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di REAKTOR (2012), Jurnal Nasional Terakreditasi DIKTI SK No. 66b/DIKTI/Kep/2011

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MSD – 11	**FRICTION ANALYSIS ON SCRATCH DEFORMATION MODES OF VISCO-ELASTIC-PLASTIC MATERIALS**	Budi Setiyana[a], I. Syafaat[a], J. Jamari[b], and D.J. Schipper[a]	[a] *Laboratory for Surface Technology and Tribology, Faculty of Engineering Technology, University of Twente, THE NETHERLANDS*

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MSD – 13	**THE APPLICATION OF B-CYCLODEXTRIN AND POLYETHYLENE GLYCOL 6000 IN THE MICRONISATION OF DRUG – POLYMER COMPOSITE WITH PARTICLE FROM GAS SATURATED SOLUTIONS (PGSS) METHOD**	Putu Riani Pradnyandari, Rizky Tetrisyanda, Prida Novarita Trisanti,Firman Kurniawansyah, and Sumarno	*Chemical Engineering Department, Faculty of Industrial Technology, Institute of Technology Sepuluh Nopember (ITS), INDONESIA*
PSE – 04	**DYNAMIC SIMULATION AND COMPOSITION CONTROL IN A 10 L MIXING TANK**	Yulius Deddy Hermawan	*Chemical Engineering Department, Faculty of Industrial Technology, UPN “Veteran” Yogyakarta, INDONESIA*
PSE - 08	**DISTRIBUTION TEMPERATURE OF ANALYSIS ON CH4-CO2 GAS MIXED IN DOUBLE PIPE HEAT EXCHANGER BY CONTROLLED FEEZE OUT AREA METHODE**	Fatma Y. Hasyim, Novi E. Mayangsari, and Sumarno Material of Laboratory	*Chemical Engineering Department, Faculty of Industry Technology, Sepuluh Nopember Institut of Technology Surabaya, INDONESIA*
SPE – 07	**EFFECT OF PH AND STIRRING SPEED ON THE COLLAGENOUS PROTEIN EXTRACTION FROM CHICKEN BONE WASTE IN A WELL AGITATED EXTRACTION SYSTEM**	Andri Cahyo Kumoro, Beatricx L. M. Tanjung, Fadilla H. Utami, Diah Susetyo Retnowati and Catarina Sri Budiyati	*Department of Chemical Engineering, Diponegoro University, INDONESIA*
SPE – 09	**SOLUBILITY EXAMINATION OF PALM KERNEL OIL IN SUPERCRITICAL CO_2 AND ITS CORRELATION WITH SOLVENT DENSITY BASED MODEL**	Wahyu Bahari Setianto[a], Priyo Atmaji[b] and Didi Dwi Anggoro[b]	[a] *Center for Agroindustrial Technology,Agency for the Assessment and Application of Technology, INDONESIA* [b] *Department of Chernical Engineering, Diponegoro University, INDONESIA*

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Dynamic Simulation and Composition Control in A 10 L Mixing Tank

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Abstract :

The open loop experiment of composition dynamic in a 10 L mixing tank has been successfully done in laboratory. A 10 L tank was designed for mixing of water (as a stream-1) and salt solution (as a stream-2 with salt concentration, c_2 constant). An electric stirrer was employed to obtain uniform composition in tank. In order to keep the liquid volume constant, the system was designed overflow. In this work, 2 composition control configurations have been proposed; they are Alternative-1 and Alternative-2. For Alternative-1, the volumetric-rate of stream-1 is chosen as a manipulated variable, while the volumetric-rate of stream-2 is chosen as a manipulated variable for Alternative-2. The composition control parameters for both alternatives have been tuned experimentally. The volumetric-rate of manipulated variable was changed based on step function. The outlet stream's composition response (c_3) to a change in the input volumetric-rate has been investigated. This research gave Proportional Integral Derivative (PID) control parameters. The gain controllers K_c [cm^6/(gr.sec)] for Alternative-1 and Alternative-2 are –34200 and 40459 respectively. Integral time constant (τ_I) and Derivative time constant (τ_D) for both alternatives are the same, i.e. τ_I = 16 second, and τ_D = 4 second. Furthermore, closed loop dynamic simulation using computer programming was also done to evaluate the resulted tuning parameters. The developed mathematical model of composition control system in a mixing tank was solved numerically. Such mathematical model was rigorously examined in Scilab software environment. As can be seen from our closed loop simulation, closed loop responses in PID control were faster than those in P and PI controls.

Keywords: Closed Loop, Open Loop, PID Control, Mixing Tank, Step function.

1. Introduction

A mixing tank is frequently used in chemical process industries, for examples as a blending tank and/or a continuous stirred tank reactor. Liquid composition in a mixing tank is one of important parameters for mixing processes or chemical reaction processes in reactor. The propagation of mass disturbance is possibly occurred in mixing processes. Therefore composition control should be implemented to overcome the propagation of mass disturbances.

Composition control parameters such as proportional gain controller (K_c), integral time constant (τ_I), and derivative time constant (τ_D) should be tuned properly, since they really affect the stability of mixing process. However designed composition control system must be able to give a stable response in facing the mass disturbances. Therefore the study on dynamic simulation and composition control is very important.

Some studies of process dynamic and control have been done. Recently, Hermawan *et al* **[2]** have presented the open loop composition dynamic in a 10 L Mixing Tank experimentally. Hermawan *et al* **[3]** have also presented the design of control configuration of non-interacting-tank system using quantitative analysis of relative gain array. Hermawan **[1]** has implemented Process Reaction Curve (PRC) for tuning of temperature control parameters in a 10 L Stirred Tank Heater. Widayati and Hermawan **[5]** have studied the mixing characteristic in a horizontal stirred tank.

The goals of this research are to propose the composition control configuration and to tune the composition control parameters (PID Control parameters) in a 10 L Mixing Tank. The resulted composition control parameters of proposed configurations are examined through dynamic simulation. In order to achieve the aims of this research, this work was done in two parts, i.e. open loop experiment in laboratory for tuning of composition control parameters and closed loop simulation using computer programming to explore dynamic behavior of controlled system. The open loop experiment in laboratory was carried out to tune composition control parameters. The volumetric rate of input stream was chosen as a manipulated variable to maintain the concentration of output stream at the constant value. In order to examine the control configuration, the mass disturbances were made based on step function. The Scilab software was utilized to carry out dynamic simulation.

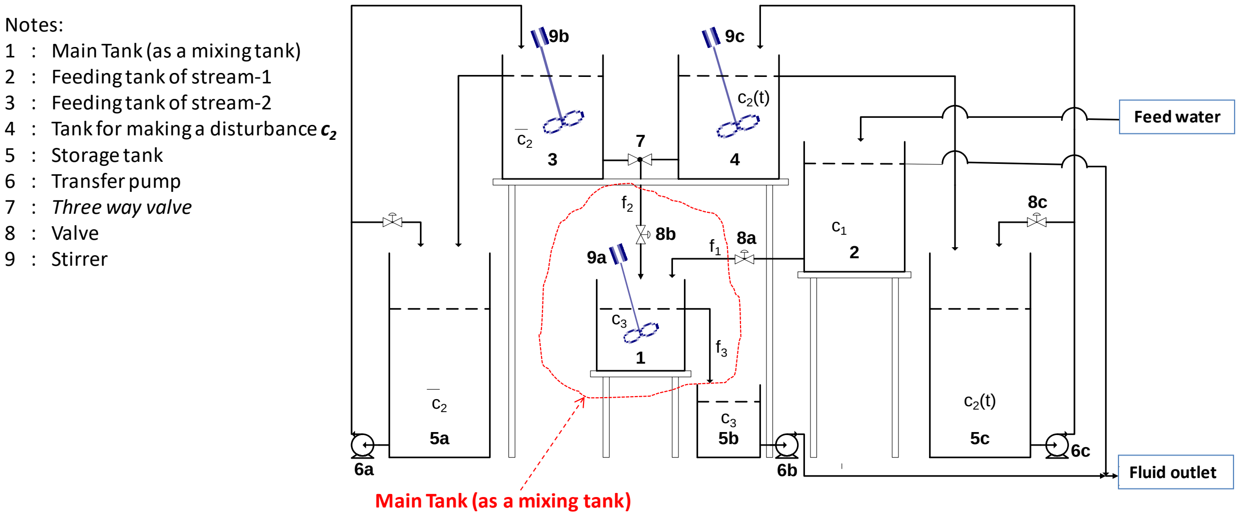


Figure1. Experimental apparatus setup.

2. Materials and Methods

Experimental apparatus setup is shown in Figure 1. As can be seen from Figure 1, No.1 is a main tank that represents a mixing tank. This mixing tank has 2 input streams, i.e. stream-1 and stream-2, and 1 output stream, i.e. stream-3. In normal condition, stream-1 and stream-2 come from the feeding tank No. 2 and No. 3 in Figure 1, respectively. In this work, water was used as a stream-1 with its volumetric rate f_1 [cm^3/sec], and salt solution as a stream-2 with its volumetric rate f_2 [cm^3/sec] and concentration c_2 [gr/cm^3]. The input concentration c_2 is constant. The output stream (stream-3) has volumetric rate f_3 [cm^3/sec] and concentration c_3 [gr/cm^3]. The concentration c_3 is measured by means of Conductivity-meter. Since the liquid volume is kept constant, the system is designed overflow. A stirrer is employed to obtain uniform composition in the mixing tank. The material balance of the mixing tank can be written as follows:

$$\frac{dc_3(t)}{dt} = \left[f_1(t)\bar{c}_1 + f_2(t)\bar{c}_2 - \left(f_1(t) + f_2(t)\right)c_3(t)\right]/V \quad (1)$$

In this research, 2 composition control configurations are proposed, i.e. Alternative-1 and Alternative-2 as shown in Figure 2. Open loop tuning experiment is done for either alternatives by changing the opening valve of stream-1 (No. 8a in Figure 1) or stream-2 (No. 8b in Figure 1) to increase/decrease its volumetric rate immediately. The output concentration (c_3) response to a change in input volumetric rate is then investigated. The resulted response will similar with that response given by first order plus dead time (FOPDT) model. PID Control parameters are then tuned by fitting the resulted FOPDT as proposed by Ziegler-Nichols **[4]**. These open loop experiments should be started from its initial (normal) conditions.

