Experimental Analysis of Process Faults of CSTR

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Abstract: - In this paper, an experimental analysis has been carried out on CSTR in the presence of process faults which can possibly occur due to sudden and unexpected change in certain process parameters. The faults like the change in agitator speed have been injected into the system simultaneously. Due to these faults, change in the output of CSTR i.e. titration end point, has been analyzed. Moreover, while varying the speed of agitators, it has been observed that fault becomes prominent at high speed of each of the agitators. From the experimental results, the nature and magnitude of faults can be visualized.

Keywords: continuous stirred tank reactor (CSTR), fault, fault detection, fault diagnosis, residuals

1. Introduction

The recent developments in the industrial manufacturing through modern process plants, has led to increase in system complexity. This is due to incorporation of advanced automation, control systems, sensors and other associated circuitry [1]. For the maintenance of high standards of safety, performance and reliability in the industrial processes, it is crucial that system errors, faults and abnormal operation are detected in a prompt manner. Moreover, the source from which the malfunction originates and its severity is diagnosed in order that the appropriate actions can be implemented well in time [2]. A fault is defined as the departure from an acceptable range of an observed variable or a calculated parameter, associated with equipment [3]. In case a fault is regarded as a system input, there must be the occurrence of a ‘diagnostic” signal, having the capability of “detecting” a fault, along with the skill to “isolate” this faulty signal from all such inputs (in the form of disturbances and other faults) that tends to disturb the system behaviour. Such a specific “diagnostic” signal is termed as a residual. These residuals must be generated corresponding to each fault. At the same time, each residual so generated must be sensitive and its nature should be crucial for only one fault [4].

Since the past two decades, the problem of on-line fault detection and isolation has caused a major concern in the field of chemical engineering. Various fault diagnosis approaches have been proposed for the processes that are functioning in the steady-state conditions i.e. continuous reactors. In such cases, it is usually difficult to apply due to the nonlinear nature of process dynamics. Moreover, in case of batch processes, the full data measurements are generally not available [5]. Present fault diagnosis approaches applied to chemical processes is roughly divided into two categories: model-free methods and model-based methods. In the present paper, the three-tank system is discussed for the CSTR system. The three-tank systems are considered to be important benchmarks that have the ability to demonstrate problems related to control design, fault detection and diagnosis. Current methods dealing with the level control of three-tank systems include those employing on-line parameter identification and fault detection [6]

1.1 Model-based Methods

Model-based methods present a form of classic approaches to the problem of fault diagnosis and have been widely studied in the literature. When the system representation is available in the form of state-space, transfer function or input-output models, these methods are employed [7]. These methods rest their foundations employ mathematical inter-relationships between different process variables and are generated from first principles, on the basis of various process parameters [8]. These methods include differential equations, state-space methods, transfer functions and are based on the foundations of control theory. Such approaches rest on the philosophy that a fault can lead to changes in some physical parameters. This eventually shall result in variation in parameters of the model or a particular state. Keeping a check on the parameter values and states makes it easy to detect and isolate a fault. This methodology requires priori knowledge regarding the existing inter-relationships between the systems, its associated faults and model parameters (how these change and which parameters are likely to undergo variation) [2]. Gertler has presented a detailed survey of the fault diagnosis methods based on parity equation. In the terminology of aerospace, the input-output models that generate residuals are termed as parity equations. These residuals tend to have zero values in case the system is free from any noise or modeling error. In the fault diagnosis parlance, the importance of residuals is such that the fault-detection capability of a system depends not only on the fault size and noise level but mainly on the "direction of residuals relative to a particular fault" [7, 9].

