AN EFFICIENT CONTROLLING SYSTEM FOR MAINTAINING THE TEMPERATURE OF CONTINUOUS STIRRED TANK HEATER

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Abstract — **Designing an efficient controller for controlling and maintaining the Continuous Stirred Tank Heater (CSTH) is one of the demanding and crucial process in recent days. For this reason, different controlling strategies such as Proportional Integral Derivative (PID), Proportional (P), and Fuzzy Logic Control (FLC) are developed in the traditional works. It mainly focuses to control the tank based on its temperature level, but it failed to reduce the error and settling time. The increased settling time can affect the chemical reactions inside the tank, so it must be maintained at certain level. Thus, this work aims to develop an optimal strategy, namely, Tri-Energy based Neural Network Controller (TENNC) for controlling and maintaining the temperature of CSTH. It is developed based on the material balance and energy balance of the tank and jacket. In this design, the output of system is compared with the input of system for estimating the error value, based on this, the controller obtains the desired output. Moreover, it focused to increase the efficiency and reduce the operating cost of the controller. The major benefits of this design are, it enabled an automated control system with increased efficiency and reduced man power. In simulation, the traditional PID, PC and FLC controlling strategies based on the measures of time, amplitude, and error. The results showed the effectiveness of the proposed controller design.**

Index Terms — **Continuous Stirred Tank Heater (CSTH), Tri-Energy based Neural Network Controller (TENNC), Proportional Integral Derivative (PID) Controller, Fuzzy Logic Controller (FLC), Jacket, Tank, Error Reduction, and Settling Time Minimization.**

I. INTRODUCTION

CONTINUOUS Stirred Tank Heater (CSTH) is one of the widely used equipment in most of the industries [1]. It requires certain temperature to maintain the chemical composition in a desired condition [2]. Recently, the CSTH is extensively used in the applications of cement plant, food processing, chemical industries, and refineries [3]. In this equipment, the fluid inside the tank is heated by circulating the fuel inside the jacket or coil [4]. Fig 1 shows the structure of CSTH, which has the stirrer, jackets and tank. Moreover, it is equipped with equal temperature in both input and output side. Normally, the chemical industries comprise the processing elements such as heat exchangers, tanks, pumps and reactors. In the existing work, different controlling methods are available for controlling and maintaining the temperature of CSTH [5]. The models [6] that used to design the PID controller are trial, error and heuristic. Moreover, various methods are put into action for controlling CSTH, which includes PID, adaptive and Internal Mode Control (IMC) based PID. It offers the granted and automated control system for increasing the efficiency [7], reducing the man power and operating cost. Some of the controllers [8, 9] are integrated with the soft computing methodologies for increasing the performance. Traditionally, the PID controller is used to control the CSTH, which calculates the gain for the tank [10, 11]. Generally, the CSTH is fine tripped that maintains equal temperature in both input and output sides.

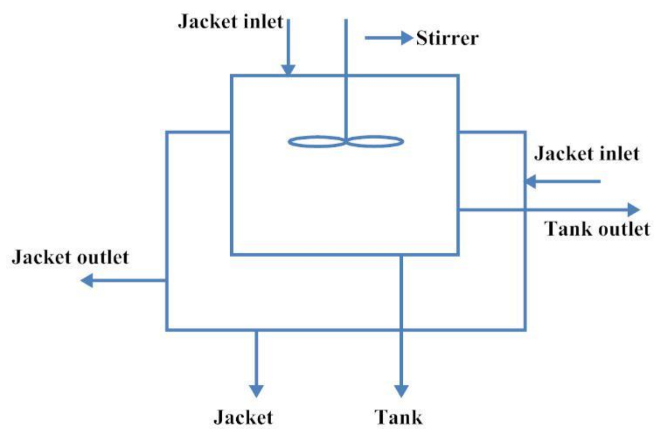

Fig 1. Structure of CSTH

A. *Objectives*

The research objectives of this paper are as follows:

- To reduce the settling time, an efficient controlling strategy, namely, Tri-Energy based Neural Network Controller (TENNC) is proposed.
- To design an optimal controller for the industrial applications, the Continuous Stirred Tank Heater (CSTH) is developed.
- To increase the efficiency and reduce the operating cost, the temperature of the CSTH is controlled and maintained.

