EXPERIMENTAL CONSTRUCTION OF A CASCADE CONTROL STRUCTURE FOR LIQUID TEMPERATURE STABILIZATION IN A STIRRED TANK

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Abstract - In food and beverage production, precise liquid temperature control is crucial for product quality. Similarly, in the nuclear industry, liquid temperature strongly affects efficiency, safety, and lifespan. This paper presents a cascade control method for liquid temperature regulation in a mixing tank, with an inner loop regulating flow rate via pump motor speed and an outer loop controlling temperature. The two-loop structure is compared with a conventional single-loop PI controller on the TecQuipment CE117 experimental module. Experimental results show that the cascade PI improves control quality, reducing settling time by approximately 17–36% under different operating conditions and halving recovery time under pump-stoppage disturbances, compared with the single-loop PI. These results indicate that the proposed cascade architecture is suitable for thermal process applications requiring accurate and robust temperature control.

Key words - Liquid temperature control; Cascade control; Process control; PID

1. Introduction

The stable control of liquid temperature in tanks on the production lines of several industries is extremely important and necessary. Specifically, in food and beverage production, temperature affects the output quality of the product, for example, it can determine the flavor, concentration, and shelf life. For the nuclear industry, temperature is a key factor directly related to operational performance and safety. An unstable temperature value deviating from the setpoint can indirectly lead to the risk of serious safety incidents. With a similar role, in the chemical and pharmaceutical industries, temperature is a prerequisite for certain chemical reactions. Temperature deviations can create low-quality final products or cause inappropriate reactions. Given these requirements, precise and stable temperature control is a topic of great interest and research to ensure quality, efficiency, and safety. In addition, factors such as ambient temperature and unstable liquid flow rate can introduce uncertainty and disturbances into the system. These factors make precise temperature control difficult. Therefore, appropriate control strategies are needed to mitigate these disturbances effectively.

Many studies have been published on the stable control of liquid temperature in industrial production processes. Using a single-loop control is one of the most basic and easily implementable structures. In this structure, the temperature variable is directly adjusted by a single controller. Document [1] designed a temperature control system for a general-purpose furnace but did not tie it to a specific application. The experimental model was simple, consisting of a furnace made of mica and 3D-printed joints. Inside the furnace, a layer of foam was placed for thermal insulation, and an LM35 temperature sensor read the temperature generated by a light bulb.

To address temperature fluctuations caused by On-Off control in aluminum ageing furnaces, reference [2] implemented a PID controller within a single-loop structure. Based on a First-Order Plus Dead-Time model of the furnace, the study performed simulations to compare various tuning methods for PI and PID controllers. The simulation results indicated that while the PID controller improved stability compared to the On-Off method, conventional tuning techniques like Ziegler-Nichols still produced significant oscillations, whereas other methods compromised the system's response speed. This work was primarily based on simulation results and did not account for complex nonlinearities and disturbances present in real-world conditions. In [3], a PID controller was used to control heat from hot gas for cooling liquid condensation. The control signal acted on the valve's opening, and simulation results showed that the temperature was maintained stably under disturbance scenarios. In [4], the temperature of a small satellite model's fuel tank was controlled. A single-loop structure was used with a PID controller that included an anti-windup component to control the heat flow rate. Simulation results, which considered periodic disturbances caused by the satellite's orbital motion, showed that the system successfully tracked the reference temperature. Document [5] used a single-loop structure based on a traditional PID controller, where a fuzzy logic technique was applied to tune the PID coefficients, acting on the valve opening in the simulation and the heater voltage in the experiment. However, designing the initial fuzzy rules and membership functions required a deep understanding of the process and was labor-intensive. The single-loop control system struggled to ensure a fast response speed.

In [6], a single-loop structure with a fuzzy-PID controller was used to control the power of a liquid heater. The main content focused on the influence of the slow response time of the temperature sensor when placed in a protective sheath. Comparative dynamic performance indicators showed that the fuzzy-PID controller was better than the PID controller, considering large time delays and process disturbances. Document [7] used a single-loop structure with a digital PID controller to adjust the electric heater's power. This paper evaluated and compared performance when using a thermometer with a small time constant to improve control quality compared to a large-inertia temperature measurement device. Conclusions from both simulation and experiments indicated that a large-inertia temperature measurement device can negatively affect the controller's quality. In [8-10], a digital PID controller was proposed to maintain a constant hot water temperature in the tank. Digital filters were used to increase system stability by eliminating the influence of random disturbances indicated by the thermometer. The controller used in the single-loop control structure was implemented only in software simulation processes.

