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PID Controller Tuning using Ziegler-Nichols Method for Temperature control of Thermal Cycler

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ABSTRACT: The control of constant temperature according to the desired value (set point) in a closed loop used PID controller system. For this, we are using a microcontroller, a temperature sensor for sensing the temperature of the closed loops. This paper deals with the controlling of temperature of thermal cycler using a PID controller. This project is designed in a way as user defined data, the user sets up the required temperature limit in the PID controller as the controller set point. A heating and cooling element i.e. Thermoelectric Cooler, is used for heating and cooling the metal block and the thermistor sensor placed in the metal block is responsible for sensing the metal block temperature. Based on the controller constant values and the temperature of the metal block is maintained. Ziegler Nichols tuning method is used for the PID controller tuning method. The performance analysis of PI and PID controllers is done for the thermal cycling system.

KEYWORDS: Thermal Cycler, Polymerase Chain Reaction, PID Controller, Ziegler Nichols method.

I. INTRODUCTION

Process control system is often non-linear and difficult to control accurately for the process. Their dynamic models of the system are more difficult to derive. The conventional PID controllers, in various combinations have been widely used for industrial processes due to their simplicity and effectiveness for linear systems, especially for first and second order systems. It has been well known that Proportional Integral Derivative (PID) controllers can be effectively used for linear systems, but usually cannot be used for higher order and non-linear systems [1]. One of its main advantages is that no mathematical modelling is required since the controller rules are especially based on the knowledge of system behavior and experience of the control engineer [2].

The inaccuracy of mathematical modelling of the plants usually degrades the performance of the controller, especially for non-linear system and complex control problems. System mainly includes: PID controller module, the control algorithm module. The PID controller algorithm involves three separate fixed parameters, and is accordingly called three-term control: the proportional, the integral and derivative values P, I, and D. Simply, these values can be interpreted in words of time: P depends on the current error, I on the accumulation of past errors, and D is a prediction of future errors, based on present position of a control valve, a damper, or the power supplied to a heating element.

Thermocyclers, or thermal cyclers, are instruments used to amplify DNA and RNA samples by the Polymerase Chain Reaction (PCR). The thermocycler raises and lowers the temperature of the samples in a holding block in discrete, pre-programmed steps, allowing for denaturation and reannealing of samples with various reagents. Amplified genetic material can be used in many downstream applications such as cloning, sequencing, expression analysis, and genotyping.

A PCR machine is also called a thermal cycler. It rapidly changes temperatures (heating and cooling) for PCR reactions, thereby allowing the reaction to cycle between primer annealing (50-60°C), DNA amplification (72°C), and strand melting cycles (94°C). Each cycle of PCR includes steps for template denaturation, primer annealing and primer extension. The initial step denatures the target DNA by heating it to 94°C or higher for 15 seconds to 2 minutes. In the denaturation process, the two intertwined strands of DNA separate from one another, producing the necessary single-stranded DNA template for replication by the thermostable DNA polymerase. In the next step of a cycle, the temperature is reduced to approximately 40–60°C. At this temperature, the oligonucleotide primers can form stable associations (anneal) with the denatured target DNA and serve as primers for the DNA polymerase. This step lasts approximately 15–60 seconds. Finally, the synthesis of new DNA begins as the reaction temperature is raised to the optimum for the DNA polymerase. For most thermostable DNA polymerases, this temperature is in the range of 70–74°C. The extension step lasts approximately 1–2 minutes. The next cycle begins with a return to 94°C for denaturation.

II. DESCRIPTION OF THERMAL CYCLER

The Thermal Cycling system consists of several things mainly Sample holder metal block, Temperature sensor, data acquisition system, controller and heating/cooling module. Here thermistor is used as the temperature sensor, DAQ is used for inter connection between sensor and controller as well as controller and driver circuit. The thermistor output is in terms of millivolt range. The working of the system is described as, when the temperature is measured by the thermistor it is converted into the voltage, which is going to the controller through DAQ. The difference between set point and actual value is applied to the controller, nothing but error. The PWM signal is produced corresponding to the output voltage of the sensor to control the temperature of the thermal cycler, it is tuned automatically and correcting the error in the process its shown figure 1. Where SP: Setpoint and PV= Process Value.

