023

Date of Submission: 5th November 2023

Student Name	Registration #
Sedra Nibal Al-Burghili	0191293
Nour Ahmad Kharisat	0194083
Donia Majdi Khalil	0197045
Sura Mohammad Froukh	0197130
Lana Mamoon Abdelnabi	0198593

Instructor: Eng. Nariman Al-Dahleh

ABSTRACT

The empirical dynamic modelling of a two-tank system's response to changes in conductivity is explored in this experiment. study investigated to analyse the system's dynamic behaviour in response to impulse and step-up changes in conductivity and establish an empirical model to describe it.

For the impulse response, a sudden change in conductivity was introduced into Tank A by adding a salt solution (conductivity: 6.86 ms/cm) to it. Tank A initially had a conductivity of 0.948 ms/cm. The ensuing dynamic behaviour, including changes in conductivity over time, was accurately recorded while maintaining the tank levels within a specified tolerance (±5 cm). However, the parameters of the impulse response could not be determined using the reaction process curve method due to the absence of a calculable gain (Kp) caused by the rapid attainment of steady state.

During the step-up change phase, the pump connected to Tank A was deactivated, and the initial conductivity of Tank B, which contained the salt solution (6.86 ms/cm), was measured. Subsequently, the three methods were employed to determine the parameters. Method 1 yielded tp = 7.8 min, t0 = 1.5 min, and Kp = 0.69. Method 2 resulted in tp = 7.50 min, t0 = 1.50 min, and Kp = 0.69. Method 3, which was like Method 2, also yielded tp = 7.50 min, t0 = 1.50 min, and Kp = 0.69. These values were found to be approximately the same, with a relative error of around 3%.

Table of Contents

List of Figures

List of Tables

INTRODUCTION

Models are a vital tool for both the chemical industry specifically and the engineering sciences. They are mathematical representations of the relationships between variables in real systems, which describe and help operators understand the behavior of a plant or a process.

Many phenomena in engineering are overly complex and there is no sufficient knowledge to develop a model from first principles; instead, we must rely on empirical correlations.

Empirical models avoid problems by making minimal structural assumptions and using only observed dynamics to make forecasts. These models are usually accurate and especially useful. However, they are only valid within an experimental domain where the parameters are determined.

Empirical dynamic model (EDM) is a powerful method for forecasting and analyzing nonlinear dynamics. It is a set of equations (including the necessary input data to solve the equations) that allows us to predict the behavior of a chemical process system.

The most commonly used model to describe the dynamics of chemical processes is the First-Order Plus Dead Time (FOPDT) model in which first order systems are those whose input-output relationship is a first-order differential equation, and the dead time is the time until the sensor detects the change from the old steady state value (time delay between input and output).

Sometimes it is difficult to obtain a system's transfer function analytically because the system closed, and its parts cannot identify. In this case, a step input submitted to the process to obtain valuable information from the system's response which can used to derive the transfer function.

In this experiment, a continuous stirred tank used to study its response to a step and impulse changes in inlet salt concentration which represented by measuring the liquid conductivity, and to see if the empirical dynamic model FOPDT is applicable for this system by comparing it with the process reaction curve.

The manipulated process input is the inlet liquid conductivity (salt concentration), and the measured process output is the outlet liquid conductivity.

THEORY

Empirical (or "black box") models merely explain the relationship between the process's observed input and output data; they do not explain the physical phenomena of the process. Instead, they are based on input/output data. These models are in use when there is not enough physical understanding of the process or when there is not enough time to construct the model.

To generate such empirical models, the step test procedure is carried out as follows:

1. Apply a step modification to the controller output signal M(t) in the process when the loop is opened (the controller is in manual mode); refer to Fig. (1). The change should be significant enough to measure the resulting change in the transmitter signal, but not so significant as to cause the process nonlinearities to distort the response. No disruptions that could impact the process should occur during the phase testing.
2. The process C(t) response is captured on a strip chart recorder or similar apparatus, ensuring sufficient resolution in terms of both amplitude and time scale. The process reaction curve is the sigmodal-shaped plot of C(t) vs time that results. The response needs to span the whole test duration, starting from the moment the step test is introduced and ending when the system reaches a new steady state.
3. Match a First Order Plus Dead Time (FOPDT) response with the process reaction curve.