In order to evaluate the resulted PID Control parameters, dynamic simulation is carried out by means of computer. A simple feedback control system is implemented to maintain liquid concentration in tank (c_3) constant by manipulating the volumetric rate of stream-1 or stream-2. Thus, the equation of manipulated variables for both of control configuration alternatives can be written as follow:

Alternative-1: $$f_1(t) = \bar{f}_1 + K_c e(t) + \frac{K_c}{\tau_I}\int e(t)dt + K_c\tau_D\frac{de(t)}{dt} \quad (3)$$

Alternative-2: $$f_2(t) = \bar{f}_2 + K_c e(t) + \frac{K_c}{\tau_I}\int e(t)dt + K_c\tau_D\frac{de(t)}{dt} \quad (4)$$

Where $e(t)$ is defined as:

$$e(t) = c_3^{SP} - c_3(t) = \text{error} \quad (5)$$

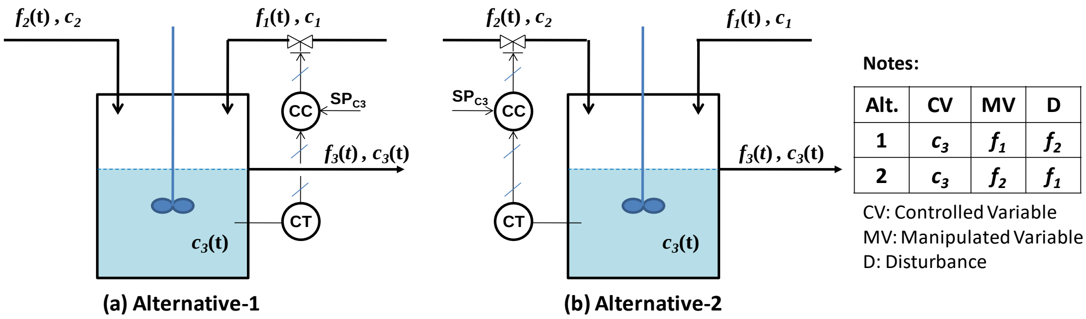


Figure 2. Composition Control Configuration: (a) Alternative-1, (b) Alternative-2.

The developed mathematical model of composition control system in the mixing tank is solved numerically with the easiest way of explicit Euler. The free software Scilab is chosen to carry out the closed loop dynamic simulation. The closed loop responses of composition control will then be explored in this work.

3. Results and Discussion

Steady state parameters of mixing tank are listed in Table 1. Based on steady state material balance, the process time constant is found 37 seconds (0.6 minutes). Therefore the system is considered quite sensitive to the changes of input disturbances.

3.1. Tuning of Composition Control Parameters for Alternative-1

For Alternative-1, volumetric rate of water (f_1) is considered as a manipulated variable to maintain liquid composition in tank (c_3). Figure 3.a shows the influence of f_1 on c_3. Volumetric rate of water is decreased by an amount of 76 cm^3/sec immediately; the concentration c_3 rises about 0.01 gr/cm^3. The tuning results of composition control parameters (P, PI, and PID) for Alternative-1 are listed in Table 2.

3.2. Tuning of Composition Control Parameters for Alternative-2

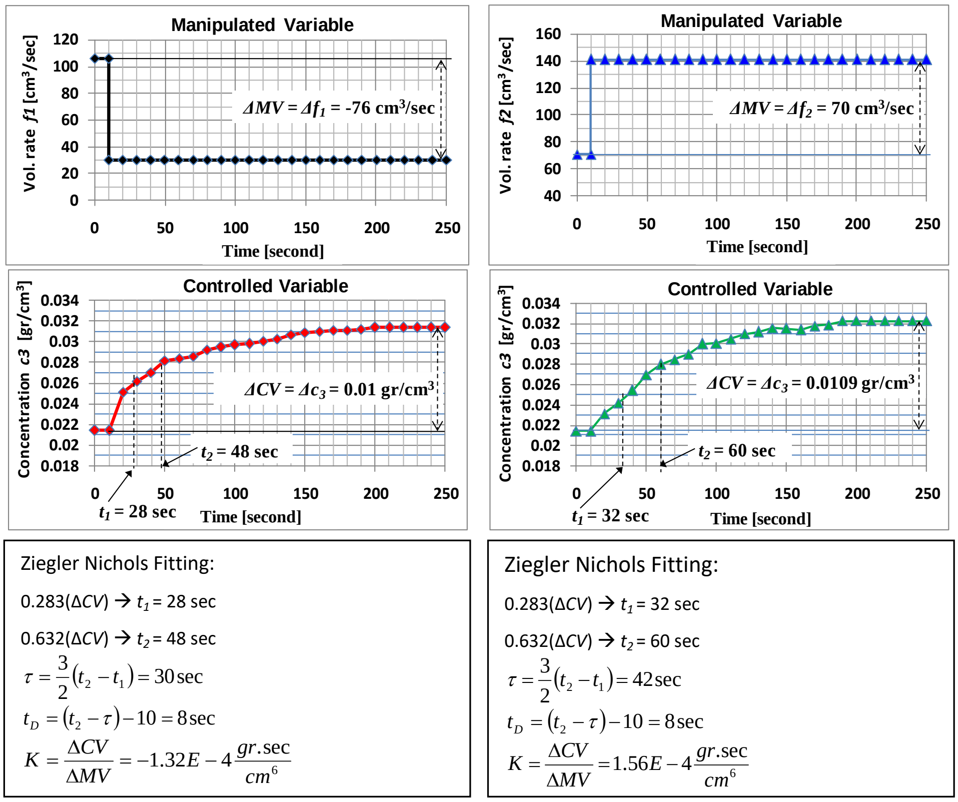
For Alternative-2, volumetric rate of salt solution (f_2) is considered as a manipulated variable to maintain liquid composition in tank (c_3). Figure 3.b shows the open loop composition response to a change in the volumetric rate f_2. The concentration c_3 increases (about 0.01 gr/cm^3) as the volumetric rate f_2 increases (about 70 cm^3/sec). The tuning results of composition control parameters (P, PI, and PID) for Alternative-2 are also listed in Table 2.

Table 1. Steady state parameters

No	Variable	Steady state
1	Volumetric rate of stream-1, f_1 (cm^3/second)	106
2	Volumetric rate of stream-2, f_2 (cm^3/second)	71
3	Volumetric rate of stream-3, f_3 (cm^3/second)	177
4	Concentration of stream-1, c_1 (gr/cm^3)	0
5	Concentration of stream-2, c_2 (gr/cm^3)	0.05
6	Concentration of stream-3, c_3 (gr/cm^3)	0.0214
7	Liquid volume in tank, V (cm^3)	6600

Table 2. Tuning results of composition control parameters.

Type of Feedback Control	*Proportional Gain* Kc [cm^6/(gr.sec)]			*Integral time* τ_I [sec]			*Derivative time* τ_D [sec]		
	Kc	Alt-1	Alt-2	τ_I	Alt-1	Alt-2	τ_D	Alt-1	Alt-2
P	$\tau/(K.t_D)$	-28500	33716	-	-	-	-	-	-
PI	$0.9\,\tau/(K.t_D)$	-25650	30344	$3.3t_D$	27	27	-	-	-
PID	$1.2\,\tau/(K.t_D)$	-34200	40459	$2t_D$	16	16	$0.5t_D$	4	4



(a) Alternative-1 **(b) Alternative-2**

Figure 3. Tuning of Composition Control Parameters: (a) Alternative-1, (b) Alternative-2.

3.3. Dynamic Simulation of Composition Control for Alternative-1

Closed loop responses to a change in volumetric rate f_2 are illustrated in Figure 4. The disturbances were made by following both functions of step increase and step decrease. For step increase's disturbance, volumetric rate f_2 is increased by an amount of 70 cm^3/sec at time equals 10 seconds. As can be seen, the composition controller (P, PI, and PID) attempts to return concentration c_3 to its normal value of 0.0214 gr/cm^3. Concentration c_3 can be returned to its set point by both of PI and PID Controls. P Control produces an offset of 0.0019 gr/cm^3. Closed loop response of PID Control is fastest compared to P and PI Controls; Concentration c_3 can be returned to its set point at time equals 150 seconds.

For step decrease's disturbance, volumetric rate f_2 is decreased by an amount of 56 cm^3/sec at time equals 10 seconds. The concentration c_3 decreases first, and then rises to its normal value. However P Control still produces an off-set of about 0.0028 gr/cm^3. Closed loop response of PID Control is the fastest; the set point of c_3 can be achieved at time equals 120 sec

3.4. Dynamic Simulation of Composition Control for Alternative-2

Figure 5 shows closed loop responses to a change in volumetric rate f_1. For this alternative, the disturbances were also made by following both functions of step increase and step decrease. For step increase's disturbance, volumetric rate f_1 is increased by an amount of 106 cm^3/sec at time equals 10 seconds. As shown in Figure 5, concentration c_3 decreases as volumetric rate f_1 increases, and then concentration c_3 can be returned to its set point by both of PI and PID Controls. P Control produces an offset of 0.0019 gr/cm^3. Closed loop response of PID Control is the fastest one; concentration c_3 can be returned to its set point at time equals 150 seconds.

For step decrease's disturbance, volumetric rate f_1 is decreased by an amount of 76 cm^3/sec at time equals 10 seconds. The concentration c_3 increases as the volumetric rate of water decreases, and then drops to its normal value for PI and PID Controls. Again, P Control still produces an off-set of about 0.0014 gr/cm^3, and PID Control gives the fastest response.