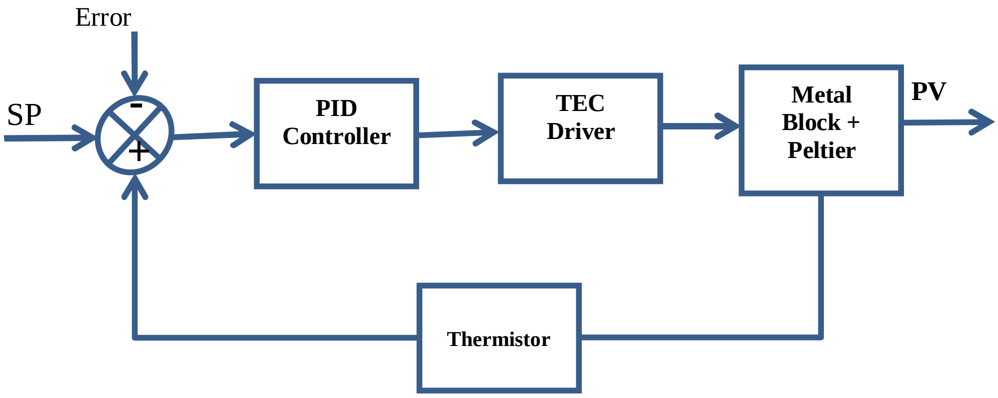


Fig 1 Block diagram of PID controller for Thermal cycler

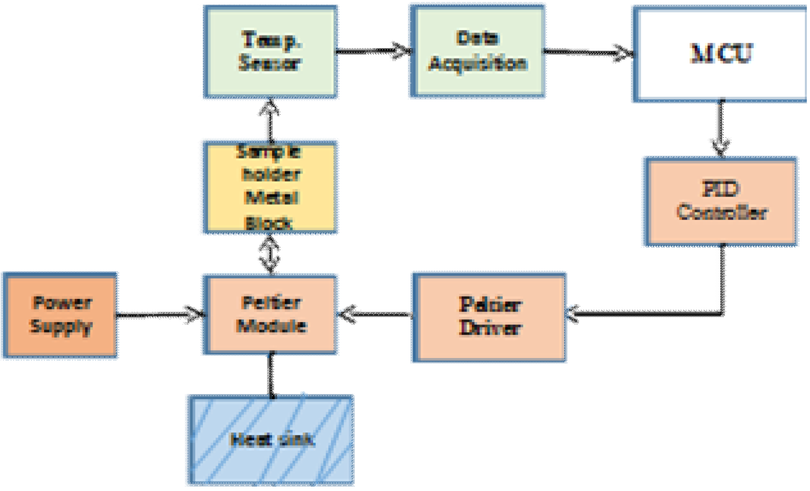


Fig 2 Block diagram of Thermal Cycler

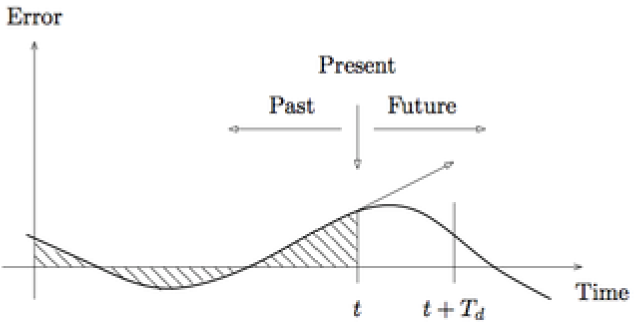
III. GOVERNING EQUATIONS

A proportional integral derivative controller (PID controller) is a generic control loop feedback mechanism (controller) widely used in industrial control systems. PID controller is most commonly used for feedback controller. A PID controller calculates an "error" value as the difference between a measured process variable and a fixed set point. The controller used to minimize the error by adjusting the process control inputs. A PID controller will be called a P, P or I, PD controller in the absence of the respective control actions.

The design and use of PID (proportional-integral-derivative) control The basic PID controller has the form

$$u(t) = k_p e(t) + k_i \int_0^t e(\tau)\,d\tau + k_d \frac{de}{dt},$$

where u is the control signal, Kp is Proportional gain, a tuning parameter, Ke is Integral gain, a tuning parameter, Kd is Derivative gain, a tuning parameter e: Error = SP – PV. t: Time or instantaneous time The control signal is thus a sum of three terms: a proportional term that is proportional to the error, an integral term that is proportional to the integral of the error, and a derivative term that is proportional to the derivative of the error.



