SSRG International Journal of Electrical and Electronics Engineering
ISSN: 2348 – 8379 / https://doi.org/10.14445/23488379/IJEEE-V8I6P104

Volume 8 Issue 6, 23-27, June 2021


*Original Article*

# Design the Temperature Controller Application for Heat Transfer System in the Laboratory

Mai Trung Thai[1], Nguyen Trong Toan[2], Nguyen Nam Trung[3]

[1,2,3]*Thai Nguyen University of Technology, Thai Nguyen city, Viet Nam*

Received Date: 08 May 2021
Revised Date: 10 June 2021
Accepted Date: 23 June 2021

***Abstract*** - *In this paper, a water temperature control system in a Pirex tank is designed for education and training purpose. Students can also use this system to conduct experiments in the scientific research topics. Our first task is to build mathematical model based on physical laws. After that the transfer function parameters are identified experimentally based on the step input response. Water temperature control system required to reach to the temperature set-point in a certain range of time and to avoid overshooting and steady-state error. Therefore, the PID controller, MPC controller and SMC controller featuring a PID-type sliding surface are designed and compared. Finally, simulation results show that the control system works stably and the short settling time and small overshoot. The main advantage of SMC and MPC is its ability to reject disturbances and deal with system uncertainties better than PID while its drawback is the chattering effect which is again addressed in literature by different techniques. In addition, it can be also used as a tested for verifying new control algorithms.*

**Keywords -** *PID-SMC, MPC, First order inertia system with delayed-time, Water temperature control.*

## I. INTRODUCTION

Temperature control is one of the main problems encountered in factory automation and process control [1 2 6-9]. It is also extremely interesting for teaching purposes, because temperature varies very slowly over time and therefore makes it possible to apply different control techniques and assess the effects of the control parameters involved. Following the development of the water temperature control system that was successfully built [3] using the equipment that is available in the lab of our major. In all fields of industry and civil, there are always variables of heat process using for in production processes. Water temperature control is one of the most widely used processes in academic laboratories and industries [3]. Students may test out the use of different types of regulators, as are currently employed in industrial applications, and the tests can be performed in highly realistic conditions, as the system is entirely made of industrial quality components. In this paper, a transfer function model of system is constructed through experiment, after that, applied the PID, MPC and SMC controllers of the system.

## II. TEMPERATURE CONTROL SYSTEM.

### *A. Describe the thermal process.*

The major components of the studying system are water tank, electric heating resistance (R=30Ω, $P_{max}$ = 1,6KW), sensor PT100, pump, flow meter, and the single-phase AC-AC converter (*phase-angle control circuit).* The physical size of the Pirex tank is 1 liter. The heating element is fixed inside the Pirex tank. The aim of this process (Fig.1) is to control the water temperature in a Pirex tank to reach to set-point, and to be kept constant at desired value. A temperature sensor is used for the measurement of the water temperature inside the tank. The output of the sensor which is proportional to the temperature is feedback to the controller to stabilize the set value. The water is taken from the general tap water for the experimental building through a centrifugal pump and is introduced into a circuit. During its forced circulation, the water reaches the Pirex tank, where it can be heated by varying the intensity of the electric current through a resistor. From the Pirex tank, the water go out. The outgoing flow is equal to the inlet flow. The flow can be adjusted through valve and measured by means of flow-meter. The value of the controlled quantity is acquired through a PT100 probe.

