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Mathematical Modeling and Simulation of Multi Loop Pilot Plant

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Abstract— This paper focuses on the identification and modeling of the pilot plant of the department. For this work, four loops of pilot plant are considered. Level loop, flow loop, cascade loop and temperature loop. Transfer function for level loop is derived by using process reaction curve and the flow loop transfer function is derived using dynamics of Control valve and specifications of process plant components. Cascade Loop is the series combination of flow and level loops. The temperature system is nonlinear in nature due to three variables initial temperature, input flow and heat supplied by heater. Hence different control schemes are considered to control the various conditions i.e. batch process, continuous Process with constant input and output flow. Also Feedback linearization is used for as a unique control scheme. Pilot plant being a multi loop system, there is interaction between the loops such as level and temperature loop. The interaction is eliminated with the help of decoupler and relative gain array to obtain non-interacting level and temperature loops such that the temperature can be controlled without affecting the level parameter of the system.

Keywords—*Mathematical Model, Pilot plant,Feedback Linearization, Relative gain array, Decoupler*

I. INTRODUCTION

A mathematical model of a system is collection of some mathematical equations which represents that system. It is important to check a plant multiple times for different inputs. Many parameters should be considered while doing this. But this repetitive process is rigorous. Hence a mathematical model is formed which also helps to tune the controller. [4]
Mathematical Models can be useful in all phases of engineering and from research and Development to plant operations, and even in business and economic studies.

It is necessary for determining chemical kinetic mechanisms and parameters from laboratory or pilot plant reaction data; in research and development, exploring the effects of different operating conditions for optimizing and control studies; aiding in scale up calculations.

In design it is to explore the sizing and arrangement of processing equipment for dynamic performance; studying the interactions of various parts of the process, particularly when material recycle, or heat integration is used; evaluating alternative process and control structures and strategies; simulating start up, shutdown, and emergency situations and procedures [5].

In plant operations, troubleshooting control and processing problems such as aiding in startup and operator training, studying the effects of and requirements of expansion, optimizing plant operation etc.
It is usually much cheaper, safer and faster to conduct the kinds of studies listed above on a mathematical model than experimentally on an operating unit. [5].

The need of mathematical modeling of a process is to develop a control system which will guarantee that the operational objectives of the process are satisfied in the presence of ever changing disturbances [3].
The basis for mathematical models is the fundamental physical and chemical laws such as the laws of conservation of mass, energy. The dynamics are studied by using them in their general form with time derivatives [3].

The objective of this paper is to develop a model for four control loops in pilot plant which are flow, level, cascade of flow and level and temperature control loop. Initially, level loop is considered which is identified by performing experiment and process reaction curve method. It is then compared with simulated response on MATLAB Simulink. Transfer functions of flow and cascade loops are also identified and verified experimentally and simulation for temperature control loop is performed.

The Pilot Plant whose mathematical model is being proposed has Level, Temperature and Flow Loops. Level Loop has an input flow and the output flow is hand valve. Temperature loop of the pilot plant is equivalent to continuous stirred tank reactor whose mathematical modeling is available in many literatures, where models are having non-linear equations. In this paper a method is proposed to linearize the nonlinear equations of the temperature loop.

II. METHODOLOGY

Level Loop.

Initially level loop of pilot plant is considered as shown in Figure 1. In level control loop, level of tank T3 is controlled by level indicator and controller by manipulating control valve FCV2. HV3 is outlet for tank T3. Water is supplied to T3 by tank T2 using pump CP2.

This loop can be modeled by different methods like first principle method and empirical method. First principle method uses dimensions and instrument specification to formulate the transfer function of system. In case of empirical method experimental input output data is used to find out the process model.

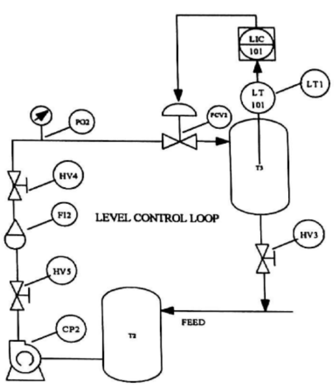

Figure 1 Level Loop

Mass Balance equation was used for calculation of this system,

Rate of mass accumulation Entering into system	−	Rate of mass exiting the system	=	Rate of mass in system		(1)

Solving, the transfer function of level control loop was obtained, which involves term $R = dh/dq_o$ which is outlet for tank T2. To calculate value of R, experiment was performed. Initially, tank T2 was filled up to 50% of its capacity. Then inlet flow was stopped and outlet valve was partially opened. The values of change in height of water and outlet flow were measured and graph of height vs. time was plotted to get value of R.