Integral action guarantees that the process output agrees with the reference in steady state and provides an alternative to including a feedforward term for tracking a constant reference input. Integral action can be implemented using automatic reset, where the output of a proportional controller is fed back to its input through a low pass filter:

$$u = k_p e + \frac{1}{1 + sT_i} u,$$

Derivative action provides a method for predictive action. The input-output relation of a controller with proportional and derivative action is

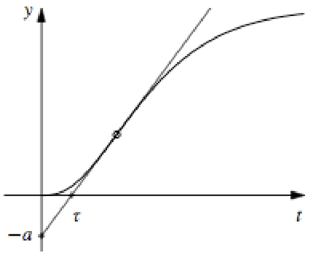
$$u = k_p e + k_d \frac{de}{dt} = k\left(e + T_d \frac{de}{dt}\right),$$

where $T_d = k_d / k_p$ is the derivative time constant. The action of a controller with proportional and derivative action can be interpreted as if the control is made proportional to the predicted process output, where the prediction is made by extrapolating the error T_d time units into the future using the tangent to the error curve.The effects of increasing each of the controller parameters Kp, Ki, Kd are summerised as below.

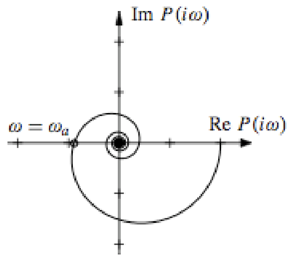
Response	Rise Time	Overshoot	Settling Time	S-S Error
K_p	Decrease	Increase	NT	Decrease
K_i	Decrease	Increase	Increase	Eliminate
K_d	NT	Decrease	Decrease	NT

NT: No Definite trend. Minor change

PID gains can be determined using Ziegler-Nichols tuning rules. The step response method characterizes the open loop response by the parameters a and τ illustrated below (left):



(a) Step response method



(b) Frequency response method

The frequency response method characterizes the process dynamics by the point where the Nyquist curve of the process transfer function first intersects the negative real axis and the frequency ω_c where this occurs (above, right). The corresponding PID gains are given in the following Table.

Type	k_p	T_i	T_d
P	1/a		
PI	0.9/a	3τ	
PID	1.2/a	2τ	0.5τ

(a) Step response method

Type	k_p	T_i	T_d
P	$0.5k_c$		
PI	$0.4k_c$	$0.8T_c$	
PID	$0.6k_c$	$0.5T_c$	$0.125T_c$

(b) Frequency response method

Integral windup can occur in a controller with integral action when actuator saturation is present. In this situation, the system runs open loop when the actuator is saturated and the integral error builds up, requiring the system to overshoot in order to remove the integrated error. Anti-windup compensation can be used to minimize the effects of integral windup by feeding back the difference between the commanded input and the actual input. A number of variations of PID controllers are useful in implementation. These include filtering the derivative, setpoint weighting and other variations in how the derivative and integral actions are formulated. PID controllers can be implemented using analog hardware, such as operational amplifiers, or via digital implementations on a computer.

The Ziegler-Nichols rule is a heuristic PID tuning rule that attempts to produce good values for the three PID gain parameters: Kp - the controller path gain, Ti - the controller's integrator time constant, Td - the controller's derivative time constant. Given two measured feedback loop parameters derived from measurements:

1. The period Pu of the oscillation frequency at the stability limit
2. The gain margin Ku for loop stability.

Closed-loop refers to the operation of a control system with the controlling device in automatic mode, where the flow of the information from sensing element to transmitter to controller to control element to process and back to sensor represents a continuous feedback loop. If the total amount of signal amplification provided by the instruments is too much, the feedback loop will self-oscillate at the system’s natural (resonant) frequency. While oscillation is almost always considered undesirable in a control system, it may be used as an exploratory test of process dynamics if the controller acts purely on proportional action providing data useful for calculating effective PID controller settings.