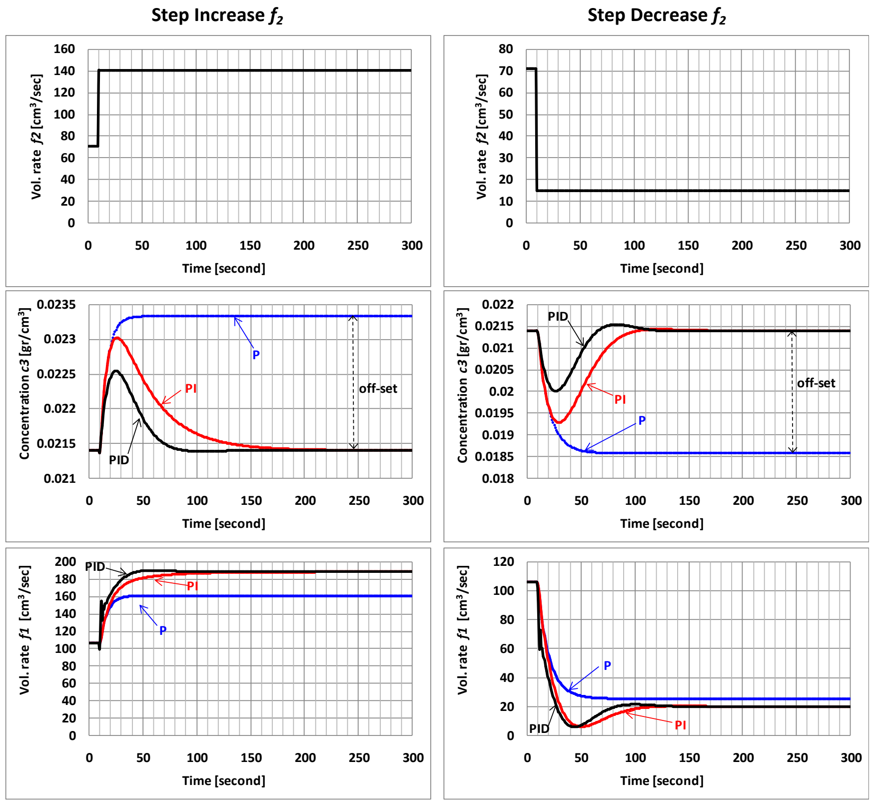


Figure 4. Closed Loop Responses of Composition Control Alternative-1 to a change in volumetric rate f_2: (a) Volumetric rate f_2, (b) Concentration c_3, (c) Volumetric rate f_1

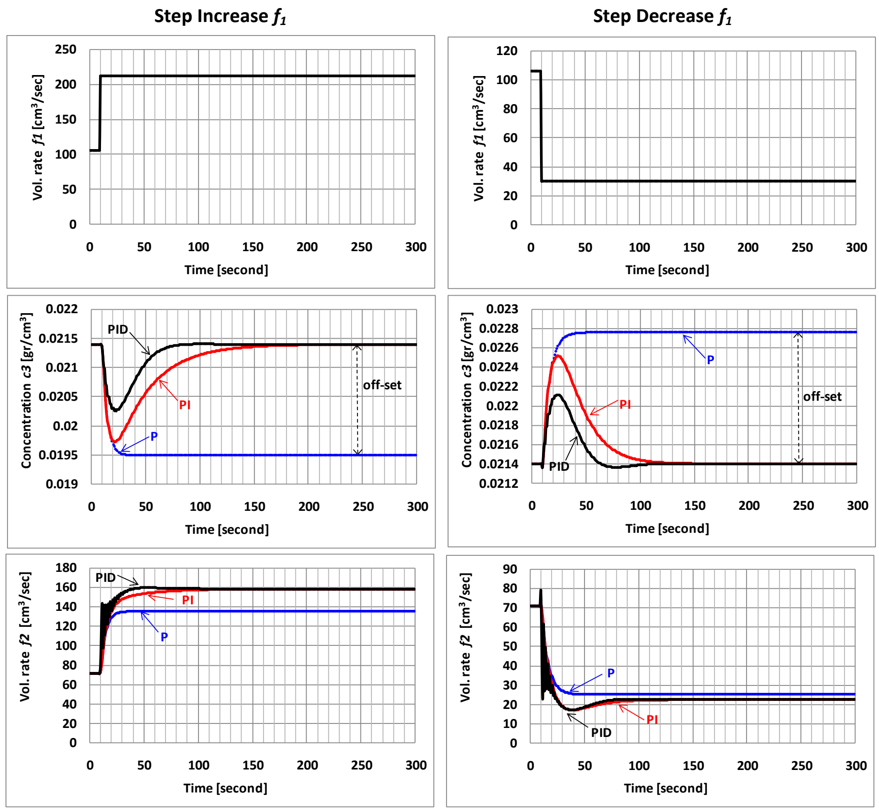


Figure 5. Closed Loop Responses of Composition Control Alternative-2 to a change in volumetric rate f_1: (a) Volumetric rate f_1, (b) Concentration c_3, (c) Volumetric rate f_2

4. Conclusions

This paper has discussed tuning of composition control parameters and dynamic simulation in a 10 L mixing tank. Two alternatives of composition control configurations have been proposed. Closed loop dynamic behaviours of the two control configurations have been explored. According to my dynamic simulation, the tuning results of composition control parameters produce stable responses. This research reveals that PID Composition Control produces the fastest responses compared to both of P and PI Composition Controls.

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Nomenclature

$c_{1,2,3}$	concentration of stream 1, 2, 3 [gr/cm^3]
c_3^{SP}	set point of liquid concentration in tank [gr/cm^3]
e	error [gr/cm^3]
$f_{1,2,3}$	volumetric rate of stream 1, 2, 3 [cm^3/second]
K	steady state gain of the process [(gr.second)/cm^6]
K_c	proportional gain controller [cm^6/(gr.second)]
t_1	time at which c_3 = 0.283 Δc_{3s} [second]
t_2	time at which c_3 = 0.632 Δc_{3s} [second]
t_D	effective process dead time [second]
V	liquid volume in tank [cm^3]
Greek letters	
ΔCV	steady state change in controlled variable [gr/cm^3]
ΔMV	step change in manipulated variable [cm^3/second]
τ	effective process time constant [second]
τ_D	derivative time constant [second]
τ_I	integral time constant [second]

References:

[1] Hermawan YD. 2011. Implementation of Process Reaction Curve for Tuning of Temperature Control Parameters in A 10 L Stirred tank Heater, *Journal of Materials Science and Engineering*, Vol. 1, No. 4 September 2011 : 572 – 577

[2] Hermawan YD, Haryono G, Agustin M, Abiad H. 2012. Composition Dynamic in A 10 L Mixing Tank, *Seminar Nasional Teknik Kimia "Kejuangan" 2012*, Department of Chemical Engineering, Faculty of Industrial, UPN "Veteran" Yogyakarta : C15-1 – C15-6. (*in Indonesian*)

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4. Results and Discussion: Detail explanation about the superiority of PID compared to PI and P Controllers is necessary. Why did PID give fastest response as compared to the other? This will help the readers to understand the fact that PID is the most suitable controller is the studied system comprehensively.
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Salam,
Yulius Deddy Hermawan

DYNAMIC SIMULATION AND COMPOSITION CONTROL IN A 10 L MIXING TANK

Yulius Deddy Hermawan[a] and Gogot Haryono

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Abstrak

Percobaan loop terbuka dinamika komposisi dalam tangki pencampur 10 L telah dilaksanakan di laboratorium. Tangki 10 L dirancang untuk proses pencampuran air (sebagai arus-1) dan larutan garam (sebagai arus-2 dengan konsentrasi garam, c_2 konstan). Pengadukan diterapkan untuk mencapai keseragaman komposisi di dalam tangki. Untuk menjaga volume cairan di dalam tangki konstan, sistem dirancang overflow. Penelitian ini mengusulkan 2 konfigurasi pengendalian komposisi, yaitu Alternatif-1 dan Alternatif-2. Untuk Alternatif-1, laju alir volumetrik arus-1 dipilih sebagai variabel yang dimanipulasi (MV), sedangkan arus-2 dipilih sebagai MV untuk Alternatif-2. Parameter-parameter pengendalian komposisi untuk kedua alternatif ditentukan melalui percobaan. Laju alir volumetrik dari MV diubah mengikuti fungsi tahap. Percobaan dilanjutkan dengan pengamatan respons komposisi keluaran tangki (c_3) terhadap perubahan input fungsi tahap. Percobaan ini menghasilkan parameter pengendalian PID (Proportional Integral Derivative). Gain pengendali K_c [cm^6/(gr.sec)] untuk Alternatif-1 and Alternatif-2 berturut-turut adalah –34200 dan 40459. Konstanta waktu integral (τ_I) dan konstanta waktu derivative (τ_D) untuk kedua alternatif adalah sama, yaitu τ_I = 16 detik, and τ_D = 4 detik. Kemudian, simulasi loop tertutup menggunakan pemrograman komputer dilaksanakan untuk mengevaluasi parameter pengendalian PID yang dihasilkan. Model matematika sistem pengendalian komposisi dalam tangki pencampur diselesaikan secara numerik dan diuji menggunakan software Scilab. Hasil simulasi menunjukkan bahwa respons loop tertutup pengendalian PID lebih cepat dibandingkan respons pengendalian P dan PI.

Kata Kunci*:* *Fungsi Tahap, Loop Terbuka, Loop Tertutup, Pengendalian PID, Tangki Pencampur.*

Abstract

The open loop experiment of composition dynamic in a 10 L mixing tank has been successfully done in laboratory. A 10 L tank was designed for mixing of water (as a stream-1) and salt solution (as a stream-2 with salt concentration, c_2 constant). An electric stirrer was employed to obtain uniform composition in tank. In order to keep the liquid volume constant, the system was designed overflow. In this work, 2 composition control configurations have been proposed; they are Alternative-1 and Alternative-2. For Alternative-1, the volumetric-rate of stream-1 was chosen as a manipulated variable, while the volumetric-rate of stream-2 was chosen as a manipulated variable for Alternative-2. The composition control parameters for both alternatives have been tuned experimentally. The volumetric-rate of manipulated variable was changed based on step function. The outlet stream's composition response (c_3) to a change in the input volumetric-rate has been investigated. This experiment gave Proportional Integral Derivative (PID) control parameters. The gain controllers K_c [cm^6/(gr.sec)] for Alternative-1 and Alternative-2 are –34200 and 40459 respectively. Integral time constant (τ_I) and Derivative time constant (τ_D) for both alternatives are the same, i.e. τ_I = 16 second, and τ_D = 4 second. Furthermore, closed loop dynamic simulation using computer programming was also done to evaluate the resulted tuning parameters. The developed mathematical model of composition control system in a mixing tank was solved numerically. Such mathematical model was rigorously examined in Scilab software environment. The results showed that closed loop responses in PID control were faster than those in P and PI controls.

