RESEARCH ARTICLE   OPEN ACCESS

Characterization of Simulator for Water Level Control in the Tank – Single Loop

Iwan Rohman Setiawan

Technical Implementation Unit for Instrumentation Development, Indonesian Institute of Sciences (LIPI)
Komplek LIPI, Gd. 30, Jl. Sangkuriang, Bandung, Indonesia.

Abstract:

The simulator industrial process has been created with one of it's aims to simulate the water level control in the tank-single loop, to obtain the characteristics of the simulator, then created of modeling mathematical and simulation using MATLAB/Simulink, the results of modeling and simulation showed that, gain of the process tank is 2654 m/s2 and the time constant is 124 seconds. Furthermore, through the Root Locus stability method and step input test, it was known that the simulator is stable.

Keywords **—Characteristic, simulator, modeling and simulation, water level control in the tank.**

I. INTRODUCTION

Liquid level control in the tank is one of the most important aspects applied to many plants in the process industry [1], such as petroleum and gas industries, chemical industry, environmental protection, water treatment, metallurgy and other industries. For the examples of level control applications in the plant of the process industry are control levels in the boiler or in the pressurized tank. The purpose of the level control is to ensure the quality and quantity of raw materials, semi-finished products, or finished products in a container by checking and adjusting the balance between the input and the material output of the container [2].

In the Research Center for Metrology – Indonesia Institute of Sciences has been created a simulator to simulate industrial process measurement and control system such as level control-single loop and cascade method using PID controller. The simulator consists of a mini plant which a used to measure and control the water level in the tank, flow rate in the pipe and it used for the industry technician training and research [3].

In this paper, a model and simulation of water level control in the tank-single loop is designed using MATLAB/Simulink to obtain the characteristics of the simulator.

II. SIMULATOR OF WATER LEVEL CONTROL

The process industry simulator that has been made is shown in Fig. 1.

Fig. 1. Process industry simulator [3]

The water level control system in the simulator is a water level control system using PID controllers in open tanks, where the water flows out from the tank by gravity (gravity flow tank) [4] as shown in piping and instrumentation diagram in Fig. 2.

The work process in Fig. 2 is described as follows: Water is sucked from the reservoir by the pump, and then flows into the tank, the water flow rate that flows into the tank is regulated by valve 2 manually in the tank, there is a valve 1 which has a function to regulate the flow rate of water flowing out from the tank.
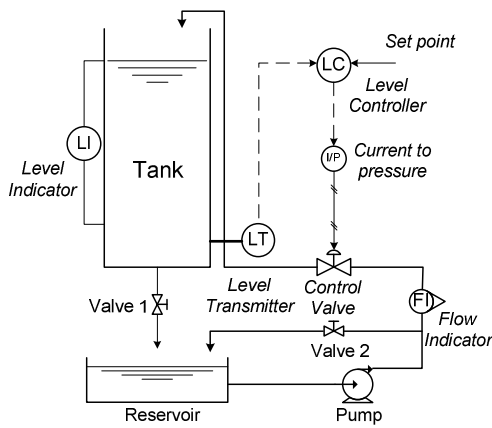
Fig. 2. P&ID of water level control-single loop on simulator

As for the working process of automatic control of the system, the level transmitter (LT) type of differential pressure measures water level in the tank. The measurement results of LT is electrical current output signal with the range is from 4 mA to 20 mA, it is become input to the level controller (LC) using PID Controller. Then LC calculates the difference between signal input value of LT with set point on LC, that is water level desired, If there is an error then the LC ordered the control valve (CV) through current to pressure (I/P) to open or close the valve. Consequently, the flow of water into the tank becomes increased or decreased. The process continues until error is zero. The work process of level control is also shown through the block diagram in Fig.3.
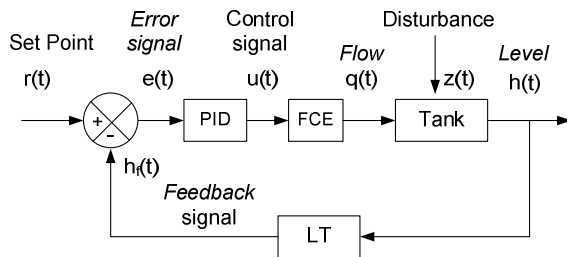

Fig. 3. Block diagram of level control [7]

III.   METHODOLOGY

The model of the components diagram block of in Fig. 3 is based on the basic parameter of the simulator design and the equipment specifications

as well as the instruments used in the system as shown in Table I.