1.2 Model-free Methods

These methods make use of cause-effect relationship to define the behaviour of the system in terms of process variables. However, such methods are restricted to systems having small number of variables as knowledge base creation becomes tedious [5]. In this category, there are various approaches like the artificial neural networks (ANN), fuzzy logic (FL), hybrid methods (involving the combined use of ANN and FL). ANNs have been applied in the fault detection and diagnosis with the training of the available data. Such an approach necessitates a large number of training samples while the available number of fault samples is generally limited in the practical industrial processes [10]. Another approach is based on the use of expert systems. These are generally rule-based systems. The benefit of this method is that it involves symbolic knowledge processing and decision-taking capabilities suitable for problems that necessitate human expertise [3]. Previous years witnessed the growth of stochastic approximation, a recursive procedure in which the roots of equation can be found in the presence of noise, for which the measurements are taking place concurrently [11]. Optimal process operation has gained importance over the years since through this the parameters of the control loop can be optimized. Focus has been directed towards the control oriented system identification, an approach using which the models can be estimated through closed-loop data. A data-driven approach can act as an alternative for tuning the control parameters obviating the need of a model estimate. Data-driven tuning procedures are being reportedly employed for systems expressed in the transfer function form. Such direct tuning methods usually are relatively less computationally complex in comparison to model identification and model-based control design approaches. Such methods are employable in spite of limited performance owing to insufficient knowledge regarding model structure [12].

During the operation of a chemical process, several faults compromise its safety and productivity. The fault occurrence moderates the process efficiency (in terms of poor quality of finished product), at times posing hazard to the personnel, causing environmental pollution and damage to equipment, in certain cases. The faults that are critical in a chemical process are:-

1. Actuator faults- disruption in electrical power supply, hindrance in the operation of pumps and valves.
2. Process faults- sudden and unexpected change in certain process parameters, unwanted reactions due to use of impure materials.
3. Sensor faults- sudden activation of wrong sensors indicating false alarms.

Due to the above, fault diagnosis as well as fault detection have become issues of crucial importance in the field. [13]

In this paper, the experimental study has been carried out on CSTR in the presence of process faults which can possibly occur due to sudden and unexpected change in certain process parameters. The faults like change in agitator speed have been injected into the system individually. Due to these faults, change in the output of CSTR i.e. titration end point, has been analyzed.