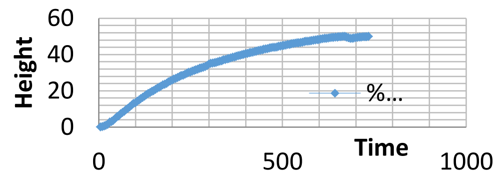

Figure 2 Process Reaction Curve

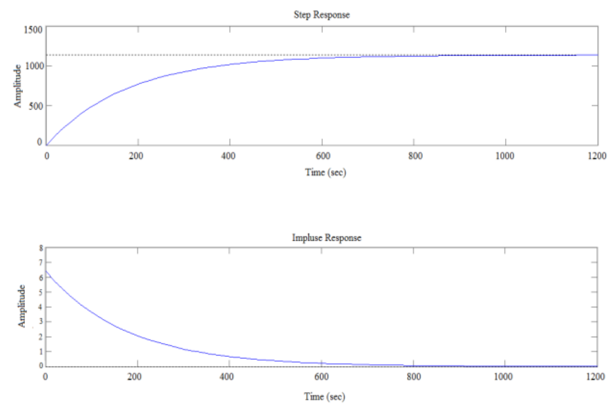

Figure 3 Level Loop Response

Flow Loop:

The diagram of flow system is given below:

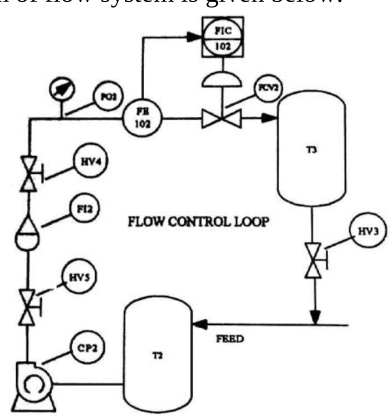

Figure 4 Flow Loop

The flow loop control has its measuring device at the inlet end of control valve. This might look as if the system is feed forward loop, but the measuring device used actually measures the outlet flow. This is because the control valve used does not store any fluid.

From control valve Equations 2

$$q(t) = C_v\, v_p(t) \sqrt{\frac{\Delta p(t)}{G}} \qquad (2)$$

Equation 2 is obtained by using mass balance equation and control valve characteristics given by valve manufacture.

Cascade Loop:

The P&ID shown in Figure 5 of the Cascade Loop, in which the primary process variable is level and secondary loop is flow. The main set-point is given to LIC 101 and then the output of this LIC is given as a set-point to the FIC102. The FIC receives the feedback signal from the FT102 which is a Turbine/Opto Coupled Flow sensor and then appropriately manipulates the flow to match the set-point given by LIC 101.

Now here the output flow of the flow loop acts as an Input to the Level Loop

I.e. $Qi(s) = Q_o(s)$

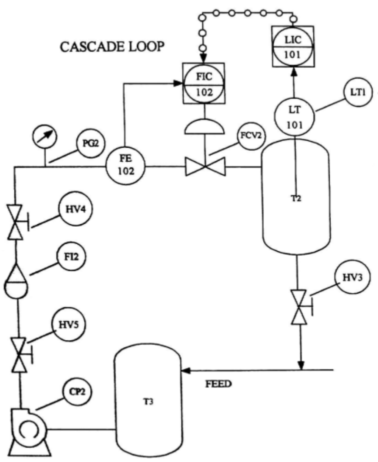

Figure 5 Cascade Loop

Using transfer functions of level loop and flow loop transfer function for cascade is obtained.