Tabel I.
BASIC PARAMETER OF WATER LEVEL CONTROL SYSTEM IN THE TANK [7].

Components	Specification
Tank height	1,25 meter
Level maximum height	0,8 meter
Level minimum height	0.2 meter
Tank diameter	0.25 meter
Maximum flow rate	19 liter/minute
Pipe diameter for water out of the tank	0.5 inch
Differential Pressure Transmitter	Input 0 to 100 IN H_2O Output 4 to 20 mA
Current to pressure (I/P)	Input 4 to 20 mA Output 0.2 to 1 bar
Controller	PID Controller
Control valve	0.5 inch

A. *Process Tank*

Process tank is representation of the water level changes in the tank. The input signal of the tank is the water flow rate q_{in} (m³/s), while the output signal is the water level in the tank, h (m). The relationship between q_{in} and h is shown in the block diagram in Fig. 4.
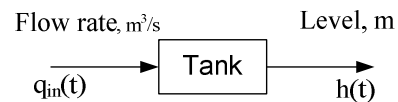

Fig.4. Block diagram of the process tank [4]

The water level in the tank h is determined to be a maximum of 0.8 m, when the maximum flow rate of water entering the tank q_{in} 19 liters/minute = 0.0003154 m³/s, obtained by adjusting the flow rate of water flowing out from the tank q_{out} through the regulated valve K1 as shown in Fig. 2.

The model of the relationship between q_{in} and the valve opening K1, q_{out} and water level in the tank h in an equilibrium condition is modeled by the gravity flow tank model as shown in Fig 5.

The water level h (m) which occurs in the tank is obtained by the following equation [5]:

$$. A\frac{dh}{dt} = q_{in}(t) - q_{out}(t) \qquad (1)$$

Where A is the area of the tank (m²), q_{in} is water flow rate filling the tank (m³/s) and q_{out} is water flow rate out of the tank (m³/s).
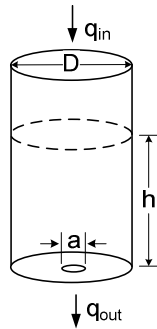

Fig.5. Model the gravity flow tank [5]

By using the Bernoulli equation, the flow rate of water flowing out from the tank bottom hole q_{out} is obtained by the following equation,

$$q_{out} = a\sqrt{2\,g\,h} \qquad (2)$$

Where g is gravity (m/s²) and a is area of opening valve K1 (m²) as shown in Fig.2.

By substituting equation (2) to equation (1), the formula of $A\frac{dh}{dt}$ is obtained as follows:

$$A\frac{dh}{dt} = q_{in} - a\sqrt{2gh} \qquad (3)$$

Then, on the steady state dh/dt = 0, the equation (3) becomes:

$$0 = q_{in} - a\sqrt{2gh} \qquad (4)$$

From equation (4) in the steady state $q_{in} = q_{out}$, in the water level h is also in the steady state, then to obtain the opening area of the valve a in order to obtain the desired water level, equation (5) is obtained as follows:

$$a = \frac{q_{in}}{\sqrt{2\,g\,h_{ss}}} \qquad (5)$$

where h_{ss} is height of water level in steady state (m).

The level h(t) that occurs due to the flow rate of water filling the tank q_{in}, can be obtained from equation (3) as shown as by equation (6):

$$\frac{dh}{dt} = \frac{q_{in}}{A} - \frac{a}{A}\sqrt{2gh} \qquad (6)$$

The deviation for the equilibrium point h is obtained by following equation:

$$h = h_{ss} + \Delta h \qquad (7)$$

where h_{ss} is water level in steady state (m). By modifying equation (5), the h_{ss} is obtained by following equation:

$$h_{ss} = \frac{q_{in\_ss}^2}{2ga^2} \qquad (8)$$

where q_{in_ss} is water flow rate flowing to the tank in the steady state condition. Then, the combination of equation (6) and equation (7) is embedded by equation as follows:

$$\frac{d}{dt}(h_{ss} + \Delta h) = \frac{q_{in}}{A} - \frac{a\sqrt{2g}}{A}\sqrt{h} \qquad (9)$$

Because h_{ss} is constant, equation (9) becomes:

$$\frac{d\Delta h}{dt} = f(q_{in}, h) = \frac{q_{in}}{A} - \frac{a\sqrt{2g}}{A}\sqrt{h} \qquad (10)$$

Using first order Tylor series, the equation (10) can be written as follows:

$$\frac{d\Delta h}{dt} = \frac{\Delta q_{in}}{A} - \frac{a\sqrt{2\,g}}{2A\sqrt{h_{ss}}}\Delta h \qquad (11)$$

So equation (11) is the model of the water level system in the tank with the gravity flow tank model where the system is linear.