Thus, a closed-loop PID tuning procedure entails disabling any integral or derivative actions in the controller, then raising the gain value of the controller just far enough that self-sustaining oscillations ensue. The minimum amount of controller gains necessary to sustain sinusoidal oscillations is called the ultimate sensitivity (Su) or ultimate gain (Ku) of the process, while the time period between successive oscillation peaks is called the ultimate period (Pu) of the process. We may then use the measured values of Ku and Pu to calculate reasonable controller tuning parameter values (Kp, τi, and/or τd). PID Tuning parameters using Ziegler-Nichols Closed-Loop method:

Ziegler Nichols Closed Loop Method			
Controller type	K_P	**Ti**	**Td**
P	$0.5*K_u$	-	-
PI	$0.45*K_u$	$0.85*P_u$	-
PID	$0.6*K_u$	$0.5*P_u$	$0.13*P_u$

Table:1 Ziegler Nichols Closed Loop Method Tuning Parameters

When performing such a test on a process loop, it is important to ensure the oscillation peaks do not reach the limits of the instrumentation, either measurement or final control element. In other words, in order for the oscillation to accurately reveal the process characteristics of ultimate sensitivity and ultimate period, the oscillations must be naturally limited and not artificially limited by either the transmitter or the control valve saturating. Oscillations characterized by either the transmitter or the final control element reaching their range limits should be avoided in order to obtain the best closed-loop oscillatory test results.

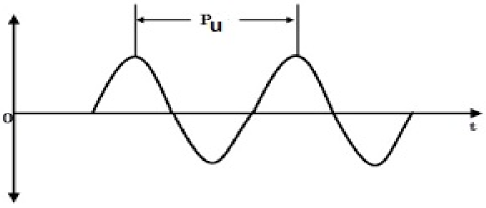
The main advantage in using the ZN tuning method is that all three tuning constants Kp, Td, and Ti, are pre-calculated and input to the system at the same time. It does not require any trial and error to achieve initial tuning. The chief disadvantage in using ZN tuning is that in order to obtain the system’s characteristic data to make the calculations, the system must be operated either closed loop in an oscillating condition, or open loop.

A. OSCILATION METHOD (CLOSED LOOP METHOD)

Using the oscillation method, we will be determining two machine parameters called the ultimate gain Ku and the ultimate period Pu. Using these, we will calculate Kp, Ti and Td.

1. Initialize all PID constants to zero. Power-up the machine and the closed loop control system.
2. Increase the proportional gain Kp to the minimum value that will cause the system to oscillate. This must be a sustained oscillation, i.e., the amplitude of the oscillation must be neither increasing nor decreasing. It may be necessary to make changes in the setpoint to induce oscillation.

3. Record the value of Kp as the ultimate gain Ku.



4. Measure the period of the oscillation waveform. The period is the time (in seconds) for it to complete one cycle of oscillation. This period is the ultimate period Tu.

IV. RESULT AND DISCUSSION

Ziegler Nichols Closed Loop Response for PID Controller for studying the performance of PI & PID Controllers as shown in figure below for the temperature control system for Thermal Cycling system.