Keywords*:* *Closed Loop, Mixing Tank, Open Loop, PID Control, Step Function.*

INTRODUCTION

A mixing tank is frequently used in chemical process industries, for examples as a blending tank and/or a continuous stirred tank reactor. Liquid composition in a mixing tank is one of important parameters for mixing processes or chemical reaction processes in reactor. The propagation of mass disturbance is possibly occurred in mixing processes. Therefore composition control should be implemented to overcome the propagation of mass disturbances.

Composition control parameters such as proportional gain controller (K_c), integral time constant (τ_I), and derivative time constant (τ_D) should be tuned properly, since they potentially affect the stability of mixing process. However, designed composition control system must be able to give a stable response in facing the mass disturbances. Therefore the study on the dynamic simulation and composition control is very important.

Some studies on process dynamic and control have been done previously. Recently, Hermawan et al., 2012 have presented the open loop composition dynamic in a 10 L Mixing Tank experimentally. Hermawan et al., 2010 have also presented the design of control configuration of non-interacting-tank system using quantitative analysis of relative gain array. Hermawan, 2011 has implemented Process Reaction Curve (PRC) for tuning of temperature control parameters in a 10 L Stirred Tank Heater. Widayati and Hermawan, 2007 have studied the mixing characteristic in a horizontal stirred tank.

The goals of this research were to propose the composition control configuration and to tune the composition control parameters (PID Control parameters) in a 10 L Mixing Tank. The resulted composition control parameters of proposed configurations were then examined through dynamic simulation. In order to achieve the aims of this research, this work was done in two parts, i.e. open loop experiment in the laboratory for tuning of composition control parameters and closed loop simulation using computer programming to explore dynamic behavior of the controlled system. The open loop experiment in the laboratory was carried out to tune composition control parameters. The volumetric rate of input stream was chosen as a manipulated variable to maintain the concentration of output stream at a constant value. In order to examine the control configuration, the mass disturbances were made based on step function. The Scilab software was utilized to carry out dynamic simulation.

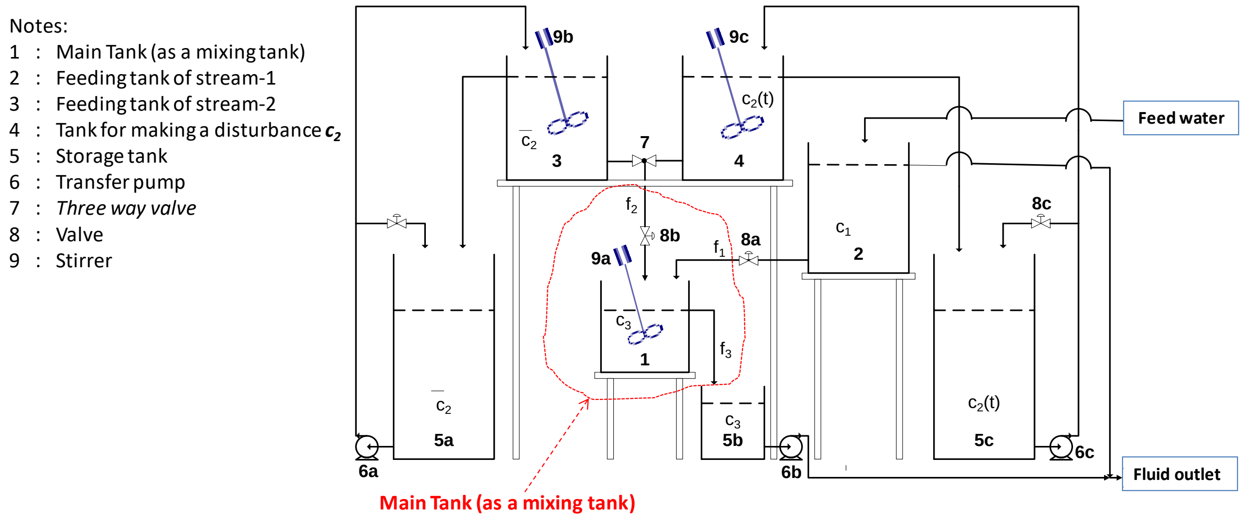

Figure 1. The experimental apparatus setup.

MATERIALS AND METHODS

The experimental apparatus setup is shown in Figure 1. As can be seen in Figure 1, No.1 is a main tank that represents a mixing tank. This mixing tank has 2 input streams, i.e. stream-1 and stream-2, and an output stream, i.e. stream-3. In normal condition, stream-1 and stream-2 come from the feeding tank No. 2 and No. 3, respectively. In this work, water was used as a stream-1 with its volumetric rate f_1 [cm^3/sec], and salt solution as a stream-2 with its volumetric rate f_2 [cm^3/sec] and concentration c_2 [gr/cm^3]. The input concentration c_2 is constant. The output stream (stream-3) has volumetric rate f_3 [cm^3/sec] and concentration c_3 [gr/cm^3]. The concentration c_3 is measured by means of Conductivity-meter. Since the liquid volume is kept constant, the system is designed overflow. A stirrer is employed to obtain uniform composition in the mixing tank. Tank No.4 was used if we want to make a concentration disturbance of stream-2. This disturbance could be made by changing the inlet concentration of stream-2 c_2 immediately. This is done by revolving the gate of three-way-valve (No. 7 in Figure 1), so that stream-2 comes from the tank No. 4 which is specifically prepared for making disturbance.

The material balance of the mixing tank can be written as follows:

$$\frac{dc_3(t)}{dt} = [f_1(t)\bar{c}_1 + f_2(t)\bar{c}_2 - (f_1(t) + f_2(t))c_3(t)]/V \quad (1)$$

In this research, two composition control configurations are proposed, i.e. Alternative-1 and Alternative-2 as shown in Figure 2. Open loop tuning experiment is done for either alternatives by changing the opening valve of stream-1 (No. 8a in Figure 1) or stream-2 (No. 8b in Figure 1) to increase/decrease its volumetric rate immediately. The output concentration (c_3) responsed to a change in input volumetric rate was then investigated. The resulted response will similar with that response given by first order plus dead time (FOPDT) model. PID Control parameters were then tuned by fitting the resulted FOPDT as proposed by Ziegler-Nichols (Smith and Corripio, 1997). These open loop experiments should be started from its initial (normal) conditions.

In order to evaluate the resulted PID Control parameters, dynamic simulation was carried out by means of a computer. A simple feedback control system was implemented to maintain liquid concentration in tank (c_3) constant by manipulating the volumetric rate of stream-1 or stream-2. Thus, the equation of manipulated variables for both of control configuration alternatives can be written as follow:

Alternative-1: $$f_1(t) = \bar{f}_1 + K_c e(t) + \frac{K_c}{\tau_I}\int e(t)dt + K_c \tau_D \frac{de(t)}{dt} \quad (3)$$

$$\text{Alternative-2: } f_2(t) = \bar{f}_2 + K_c e(t) + \frac{K_c}{\tau_I}\int e(t)dt + K_c \tau_D \frac{de(t)}{dt} \tag{4}$$

Where $e(t)$ is defined as:

$$e(t) = c_3^{SP} - c_3(t) = \text{error} \tag{5}$$

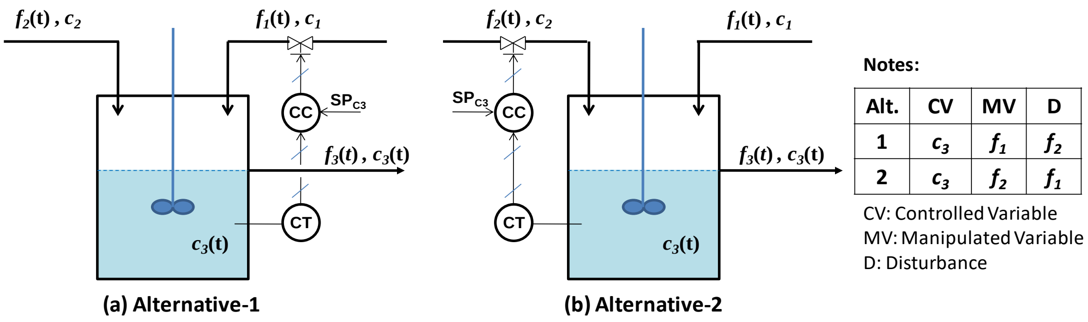

Figure 2. Composition Control Configuration: (a) Alternative-1, (b) Alternative-2.

The developed mathematical model of composition control system in the mixing tank was solved numerically with the easiest way, that was Explicit Euler. The free software Scilab was chosen to carry out the closed loop dynamic simulation. The closed loop responses of composition control could then be explored in this work.

RESULTS AND DISCUSSION

Steady state parameters of the mixing tank are listed in Table 1. Based on steady state material balance, the process time constant is found to be 37 seconds (0.6 minutes). Therefore the system is considered quite sensitive to the changes of input disturbances.

Tuning of Composition Control Parameters for Alternative-1

For Alternative-1, volumetric rate of water (f_1) is considered as a manipulated variable to maintain liquid composition in tank (c_3). Figure 3.a shows the influence of f_1 on c_3. Volumetric rate of water decreases by an amount of 76 cm^3/sec immediately; the concentration c_3 rises about 0.01 gr/cm^3. The tuning results of composition control parameters (P, PI, and PID) for Alternative-1 are listed in Table 2.