Laplace transform of equation (11) with assuming $\Delta h(0) = 0$ can be obtained from the equation as follows:

$$s\,\Delta h = \frac{\Delta q_{in}}{A} - \frac{a\sqrt{2\,g}}{2A\sqrt{h_{ss}}}\Delta h \qquad (12)$$

Then, the algebraic equation for $\Delta h(s)$ can be written as follow:

$$\Delta h = \frac{\frac{1}{A}}{s + \frac{a\sqrt{2\,g}}{2\,A\sqrt{h_{ss}}}} \Delta q_{in} \qquad (13)$$

Because transfer function for G(s) is,

$$G(s) = \frac{\Delta h}{\Delta q_{in}} = \frac{\frac{1}{A}}{s + \frac{a\sqrt{2\,g}}{2\,A\sqrt{h_{ss}}}} \qquad (14)$$

Then equation (14) is solved to obtain gain and time constant, now, equation (14) can be written as follow:

$$G(s) = \frac{\frac{\sqrt{2\,h_{ss}}}{a\sqrt{g}}}{\frac{A\sqrt{2\,h_{ss}}}{a\sqrt{g}}s + 1} \qquad (15)$$

Or by using equation (15) can be written in another form as written by equation (16) as follows:

$$G(s) = \frac{\frac{q_{in\_ss}}{a^2 g}}{\frac{A q_{in\_ss}}{a^2 g}s + 1} \qquad (16)$$

Equation (16) is a form of a first-order transfer function commonly shown by equation (17).

$$G(s) = \frac{K}{Ts + 1} \qquad (17)$$

where K is gain and τ is time constant (seconds) so from equation (15), K and τ is obtained as follow:

$$K = \frac{\sqrt{2\,h_{ss}}}{a\sqrt{g}} \qquad (18)$$

and,

$$\tau = \frac{A\sqrt{2\,h_{ss}}}{a\sqrt{g}} \qquad (19)$$

Then, K and τ from equation (16) is obtained as follow:

$$K = \frac{q_{in\_ss}}{a^2 g} \qquad (20)$$

and,

$$\tau = \frac{A q_{in\_ss}}{a^2 g} \qquad (21)$$

The equations 18, 19, 20 and 21 are linear model equations for obtaining K and τ. Then for validation, the equations are compared with the calculation result. The simulation result with the non linear model equation, equation (6) and the gain K from non-linear model simulation results is obtained through equation (22), as follows: [6]

$$K = \frac{\text{output on steady state}}{\text{intput on steady state}} = \frac{\Delta y}{\Delta x} \qquad (22)$$

As for obtaining the time constant, the equation (23) is used: [8]

$$\tau = K\,A \qquad (23)$$

where A is tank area (m^2)

B. Level Transmitter

Level Transmitter (LT) is an instrument to measure water level in the tank. The type of LT which is used in this experiment is the differential pressure transmitter. The LT measures the level by measuring the pressure difference P (Pa) between the pressure inside the tank caused by the water level with the relative pressure to the atmosphere, as shown in Fig. 6 [6.7],
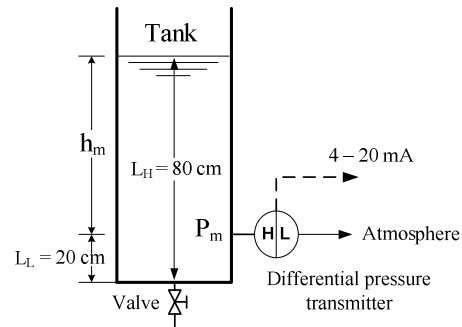

Fig. 6. Measuring the water level in the tank on the simulator [3]

Where h_m is level measuring span (m), L_H is maximum water level (m) measured from the bottom of the tank, L_L is minimum level of measurement (m) and P_m is pressure of measurement (Pa).