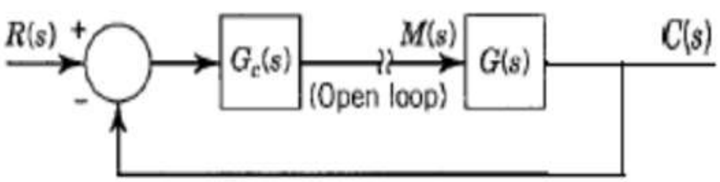

Figure 1: Block diagram for a typical open loop to generate the process reaction curve. (2)

The process reaction curve is considered one of the most used methods for identifying dynamic models. It is a relatively simple and straightforward approach that, while not the most comprehensive, can provide satisfactory models for many applications. In this method, the process is explained and demonstrated using an example. Subsequently, a critical evaluation is conducted, highlighting both the strengths and weaknesses of the approach.

The parameters for a first order with dead time model can be determined using graphical calculations based on the process reaction curve. This specific model is limited to this form.

To estimate the dead time (t0) and time constant (tp) there are three methods to find them:

- **Method (1):**

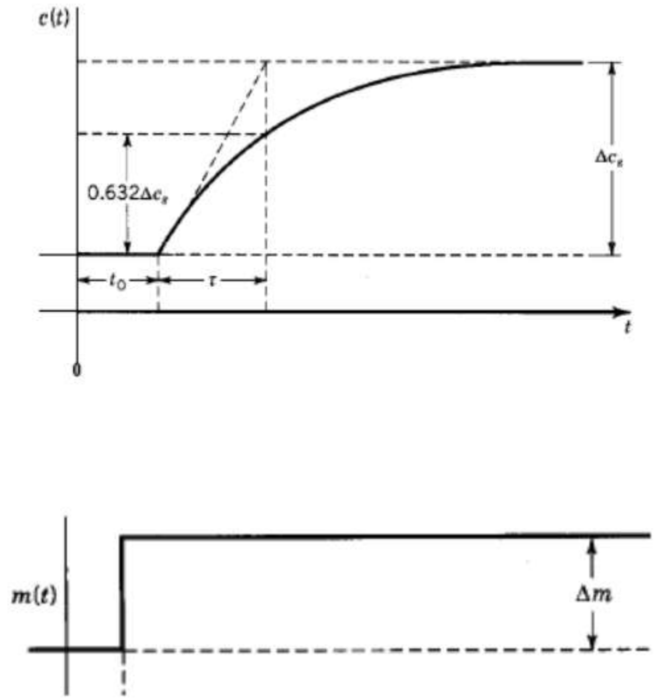

Figure 2: Method (1) estimation of the dead time and the process time constant from the process reaction curve. (2)

- **Method (2):**

Another technique, known as Method (2), utilizes graphical calculations as depicted in Figure 3. The intermediate values obtained from the graph include the magnitude of the input change, denoted as Δt; the magnitude of the steady-state change in the output, denoted as ΔC; and the time points at which the output reaches 28% and 63% of its final value.

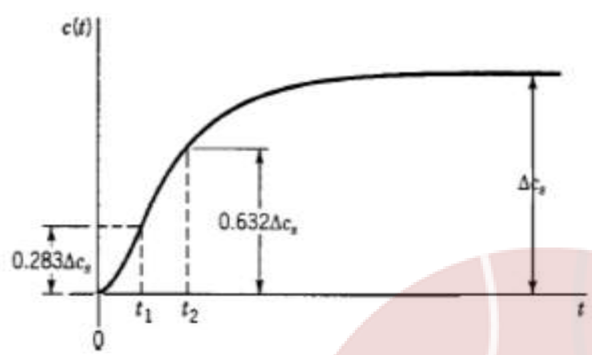

Figure 3: Method (2) estimation of the dead time and the process time constant from the process reaction curve. (2)

By using method (2) given in figure (3) the process time constant and the dead time are estimated as follows:

- $t_p = \frac{3}{2}(t_2 - t_1) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (1)$
- $t_0 = (t_2 - t_p) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (2)$

► **Method (3):**

Method (3) utilizes the inflection point of the process reaction curve, as depicted in Figure 4, to estimate the parameters of the First Order Plus Dead Time (FOPDT) model. This approach leverages the characteristics of the inflection point to determine the appropriate values for the model parameters.