B. *Organization*

The remaining sections in the paper are organized as follows: the existing controlling techniques and strategies related to CSTH are surveyed in Section II with its advantages and disadvantages. The clear description about the proposed methodology is presented with its block diagram in Section III. The simulation results of both the existing and proposed controlling techniques are evaluated in Section IV. Finally, the overall paper is summarized and its future work is stated in Section V.

II. RELATED WORKS

Jin, et al [12] *designed* a computational framework for evaluating the Fuzzy Intelligent Traffic Signal (FITS) control system. Here, the autonomic features that includes self-calibration, self-diagnostics, and self-adaptation of the FITS system were analyzed for identifying the malfunctioning detectors. In this design, the SUMO simulator was utilized that updated the states and detection information of the vehicles. The merit of the system was, it implemented the suggested control system in a single board computing device. But, it failed to prove the effectiveness of this controller design, which was the limitation of this work. *Mendoza, et al* [13] introduced an oil free co-rating scroll machine for performing water injection. The aim of this paper was to increase the isothermal efficiency and output power of the co-rotating machine. Also, the leakage of water was reduced by using the proper guidelines of the prototype design. The major contributions of this paper were as follows:

- It worked under various operating conditions
- It analyzed the behavior of leakage area based on the water injection, rotor speed, and flank clearance
- A set of guidelines were provided to assess the technical potentials

Also, the mechanical power and exhaust temperature were predicted. Still, this paper required to reduce the internal leakage of water injection. *Abdullah, et al* [14] formed a hierarchical structure for designing the optimal control system. The major objectives that focused in this work were as follows:

- It maintained the plant in a safe operation mode
- It satisfied the demands with improved product quality and economical usage
- Also, it maximized the production profit

In the optimal controller design, the size pumps were utilized to compute the energy of the system. Moreover, the controlled variable such as temperature and level were maintained at the set points. The advantage behind this design was, it does not require any process derivatives, so it was more suitable for the industrial applications. *Lu, et al* [15] designed a Full-wave Signal Construction (FSC) strategy for performing the fault diagnosis. The aims of this paper were to construct the full wave signal with increased Signal to Noise Ratio (SNR), and to obtain the better output from the Stochastic Resonance (SR). Here, the periodic component was enhanced with increased periodicity. The advantage of this design was, it has the capability to detect the weak signals with various noise intensities and duty cycles. *Niederer, et al* [16] used a nonlinear predictive model for designing the controller by estimating the current system state and optimal trajectories. The intentions of this paper were to increase the system throughput and minimize the energy consumption. Here, the Gauss newton method was utilized to solve the dynamic optimization problem in a numerical way. Moreover, the gradient and hessian matrices were computed by using the adjoint-based method. Also, the high fidelity simulation model was utilized to evaluate this controller design. This hierarchical system contains the following controls:

- Process control system
- Model predictive control
- Velocity and fuel control
- State estimator

During simulation, the production time and control accuracy were evaluated to analyze the efficiency of this controller system. *Lechappe, et al* [17] suggested the some possible solutions to design the predictive control strategy with reduced delay. Here, the uncertainties and external disturbances were analyzed to evaluate the robustness of the system. This paper required to theoretically prove the performance of the closed loop system with delay estimation. *Hashimoto, et al* [18] introduced a self-triggered model for reducing the communication load in the nonlinear systems. Here, the Model Predictive Control (MPC) was applied with the event triggered mechanism. In this system, the plant actuator and sensor system were connected with the controller via wired and wireless links. Also, this paper aimed to reduce the communication load by adaptively selecting the sampling intervals. Moreover, both linear and non-linear samples were utilized to test this framework. The limitation behind this work was, it required to analyze the self-triggered strategies under various additive noise. *Kantha, et al* [19] implemented a Hybrid Genetic Algorithm with Swarm Intelligence (GA-PSO) technique for tuning the PID controller to analyze the chemical reactions on the industries. In this paper, various methods that used for tuning PID controller were evaluated to control the concentration of isothermal continuous stirred tank reactor.