The level measurement using differential pressure transmitter is represented in the block diagram as shown in Fig. 7. [4]
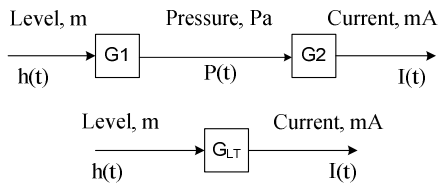
Fig. 7. Block diagram of level measurement
using differential pressure transmitter [4]

In Fig. 7, block diagram G1 shows the relationship between pressure P with level h using the following equation: [4][7]

$$P(t) = \rho\, g\, h(t) \qquad (24)$$

Where P in Pascal (Pa), ρ is water density (kg/m^3) and g is gravity (m/s^2). By substituting the values of ρ and g into equation (24), G1 is obtained.
Furthermore, based on Fig. 8, the gain of G1 is obtained by the following equation [4]:

$$G1 = \frac{[P(t)]}{[h(t)]} \qquad (25)$$

Block diagram G2 is the relationship between the pressure input signal with the output signal electric current [4].
To obtain the value of G2, the differential pressure transmitter specification is used as shown in table 1.
Furthermore, based on the pressure input specification of the differential pressure transmitter, the differential pressure is can be known by:

$$\Delta P = \Delta p_{max} - \Delta P_{min} \qquad (26)$$

Where ΔP is the pressure measurement span of the differential pressure transmitter (Pa), Δp_{max} is the maximum pressure measuring point of the differential pressure transmitter and ΔP_{min}, is the minimum pressure measuring point of the differential pressure transmitter.
The maximum height level Δh which can be measured by the differential pressure transmitter is obtained with the following equation:

$$\Delta h(t) = \frac{\Delta P(t)}{\rho\, g} \qquad (27)$$

From Figure 6, the span level h_m measurement on the simulator uses the following equation:

$$h_m = L_H - L_L \qquad (28)$$

The equation for the maximum measurement pressure signal P_m of the differential pressure transmitter is obtained from equation (29):

$$P_m = \frac{\Delta P}{\Delta h}\, h_m \qquad (29)$$

The differential pressure transmitter convert the pressure input signal, into an output current signal with a range of 4 to 20 mA.
Thus, G2 differential pressure transmitter gain is obtained by the following equation:

$$G2 = \frac{I(t)}{P(t)} = \frac{I_{max} - I_{min}}{P_m} \qquad (30)$$

Where I_{max} = 20 mA and I_{min} = 4 mA

Then, G_{LT} in Fig.7 is obtained by the following equation:

$$G_{LT} = G1\, G2 \qquad (31)$$

C. Final Control Element (FCE)

The final control element using control valve as shown in Fig. 8, the control valve as an actuator to control the flow rate of water filling in the tank.
The valve is mounted to the pipe where water flows through the valve body. The size of opening that the liquid flows through is given by the position of the valve stem. This is controlled by changing the pressure on one side of the diaphragm which causes a change in the position of the plug. It can be done because it is controlled by the pressure changes that occur in the diaphragm, it causes the position of the plug changed. The pressure signal to the diaphragm is obtained from the current to pressure converter (I/P), it is a device that converts an electrical signal (4 mA to 20 mA) to a proportional pressure signal output (0.2 bar to 1 bar or 20 kPa to 100 kPa) [4].
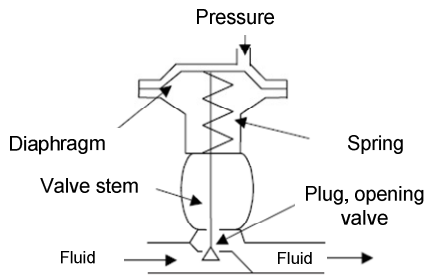
Fig. 8. Diagram of Control Valve [4]

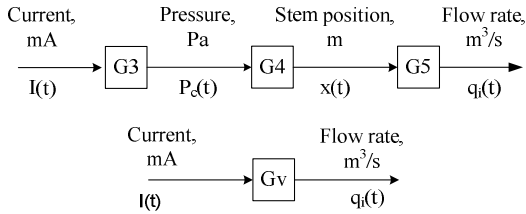The control valve is illustrated in the block diagram as shown in Fig. 9,

Fig.9. Block diagram of control valve [4]

The G3 block diagram is the gain of current to pressure converter (I/P) which is obtained by equation as written as follows [4]:

$$G3 = \frac{P_c(t)}{I(t)} = \frac{P_{max} - P_{min}}{I_{max} - I_{min}} \qquad (32)$$

Where P_c is output pressure signal (kPa) from I/P, and I is input signal to I/P (mA) as shown in tabel I.