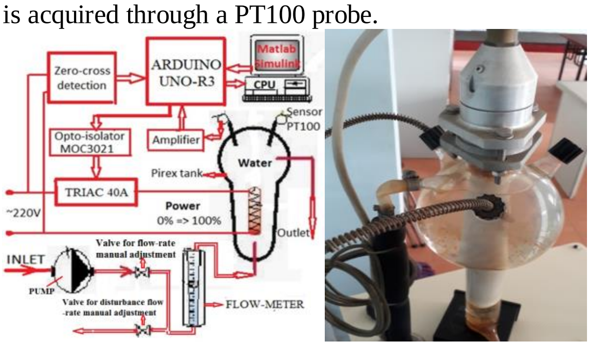


**Fig. 1 The system model**

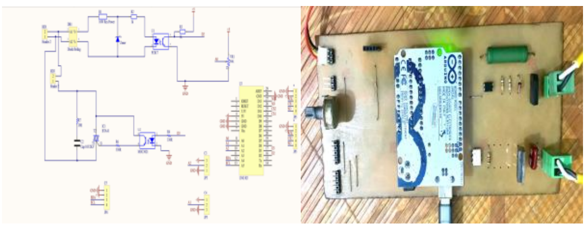

**Fig. 2 The phase-angle control circuit**

### *B. Thermal model of the water tank [3]*

Thermal model of the water tank is established in [3]:

$$\frac{T}{Q} = \frac{R_T}{R_T C_T s + 1} e^{-\tau s} = \frac{K}{Ts+1} e^{-\tau s} \quad (2)$$

Note that, the time constant of the system is:

$$R_T C_T = T \quad (3)$$

The constrained condition of the control function is:

$$0 \le Q \le 1 \quad (4)$$

With *0, 1* are the under and upper limit of the supplied power respectively (W).

### *C. Parameter identification of the system[3]*

In this experiment, we will derive a model for the thermal dynamics of the water tank based on the step response data recorded. That is, we will fit a model to the data without any consideration of the underlying physics of the system. Examination of the recorded data indicates that the thermal dynamics of the water tank are approximately first order with delayed time. Therefore, we will fit a transfer function to the data of the form shown below. In order to identify the parameter of the system, a step response is obtained as shown in Fig. 2, where the type of input is step function with amplitude of 80% of the power and the sampling time is $T_s = 1s$ and flow rate is 12kg/h.

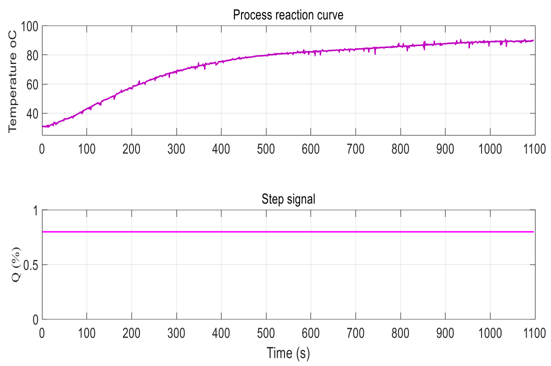


**Fig. 3 Step response of the water tank**

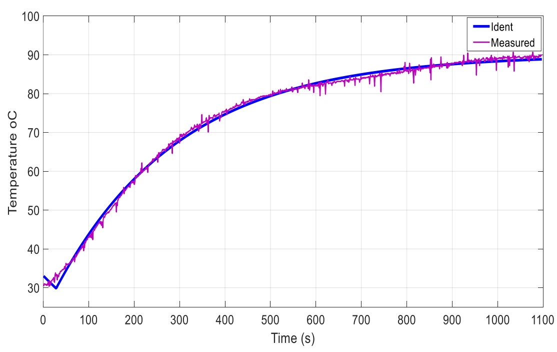


**Fig. 4 Best Fits 94.51%**

From inspection of the given step response data, the ambient temperature (initial water temperature) appear to be approximately 32 degrees C, while the steady-state water temperature appears to be about 88 degrees C. Based on the step response and using System Identification Toolbox in Matlab, the process model is obtained as follows:

$$G(s) = \frac{K}{Ts+1} e^{-\tau s} = \frac{131,72}{240,1s+1} e^{-30s} \quad (5)$$

Where $K$ is the static transfer coefficient, $\tau$ is the delayed time (s), $T$ is the time constant of system (s)

## III. DETERMINING THE PARAMETERS OF CONTROLLERS

The designed system consists of a Pirex tank, made of glass, a 30 Ω resistance, a temperature sensor PT100, an Arduino Uno-R3, a triac 40A and 220 V–50 Hz power supply. The test circuit uses a small power Triac with incandescent lamp while running with 1600w load will use Triac 40A. Arduino is used to control a Triac's gate in the phase angle control circuit using Arduino. More details about the experiment and its results can be found at: https://www.youtube.com/watch?v=V-R7BOXrL14&feature=youtu.be&fbclid=IwAR3iV6Wu938dV2CsV0WMSqTx55s8ixb6ymrJHasYT0z08i2uAP0okf0iUVc