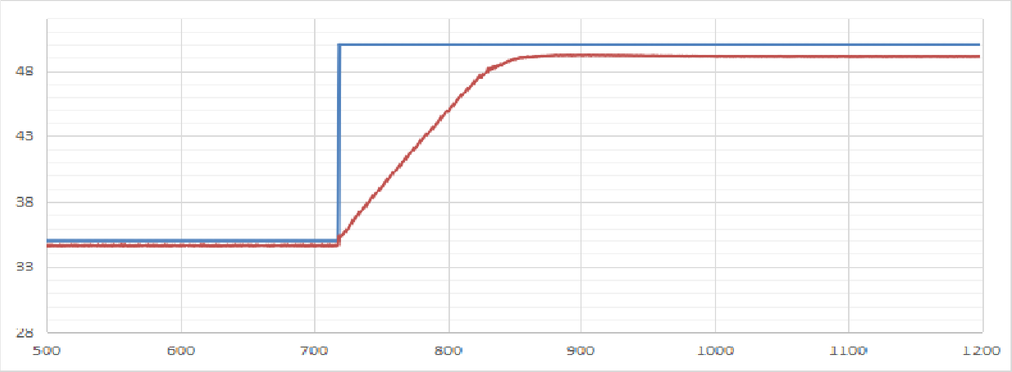


Fig 3 Step Response when Kp =40

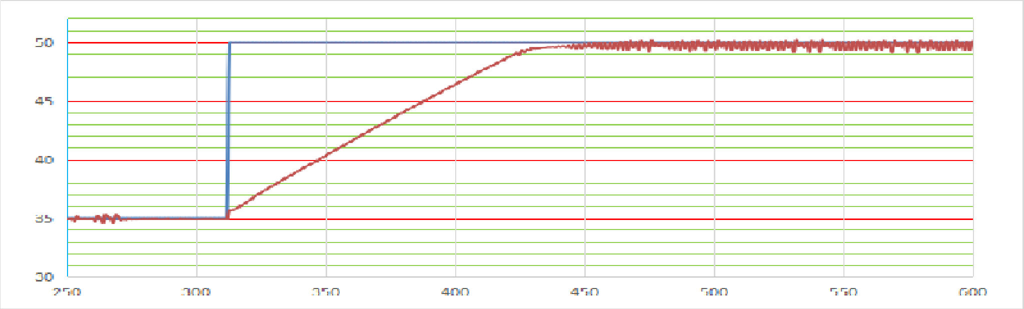


Fig 4 Step Response when Kp =100

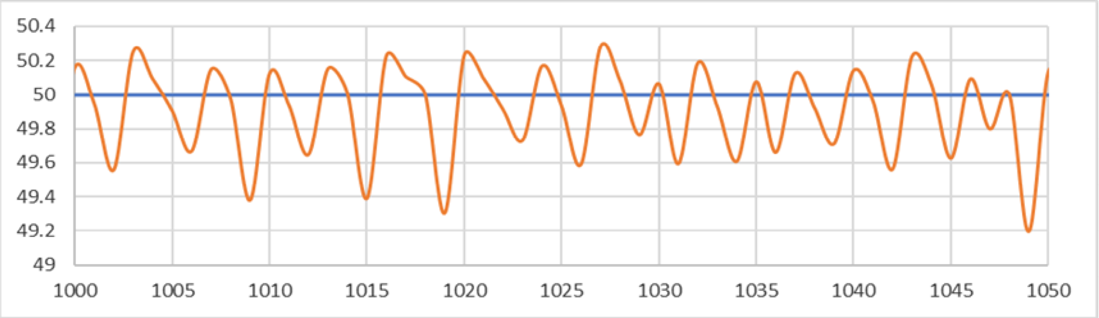


FiG 5 Oscillations when Kp =180

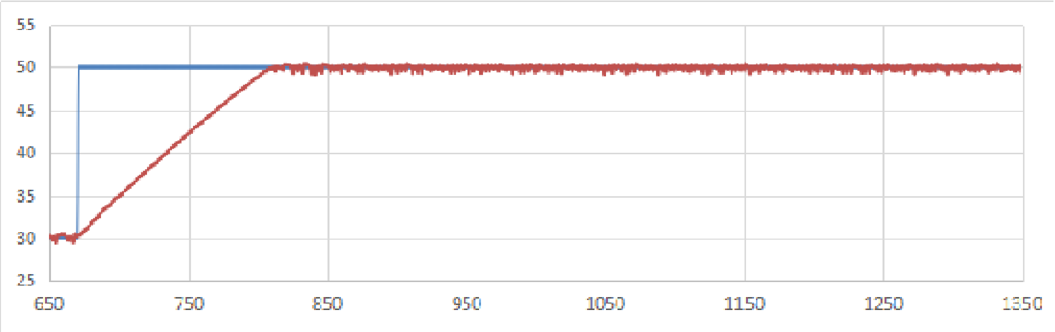


Fig 6 Step Response when Kp =200

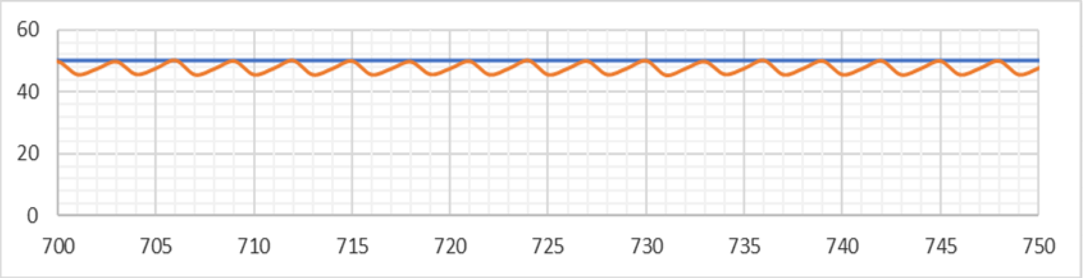


Fig 7 Oscillations when Kp =200

The Values of KP, Ti and Td values of PID Controller is shown in below table are obtained by using the Ziegler Nichols method. When Ku = 200, Pu = 0.0453 min.