In the G4 block diagram is the relation between the pressure acting on the diaphragm to the valve stem position is obtained using the following equation:

$$P_c(t) \, A_d = K_s \, x(t) \qquad (33)$$

Where A_d is diaphragm area (m^2), K_s is spring stiffness constant (N/m) and x is change in stem position (m).
Equation (33) is solved to obtain x(t) so that the equation for x(t) can be written as follows:

$$x_{(t)} = \frac{A_d}{K_s} P_c(t) \qquad (34)$$

Then G4 gain is obtained by using equation as follows:

$$G4 = \frac{x(t)}{P_c(t)} \qquad (35)$$

The G5 diagram block is relationship between valve stem position with flow rate of water flowing out of valve.
The flow rate of water q(t) (m^3/s) that passes through the valve is given by the following equation [4]:

$$q(t) = \alpha(t) C_v \sqrt{\frac{\Delta P(t)}{\rho}} \qquad (36)$$

Where $\alpha(t)$ is the fractional opening of the valve (m), C_v is the flow coefficient of the valve, $\Delta P(t)$ is the is pressure drop across the valve (Pa) and ρ is the density of the liquid (kg/m^3). Using linear valve type, the value of α is the stem position $x(t)$ of the valve. Assume that pressure drop across the valve is constant, the water flow through the valve is linearly related to the valve stem position. Hence the process valve model is given by the following equation [4]:

$$q(t) = G5 \, x(t) \qquad (37)$$

From equation (37) G5 is obtained by equation (38):

$$G5 = \frac{q(t)}{x(t)} = \frac{m^3/s}{m} \qquad (38)$$

Since the used valve has linear characteristics, the G5 gain is calculated as follows:

$$G5 = \frac{q_{max}}{change \ in \ stem \ position \ 100\%} \qquad (39)$$

Where q_{max} is flow rate maximum of water (m^3/s).
Then G_V in Fig. 9 is obtained by following equation:

$$G_V = G3 \, G4 \, G5 \qquad (40)$$

IV. RESULT AND DISCUSSION

A. *Process Tank*

For the water level h in the tank will reach a maximum height of 0.8 m with the flow rate of water filling to a tank q_{in} set to a maximum of 19 liters/min or 0.0003154 m³/s and g = 9.8 m/s² obtained by adjusting the opening of the valve K1 as shown in Figure 2. Then by using equation (5), it is found that the opening area of the valve K1 is 7.97 x 10⁻⁵ m², as shown in Fig. 5.

Further, based on equation (6) a simulation for obtaining process dynamics at the level h(t) that occurs when the water flow rate q_{in} = 0.0003154 m³/s fills in the tank and a = 7.97 x 10⁻⁵ m², using Simulink as shown in Fig.10, the simulation results as shown in Fig. 11.
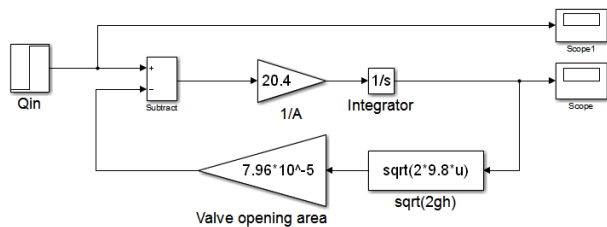
Fig.10. Programming to get the process dynamic of the tank