***A. PID Controller Design*** [3].

***B. SMC Controller Design*** [10 13].

The sliding mode controller is developed based on the first-order Taylor series expansion:

$$\frac{T}{Q} = \frac{K}{T_1 s + 1} e^{-\tau s} = \frac{K}{T_1 s + 1} \cdot \frac{1}{\tau s + 1}$$

In differential equation form

$$T_1 \tau \frac{d^2 \Delta T(t)}{dt^2} + (T_1(t) + \tau) \frac{d \Delta T(t)}{dt} + T_1 = KQ(t)$$

There are many options to select the sliding surface, in our case *S(t)* was selected based on PID algorithm acting on the tracking error e

$$S(t) = \frac{de}{dt} + \lambda e + \lambda^2 \int_0^t e dt \quad (6)$$

Then, the complete SMC controller can be represented as follows

$$Q(t) = \frac{T\tau}{K} \left[ \frac{\Delta T}{T\tau} + \lambda^2 e \right] + Kd \; signS(t) \quad (7)$$

Where: $\lambda = \dfrac{T_1 + \tau}{2 T_1 \tau}$

In control law (7), the switch term *sign* is a robust term used to overcome disturbances. However, lager value of *Kd* may cause chattering of control input. Moreover, to reduce chattering we can also choose from several types of Lyapunov functions introduced in the documentation [13].

The stability analysis is performed with the Lyapunov candidate shown in the equation

$$V = \frac{1}{2} S^2(t)$$

We proceed for the analysis to derive the equation

$$\dot{V} = S\dot{S} = S\left[ -\frac{K}{T_1 \tau} Kd.signS(t) \right] = -\frac{K}{T_1 \tau} Kd \left| S \right| < 0 \quad (8)$$

***C. MPC controller design*** [11 12].

MPC is a model based control technique and it uses process model to optimize the control signal without violating input or output constraints by minimizing the cost function. The basic structure of MPC is shown in Fig. 5

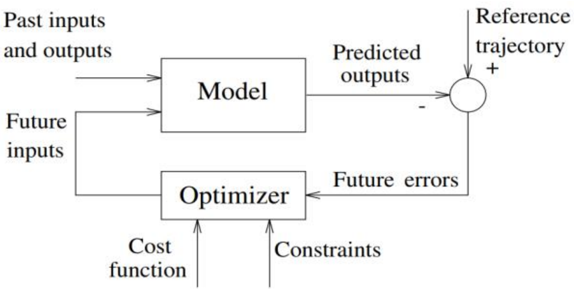


**Fig. 5 Basic structure of MPC**

The MPC is based on a model and optimizer. A model is used to predict the future plant outputs, based on past and current values and on the control signal calculated by the optimizer taking into account the cost function where the future tracking error and the constraints are considered.

One of the most popular MPC methods is generalized predictive control (GPC) which makes an explicit use of a model of the process to obtain the control signal by minimizing an objective function:

$$J(N_1, N_2, N_u) = \sum_{j=N_1}^{N_2} [\hat{y}(t+j/t)-w(t+j)]^2 + \sum_{j=1}^{N_u} \lambda[\Delta u(t+j-1)]^2 \quad (9)$$

Where $y(t+j/t)$ is an optimum j-step ahead prediction of the system output on data up to time t, N1 and N2 are the minimum and maximum costing horizons, Nu is the control horizon, $\lambda(j)$ are the weighting sequences (normally chosen as a constant $\lambda$), and $w(k+j)$ is the future reference trajectory.