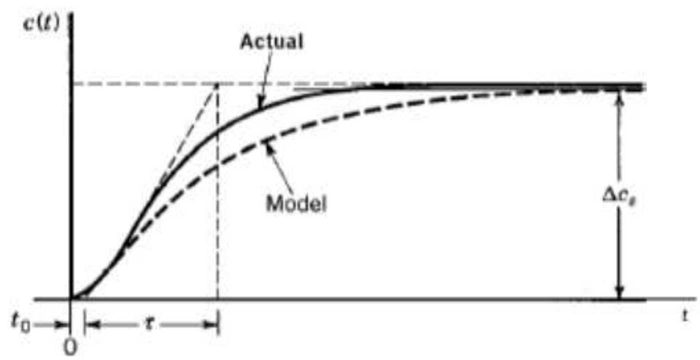

Figure 4: Method (3) estimation of the dead time and the process time constant by drawing a slope to the process reaction curve passing through the inflection point. (2)

The FOPDT transfer function is given by:

$$C(s) = \frac{K_p e^{-t_0 s}}{t_p s + 1} \cdot \frac{Dm}{s} \ldots\ldots\ldots\ldots \quad (3)$$

The above equation can be inverted back to the time domain:

$$C(t) = K_p \cdot \Delta M \cdot \left(1 - e^{\frac{-(t-t_0)}{t_p}}\right) \ldots\ldots\ldots\ldots \quad (4)$$

$$C(t) = c(t) = c_0(t) \ldots\ldots\ldots\ldots \quad (5)$$

- Where C(t) is the output variable in the deviation form.

The three model parameters are estimated from the process reaction curve as follows:

$$K_p = \frac{dc}{dM} \ at\ steady\ state \ldots\ldots\ldots\ldots \quad (6)$$

APPARATUS

The "UCPCNCV," or computer-controlled process control system (with electronic control valve + pneumatic control valve + variable speed drive), was created by EDIBON and allows for the study of various automatic control types. It can be used in a variety of ways to control various variables, including conductivity, pH, temperature, pressure, flow, level, and TDS.

Using a variable speed drive, an electronic valve, or a pneumatic control valve, the control is carried out automatically.

The apparatus consists of two interacting tanks equipped with continuous stirrers and rulers to measure the tank levels. Additionally, there is a conductivity meter to measure conductivity over time for each response. Below the interacting tanks, there are non-interacting tanks that facilitate the flow of water as input. The flow rate for each tank is controlled independently using valves. Two pumps, one for each tank, are responsible for transporting water from the non-interacting tanks to the interacting tanks. To maintain a steady state, discharge valves are present to control water flow during device operation or to drain all the water from the tanks.

Figure 5: computer controlled process control system.

PROCEDURE

The initial tank conductivity should be measured using tank A (which contains tap water), and it should be recorded on the data sheet.

1. The conductivity meter should be brought back to the process tank (consisting of two interacting tanks).
2. The pump (A) should be turned on.
3. The mixer should be turned on to ensure continuous mixing.
4. Continuous input and output should be ensured, and it should be verified that the flow rate of the input is equal to the output (keeping the level constant).
5. For the **impulse response:**
   - A salt solution should be prepared (using KCL salt, for example).
   - The sudden change should be applied quickly to the process tank using a syringe to create the impulse response.
   - The change in the conductivity of the process tank should be recorded over time.
   - The level of the tank should be maintained constant, with a tolerance of plus or minus 5 cm.
6. For the **step-up change:**
   - Pump A should be turned off.
   - The conductivity of tank B, which contains a salt solution, should be measured.
   - The conductivity meter should be brought to the process tank.
   - Pump B should be turned on.
   - The process should be controlled as in the previous part to ensure steady processing.
   - The conductivity change with time should be recorded, like the first part of the experiment.

RESULTS

Part 1: Step Up response.

Table 1: Calculations of some parameters to find Kp (step up response).

ΔC (ms/cm)	ΔM (ms/cm)
4.07	5.91

Table 2: Parameters of Step-up response.