Some works on liquid temperature control, however, have used a cascade control structure. This approach is widely applied to overcome the limitations of single-loop control, such as handling large inertia and time delays. The cascade control structure consists of two nested control loops: a primary (outer) loop and a secondary (inner) loop [11-13]. As in [14], a cascade control structure was used to control the temperature of scientific experimental racks on a space station. The cascade control structure acted on the pump and the opening of electric regulating valves. The enhanced fuzzy logic controller demonstrated improved control capabilities in terms of response time through simulation results.

In [15], the liquid temperature was controlled for a high-precision temperature control system in semiconductor manufacturing. A cascade structure with a PI controller in the outer loop and a P controller in the inner loop adjusted the heater power signal. The design considered thermal inertia and large time delays. Experimental results showed that the system prevented oscillations and improved temperature control precision. Document [16] used cascade control to manage the output temperature of a shell-and-tube heat exchanger. Two PID controllers were used, acting on the inlet fluid flow rate. The uncertainty factor was a disturbance caused by the inlet fluid flow. Simulation results showed that the temperature response tracked the setpoint even with unstable fluid flow. Works [17-19] all used cascade control to stabilize the liquid temperature in a tank, with an external temperature control loop and an internal flow/valve control loop. In these studies, [17] was for a single-tank system, [18] for a two-tank system, and [19] for a three-tank system. Both the inner and outer loops used PID controllers, ultimately acting on the opening of the control valve for the heat transfer fluid under disturbances such as ambient temperature and thermal load variations. Software simulation results showed good dynamic performance for the output temperature response. In [20], the fuel temperature in aircraft tank systems was controlled for both single-tank and two-connected-tanks cases, considering disturbances like pump power changes and inlet flow fluctuations. The structure used an LQR controller acting on the fuel mixing valve and the flow control valve through the cooler. Software simulation results showed that in the single-tank system, there was a remaining issue of temperature overshoot with sudden disturbances.

As a result, the following issues can be identified from studies on liquid temperature regulation in tanks.

First, many studies rely on the single-loop structure even when employing sophisticated controllers such as LQR, PID with anti-windup, or Fuzzy-PID. This limits the exploitation of the cascade control architecture's potential benefits when applied to the same plant.

Second, the results of many studies employing the cascade structure for temperature control are limited to software simulations or experiments conducted on thermal equipment systems that differ substantially from the TecQuipment CE117 benchmark. Therefore, directly applying these findings to a commonly used experimental platform like the CE117 is constrained.

Finally, when cascade control structures are implemented, the secondary loop often manipulates the control valve or heater power, and actuator faults (such as pump stoppage) are rarely investigated experimentally. Consequently, systematic quantitative comparisons between cascade and single-loop control under setpoint change and disturbance scenarios remain limited. Meanwhile, the CE117 experimental model has the characteristics of a liquid tank system in industrial production, including a temperature control loop, a heating control loop, and a flow control loop via pump speed [21]. The novelty of this work lies in a systematic real-time experimental validation on the CE117 platform, including actuator-fault (pump stoppage) scenarios and quantitative performance metrics, rather than in proposing a new controller structure. Therefore, this paper proposes using a cascade control structure to stabilize the liquid temperature in a stirred tank of the given real model.

The paper focuses on the design and application of the proposed system on an experimental model to evaluate response speed, time delay, and the impact of disturbances on control quality. The contributions of this paper are as follows:

Experimental identification: We experimentally identify the mathematical model of the process from the perspective of a two-loop cascade system, which involves more equipment than a single-loop case.

Real-time implementation: We establish a computer-based experimental system using Simulink Desktop Real-Time and a PCIe-6321 card to perform and evaluate the effectiveness of the cascade control structure directly.

Performance comparison: We compare the control quality of the two-loop PID cascade structure with the classical single-loop control structure on the same experimental system.

Actuator influence: The control signal acts on the pump speed to adjust the liquid flow rate in the secondary loop, while the primary control loop acts on the system's output temperature.

In this work, PI controllers are intentionally adopted to isolate the effect of the cascade architecture. Advanced control algorithms (fuzzy-PID, adaptive PI, or MPC) are beyond the scope of this paper and will be investigated in future work on the same CE117 platform.