a. Step input, flow rate of water = 0,0003154 m³/s

b. Output response curve, water level in the tank
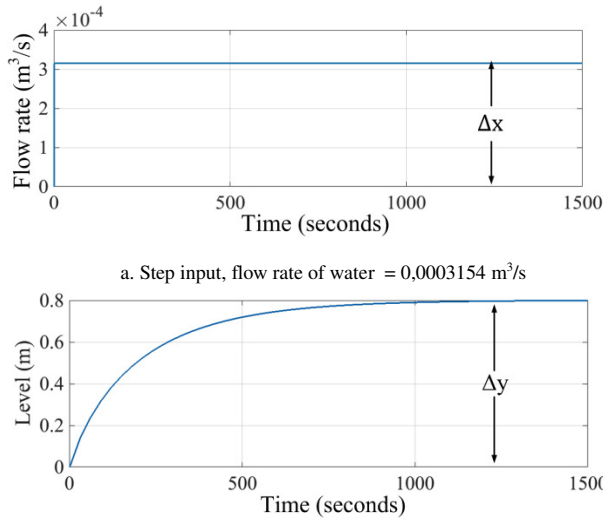
Fig. 11. Simulation response curve, non-linear model of the tank

Based on the response curve of Fig. 11 and the equation (22) the gain K = 2536.46 s/m² can be obtained. Then using equation (23), where the tank area A = 0.05 m2, the time constant is τ = 124 seconds.

The values of K and τ are obtained by the equation of the non-linear model of the process tank equation (22) and equation (23). As for the linear model, from the simulation results and comparing the results of non-linear model calculations by using equation (18) and equation (19), the water level at steady state h_{ss} is obtained, where the level at steady state is 0.2 m.

The flow rate of water at steady state q_{oss} using equation (20) and equation (21) is obtained, q_{oss} = 0.0001577 m³/s.

For validation of the linear tank model, where h_{ss} = 0.2 m and q_{in_ss} = 0.0001577 m³/s, by simulation using Simulink, the linear model tank response curve and non-linear model of water level in the tank are compared the flow rate of water input is in steady state, transfer function of linear model using value of K and τ obtained by equation of non linear model as follows:

$$G(s) = \frac{2536,46}{124,44\ s+1}$$

The Simulink programming for validation is shown in Fig. 12.
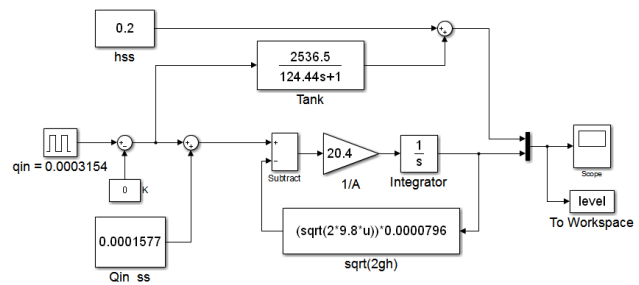

Fig. 12. Programming to compare between non-linear tank model and linear tank model. [5]

Then, result of the simulation is shown in Fig. 13 is known that the steady state of level response curve for linear tank model is equal to the non-linear tank model, or the steady state of level response curve for linear tank model is coinciding with the non-linear tank model.
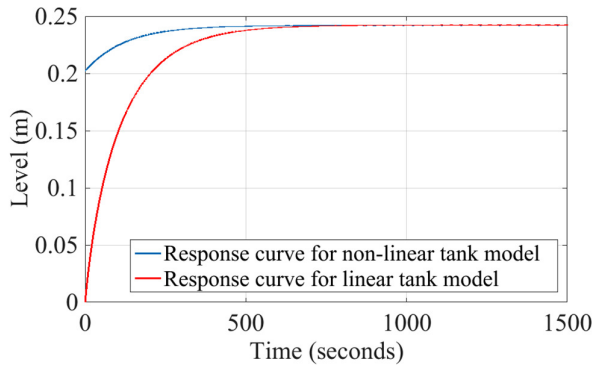
Fig.13. Water level response curve in linear model tank, and non-linear model, to steady-state flow rate of water input q_{in_ss}= 0.0003154 m³/s

Thus, the linearity of the tank model with K = 2536.46 and time constant = 124 seconds is validated. The block diagram of Fig. 4 can be simplified as shown in Fig. 14.
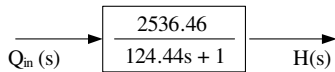