Tuning of Composition Control Parameters for Alternative-2

For Alternative-2, volumetric rate of salt solution (f_2) is considered as a manipulated variable to maintain liquid composition in tank (c_3). Figure 3.b shows the open loop composition response to a change in the volumetric rate f_2. The concentration c_3 increases (about 0.01 gr/cm^3) as the volumetric rate f_2 increases (about 70 cm^3/sec). The tuning results of composition control parameters (P, PI, and PID) for Alternative-2 are also listed in Table 2.

Table 1. Steady state parameters

No	Variable	Steady state
1	Volumetric rate of stream-1, f_1 (cm^3/second)	106
2	Volumetric rate of stream-2, f_2 (cm^3/second)	71
3	Volumetric rate of stream-3, f_3 (cm^3/second)	177
4	Concentration of stream-1, c_1 (gr/cm^3)	0
5	Concentration of stream-2, c_2 (gr/cm^3)	0.05
6	Concentration of stream-3, c_3 (gr/cm^3)	0.0214
7	Liquid volume in tank, V (cm^3)	6600

Table 2. Tuning results of composition control parameters.

Type of Feedback Control	*Proportional Gain* Kc [cm^6/(gr.sec)]			*Integral time* τ_I [sec]			*Derivative time* τ_D [sec]		
	Kc	**Alt-1**	**Alt-2**	τ_I	**Alt-1**	**Alt-2**	τ_D	**Alt-1**	**Alt-2**
P	$\tau/(K.t_D)$	-28500	33716	-	-	-	-	-	-
PI	$0.9\,\tau/(K.t_D)$	-25650	30344	$3.3t_D$	27	27	-	-	-
PID	$1.2\,\tau/(K.t_D)$	-34200	40459	$2t_D$	16	16	$0.5t_D$	4	4

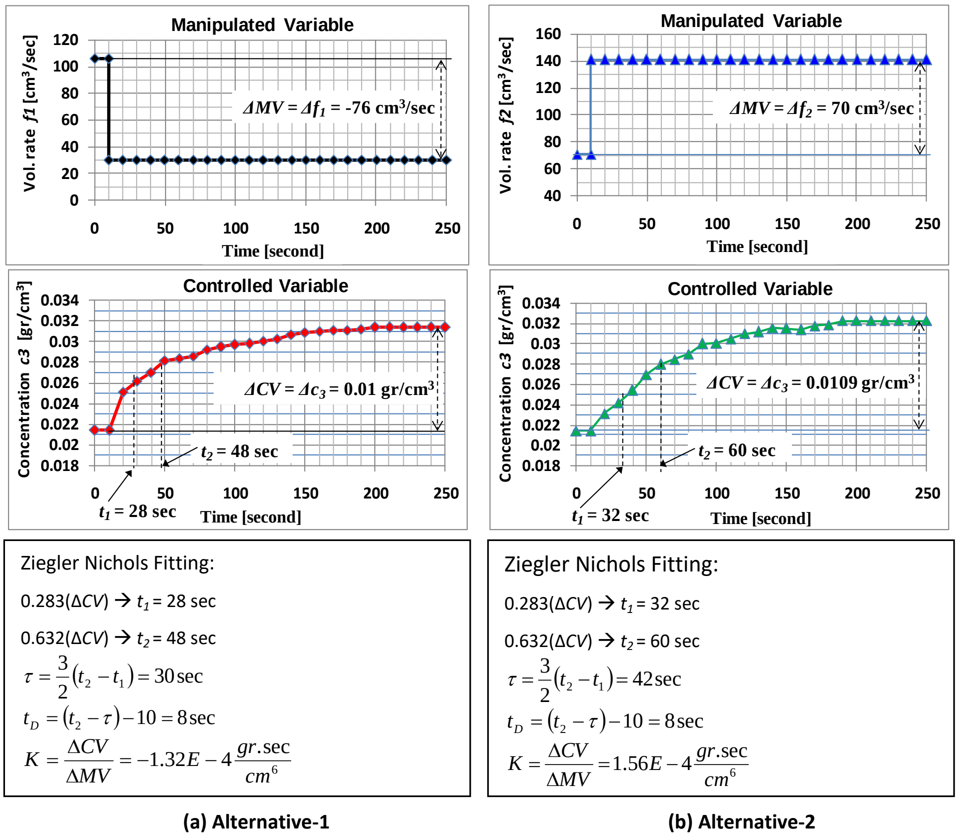

Figure 3. Tuning of Composition Control Parameters: (a) Alternative-1, (b) Alternative-2.

Dynamic Simulation of Composition Control for Alternative-1

Closed loop responses to a change in volumetric rate f_2 are illustrated in Figure 4. The disturbances were made by following both functions of step increase and step decrease. For step increase's disturbance, volumetric rate f_2 is increased by an amount of 70 cm^3/sec at time equals 10 seconds. As can be seen, the composition controller (P, PI, and PID) attempts to return concentration c_3 to its normal value of 0.0214 gr/cm^3. P Control produces an offset of 0.0019 gr/cm^3. Combination of proportional and integral control modes leads to eliminate an offset. Concentration c_3 can be returned to its set point by both of PI and PID Controls. Closed loop response of PID Control is fastest compared to P and PI Controls; Concentration c_3 can be returned to its set point at time equals 150 seconds.

For step decrease's disturbance, volumetric rate f_2 is decreased by an amount of 56 cm^3/sec at time equals 10 seconds. The concentration c_3 decreases first, and then rises to its normal value. However P Control still produces an off-set of about 0.0028 gr/cm^3. Closed loop response of PID Control is the fastest; the set point of c_3 can be achieved at time equals 120 sec.

Combination of the three control modes (PID control) gives a closed loop response which has in general the same qualitative dynamic characteristics as those resulting from PI control. To increase the speed of the closed loop response we can increase the value of proportional gain (K_c) and/or decrease the value of integral time constant (τ_I). But increasing K_c and/or decreasing τ_I, the response become more oscillatory and may lead to instability. The introduction of the derivative mode brings a stabilizing effect to the system. Therefore, the derivative control action not only produces faster response but also produce more robust response.

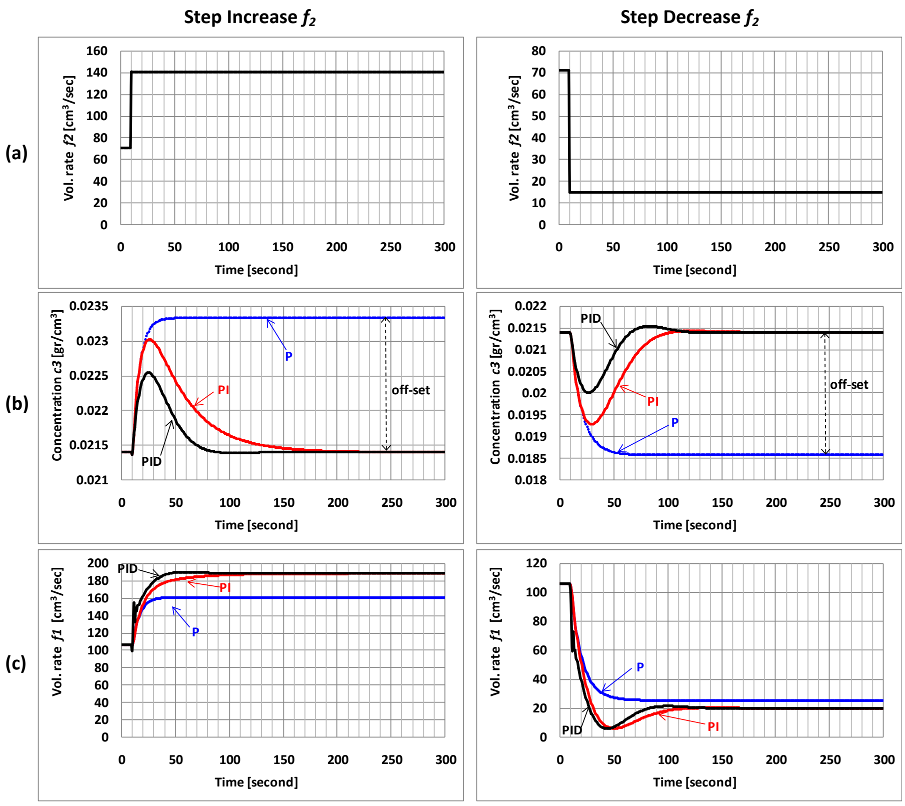

Figure 4. Closed Loop Responses of Composition Control Alternative-1 to a change in volumetric rate f_2: (a) Volumetric rate f_2, (b) Concentration c_3, (c) Volumetric rate f_1

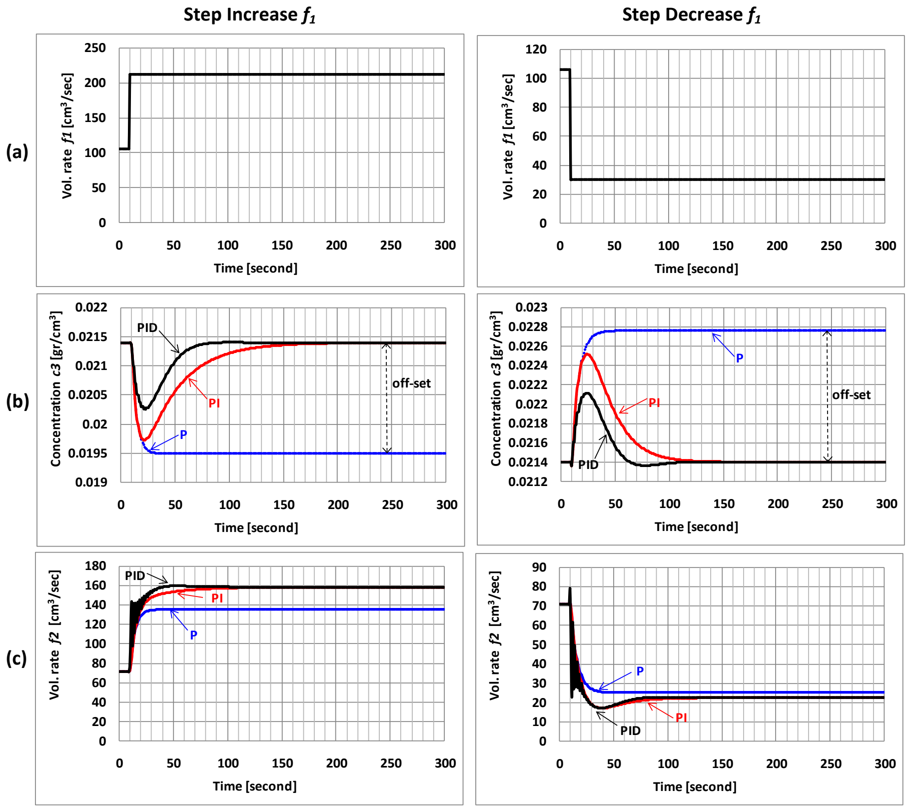

Figure 5. Closed Loop Responses of Composition Control Alternative-2 to a change in volumetric rate f_1: (a) Volumetric rate f_1, (b) Concentration c_3, (c) Volumetric rate f_2