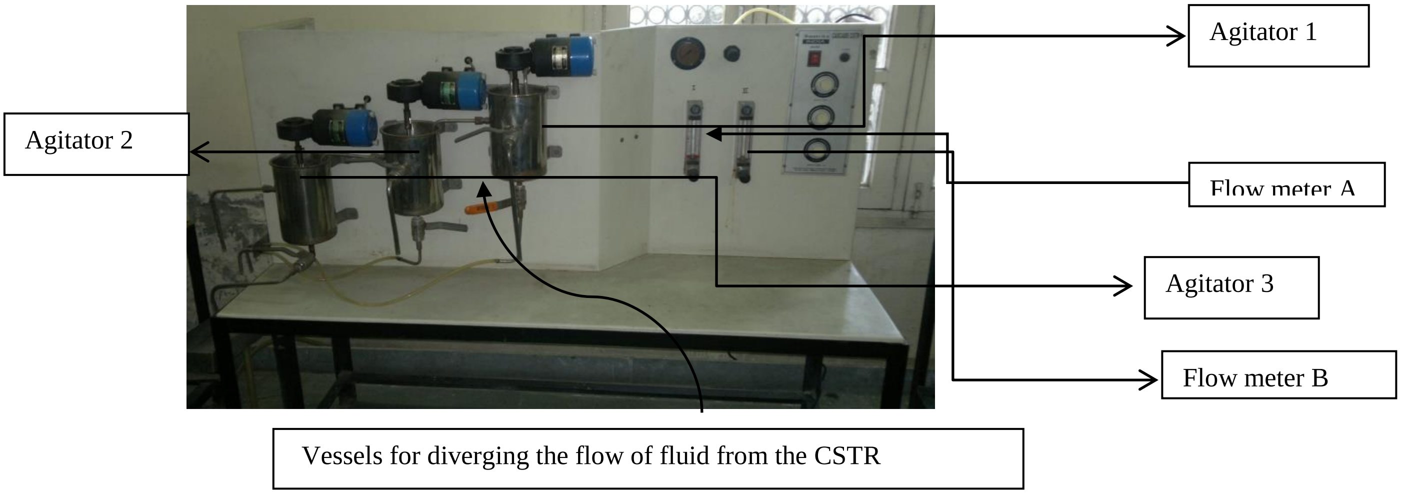

Figure 1: Experimental Set-up for CSTR

2. Experimental Study of CSTR

The process under study is a Cascade CSTR is as shown in figure 1, where continuous stirring has been done to mix the two liquids with a variable flow rate. Continuous operation is the preferred mode of operation for many chemical processes. Streams of the reactants are continuously fed into the vessels and product streams are withdrawn. The cascade CSTR employs mixing of reactants ethyl acetate and sodium hydroxide using phenolthalin as indicator, which was contained in the tanks shown in figure 2 below. The solution of ethyl acetate and sodium hydroxide was first prepared and put in the tanks 1 and 2 respectively. After this, both these solutions get mixed with each other and the resultant solution flows in the first vessel (corresponding to agitator 1), as shown in figure 1.This solution further passes on to the next subsequent vessel and resultant solution comes out of the last and final vessel (corresponding to agitator 3). With each successive observation obtained, the volumes in both the tanks keep decreasing.

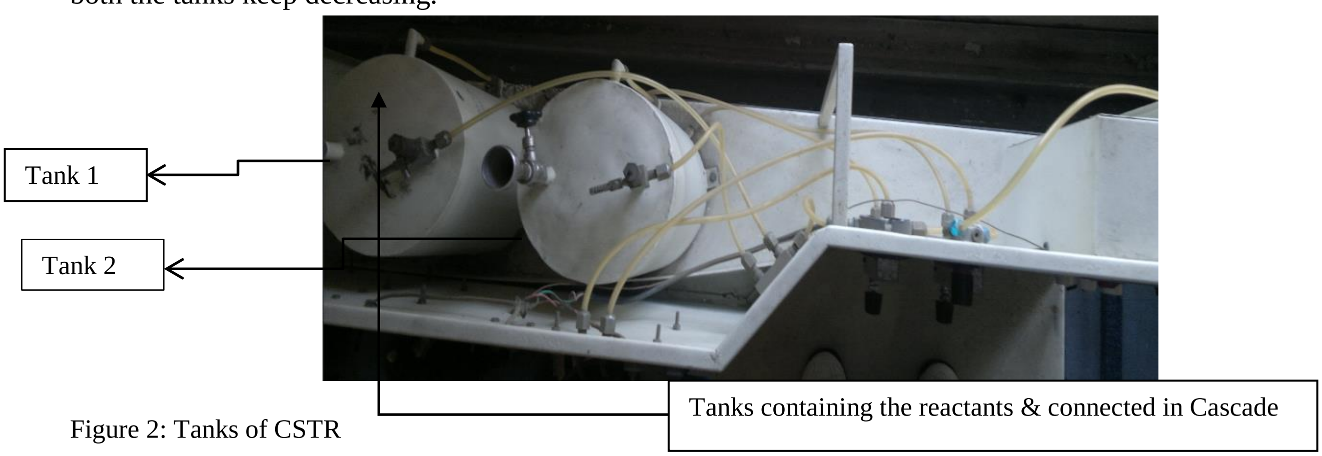

Figure 2: Tanks of CSTR

The interconnection of the different volumes from each of the vessels as indicated in figure 1 can be represented as a block diagram depicted in figure 3. Here the output of each preceding vessel acts as an input to the succeeding one.

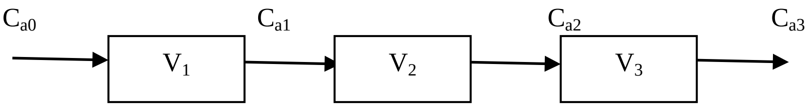

Figure 3: Block Diagram of CSTR

V_1, V_2, V_3 are the volumes of the vessels and C_{a1}, C_{a2}, C_{a3} are the concentration of the reactants.

The governing equations pertaining to the dynamic variations occurring in the amounts of reactants, for each of the three tanks are given below:-

$$\frac{dC_{a_1}}{dt} = \frac{1}{\tau}(C_{a_0} - C_{a_1}) - kC_{a_1} \qquad (1)$$

$$\frac{dC_{a_2}}{dt} = \frac{1}{\tau}(C_{a_1} - C_{a_2}) - kC_{a_2} \qquad (2)$$

$$\frac{dC_{a_3}}{dt} = \frac{1}{\tau}(C_{a_2} - C_{a_3}) - kC_{a_3} \qquad (3)$$