Fig.14. The tank model has been linear

B. Level Transmitter

In the block diagram of Fig. 8, the G1 is obtained as follows:
by using the equation (24), where $\rho \approx 1000$ kg/m³ and g = 9.8 m/s², So, $P(t) = 9810\ h(t)$.
Then, using equation (25), G1 gain is obtained,
$G1 = 9810\ {}^{Pa}/_m$
Furthermore G2, based on the differential pressure transmitter specification, it is known, that is,
ΔP_{max} = 100 IN H₂O $\approx$ 25000 Pa, ΔP_{min} = 0
Then, using equation (26) is obtained ΔP,
ΔP = 25000 Pa.
The maximum level measured by the differential pressure transmitter be calculated by using equation (27) and the result is,
Δh = 2.55 meter.
Then, using equation (28) and Fig. 6, where LH = 0.8 m and LL = 0.2 m, the span measuring the water level in the tank h_m 0.6 meter.
Thus, using equation (29), the maximum pressure measured by the differential pressure transmitter P_m is obtained P_m = 5864.55 Pa and

the pressure range measured by the differential pressure transmitter is 0 to 5864.55 Pa.

The pressure input is converted by the differential pressure transmitter into an output current signal of 4 mA to 20 mA. By using equation (30), G2 gain is obtained,
$G2$ = 0.00273 mA/Pa
Then, using equation (31), the gain of G_{LT} is obtained,
G_{LT} = 26.76 mA/m.
So the block diagram of level measurement using differential pressure transmitter becomes as shown in Fig. 1:
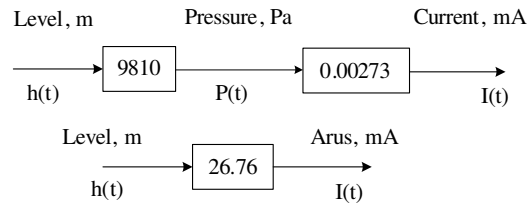

Fig. 15. The component values of the LT block diagram

Now the block diagram for G_{LT} in the form of Laplace transform ca be presented as shown in Fig. 16.
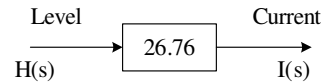

Fig.16. Block diagram of LT with gain

C. Final Control Element (FCE)

The final control element (FCE) in this system is a control valve with a linear characteristic.
The block diagram G3 as shown in Fig.10, consists of current input signal I between 4 mA to 20 mA to I/P. It produces a pressure output P_c between 0.2 bar to 1 bar = 20 kPa to 100 kPa. By using the equation (32), G3 gain is obtained,
G3 = 5 kPa/mA
Assume that the diaphragm area A_d is 0.022 m² and the spring constant K_s is 173228 N/m. By using equation (34), G4 gain is obtained,
G4 = 1.27 x 10⁻⁷ m³/N
Or by using equation (35) G4 gain is 1.2 x 10⁻⁷ m/Pa.

In block diagram G5, the maximum flow rate of water flowing in the industrial plant process simulator is 19 liters/min = 0.0003154 m³/s. Because the input changes of the stem is in meter and it is known that the size of the diameter of the used valve is 0.5 Inch (as shown in table 1), the full range input change of the stem is 0 to 0.0127 m. G5 can be obtained for change valve stem of 1 mm or 0.001 m with 7.874% of the full range.

By using equation (38), G5 gain is obtained, G5=0.02.5 m³/s/m.

By using equation (40), G_v gain is also obtained, $G_V = 1.577 \times 10^{-5}$ m³/s/mA.

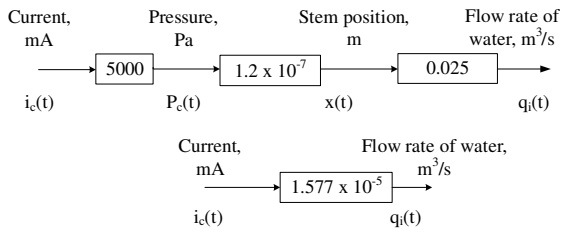Then, diagram block diagram in Fig. 9 can be presented as follow:

Fig. 17. The component values of the control valve block diagram

and Gv diagram block in Laplace transform is shown in Fig.18.

Fig. 18. Block diagram of control valve with gain

D. Stability

By entering the values that have been obtained for G_V, G_{LT}, Level, also the value of K for $G_C = 1$ into the block diagram of Fig. 3, then block diagram can be presented as shown in Fig.19.