The experimental results of this study show the advantages of the cascade control structure over the single-loop structure in improving response speed and stability when changes in the setpoint and actuator faults occur.

2. CE117 Experimental Model

The experimental subject used by the authors for research is the CE117 Process Trainer model from TecQuipment, as shown in Figure 1. The model consists of two systems: level control and temperature control. This paper primarily discusses the temperature control system of this model.

Figure 1. *Model CE117*

The liquid temperature control system includes devices such as: a heating tank, a DC pump motor, a heat exchanger coil, a mixing tank, a flow sensor, and temperature sensors, as shown in Figure 2. The specifications of the devices are shown in Table 1. The operating principle of the model for liquid temperature: Water, heated to a maximum of 60°C in the heating tank, is pumped by the DC pump motor to the heat exchanger coil to control the liquid in the mixing tank. The water passing through the heat exchanger coil will lose heat and return to the heating tank. This process will be continuously repeated until the system is stopped [21].

Table 1. *The specifications of the devices are shown in the model*

Device		Analog Signal	Unit Conversion
Temperature Transmitters	TT1 TT2 TT5	0 – 10 VDC Output Linear	10°C/Volt 0°C = 0V 100°C = 10V
Flow Transmitters	FT1 FT2	0 – 10 VDC Output	1 L/min per Volt 0V = No flow
Level Transmitter	LT	0 – 10 VDC Output Non Linear	0V = Empty Vesel 10V = Max Level
Electric Heater		0 – 10 VDC Input	75W/Volt 0V = Heater off 10V = 750W
Proportional Valve	S	0 – 10 VDC Input	0V = Closed 10V = Open
Pump 1 Pump 2		0 – 10 VDC Input	0V=No flow 10V = Max flow

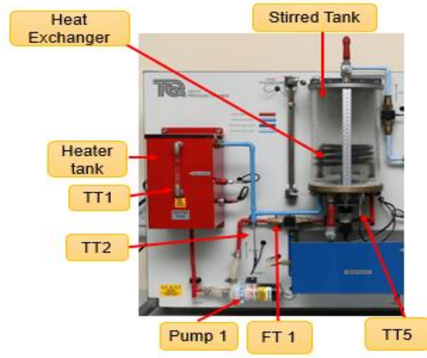


Figure 2. *Temperature control model*

3. Control System

The advantages of the cascade control method are evident, and it is widely used in industrial automatic control systems. However, this method has been relatively less studied experimentally [12-13]. Therefore, the design and implementation of a two-loop closed control structure is proposed and experimentally carried out. Specifically, the paper designs: an inner loop to control the liquid flow rate, an outer loop to control temperature, with a linear PI controller being used. The system structure for liquid level control is shown in Figure 3.

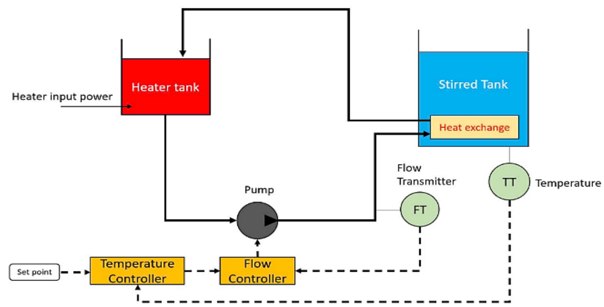


Figure 3. *Diagram of the liquid temperature control structure*

3.1. Process identification

Experimental-based identification has the advantage of allowing relatively accurate determination of model parameters using real data, making it highly applicable and reliable [3],[10]. In this approach, identification based on transient characteristic graphs is applied to identify the real system, focusing on the important variables of liquid temperature and flow rate, while reducing unnecessary signals and improving the accuracy of the analysis [14-15].

The CE117 model is connected to the computer via the CE2000 module, CE120 card, and the Simulink diagram is set up as shown in Figure 4.

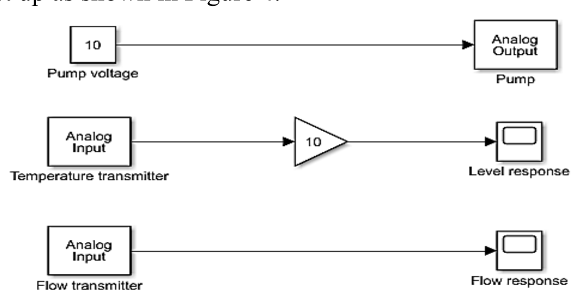


Figure 4. *Temperature data acquisition diagram on Simulink*

Then, monitor the temperature results via Scope screen, Figure 5.