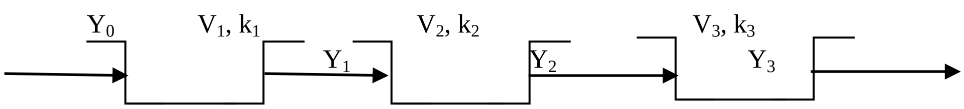

Figure 4:- Flow diagram of the different process variables in CSTR

Figure 4 gives the process flow from the start, where the mixing of the two reagents ethyl acetate and sodium hydroxide takes place onto the first vessel. This continues up to the next vessel and further to the last and final vessel from where the mixture drains out. Here k_1, k_2 and k_3 correspond to the reaction rates of the different stages. The small letter k, however, pertains to the gain.

2.1 Governing Equations for Flow of Volume

Accumulation of Volume = Input volume – Output volume- consumption of volume due to reaction

Mathematically, this implies the following

$$V_1 \frac{dC_{a_3}}{dt} = F(C_{a_0} - C_{a_1}) - V_1 k_1 C_{a1} \qquad (4)$$

$$V_2 \frac{dC_{a_2}}{dt} = F(C_{a_1} - C_{a_2}) - V_2 k_2 C_{a_2} \quad (5) \text{ and } V_3 \frac{dC_{a_3}}{dt} = F(C_{a_2} - C_{a_3}) - V_3 k_3 C_{a_3} \quad (6)$$

Reaction rate is given by Arrehenius equation $k_n = \alpha e^{-E/RT_n}$ - (7) where n= 1, 2, 3…. denotes the stage number, as indicated by equations (4), (5) and (6) and (7) [14].

Parameters, concentration and constants of different components of chemical reactor used in the experiment are as given in Table 1, 2 and 3 respectively.

Table 1: Nominal parameters and their specific values

S.No.	Parameter	Value	Corresponding to Equation
1.	Reaction constant τ	0.2	1,2 and 3
2.	Gain k	0.5	1,2 and 3
3.	Perfect Gas Constant R	1.99cal/ g. mol-K	7

Table 2: Concentration of Reactors

S.No.	Reactor	Concentration (kmol/m^3)	Corresponding to Equation
1.	Initial C_{a0}	1.8	1 and 4
2.	C_{a1}	0.4	1,2,4 and 5
3.	C_{a2}	0.2	2,3,5 and 6
4.	C_{a3}	0.1	3 and 6

Table 3: Working parameters of the CSTR

S.No.	Parameter of tank	Value
1.	Height of the tank	200 mm
2.	Inside Diameter	140 mm
3.	Volume of Tank	3.078 Litres
4.	Height of Liquid in the tank	160mm
5.	Working volume of tank	2.46 litres
6.	Agitation speed (variable)	0-350 rpm
7.	Fluid used	Ethyl acetate, sodium hydroxide
8.	Fluid flow measurement	0-19 litres per hour

3. Experimental Observations

Under the normal condition of chemical reactor, the flow rates of sodium hydroxide and ethyl acetate and the speed of agitators should be the same. Variation in either flow rate or agitator speed results in change in the output which can be referred to as fault present in the system. To monitor the behaviour of the system in the presence of faults i.e. intentional faults were introduced in the CSTR available in the laboratory.

Case I: When no fault is present in the system and all the agitator speeds are at normal.

Case II: When agitator's speed is varied to low speed (in either of stirrers 1, 2 or 3)

Case III: When agitator's speed is varied to medium speed (in either of stirrers 1, 2 or 3)

Case IV: When agitator's speed is varied to high speed (in either of stirrers 1, 2 or 3)

which are summarized in Table 4.

Table 4: Summary of Intentional Faults

Injected Fault	Description
F1	Agitator speed of Stirrer 1,2 and 3 low
F2	Agitator speed of Stirrer 1,2 and 3 medium
F3	Agitator speed of Stirrer 1,2 and 3 high

Table 5: Observations taken under ideal conditions

Sr. No.	**Flow Rate A**	**Flow Rate B**	**Time Elapsed**	**1**
				ON
1	5	5	300	25.6
2	5	5	500	25.8
3	5	5	700	26.0
4	5	5	900	25.9
5	5	5	1100	26.1
6	8	8	1300	26.0
7	8	8	1500	25.9