To test the stability of the simulator, in this paper, the Root Locus of the closed-loop transfer function is used as shown in Fig. 20. The detailed analysis in MATLAB is shown in Fig. 21.
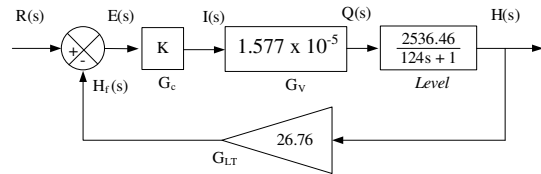

Fig. 19. Component values of block diagram water level control in the tank on the simulator
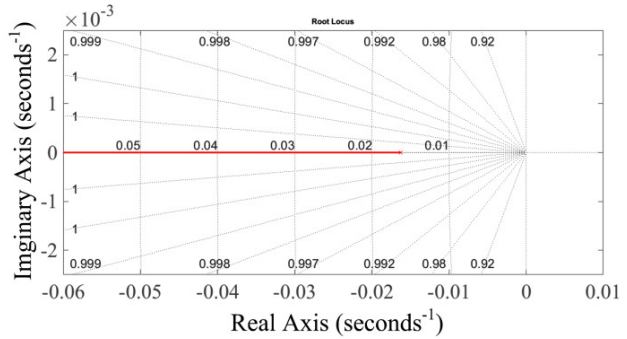

Fig. 20. Root locus of water level control on simulator

Fig. 20 shows the location of the pole on the left side of the s-plane with a real value of -0.0162, this mean that the simulator is stable. From Fig. 20, it is also known that if the gain continues to increase, the system will remain stable. As shown in Fig. 21.

Then, with the step input of the transfer function in Fig. 19, which in this paper is given a gain K from 1 to 1000, from the output response curve of the closed-loop transfer function, the simulator will remain stable. As shown in Fig. 21,
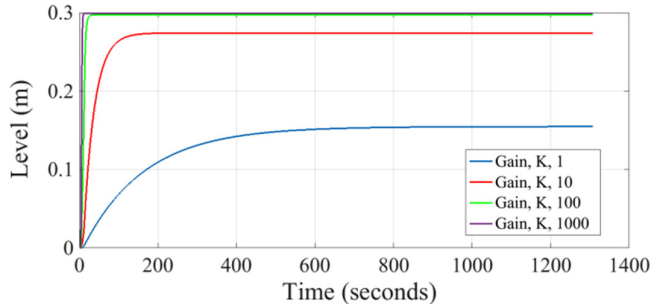

Fig. 21. The response curves to the step input of the water level control in the simulator

V. CONCLUTION

The water level in the tank of the simulator can reach a maximum of 80 cm it is obtained with the input of flow rate of water filling the tank as much as 19 liters/minute, and the valve opening area for water out of the tank of 7.97 x 10^{-5} m^2.

So it is also obtained that the tank has a gain of 2536.46 and the time constant 124 seconds.

Furthermore, the stability of the simulator based on Root Locus and the response to the step input is stable.

ACKNOWLEDGEMENT

Note:
Since June 24, 2014 the name of Research Center for Calibration, Instrumentation and Metrology - Indonesian Institute of Sciences (Research Center for KIM-LIPI), changed to Research Center for Metrology - Indonesian Institute of Sciences (Research Center for Metrology-LIPI).
Source:
http://pui.ristekdikti.go.id/index.php/lembaga/profil/q2O7rn7

REFERENCES

1. *The Control Handbook, CRC Press (1999)*

2. *H. Y. Cao, Na Deng, "Design of water tank level cascade control system based on siemens S7—200", 11th Conference on Industrial Electronics and Applications (ICIEA), IEEE, 2016.*

3. *I. R. Setiawan, "Pembuatan Mini Plant Sebagai Simulator Instrumentasi Untuk Pengukuran dan Pengendalian Proses dan SCADA di Industri", PPI-KIM, 2010.*

4. *Wilkie, A. M. Johnsons, R. Katebi, "Control Engineering: An Introductory Course", Palgrave Macmillan, 2002.*

5. *K. Muller, "Simulation and Process Control", University of Applied Scinces Bremerhaven.*

6. *I. R. Setiawan, "Penalaan PID Kontroler dengan Metode Ziegler-Nichols pada Sistem Pengendalian Bertingkat LC-FC", (Thesis), Universitas Nasional, Jakarta, 2002.*

7. *N. A. Anderson, "Instrumentation For Process Measurement and Control", Chilton Company Radnor, Pennsylvania.*