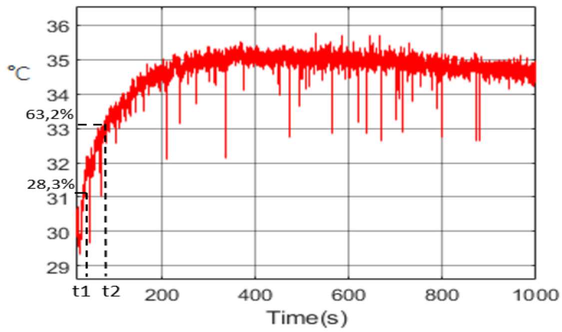


Figure 5. *Transient temperature characteristics*

To describe the dominant dynamics of the CE117 thermal tank, the temperature loop is approximated by a first-order-plus-dead-time (FOPDT) model, while the inner flow loop is approximated by a first-order (FO) model. Let $u(t)$ = 10V be the manipulated input and $y(t)$ be the measured output. For the temperature response (Fig. 5), the FOPDT transfer function is written as:

$$G_t(s) = \frac{k}{(1+Ts)} e^{-ts}$$

where k is the steady-state gain, t is the apparent dead time, and T is the time constant.

In this case, the two-point method is used to determine the mathematical model of the thermal process response.

Draw the asymptotic line of y(t) of $t \to \infty$ to determine $y(\infty)$, then derive the parameter:

$$k = \frac{y(\infty)}{u_0} = \frac{35{,}2-29{,}5}{10} = 0{,}57 \qquad (1)$$

(Note: Decimal commas are used throughout per European convention.)

Determine the point where the ordinate equals $0{,}632y(\infty)$ of y(t).

The abscissa of this point is the parameter $t_2 = 93s$

Similarly, determine the point where the ordinate equals $0{,}283y(\infty)$ of y(t), the abscissa of this point is the parameter $t_1 = 36s$. Continuing with the two-point reference method to determine the model parameters, we have the parameters as follows:

$$T = 1{,}5(t_2 - t_1) = 1{,}5(93 - 36) = 57s \qquad (2)$$

$$t = 1{,}5t_1 - 0{,}5t_2 = 1{,}5.36 - 0{,}5.92 = 8s \qquad (3)$$

Mathematical model representing the thermal process:

$$G_t(s) = \frac{0{,}57}{(1+57s)} e^{-8s} \qquad (4)$$

From the Temperature data acquisition diagram on Simulink, the flow rate response is obtained Figure 6 with u(t) = 10V (the flow-rate value is then converted into an electrical signal).

Figure 6. *Transient flow characteristics*

The mathematical model of the flow process is determined to be of first-order type:

$$G_f(s) = \frac{k_1}{(T_1 + 2{,}7s)}$$

Based on the classical method of drawing a tangent line on the transient response curve of the output to determine the process model parameters. Draw the asymptotic line of y(t) as $t \to \infty$ to obtain y(∞), and the derive the parameter

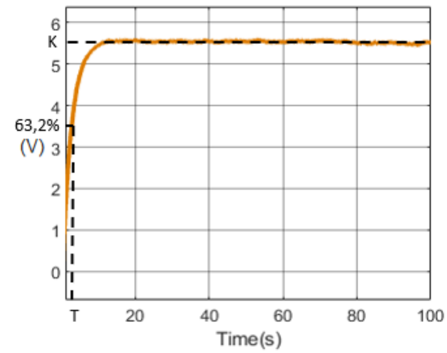
$$k_1 = \frac{y(\infty)}{u_0} = \frac{5{,}55}{10} = 0{,}555 \qquad (5)$$