The objective of GPC is to compute the future control sequence $u(t), u(t+1), ...$ in such a way that the future plant output $y(k+j)$ is driven close to $w(k+j)$ by minimizing the quadratic cost function $J(N_1, N_2, N_u)$

Given a process modeled by a discrete transfer function in the backward shift operator $z^{-1}$

$$\frac{T}{Q} = \frac{B(z^{-1})}{A(z^{-1})} z^{-d} = \frac{bz^{-1}}{1-az^{-1}} z^{-d} \quad (10)$$

And perturbed by an output additive noise given by

$$\frac{1}{\left(1-z^{-1}\right)A(z^{-1})} n(t)$$

Where $n(t)$ is a white noise with zero mean

The used cost horizons are $N_1 = d + 1$ and $N_2 = d + 1 + N$, $N$ being the prediction horizon

Where the discrete parameters a, b and d can easily be derived from the continuous parameters by discretization of the continuous transfer function (4), resulting in the following expressions:

$$a = e^{-T_1/\tau} = 0.9958 \quad b = K(1-a) = 0.5475 \quad d = \frac{\tau}{T_s} = 30$$

Using a sample time $T_s = 1s$ the obtained discrete plant is:

$$G = \frac{0.5475z^{-1}}{1-0.9958z^{-1}} z^{-30} \quad (11)$$

To convert it in discrete time state-space model as shown in Eq.(12).

$$x_{k+1} = Ax_k + BQ_k$$
$$T_k = Cx_k$$
$$\Delta x_{k+1} = x_{k+1} - x_k = A\Delta x_k + B\Delta Q_k$$
$$T_{k+1} - T_k = CA\Delta x_k + CB\Delta Q_k$$
$$x_{k+1} = \begin{pmatrix} A & 0 \\ CA & 1 \end{pmatrix} x_k + \begin{pmatrix} B \\ CB \end{pmatrix} \Delta Q_k \quad (12)$$
$$T_k = \begin{pmatrix} 0 & 1 \end{pmatrix} x_k$$
$$T = \left[ T_{(k_i+1|k_i)}, T_{(k_i+1|k_i)}, ...T_{(k_i+1|k_i)} \right]^T$$
$$\Delta Q = \left[ \Delta Q_{(k_i)}, \Delta Q_{(k_i+1)}, ...\Delta Q_{(k_i+N-1)}, \right]^T$$
$$T = Fx_{k_i} + \phi\Delta Q \quad (13)$$

The minimum of J, assuming there are no constraints on the control signals, can be found by making the gradient of J equal to zero, which leads to:

$$\Delta Q = (\phi^T\phi + R)^{-1}\phi^T R_S - Fx_k \quad (14)$$

Using only the first value of $\Delta$U

$$\Delta Q(k) = k_y r_{k_i} - k_{mpc} x_{k_i}$$

Where:

$k_y$ is the first value of matrix $\left(\phi^T\phi + R\right)^{-1}\phi^T R_S$

$k_{mpc}$ is the first row of matrix $\left(\phi^T\phi + R\right)^{-1}\phi^T R_S$

$$x_{k+1} = Ax_k + Bk_{mpc}x_k + Bk_y r_k$$

The constrained condition of the control function and outlet temperature response

$$Q^{\min} \le Q(k) \le Q^{\max}$$
$$T^{\min} \le T(k) \le T^{\max}$$
$$\Delta Q^{\min} \le \Delta Q \le \Delta Q^{\max} \quad (15)$$

$\Delta Q^{min}$ and $\Delta Q^{max}$ are column vectors with $N_c$ elements. Similarly output constraints are presented in terms of $\Delta$Q.

$$T^{\min} \le Fx(k_i) + \phi\Delta Q \le \Delta T^{\max} \quad (16)$$

Transforming the above Eq. in more compact form as shown in equation below and use it to find an optimized control without violating the constraints.

$$M\Delta Q \le \gamma \quad (17)$$

Where, M is a vector of constraints with its rows equal to number of constraints and columns equal to dimension of $\Delta Q$.

To solve this optimization problem we can use Toolbox optimization in Matlab for Quadratic programming method or use alternating directions of multipliers method for convex convex optimization problem to find out optimal value of $\Delta$Q.