	Method 1	Method 2	Method 3
Kp	0.69	0.69	0.69
tp (min)	7.80	7.50	7.60
t0 (min)	1.20	1.50	1.50

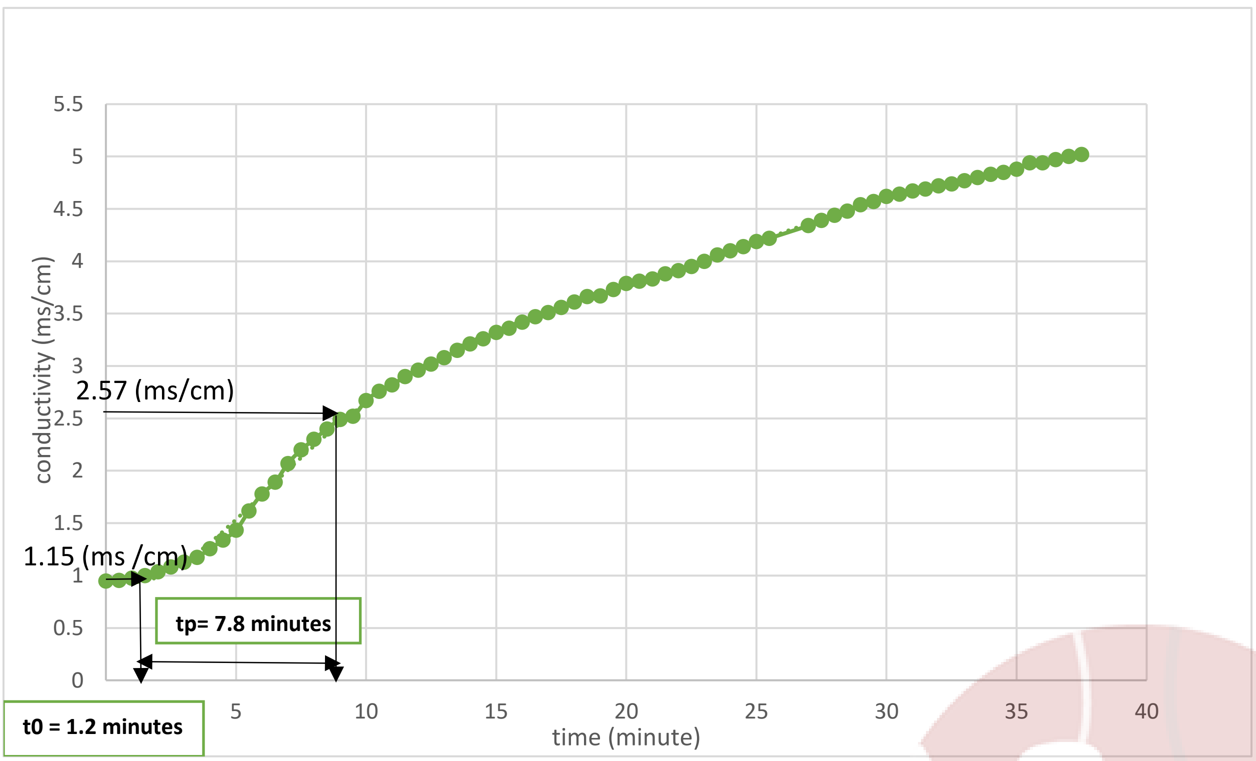

Figure 6: Conductivity vs. time for step up response (method 1).