Determine the point with an ordinate equal to $0{,}632y(\infty)\ of\ y(t)$

The abscissa of this point is the parameter T=2.7s

Thus, the identified parameters are T=2.7s, k=0.555 and the mathematical model representing the flow-rate is given by equation:

$$G_f(s) = \frac{0{,}555}{(1+2{,}7s)} \qquad (6)$$



3.2. Controller Design

The authors used Kuhn's total T method to design the PI controller for the temperature loop and the flow loop [16-17]. Kuhn's total-T tuning was selected because it is directly applicable to the identified FO/FOPDT process models and provides conservative controller gains suitable for real-time experiments. In particular, the CE117 temperature loop exhibits large inertia and dead time, and the measured signal may contain occasional spikes; therefore, overly aggressive tuning can easily lead to oscillations and actuator saturation. Kuhn's total-T rule is one of the classical tuning methods for processes with dead time and typically yields more conservative controller gains and higher robustness margins than Ziegler–Nichols for such cases, which is advantageous for the delayed thermal process considered here [22-23]. IMC-based PI tuning is also a viable option; however, it requires selecting an additional robustness parameter (filter/closed-loop time constant), and the resulting performance depends strongly on this design choice. For these reasons, Kuhn's method was adopted to ensure stable and repeatable experimental implementation.

From equation (4), the transfer function of the liquid temperature process is:

$$G_f(s) = \frac{0{,}57}{(1+57s)} e^{-8s}$$

Calculate the parameters of the PI controller using Kuhn's total T method:

Total time constant: $T_\Sigma = T_j^m + T$= 57+8 = 65 (7)

Proportional gain: $k_p = \frac{1}{2 * 0{,}57} = 0{,}877$ (8)

Integral time constant: $T_I = \frac{T_\Sigma}{2} = \frac{65}{2} = 32{,}5$ (9)

Transfer function of the temperature controller is given by:

$$R_t(s) = 0{,}877\left(1 + \frac{1}{32{,}5s}\right) \quad (10)$$

From equation (6), the transfer function of the flow rate is:

$$G_f(s) = \frac{0{,}555}{(1 + 2{,}7s)}$$

Calculate the parameters of the PI controller using Kuhn's total T method:

Total time constant: $T_\Sigma = T_1^m = 2.7$ (11)

Proportional gain: $k_p = \frac{1}{2 * 0{,}555} = 0{,}901$ (12)

Integral time constant: $T_I = \frac{T_\Sigma}{2} = \frac{2{,}7}{2} = 1{,}35$ (13)

Transfer function of the temperature controller is given by:

$$R_f(s) = 0{,}901\left(1 + \frac{1}{1{,}35s}\right) \quad (14)$$

Before conducting the experiments, we simulate the temperature control system structure with the transfer function and the calculated PI controller parameters on Matlab Simulink, as shown in Figure 7 and Figure 8.

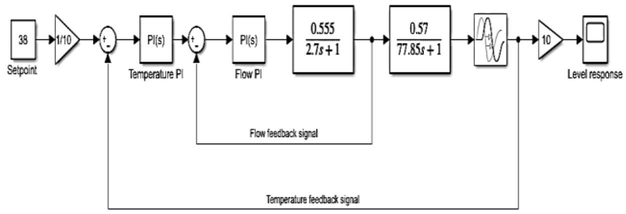


Figure 7. *Two-loop feedback temperature control structure*

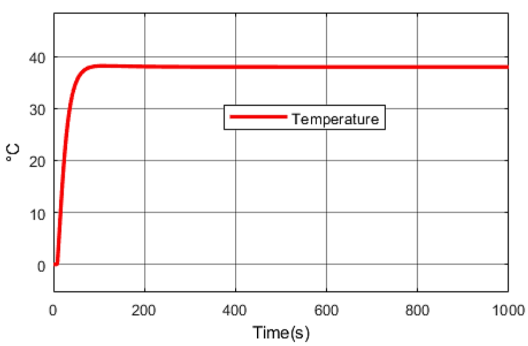


Figure 8. *Temperature simulation results on Simulink*

4. Experimental Results

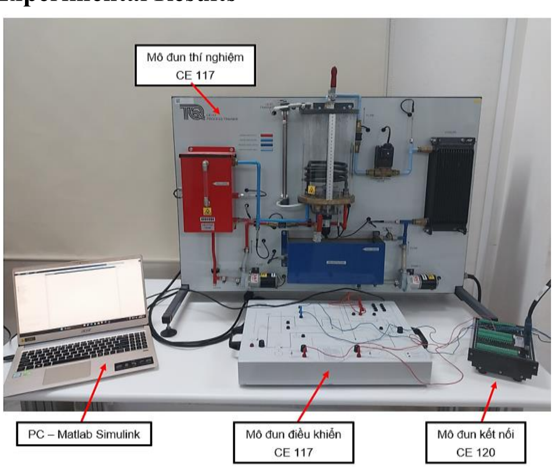


Figure 9. *System connection diagram*

In this section, the paper primarily presents the experimental results of liquid temperature control and provides some results of liquid level control in the mixing tank, as these two systems interact with each other. The experiments used two control methods: single-loop feedback control and cascade control with two feedback loops. The comparison and evaluation highlight the advantages of the cascade control method for both temperature and liquid level control. The experimental results were carried out on the CE117 model from TecQuipment. The system is connected as shown in Figure 8, and the experimental setup is built in Simulink as shown in Figure 9.