Temperature control loop:

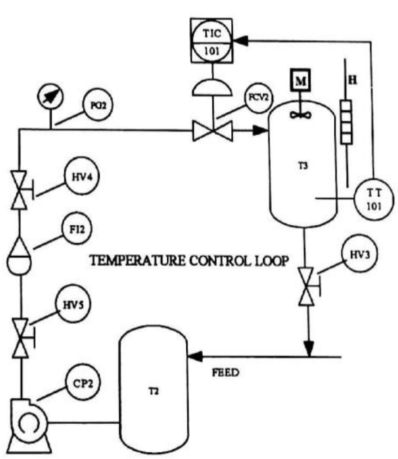

Figure 6 Temperature Loop

The Temperature Loop of the system is shown Figure 6. It consists of a level indicator, temperature indicator (RTD) and controllers (LIC 101). The final control elements are Control valve 2 and Heaters of 3KW power.

Temperature Loop Transfer function

The transfer function of the temperature loop of Figure 6 is to be obtained. The problem in output temperature is due to changes occurred in the input condition, either in the manipulated variable or the disturbance. Inlet flow rate and its temperature are the input condition which can undergo a change and in such situation, the content of mass and energy (state variables) of the tank would show a progression. In normal situation, flow rate or temperature of an inlet flow does not have a potential to displace the tank physically from its normal position. Hence, there is no need to calculate momentum of the tank. That means no need to carry out momentum balance operation on this process, rather mass and energy balance operation would be enough.

Using **Material Balance Equation** relation between input flow and height found is

$$q_i(t) - \frac{2h}{R} = A\frac{dh(t)}{dt} \qquad (3)$$

Using Energy balance Equation

Rate of accumulation of heat = rate of heat in − rate of heat out + rate of heat supplied

$$Ah\frac{dT}{dt} = F_i\,(T_i - T) + \frac{Q}{\rho c_p} \qquad (4)$$

Degrees of Freedom

Total number of variables: 5 (h, T, F_i, T_i, Q)
Total number of equations: 2

h= Height, T= temperature, F_i= input flow, T_i= input flow temperature and Q= heater input supply.

Procedure 1: This procedure involves regulation of water temperature in tank T3, keeping the level of water in tank constant (Input flow= 0 L/hr, Output flow = 0 L/hr).

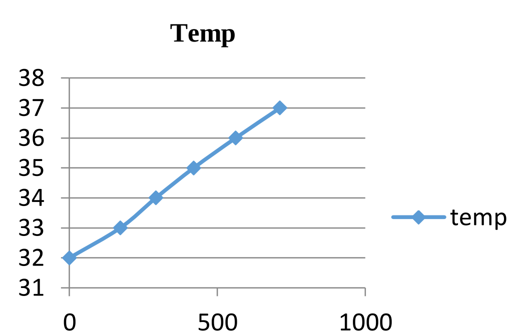

Figure 7 Actual Temperature Response

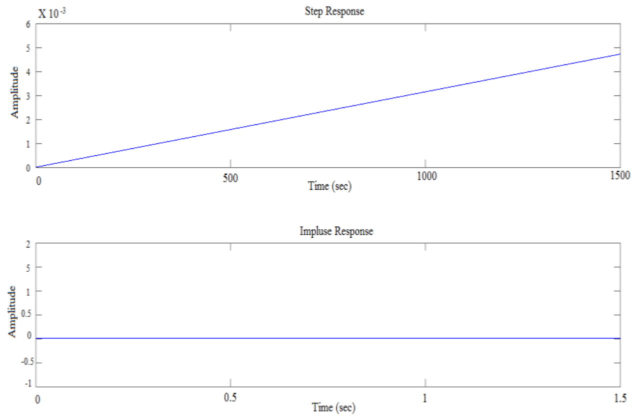

Figure 8 Procedure 1 Simulated Response

Procedure 2:
Keeping water level constant in tank and the input, output flow are kept in such a way that they are constant and water level is constant.(So, $F_i \rightarrow$constant ,h$\rightarrow$ constant $\rightarrow h_c$)