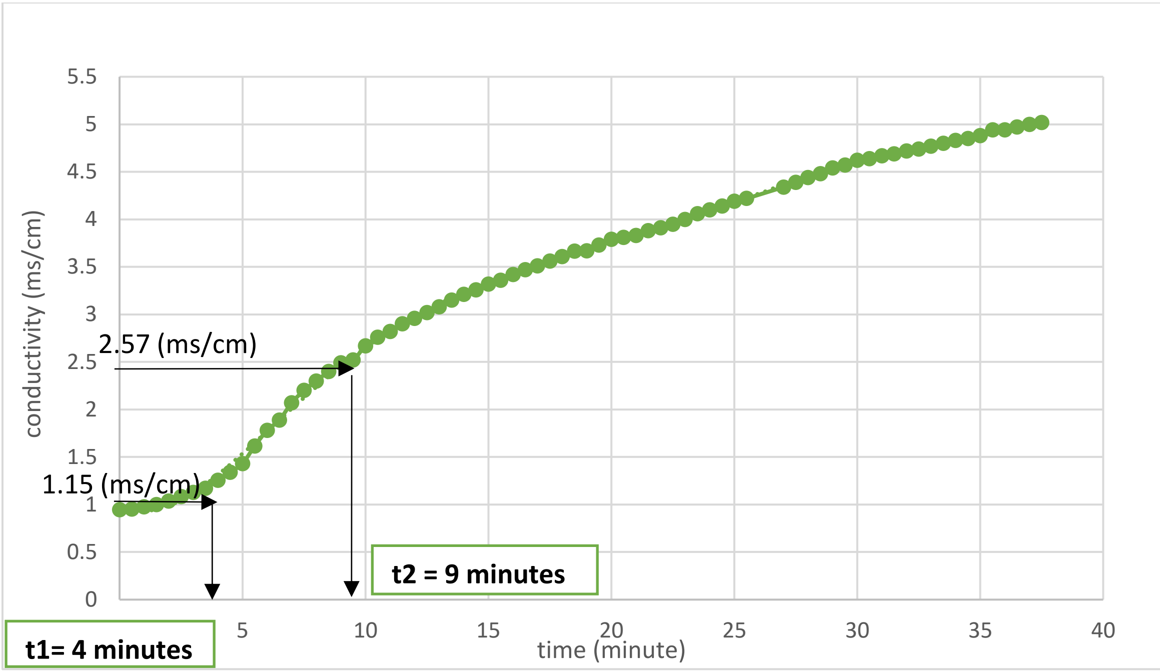

Figure 7: Conductivity vs. time for step up response (method 2).

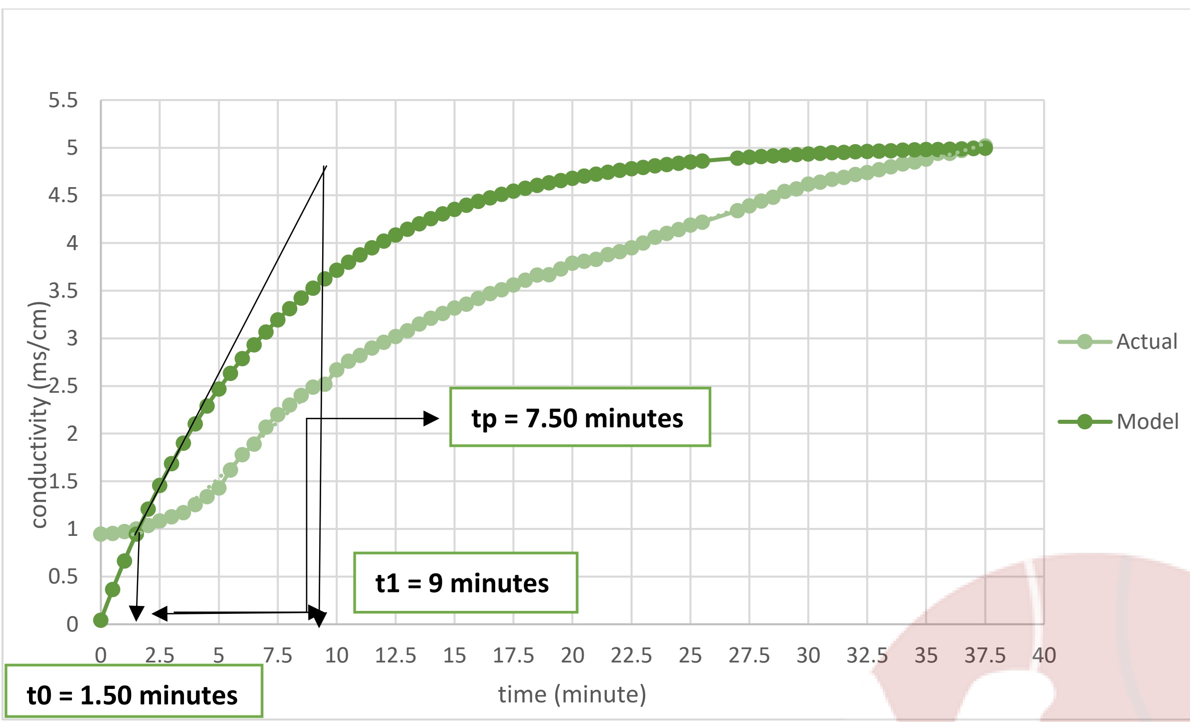

Figure 8: Conductivity vs. time for step up response (method 3).

Part 2: Impulse response

Table 3: Calculations of some parameters to find Kp (impulse response).

ΔC (ms/cm)	ΔM (ms/cm)
0.00	0.00

Table 4: Parameters of impulse change.