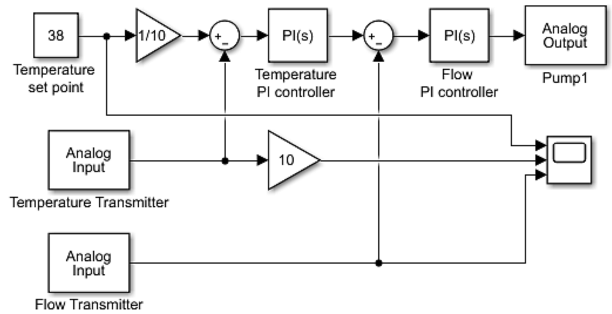
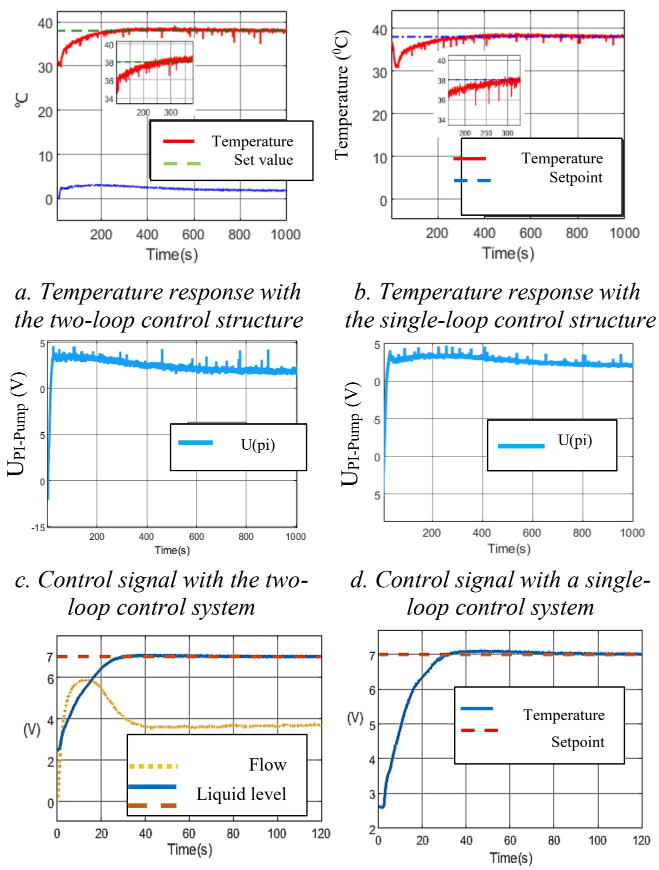


Figure 10. *Experimental run diagram on Simulink*

4.1. When the setpoint is constant

With a temperature setpoint of 38°C and a level setpoint of 7V, the temperature and liquid level responses are as follows:



a. Temperature response with the two-loop control structure

b. Temperature response with the single-loop control structure

c. Control signal with the two-loop control system

d. Control signal with a single-loop control system

e. Level response with the two-loop control structure

f. Level response with the single-loop control structure

Figure 11. *Liquid temperature and liquid level control results*

Figure 11 and Table 2 show that POT and Settling time of the two-loop control structure are smaller than those of the single-loop control structure when controlling temperature. Using a cascade control structure for temperature control results in a response time that is about 40 seconds faster than a single-loop control structure. The response time is significantly shortened, which demonstrates that the quality of this control method is very good for temperature control. Additionally, Figures 10(e,f) clearly demonstrate that liquid level control using the two-loop control structure has a faster settling time and smaller undershoot. Therefore, the results indicate that temperature and liquid level control using the cascade control structure achieve better quality.