Dynamic Simulation of Composition Control for Alternative-2

Figure 5 shows closed loop responses to a change in volumetric rate f_1. For this alternative, the disturbances were also made by following both functions of step increase and step decrease. For step increase's disturbance, volumetric rate f_1 is increased by an amount of 106 cm^3/sec at time equals 10 seconds. As shown in Figure 5, concentration c_3 decreases as volumetric rate f_1 increases, and then concentration c_3 can be returned to its set point by both of PI and PID Controls. P Control produces an offset of 0.0019 gr/cm^3. Closed loop response of PID Control is the fastest one; concentration c_3 can be returned to its set point at time equals 150 seconds.

For step decrease's disturbance, volumetric rate f_1 is decreased by an amount of 76 cm^3/sec at time equals 10 seconds. The concentration c_3 increases as the volumetric rate of water decreases, and then drops to its normal value for PI and PID Controls. Again, P Control still produces an off-set of about 0.0014 gr/cm^3, and PID Control gives the fastest response.

CONCLUSIONS

This paper discussed tuning of composition control parameters and dynamic simulation in a 10 L mixing tank. Two alternatives of composition control configurations have been proposed. Closed loop dynamic behaviours of the two control configurations have also been explored. According to the dynamic simulation, the tuning results of composition control parameters produce stable responses. This research reveals that PID Composition Control produces the fastest responses compared to both of P and PI Composition Controls.

ACKNOWLEDGEMENTS

I appreciate the technical support on the use of free software SCILAB. I also thank Agustin, M. and Abia, H. for helping me during my research in laboratory.

NOMENCLATURE

ΔCV	steady state change in controlled variable [gr/cm^3]
ΔMV	step change in manipulated variable [cm^3/second]
τ	effective process time constant [second]
τ_D	derivative time constant [second]
τ_I	integral time constant [second]
$c_{1,2,3}$	concentration of stream 1, 2, 3 [gr/cm^3]
c_3^{SP}	set point of liquid concentration in tank [gr/cm^3]
e	error [gr/cm^3]
$f_{1,2,3}$	volumetric rate of stream 1, 2, 3 [cm^3/second]
K	steady state gain of the process [(gr.second)/cm^6]
K_c	proportional gain controller [cm^6/(gr.second)]
t_1	time at which $c_3 = 0.283\ \Delta c_{3s}$ [second]
t_2	time at which $c_3 = 0.632\ \Delta c_{3s}$ [second]
t_D	effective process dead time [second]
V	liquid volume in tank [cm^3]

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   Introduction has been revised.

3. Materials and methods: please refer to the suggested revision in the hard copy of your original manuscript. In addition, the author should also explain the roles of tank 4 in the experiment. No such explanation has been made.

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4. Results and Discussion: Detail explanation about the superiority of PID compared to PI and P Controllers is necessary. Why did PID give fastest response as compared to the other? This will help the readers to understand the fact that PID is the most suitable controller is the studied system comprehensively.

Results and Discussion have been revised.

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Terima kasih atas kesediaan menambah satu penulis lagi sesuai permintaan dari reviewer.

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DYNAMIC SIMULATION AND COMPOSITION CONTROL IN A 10 L MIXING TANK

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Abstract

The open loop experiment of composition dynamic in a 10 L mixing tank has been successfully done in laboratory. A 10 L tank was designed for mixing of water (as a stream-1) and salt solution (as a stream-2 with salt concentration, c_2 constant). An electric stirrer was employed to obtain uniform composition in tank. In order to keep the liquid volume constant, the system was designed overflow. In this work, 2 composition control configurations have been proposed; they are Alternative-1 and Alternative-2. For Alternative-1, the volumetric-rate of stream-1 was chosen as a manipulated variable, while the volumetric-rate of stream-2 was chosen as a manipulated variable for Alternative-2. The composition control parameters for both alternatives have been tuned experimentally. The volumetric-rate of manipulated variable was changed based on step function. The outlet stream's composition response (c_3) to a change in the input volumetric-rate has been investigated. This experiment gave Proportional Integral Derivative (PID) control parameters. The gain controllers K_c [cm^6/(gr.sec)] for Alternative-1 and Alternative-2 are -34200 and 40459 respectively. Integral time constant (τ_I) and Derivative time constant (τ_D) for both alternatives are the same, i.e. τ_I = 16 second, and τ_D = 4 second. Furthermore, closed loop dynamic simulation using computer programming was also done to evaluate the resulted tuning parameters. The developed mathematical model of composition control system in a mixing tank was solved numerically. Such mathematical model was rigorously examined in Scilab software environment. The results showed that closed loop responses in PID control were faster than those in P and PI controls.

Keywords: *closed loop; mixing tank; open loop; pid control; step function*

Abstrak

DINAMIKA SIMULASI DAN PENGENDALIAN KOMPOSISI DALAM TANGKI PENCAMPUR BERKAPASITAS 10 L. *Percobaan loop terbuka dinamika komposisi dalam tangki pencampur 10 L telah dilaksanakan di laboratorium. Tangki 10 L dirancang untuk proses pencampuran air (sebagai arus-1) dan larutan garam (sebagai arus-2 dengan konsentrasi garam, c_2 konstan). Pengadukan diterapkan untuk mencapai keseragaman komposisi di dalam tangki. Untuk menjaga volume cairan di dalam tangki konstan, sistem dirancang overflow. Penelitian ini mengusulkan 2 konfigurasi pengendalian komposisi, yaitu Alternatif-1 dan Alternatif-2. Untuk Alternatif-1, laju alir volumetrik arus-1 dipilih sebagai variabel yang dimanipulasi (MV), sedangkan arus-2 dipilih sebagai MV untuk Alternatif-2. Parameter-parameter pengendalian komposisi untuk kedua alternatif ditentukan melalui percobaan. Laju alir volumetrik dari MV diubah mengikuti fungsi tahap. Percobaan dilanjutkan dengan pengamatan respons komposisi keluaran tangki (c_3) terhadap perubahan input fungsi tahap. Percobaan ini menghasilkan parameter pengendalian PID (Proportional Integral Derivative). Gain pengendali K_c [cm^6/(gr.sec)] untuk Alternatif-1 and Alternatif-2 berturut-turut adalah -34200 dan 40459. Konstanta waktu integral (τ_I) dan konstanta waktu derivative (τ_D) untuk kedua alternatif adalah sama, yaitu τ_I = 16 detik, and τ_D = 4 detik. Kemudian, simulasi loop tertutup menggunakan pemrograman komputer dilaksanakan untuk mengevaluasi parameter pengendalian PID yang dihasilkan. Model matematika sistem pengendalian komposisi dalam tangki pencampur diselesaikan secara numerik dan diuji menggunakan software Scilab. Hasil simulasi menunjukkan bahwa respons loop tertutup pengendalian PID lebih cepat dibandingkan respons pengendalian P dan PI.*

Kata kunci: *loop tertutup; tangki pencampur; loop terbuka; pengendalian pid; fungsi tahap*

INTRODUCTION

A mixing tank is frequently used in chemical process industries, for examples as a blending tank and/or a continuous stirred tank reactor. Liquid composition in a mixing tank is one of important parameters for mixing processes or chemical reaction processes in reactor. The propagation of mass disturbance is possibly occurred in mixing processes. Therefore composition control should be implemented to overcome the propagation of mass disturbances.

Composition control parameters such as proportional gain controller (K_c), integral time constant (τ_I), and derivative time constant (τ_D) should be tuned properly, since they potentially affect the stability of mixing process. However, designed composition control system must be able to give a stable response in facing the mass disturbances. Therefore the study on the dynamic simulation and composition control is very important.

Some studies on process dynamic and control have been done previously. Recently, Hermawan *et al.* (2012) have presented the open loop composition dynamic in a 10 L Mixing Tank experimentally. Hermawan *et al.* (2010) have also presented the design of control configuration of non-interacting-tank system using quantitative analysis of relative gain array. Hermawan (2011) has implemented Process Reaction Curve (PRC) for tuning of temperature control parameters in a 10 L Stirred Tank Heater. Widayati and Hermawan (2007) have studied the mixing characteristic in a horizontal stirred tank.

The goals of this research were to propose the composition control configuration and to tune the composition control parameters (PID Control parameters) in a 10 L Mixing Tank. The resulted composition control parameters of proposed configurations were then examined through dynamic simulation. In order to achieve the aims of this research, this work was done in two parts, i.e. open loop experiment in the laboratory for tuning of composition control parameters and closed loop simulation using computer programming to explore dynamic behavior of the controlled system. The open loop experiment in the laboratory was carried out to tune composition control parameters. The volumetric rate of input stream was chosen as a manipulated variable to maintain the concentration of output stream at a constant value. In order to examine the control configuration, the mass disturbances were made based on step function. The Scilab software was utilized to carry out dynamic simulation.