	Method 1	Method 2	Method 3
Kp	cannot be determined	cannot be determined	cannot be determined
tp (min)	cannot be determined	cannot be determined	cannot be determined
t0 (min)	cannot be determined	cannot be determined	cannot be determined

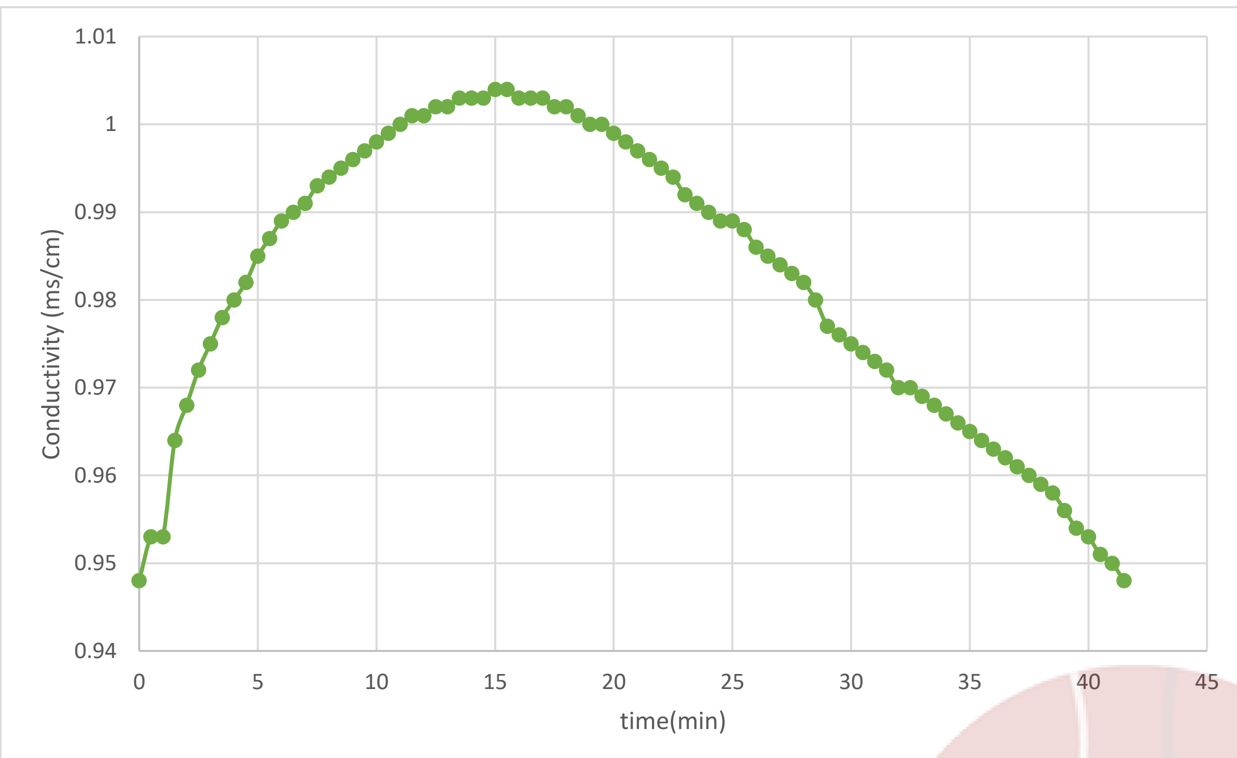

Figure 9: Conductivity vs. time for Impulse response.

DISCUSSION

An analytical and predictive approach for nonlinear dynamical systems is called empirical dynamic modeling, or EDM. It can be regarded as a methodology for time series analysis, machine learning, predictive analytics, dynamic system analysis, and data modeling. The experiment focused on three distinct types of responses: step up, step down, and impulse responses. The experiments involved the measurement of impulse and step-up responses. The obtained results for the step-up response, as shown in Figure (6), were used to graphically determine the parameters using three methods. Method 1 yielded tp = (7.8 min), t0 = (1.5 min), and Kp = (0.69), while Method 2 resulted in tp = (7.50 min), t0 = (1.50 min), and Kp = (0.69) and method 3 Method 2 resulted in tp = (7.50 min), t0 = (1.50 min), and Kp = (0.69). These values were found to be the same with around 3% relative error.

However, estimating the parameters of the impulse response was challenging. The rapid change in conductivity rendered method 1 method 2 and method 3 are ineffective, as they consistently provided zero values. The impulse response does not have a gain (Kp) that can be calculated due to its fast response, which quickly reaches steady state. Therefore, the parameters of the impulse response in Figure (9) could not be determined using the methods. The magnitude of the change was sufficiently large to detect alterations in the transmitter signal without causing disturbances.