Table 2. *Comparison of temperature control quality between the two control methods*

Controller	POT (%)	Settling time (s)	Steady-state error (%)	IAE (°C.s)	ISE (°C^2.s)
Two-loop control structure	1.3	200	0.52	50	25
Single-loop control structure	2.1	240	0.52	84	48

This control method divides the system into two parts with different dynamic characteristics: the inner loop quickly controls the intermediate variable (heat flow), helping to stabilize and respond rapidly to input changes, while the outer loop only needs to control the slower variable (liquid temperature). By breaking the control problem into smaller parts, the overall delay is reduced, and each PI controller can operate more effectively based on the specific dynamics of its respective part, thereby shortening the overall response time of the system.

4.2. When the setpoint changes

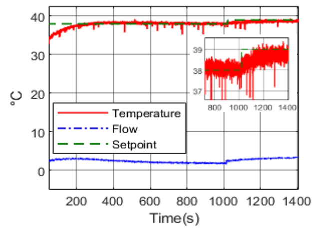
4.2.1. From 38°C to 39°C

At 1020 seconds, the authors increased the setpoint from 38°C to 39°C. The response of the liquid temperature was then monitored.

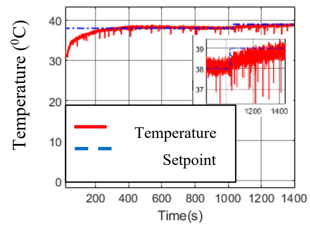
Figure 12 and Table 3 show that the temperature settling time using the cascade control method is 100 seconds faster than the single-loop feedback control method. This demonstrates that the cascade control method is highly effective, significantly reducing the temperature settling time when the setpoint changes. Indeed, the two-loop feedback control structure also provides better temperature control quality compared to the single-loop feedback structure when the setpoint is adjusted.

Table 3. *Comparison of temperature control quality between the two control methods*

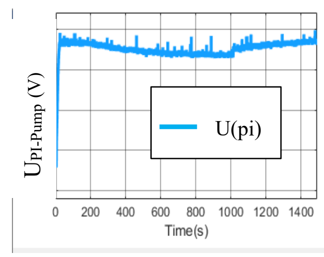
Controller	POT (%)	Settling time (s)	Steady-state error (%)	IAE (°C.s)	ISE (°C^2.s)
Two-loop control structure	0.77	180	0.26	90	90
Single-loop control structure	0.77	280	0.26	168	101



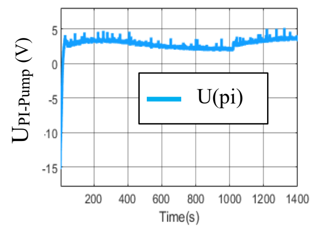
a. Temperature response with the two-loop control structure



b. Temperature response with the single-loop control structure



c. Control signal with the two-loop control system

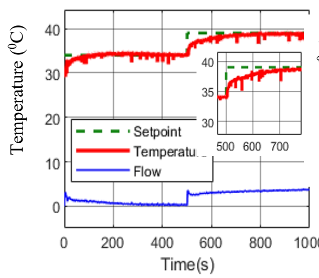


d. Control signal with the single-loop control system

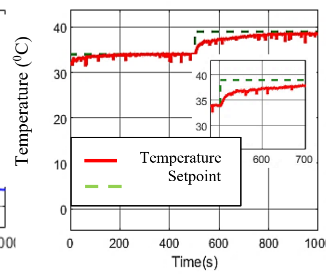
Figure 12. *Liquid temperature control results*

4.2.2. From 34°C to 39°C

Initially, the author set the temperature setpoint to 34°C. At the time of 500 seconds, the setpoint was increased to 39°C. Monitor the temperature response results.



a. Temperature response with the two-loop control structure



b. Temperature response with the single-loop control structure

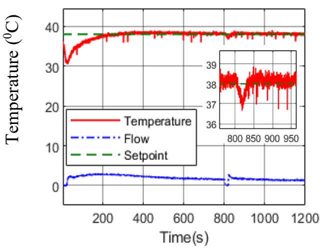
Figure 13. *Liquid temperature control results*

According to Figure 13, when the temperature setpoint is 34°C, the temperature settling time of the cascade control structure is approximately 50 seconds, while that of the single-loop structure is around 100 seconds. When the setpoint is increased to 39°C, the settling time of the cascade structure is about 200 seconds, whereas the settling time of the single-loop structure exceeds 500 seconds. These results indicate that the temperature response quality of the cascade control structure is better.