Control type	**Kp**	**Ti (min)**	**Td (min)**
P	**100**	**-**	**-**
PI	**90**	**0.038533333**	**-**
PID	120	0.022666667	0.005893333

Table 1. The Values of Kp, Ti and Td values of PID Controller

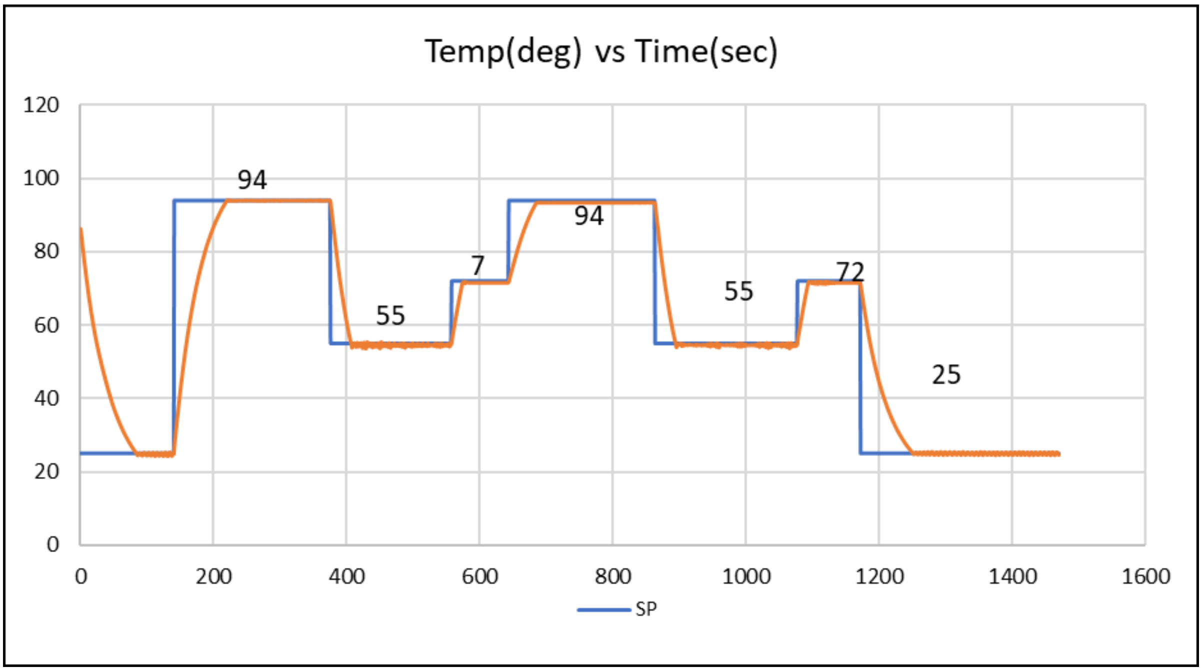


Fig 8 PID output of thermal cycler

V. CONCLUSION

In this paper the temperature process and the control strategy adopted is PID controller. The temperature controller was identified based the simulation output curve of PI, PID responses respectively with this rise time, settling time, delay time and maximum peak overshoot values. It is clear that the PID controller has the less settling time, delay time, rise time and maximum peak overshoot when compared to the other controllers by using the transfer function model, simulation of Proportional Integral Derivative controller was implemented.

This controller controls the temperature of the metal block and also maintains it while comparing with the other controllers this PID controller enhances different tuning methods for sensing and controlling the temperature. In future, we are planning to do the modifications in the control of temperature by controlling the Fan and by using different controllers. By this we conclude that this method is efficient in maximum temperature tracking capability.

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