## IV. SIMULATION RESULTS AND DISCUSSION

In order to make the modeling diagram presented, in this part, we have modeled as follows. We use the Matlab software to simulate output response with controllers PID, SMC and MPC.

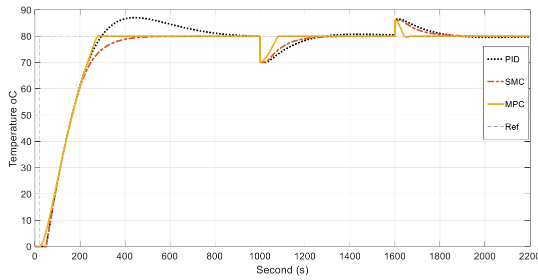


**Fig. 6 Outlet response with step function**

From Fig.6 it is clear that Water-Bath temperature reaches the desired value of 80°C in 240 seconds and the MPC control signal first gets to the peak value of 1.6kW and finally gets off in Fig.7. So from Figs. 6 and Figs. 7 it is evident that MPC successfully regulates the temperature of Water-bath system without violating the input constraints but with only little time delay.

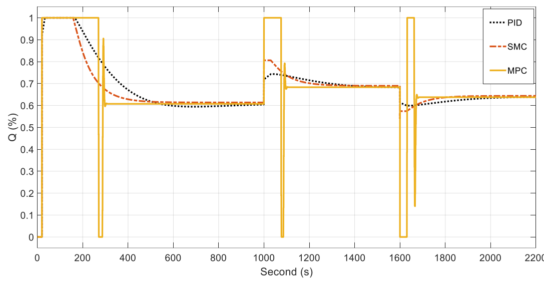


**Fig. 7 The controller outlets with input constraints**

Despite the added noise kicking in after 1000 and 1500 steps respectively, as a result of the model mismatch, some degradation in the response is visible, notably the controller needs a little more time to achieve and maintain tracking. The Q% variable settles in at about 0.6 after the initial part of the simulation (steps from 600 to 1000), at about 0.7 to reject the measured noise (steps from 1300 to 1600), and at about 0.64 to reject both noises (steps from 1900 to 2200). The controller is still able to track the output reference. After all, the controller is still able to track the output reference.

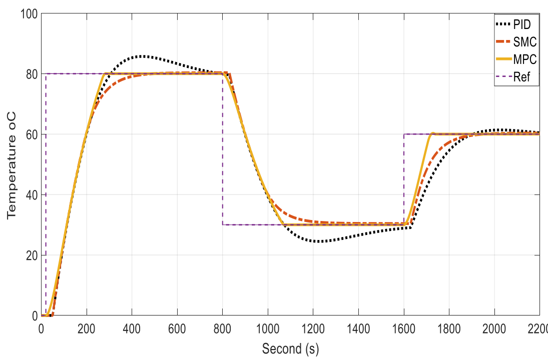


**Fig. 8 Temperature control at different set-points**

The simulation results of controllers with set-points of 80°C, 30°C, and 60°C at different times are shown in Fig.8. In this picture, MPC most effectively regulates the temperature at different set-points.

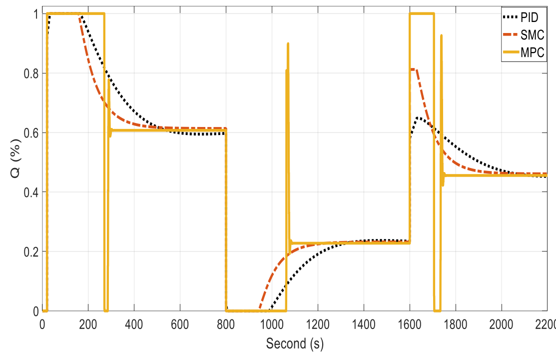


**Fig. 9 Temperature control with input constraints**

The simulation results for two cases are shown in Fig. 8 and Fig. 9, respectively. The settling times of closed-loop systems produced by the SMC, MPC, and PID controllers are 420, 220 and 800 seconds, respectively. The overshoots in percentage made by these controllers are 0.1%, 0% and 6.6%, respectively. MPC controller performs better in dynamic environment by regulating the desired temperature of Pirex tank with different flow rates.