8	8	8	1700	25.8
9	8	8	1900	25.7
10	8	8	2100	25.9
11	11	11	2300	25.8
12	11	11	2500	26.0
13	11	11	2700	26.0
14	11	11	2900	26.1
15	11	11	3100	26.2
16	15	15	3300	26.0
17	15	15	3500	25.9
18	15	15	3700	25.7
19	15	15	3900	25.5
20	15	15	4100	25.6
21	19	19	4300	25.8
22	19	19	4500	25.7
23	19	19	4700	25.9
24	19	19	4900	26.0
25	19	19	5100	26.1

ON- Output at normal speed

The last column pertains to the output and is measured in milliliters (ml.).

This is the ideal case of readings when all the agitators are operating at their normal speeds.

Case II: In this case, the variations of the expected output and observed output are plotted in order to ascertain the behaviour of the CSTR, when the speed of the agitator is operating under low speed. The different multipliers (with regard to the input values) are taken into account for the observed response and these are then plotted against the expected response characteristics.

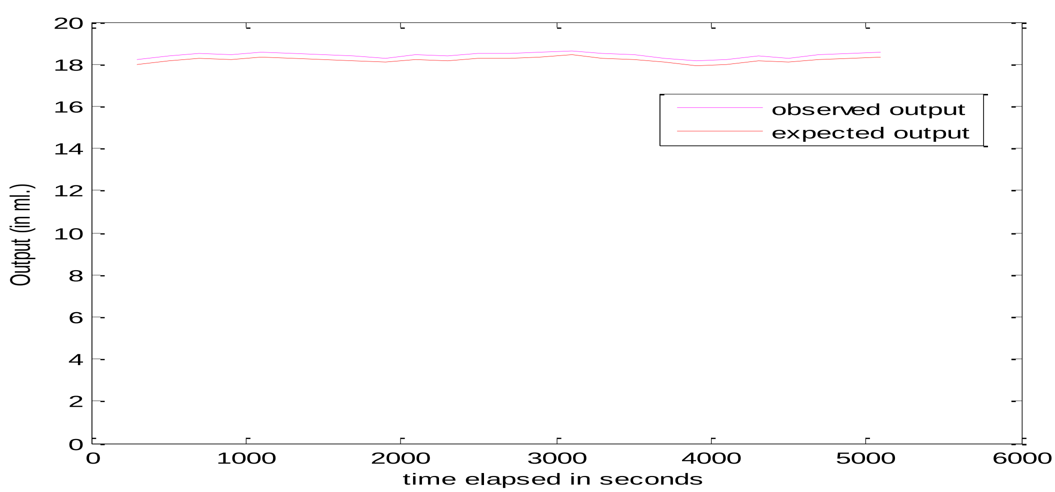

Figure 5: Variations in case of low speed

In the plot given in figure 5, it is observed that the observed output is slightly above the expected output.
Case III: In this case, the variations of the expected output and observed output are plotted in order to ascertain the behaviour of the CSTR, when the speed of the agitator is operating under medium speed. The different multipliers (with regard to the input values) are taken into account for the observed response and these are then plotted against the expected response characteristics.