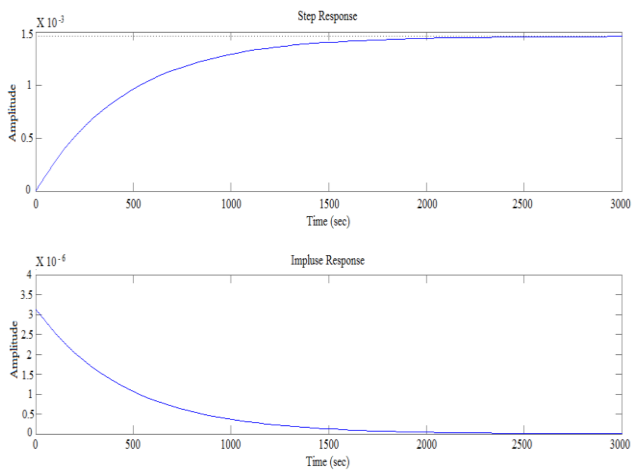

Figure 9 Procedure 2 Simulated Response

Procedure 3: In this method, using both inputs, to linearize this system the heater input is given such that it will cancel out the non-linear terms by using Feedback Linearization.

Pilot Plant as Interacting Loop

Here $m_1(s) = Q(s)$, $m2(s) = F_i(s)$.

$$H_{11}(s) = \frac{1}{(c_p \rho A\ hc\ s)} Q(s) \qquad H_{21}(s) = 0$$

$$H_{12}(s) = \left(\frac{1}{s} - \frac{e^{-250s}}{s}\right) + \frac{e^{-250s}}{(s-0.004)} - \frac{e^{-250}}{(s-0.004)}$$

$$H_{22}(s) = \frac{R/2}{(RA/2)s+1} \qquad (5)$$

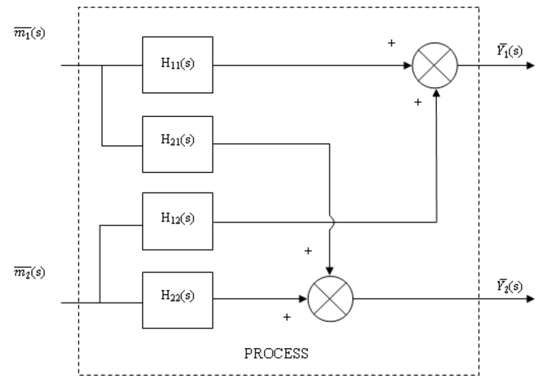

Figure 10 Interacting Loops

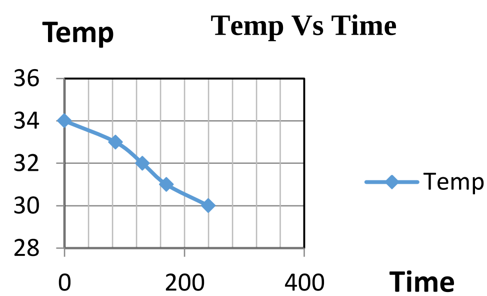

Figure 11 Experimental Response

As per the graph Figure 11, found the Transfer Function of Temperature vs. Input Flow is given by Equation 6

$$TF(s) = \left(\frac{1}{s} - \frac{e^{-250s}}{s}\right) + \frac{e^{-250s}}{(s-0.004)} - \frac{e^{-250}}{(s-0.004)} \qquad (6)$$

This type of system can be separated using Decouplers.

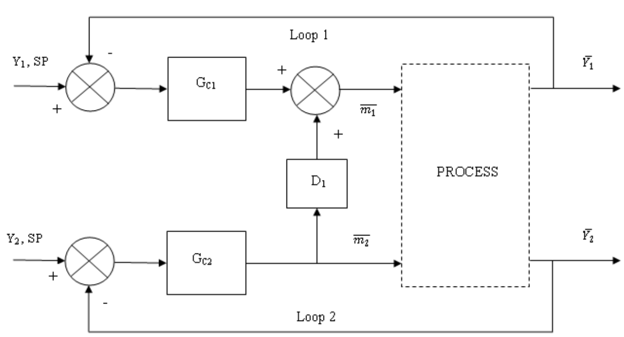

Figure 12 Decoupler Loop

Here $D_1(s) = -\frac{H_{12}(s)}{H_{11}(s)}$

$$D_1(s) = -\frac{H_{12}(s)}{H_{11}(s)} = -\frac{e^{-s\tau}/(\tau s-1)}{1/(c_p\,\rho\,A\;hc\,s)} \quad (7)$$

After doing this the system becomes a non-interacting system.