It is important to note that certain sources of error may have affected the experiment. Unmeasured disturbances could have influenced the data and led to errors in sensor readings. Additionally, there might be several irregularities present in the data. These irregularities could arise from factors such as incomplete emptying of the tubes, resulting in value inaccuracies due to residual product. Moreover, incomplete mixing of reactants during chemical preparation may have introduced inaccuracies in the conductivity measurements.

CONCLUSION AND RECOMMENDATIONS

- The First Order Plus Dead Time model gives a good representation for the stirred tank system.
- Method (2) for obtaining the FOPDT model parameters is the simplest and more accurate method, unlike method (3) which contains some complexity to find the inflection point and method (1) which depends on human accuracy. However, all methods gave approximately the same result.
- The impulse response parameters could not be determined due to its fast response.
- It is recommended to wait for the system to reach a steady state, to obtain more accurate data.
- It is recommended to install a flow meter at the outlet valve to maintain a constant tank level by adjusting it to equal the inlet flow rate. Since we want to study the manipulation of one variable which is the inlet liquid concentration.
- It is recommended to keep the outlet valve from the first tank closed, to minimize system disturbances and to obtain more accurate data, since some of the liquid flow out from this valve and doesn't flow to the tank which contains the stirrer and the conductivity meter.

REFERENCES

1) B. Wayne Bequette, “Process Dynamics Modeling, Analysis and Simulation.”
2) Chemical Engineering Laboratory (4) Manual Sheet. (2022). 1st ed. University of Jordan School of Engineering Department of Chemical Engineering.
3) Edibon. (n.d.). *Computer Controlled Process Control Unit (Electronic + Pneumatic Valve and Speed Controller) | EDIBON ®*. [online] Available at: https://www.edibon.com/en/computer-controlled-process-control-unit-electronic-pneumatic-valve-and-speed-controller [Accessed 2 Nov. 2023].
4) Marlin, T.E. (2000). Process control: designing processes and control systems for dynamic performance. Boston: McGraw-Hill.
5) Team, T.A. (n.d.). *Classic Methods for Identification of First Order Plus Dead Time… – Towards AI*. [online] towardsai.net. Available at: https://towardsai.net/p/artificial-intelligence/classic-methods-for-identification-of-first-order-plus-dead-time-fopdt-systems.
6) Werner, S. (n.d.). *Chemical process models – from first principle to hybrid models*. [online] blog.navigance.com. Available at: https://blog.navigance.com/chemical-process-models.

NOTATIONS

Symbol	Definition	[Unit]
K_p	Gain	Dimensionless
t_0	Dead Time	Minutes
t_p	Time constant	Minutes
ΔC	Difference between the initial value of the tap water conductivity and the final tank conductivity	Milli Siemens per centimeter. (ms/cm)
ΔM	Difference between initial solution tank conductivity and the initial tank conductivity	Milli Siemens per centimeter. (ms/cm)

APPENDICES

I. Sample of calculations:

- **Step up changes.**
  - **Method (1):**
    - Calculating the change in conductivity in the time domain and step change in the input of the process respectively:
      - $\Delta C = C_f - C_i = 5.02 - 0.947 = 4.073\ \frac{ms}{cm}$.
      - $\Delta C = conductivity\ in\ tank\ B - conductivity\ at\ initial = 6.86 - 0.947 = 5.913\ \frac{ms}{cm}$.
    - Calculating process gain:
      - $K_p = \frac{\Delta C}{\Delta M} = 0.6889$.
    - Approximately reading dead time t_0 from figure (4):
      - $t_0 \approx 1\ min$.
    - Calculating process time constant t_p:

$t_p = time\ at\ 0.632\Delta C$

$0.632\Delta C = 0.632 * 4.07 = 2.574\ \frac{ms}{cm}$.

$t_p = 9\ min$.

$\tau = t_p - t_0 = 9 - 1 = 8\ min$.

  - **Method (2):**
    - Calculating process time constant t_p:

$t_1 = \text{time at } 0.283\Delta C$

$0.283\Delta C = 0.283 \times 4.073 = 1.153\ \frac{ms}{cm}$.

$t_1 = 4$ min.