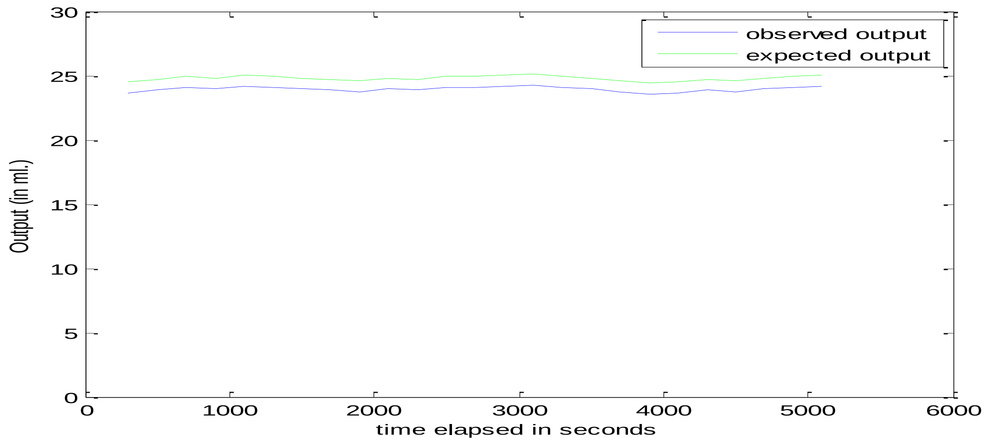

Figure 6: Variations in case of medium speed

In the plot given in figure 6, it is observed that the observed output is slightly below the expected output.
Case IV: In this case, the variations of the expected output and observed output are plotted in order to ascertain the behaviour of the CSTR, when the speed of the agitator is operating under high speed. The different multipliers (with regard to the input values) are taken into account for the observed response and these are then plotted against the expected response characteristics.

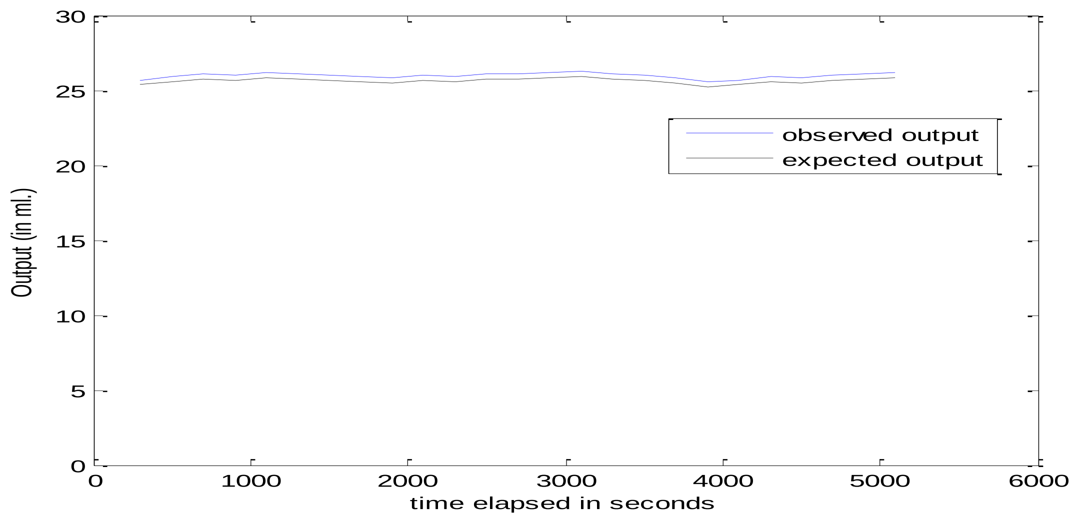

Figure 7: Variations in case of high speed
In the plot, given in figure 7, it is observed that the observed output is slightly above the expected output.

4. Conclusion

The paper presents the experimental procedure for the chemical reactor (in this case, the CSTR), adopted for the purpose of fault diagnosis. This experimental set-up investigates the practical aspects of a practical industrial process. The experiment explores the feasibility of identifying expected and observed values and the desired results have been obtained in the process simulation of CSTR. Through the plots obtained from the experimental results of CSTR, the generation of outcomes of the agitators 1, 2, and 3 has been depicted in figures 5, 6 and 7. It has been observed that in case of low and high speeds of the agitators (1, 2 and 3), the observed output is found to be slightly above the expected output. The present work is targeted towards providing useful information which supports the decision-making of the operator, dealing with the chemical reactor.

Nomenclature

$V_{1,} V_{2,} V_3$	volumes of the vessels in which the agitators are running, m^3
$C_{a0}, C_{a1}, C_{a2}, C_{a3}$ initial	concentrations of the reactants, $kmol/m^3$
Y_0, Y_1, Y_2, Y_3	variable throughputs, m^3/min.
$F_{A,} F_B$	flow meters A and B, m^3/ hour
$k_1, k_{2,} k_3$	reaction rates under different stages (min^{-1})
k	gain (a constant)
τ	time constant being volume per unit flow rate with units of minutes
$\frac{dC_{a_3}}{dt}$	time rate of change of concentration inside the tank, $kmol/m^3$/second.
E	activation energy (in cal/g-mol)
α	relative volatility

5. References

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