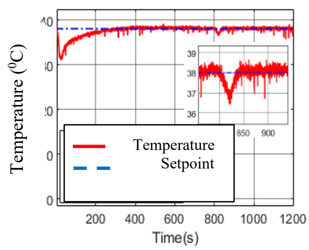
In the cascade control structure, the inner loop directly controls the heat transfer flow rate, which is a fast-responding intermediate variable that directly affects the heating rate. When the temperature setpoint increases, the outer loop quickly adjusts the flow rate setpoint for the inner loop. The inner loop then modifies the heat transfer flow rate almost instantly, resulting in a rapid increase in the thermal energy supplied to the liquid and enabling the temperature to reach the new setpoint more quickly. In contrast, in the single-loop structure, the controller must estimate the required flow rate solely based on the slow-changing liquid temperature, leading to a slower response and a longer adjustment time.

4.3. When a pump failure occur

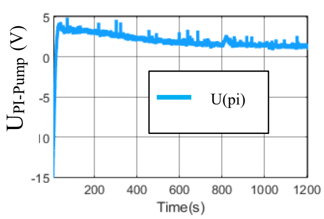
In this case, the authors induced a pump failure in the temperature control system, stopping its operation for 20 seconds at 800 seconds, and halted the pump in the liquid level control system for 5 seconds at 145 seconds.



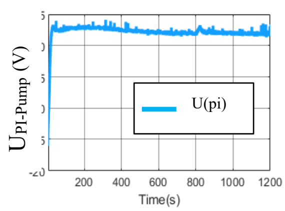
a. Temperature response with the two-loop control structure



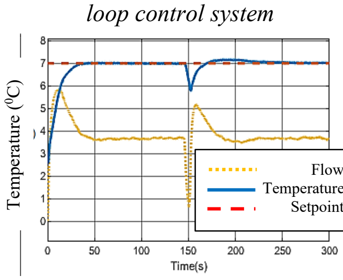
b. Temperature response with the single-loop control structure



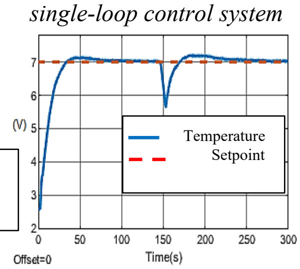
c. Control signal with the two-loop control system



d. Control signal with a single-loop control system



a. Temperature response with the two-loop control structure



b. Temperature response- the single-loop control structure

Figure 14. *Liquid temperature and liquid level control results*

Table 4. *Comparison of temperature control quality between the two control methods*

Controller	POT (%)	Settling time (s)	Steady-state error (%)	IAE (°C.s)	ISE (°C^2.s)
Two-loop control structure	1.4	10	0.65	6	12
Single-loop control structure	1.4	20	0.65	7.2	14.4

Figure 14 and Table 4 show that the two-loop control structure has a slightly faster temperature recovery time compared to the single-loop control structure when a pump failure occurs. For liquid level control, the recovery time of the cascade control method is 70 seconds, whereas the recovery time of the single-loop feedback method is 90 seconds. This highlights the advantages of the cascade control method for temperature and liquid level control systems.

When the pump stops operating for 20 seconds, there is no heat flow to the heat exchanger, causing the tank temperature to drop by approximately 1°C. The system becomes unstable, and the control signal decreases. Once the pump resumes operation, the inner loop of the cascade control structure, which controls the heat flow, can respond immediately to restore the required heat input, while the outer loop only needs to readjust the liquid temperature to the setpoint. This enables the system to return to a stable and accurate state more quickly.

5. Conclusion

In this paper, a cascade control structure for liquid temperature regulation is presented and implemented on the CE117 experimental platform. Experimental results show that, compared with a single-loop PI structure, the proposed cascade approach achieves faster and more accurate temperature responses under setpoint changes, with improved disturbance-rejection and recovery behavior. These characteristics indicate that the proposed structure is suitable for thermal process applications requiring high productivity and precision, such as food and beverage processing, chemical manufacturing, and pharmaceutical production. Future work will investigate more advanced control strategies (e.g., fuzzy-PID, adaptive PI, and MPC) on the same platform and will extend the evaluation to robustness analysis under wider operating conditions, nonlinearities, and measurement/actuator uncertainties.

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