$t_2 = \text{time at } 0.632\Delta C = 9$ min.

$$t_p = \frac{3}{2}(t_2 - t_1) = \frac{3}{2} \times (9 - 4) = 7.5 \text{ min.}$$

- Calculating dead time t_0:

  - $t_0 = t_2 - t_p = 9 - 7.5 = 1.5\ min.$

- **Method (3):**

⇨ **To Plot the model for method 3 (Step Up response) :**

Taking the first raw from the data sheet (see below):

t (min)	C(t)	C(t)+0.947
0	-0.903	0.0437

⇨ **Using transfer function :**

$$C(s) = \frac{K_p e^{-t_0 s}}{t_p s + 1} \cdot \frac{Dm}{s}$$

Then convert it to the time domain:

$$C(t) = K_p \,.\, \Delta M \,.\left(1 - e^{\frac{-(t-t_0)}{t_p}}\right)$$

Now, subsitute in the equation at $t = 0, t_0 = 1.5$ and $t_p = 7.5$,

$$C(0) = 0.69 \,.\, 5.913 \,.\left(1 - e^{-\frac{0-1.5}{7.5}}\right)$$

$$C(0) = -0.9033$$

But , this value is in deviated form

To find $c(t) = C(t) - c_0(t)$

$$c(t) = -0.09033 + 0.947 = 0.0436 \text{ ms/cm}$$

This procedure will repeat for all the times for this response to get the model then:

- Approximately reading dead time t_0 and t_1 from figure (6):

  - $t_0 \approx 1.5\ min.$
  - $t_1 \approx 9\ min.$

- Calculating process time constant t_p:

  - $t_p = 9 - 1.5 = 7.5$ min.

II. Datasheets:

October, 2022

Empirical Dynamic Models Data Sheet

1. Impulse response:

Initial pure water conductivity: 948 μs/cm

Injection Solution conductivity: 6.86 ms /cm

Time(min)	Conductivity (μS/cm)	Time(min)	Conductivity (μS/cm)	Time(min)	Conductivity (μS/cm)
0	948	14	1003	33	969
0.5	953	14.5	1003	33.5	968
1	959	15	1004	34	967
1.5	964	15.5	1004	34.5	966
2	968	16	1003	35	965
2.5	972	16.5	1003	35.5	964
3	975	17	1003	36	963
3.5	978	17.5	1002	36.5	962
4	980	18	1002	37	961
4.5	982	18.5	1001	37.5	960
5	985	19	1000	38	959
5.5	987	19.5	1000	38.5	958
6	989	20	999	39	956
6.5	990	20.5	998	39.5	954
7	991	21	997	40	953
7.5	993	21.5	996	405	951
8	994	22	995	41	950
8.5	995	22.5	994	41.5	948
9	996	23	992	42	9
9.5	997	23.5	991		
10	998	24	990		
10.5	999	24.5	989		
11	1000	25	989		
11.5	1001	25.5	988		
12	1001	26	986		
12.5	1002	265	985		
13	1002	27	984		
13.5	1003	27.5	983		
		28	982		
		28.5	980		
		29	977		
		29.5	976		
		30	975		
		30.5	974		
		31	973		
		31.5	972		
		32	970		
		32.5	970		

[illegible]

62

2. Step up response:

Initial tank conductivity: 947 μS/cm

Initial solution tank conductivity: 6.86 mS/cm

Time(min)	Conductivity (μS/cm)
0	947
0.5	953
1	975
1.5	1000
2	1036
2.5	1083
3	1127
3.5	1173
4	1255
4.5	1340
5	1432
5.5	1617
6	1780
6.5	1890
7	2070
7.5	2200
8	2300
8.5	2400
9	2490
9.5	2580
10	2670
10.5	2760
11	2820
11.5	2900
12	2960
12.5	3020
13	3080
13.5	3150
14	3210
14.5	3260
15	3320
15.5	3360
16	3420
16.5	3470
17	3510
17.5	3560
18	3610
18.5	3664
19	3669
19.5	3730
20	3790
20.5	
21	3830
21.5	3880
22	3910
22.5	3950
23	4000
23.5	4060
24	4100
24.5	4140
25	4190
25.5	4220
26	4270
26.5	4300
27	4340
27.5	4390
28	4440
28.5	4480
29	4540
29.5	4570
30	4620
30.5	4640
31	4670
31.5	4690
32	4720
32.5	4740
33	4770
33.5	4800
34	4830
34.5	4850
35	4880
35.5	4910
36	4940
36.5	4970
37	5000
37.5	5020
38	

م. نارمان الرجلة

٢٢-١٠-٢٠٢٢