## V. CONCLUSION

This paper has shown the synthesis of the controllers based on a first order inertia system with delayed-time model of the experimental process. MPC is a model based control but SMC is model-free control. The controller parameters are adjusted automatically, on-line, to overcome the disturbances and parameter variations. Simulation tests for the water tank in the laboratory show that the controllers provide very good performance in comparison with the PID. The advantage of the SMC and MPC controllers is simple and practical to implement, ensure the stability of system and have relative lower requirements for precision of model of object. It would take into account the constrained inputs of the control signal ($0 \leq Q \leq 1$) for the controllers and exploit the advantages of both controllers. Simulation results demonstrate that the performance of proposed controller is superior to that of conventional PID controller in both set-point regulation and reference tracking control. Experimental results with controllers will be performed by students in the next step. Thus, it will be easier for students to tune controller parameters and collect data for writing reports. For education and training purpose, it is necessary for student analyzing and performing experimental tasks such as system identification, controller design, and has experience of real-time control.

## ACKNOWLEDGMENT

The work described in this paper was supported by Thai Nguyen University of Technology (http://www.tnut.edu.vn/).

## REFERENCES


[1] Mai Trung Thai., Applying Second-Order Padé Approximation in Optimal Control Problem for a Distributed Parameter System with Delayed-Time. SSRG International Journal of Electrical and Electronics Engineering 8(6)(2021) 1-7.

[2] Mai Trung Thai, Nguyen Nam Trung., Comparison of two Replacing Methods a delayed Object in Optimal Control Problem for a Distributed Parameter System, ISSN 2348-8379, International Journal of Electrical and Electronics Engineering (IJEEE), 7(6)(2020) 11-16.

[3] Mai Trung Thai, Nguyen Nam Trung., Design a Liquid Temperature Controller. Application for Heat Transfer System. SSRG International Journal of Electrical and Electronics Engineering 7(6)(2020) 22-26

[4] Nguyen Trong Toan, Nguyen Nam Trung., Auto-tuning controllers of a class of plants using gradient descent algorithm., International Journal of Engineering and Applied Sciences (IJEAS) ISSN: 2394-3661, 6(6)(2019).

[5] Tran Thien Dung, Nguyen Nam Trung, Nguyen Van Lanh., Control design using backstepping technique for a cart-inverted pendulum system, International Journal of Engineering and Applied Sciences (IJEAS) ISSN: 2394-3661, 6(1)(2019).

[6] Mangesh Sunil Shinde, Varadraj Shridhar Gramopadhye and Vikas Sanjay Bhandari., ZigBee Based Industrial Water Parameter Monitoring and Control System, SSRG International Journal of Electronics and Communication Engineering 3.2 (2016).

[7] Nguyen Nam Trun., Optimal control method for distribution parameter system with delayed time for metal burning process, Vietnam Journal of Science and Technology (VJST) ISSN: 2525-2518., 48(2A)(2010) 780-789.

[8] Verma, O. P., R. Singla and R. Kumar., Intelligent Temperature Controller for Water Bath System., World Academy of Science, Engineering and Technology, International Journal of Computer, Information, Systems and Control Engineering 6(9)(2012).

[9] Long, H.V, Trung, V.Q, Trung, N.N., Điều khiển hệ thống gia nhiệt sử dụng Arduino. Đồ án tốt nghiệp K50, Đại học Kỹ thuật Công Nghiệp Thái Nguyên.

[10] Yangmin Li., Adaptive Sliding Mode Control With Perturbation Estimation and PID liding Surface for Motion Tracking of a Piezo-Driven Micromanipulator. IEEE Transactions on Control Systems Technology, 18(4)(2010) 798-810.

[11] Maciejowski, M.J. (2011): Predictive control with constrains. Prentice Hall

[12] Professor E. F. Camacho, Associate Professor C. Bordons (auth.) Model Predictive control (2007).

[13] A.S.I. Zinober, Variable Structure and Liapunov Control, Springer–Verlag, London, (1994).