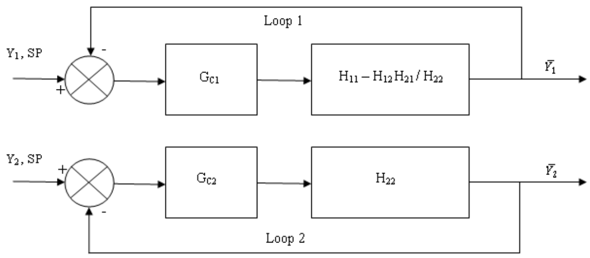

Figure 13 Non Interacting Loops

III. RESULTS AND DISCUSSION

Level control loop transfer function:

$$\frac{H(s)}{Q_i(s)} = \frac{R/2}{\left(\frac{RA}{2}\right)s+1} \;;\; \frac{H(s)}{Q_i(s)} = \frac{K}{\tau s+1} = \frac{1134}{177.16s+1} \quad (8)$$

Where, A=cross sectional area of tank
= 0.15623 m^2

R= Resistance = $\frac{dh}{dqo} = \frac{2h}{qo}$ = 2268 s/ m^2

Flow control loop transfer function:

$$\frac{Q_o}{V(s)} = K_F \quad (9)$$

$$K_F = K_L\sqrt{\frac{\Delta p(t)}{G}} \quad (10)$$

$\Delta p(t)$ = Pressure drop across CV
G = Specific Gravity

Cascade control loop transfer function:

$$\frac{H(s)}{K\,V(s)} = \frac{K}{(\tau s+1)}$$

$$\frac{H(s)}{V(s)} = \frac{K*K_F}{(\tau s+1)} = \frac{K_c}{(\tau s+1)} \quad (11)$$

Temperature Control loop transfer function:
Procedure 1:

$$\frac{T(s)}{Q(s)} = \frac{1}{3.18\times 10^5\,s} \quad (12)$$

Procedure 2:

$$\frac{T(s)}{Q(s)} = \frac{1}{(318136s+685.6668)} \quad (13)$$

Procedure 3:

$$\frac{T(s)}{F_i(s)} = \frac{k_2}{As-k_1} \quad (14)$$

Where k_2 and k_1 are constants, they need to be chosen in such a way that system dynamics should be obeyed.

IV. CONCLUSION AND FUTURE SCOPE

The modeling of pilot plant and identification of the parameters helps to better understand the processes, yielding results comparable to the actual processes in the pilot plant. The Methodology proposing control schemes for the Temperature loop are useful in different situations, like Procedure 1 can be useful for batch process heating of the liquid, and Procedure 3 can be helpful for perfect control of the temperature loop using Internal Model Control and heater input as the feedback linearization element. The proposed decoupler used for removing interaction between the temperature and level loops gives control of individual parameters without affecting the other parameter. The methodology presented in this paper can be used to any such plant having mixed loops. The responses obtained from model and actual plants are compared which found that, they are similar. So the models derived in this work are also acceptable.

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Appendix – I: Pilot Plant Photo

Appendix – 2: Tag Numbers

ID	NAME	DESCRIPTION
T1-T3	TANK T1-T3	Three tanks with capacity of 175 Liters.
FCV2	Control Valve	1” Globe control valve ;C_v=5 (Fail to Close) Valve to control flow from tank T2 to tank T3
HV3	Hand Valve	1.5”Ball valve Provides restriction(R) for output flow through tank T3
CP2	Centrifugal Pump	¼ HP, 2000LPH, 2.1 kg Water is supplied to T3 by tank T2 using pump CP2.
LIC 101	Level Indicator and Controller	PID/Fuzzy Logic Compares level of T3 with set point and manipulate flow through FCV2
FIC102	Flow Indicator and Controller	RTU PID/Fuzzy logic Compares flow measured by FE102 and manipulates flow through FCV2
FE102	Flow Element	1200 LPH, Turbine hall effect Measures flow rate into tank T3 coming from tank T2
TT101	Temperature Transmitter	RTD (Thermowell type) Measures temperature of fluid in tank T3
H	Heater	230V, 3KW Heater Heater for tank T3