MATERIALS AND METHODS

The experimental apparatus setup is shown in Figure 1. As can be seen in Figure 1, No.1 is a main tank that represents a mixing tank. This mixing tank has 2 input streams, i.e. stream-1 and stream-2, and an output stream, i.e. stream-3. In normal condition, stream-1 and stream-2 come from the feeding tank No. 2 and No. 3, respectively. In this work, water was used as a stream-1 with its volumetric rate f_1 [cm^3/sec], and salt solution as a stream-2 with its volumetric rate f_2 [cm^3/sec] and concentration c_2 [gr/cm^3]. The input concentration c_2 is constant. The output stream (stream-3) has volumetric rate f_3 [cm^3/sec] and concentration c_3 [gr/cm^3]. The concentration c_3 is measured by means of Conductivity-meter. Since the liquid volume is kept constant, the system is designed overflow. A stirrer is employed to obtain uniform composition in the mixing tank. Tank No.4 was used if we want to make a concentration disturbance of stream-2. This disturbance could be made by changing the inlet concentration of stream-2 c_2 immediately. This is done by revolving the gate of three-way-valve (No. 7 in Figure 1), so that stream-2 comes from the tank No. 4 which is specifically prepared for making disturbance.

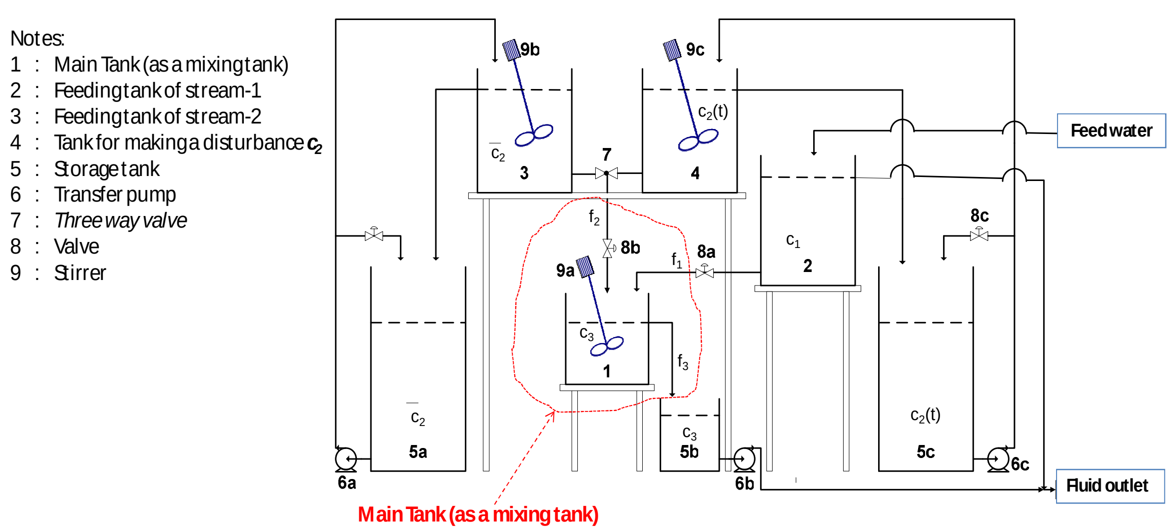


Figure 1. The experimental apparatus setup

The material balance of the mixing tank can be written as follows:

$$\frac{dc_3(t)}{dt} = \left[f_1(t)\bar{c}_1 + f_2(t)\bar{c}_2 - (f_1(t)+f_2(t))c_3(t)\right]/V \qquad (1)$$

In this research, two composition control configurations are proposed, i.e. Alternative-1 and Alternative-2 as shown in Figure 2. Open loop tuning experiment is done for either alternatives by changing the opening valve of stream-1 (No. 8a in Figure 1) or stream-2 (No. 8b in Figure 1) to increase/decrease its volumetric rate immediately. The output concentration (c_3) response to a change in input volumetric rate was then investigated. The resulted response will similar with that response given by first order plus dead time (FOPDT) model. PID Control parameters were then tuned by fitting the resulted FOPDT as proposed by Ziegler-Nichols (Smith and Corripio, 1997). These open loop experiments should be started from its initial (normal) conditions.

In order to evaluate the resulted PID Control parameters, dynamic simulation was carried out by means of a computer. A simple feedback control system was implemented to maintain liquid concentration in tank (c_3) constant by manipulating the volumetric rate of stream-1 or stream-2. Thus, the equation of manipulated variables for both of control configuration alternatives can be written as follow:

Alternative-1:

$$f_1(t) = \bar{f}_1 + K_c e(t) + \frac{K_c}{\tau_I}\int e(t)dt + K_c\tau_D\frac{de(t)}{dt} \qquad (2)$$

Alternative-2:

$$f_2(t) = \bar{f}_2 + K_c e(t) + \frac{K_c}{\tau_I}\int e(t)dt + K_c\tau_D\frac{de(t)}{dt} \qquad (3)$$

Where $e(t)$ is defined as:

$$e(t) = c_3^{SP} - c_3(t) = \text{error} \qquad (4)$$

The developed mathematical model of composition control system in the mixing tank was solved numerically with the easiest way, that was Explicit Euler. The free software Scilab was chosen to carry out the closed loop dynamic simulation. The closed loop responses of composition control could then be explored in this work.

RESULTS AND DISCUSSION

Steady state parameters of the mixing tank are listed in Table 1. Based on steady state material balance, the process time constant is found to be 37 seconds (0.6 minutes). Therefore the system is considered quite sensitive to the changes of input disturbances.

Tuning of Composition Control Parameters for Alternative-1

For Alternative-1, volumetric rate of water (f_1) is considered as a manipulated variable to maintain liquid composition in tank (c_3). Figure 3.a shows the influence of f_1 on c_3. Volumetric rate of water decreases by an amount of 76 cm^3/sec immediately; the concentration c_3 rises about 0.01 gr/cm^3. The tuning results of composition control parameters (P, PI, and PID) for Alternative-1 are listed in Table 2.

Tuning of Composition Control Parameters for Alternative-2

For Alternative-2, volumetric rate of salt solution (f_2) is considered as a manipulated variable to maintain liquid composition in tank (c_3). Figure 3.b shows the open loop composition response to a change in the volumetric rate f_2. The concentration c_3 increases (about 0.01 gr/cm^3) as the volumetric rate f_2 increases (about 70 cm^3/sec). The tuning results of composition control parameters (P, PI, and PID) for Alternative-2 are also listed in Table 2.

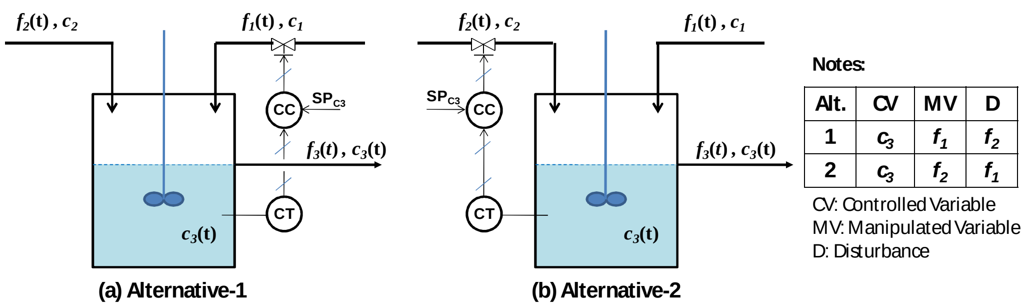


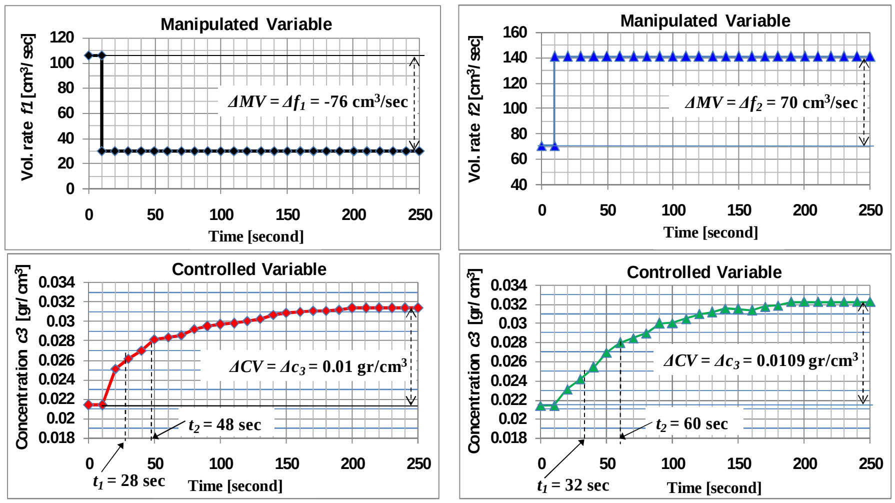
Figure 2. Composition Control Configuration: (a) Alternative-1, (b) Alternative-2.

Table 1. Steady state parameters

No	Variable	Steady state
1	Volumetric rate of stream-1, f_1 (cm^3/second)	106
2	Volumetric rate of stream-2, f_2 (cm^3/second)	71
3	Volumetric rate of stream-3, f_3 (cm^3/second)	177
4	Concentration of stream-1, c_1 (gr/cm^3)	0
5	Concentration of stream-2, c_2 (gr/cm^3)	0.05
6	Concentration of stream-3, c_3 (gr/cm^3)	0.0214
7	Liquid volume in tank, V (cm^3)	6600

Table 2. Tuning results of composition control parameters

Type of Feedback Control	*Proportional Gain* Kc [cm^6/(gr.sec)]			*Integral time* τ_I [sec]			*Derivative time* τ_D [sec]		
	Kc	Alt-1	Alt-2	τ_I	Alt-1	Alt-2	τ_D	Alt-1	Alt-2
P	$\tau/(K.t_D)$	-28500	33716	-	-	-	-	-	-
PI	$0.9\,\tau/(K.t_D)$	-25650	30344	$3.3t_D$	27	27	-	-	-
PID	$1.2\,\tau/(K.t_D)$	-34200	40459	$2t_D$	16	16	$0.5t_D$	4	4



Ziegler Nichols Fitting:

$0.283(\Delta CV) \rightarrow t_1 = 28$ sec

$0.632(\Delta CV) \rightarrow t_2 = 48$ sec

$$\tau = \frac{3}{2}(t_2 - t_1) = 30\text{sec}$$

$$t_D = (t_2 - \tau) - 10 = 8\text{sec}$$

$$K = \frac{\Delta CV}{\Delta MV} = -1.32E-4\,\frac{gr.\sec}{cm^6}$$

Ziegler Nichols Fitting:

$0.283(\Delta CV) \rightarrow t_1 = 32$ sec

$0.632(\Delta CV) \rightarrow t_2 = 60$ sec

$$\tau = \frac{3}{2}(t_2 - t_1) = 42\text{sec}$$

$$t_D = (t_2 - \tau) - 10 = 8\text{sec}$$

$$K = \frac{\Delta CV}{\Delta MV} = 1.56E-4\,\frac{gr.\sec}{cm^6}$$

(a) Alternative-1 **(b) Alternative-2**

Figure 3. Tuning of Composition Control Parameters: (a) Alternative-1, (b) Alternative-2.

Dynamic Simulation of Composition Control for Alternative-1

Closed loop responses to a change in volumetric rate f_2 are illustrated in Figure 4. The disturbances were made by following both functions of step increase and step decrease. For step increase's disturbance, volumetric rate f_2 is increased by an amount of 70 cm^3/sec at time equals 10 seconds. As can be seen, the composition controller (P, PI, and PID) attempts to return concentration c_3 to its normal value of 0.0214 gr/cm^3. P Control produces an offset of 0.0019 gr/cm^3. Combination of proportional and integral control modes leads to eliminate an offset. Concentration c_3 can be returned to its set point by both of PI and PID Controls. Closed loop response of PID Control is fastest compared to P and PI Controls; Concentration c_3 can be returned to its set point at time equals 150 seconds.

For step decrease's disturbance, volumetric rate f_2 is decreased by an amount of 56 cm^3/sec at time equals 10 seconds. The concentration c_3 decreases first, and then rises to its normal value. However P Control still produces an off-set of about 0.0028 gr/cm^3. Closed loop response of PID Control is the fastest; the set point of c_3 can be achieved at time equals 120 sec.

Combination of the three control modes (PID control) gives a closed loop response which has in general the same qualitative dynamic characteristics as those resulting from PI control. To increase the speed of the closed loop response we can increase the value of proportional gain (K_c) and/or decrease the value of integral time constant (τ_I). But increasing K_c and/or decreasing τ_I, the response become more oscillatory and may lead to instability. The introduction of the derivative mode brings a stabilizing effect to the system. Therefore, the derivative control action not only produces faster response but also produce more robust response.

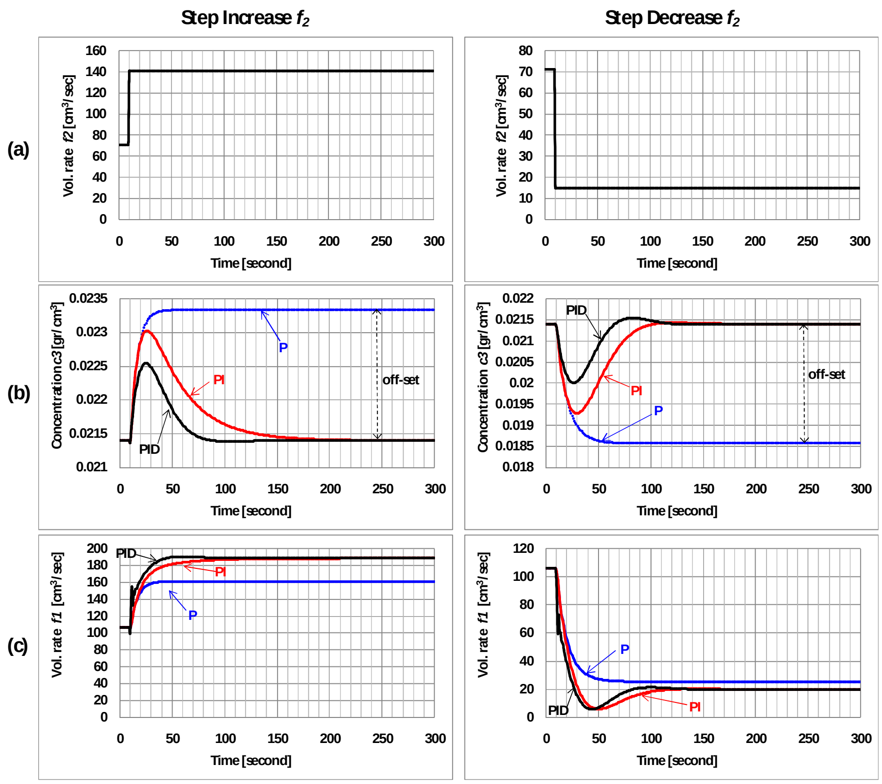


Figure 4. Closed Loop Responses of Composition Control Alternative-1 to a change in volumetric rate f_2: (a) volumetric rate f_2, (b) concentration c_3, (c) volumetric rate f_1

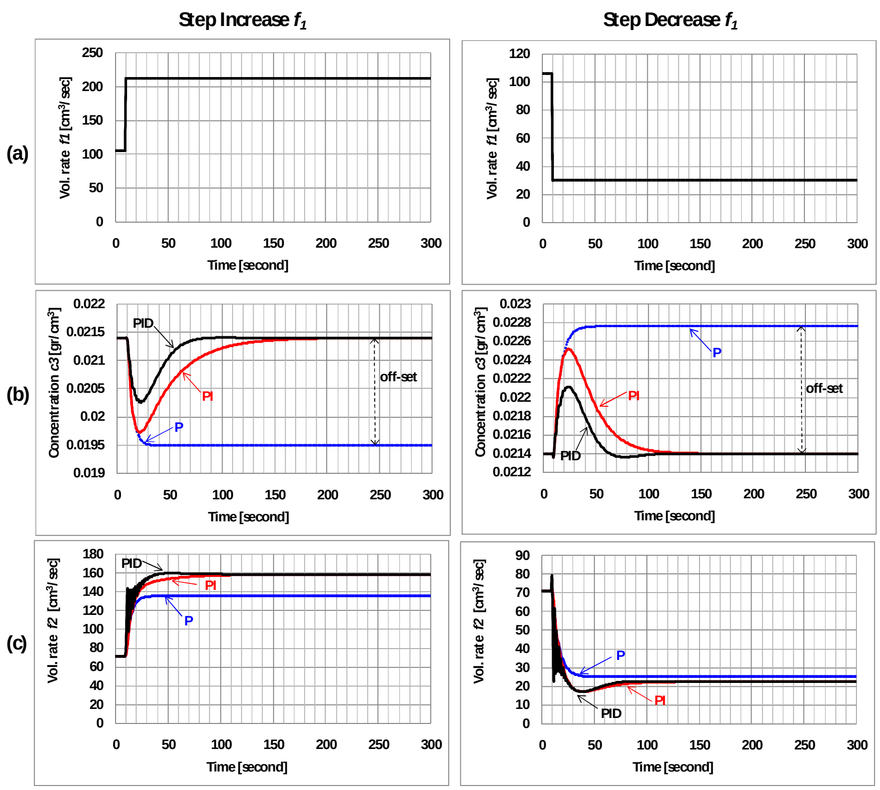


Figure 5. Closed Loop Responses of Composition Control Alternative-2 to a change in volumetric rate f_1: (a) volumetric rate f_1, (b) concentration c_3, (c) volumetric rate f_2

Dynamic Simulation of Composition Control for Alternative-2

Figure 5 shows closed loop responses to a change in volumetric rate f_1. For this alternative, the disturbances were also made by following both functions of step increase and step decrease. For step increase's disturbance, volumetric rate f_1 is increased by an amount of 106 cm^3/sec at time equals 10 seconds. As shown in Figure 5, concentration c_3 decreases as volumetric rate f_1 increases, and then concentration c_3 can be returned to its set point by both of PI and PID Controls. P Control produces an offset of 0.0019 gr/cm^3. Closed loop response of PID Control is the fastest one; concentration c_3 can be returned to its set point at time equals 150 seconds.

For step decrease's disturbance, volumetric rate f_1 is decreased by an amount of 76 cm^3/sec at time equals 10 seconds. The concentration c_3 increases as the volumetric rate of water decreases, and then drops to its normal value for PI and PID Controls. Again, P Control still produces an off-set of about 0.0014 gr/cm^3, and PID Control gives the fastest response.

CONCLUSIONS

This paper discussed tuning of composition control parameters and dynamic simulation in a 10 L mixing tank. Two alternatives of composition control configurations have been proposed. Closed loop dynamic behaviours of the two control configurations have also been explored. According to the dynamic simulation, the tuning results of composition control parameters produce stable responses. This research reveals that PID Composition Control produces the fastest responses compared to both of P and PI Composition Controls.

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NOMENCLATURE

ΔCV	steady state change in controlled variable [gr/cm^3]
ΔMV	step change in manipulated variable [cm^3/second]
τ	effective process time constant [second]
τ_D	derivative time constant [second]
τ_I	integral time constant [second]
$c_{1,2,3}$	concentration of stream 1, 2, 3 [gr/cm^3]
c_3^{SP}	set point of liquid concentration in tank [gr/cm^3]
e	error [gr/cm^3]
$f_{1,2,3}$	volumetric rate of stream 1, 2, 3 [cm^3/second]
K	steady state gain of the process [(gr.second)/cm^6]
K_c	proportional gain controller [cm^6/(gr.second)]
t_1	time at which $c_3 = 0.283\ \Delta c_{3s}$ [second]
t_2	time at which $c_3 = 0.632\ \Delta c_{3s}$ [second]
t_D	effective process dead time [second]
V	liquid volume in tank [cm^3]

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