Rabiee, et al [20] *introduced* a Non-linear Model Predictive Control (NMPC) technique for controlling the continuous stirred tank heater. The aim of this paper was to provide the optimal solution for the control trajectory by using the Genetic Algorithm (GA). Also, it intended to increase the generalization performance of the optimization. *Albagul, et al* [21] designed a Continuous Stirred Tank Reactor (CSTR) system for implementing both PI and Proportional Plus Integral Fuzzy Logic (PIFL) controllers. The aim of this paper was to control the concentration of linear CSTR. Moreover, the Ziegler Nichols response method was utilized to tune the PI controller. In this model, the Fuzzification process was interpreted with the linguistic values, which determined the output sets. The performance of these controllers were validated based on the characteristics of rise time, overshoot, settling time and error. *Laszczyk, et al* [22] *introduced* a hybrid CSTR plant for analyzing the static and dynamic behavior of the reactor system. It contains the jacketed vessel and labVIEW based simulator for analyzing the chemical reaction of the system. Based on the bifurcation analysis, the dynamical behavior of the CSTR was determined. *Ameur* [23] analyzed the energy efficiency of various stirred tank reactors, where four impellers such as maxblend, anchor, gate and DHR impeller were utilized. Here, the numerical simulations were performed based on the Computational Fluid Dynamics (CFD), which illustrated the energy efficiency and power consumption of the stirred tank reactor. *Deepa and Baranilingesan* [24] introduced a Deep

Learning Neural Network Model Predictive Controller (DLNNMPC) for analyzing the performance of the CSTR with respect to serial and parallel reactions. The state space model was utilized to generate the data for training this controller. Moreover, various algorithms such as Particle Swarm Optimization (PSO), Gravitational Search Algorithm (GSA) and DLNN were analyzed for evaluating the betterment of the DLNNMPC. *Abdelkader, et al* [25] developed a non-linear high gain observer for reconstructing the state of oil waste esterification process. The motive of this paper was to balance the energy from the material based on the following assumptions:

- The jacket and reactor was presumed as perfectly stirred.
- An antoine equation was applied to determine the saturation vapor pressure of the components.

Moreover, the algebraic relationship was defined for deriving the evaporation flow rate with respect to time. The robustness of the observer was evaluated by using the full state system without any additional calculations. *Khapre, et al* [26] aimed to optimized the CSTR by performing an entropy generation minimization. Here, two cases such as constant wall temperature and heat flux thermal boundary conditions were considered. Also, the authors determined the bejan number for showing the effectiveness of the system. Moreover, the energy is calculated with respect to varying Reynolds number, impeller rotation, impeller clearance, and impeller blade. *Scholar* [27] analyzed some conventional controllers for developing a modified CSTR system. The aim of this work was to optimize the performance of hyperbaric reactor system by deriving the transfer function from the real time online system. In this paper, it was stated that the PI controller was widely used due to its quick tuning and fast response. *Ramli and Mohamad* [28] developed a fuzzy logic control system to decide whether the rules were to be implemented in the membership function. Here, the multi-valued logic was utilized in the fuzzy logic in a machinery control. From the study, it was observed that the fuzzy logic does not require any mathematical modelling, which efficiently solved the complex non-linear problem.

From the survey, it is analyzed that the existing techniques have both advantages and disadvantages, but it mainly lacks with the following drawbacks:

- Increased settling time and error rate
- Not highly efficient

To solve these problems, this paper focuses to develop a new controlling strategy by implementing an efficient technique.

III. Existing Controlling Strategies

Traditionally, different controlling techniques such as Proportional Integral Derivative Controller (PID), and Fuzzy Logic Controller (FLC) are available for controlling the CSTH with increased performance. In which, PID is a kind of control loop feedback mechanisms that is implemented in an industrial applications. It continuously calculates the error value based on the difference between the desired set point and measured process variable. Also, it proceeds the correction based on proportional, integral and derivative terms. Fig 2 (a) shows the block diagram of PID controller, which produces the output based on three derivatives.

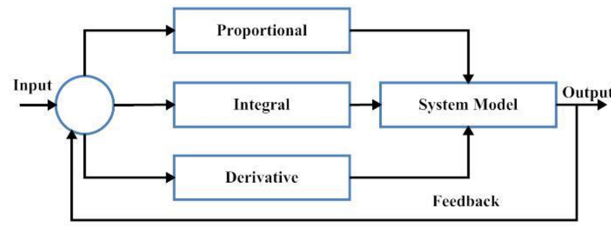

Fig 2 (a). PID controller

A fuzzy logic control system is developed based on the fuzzy logic, which investigates the analog input values based on the logical variables and, it takes a continuous value between 0 and 1. Fig 2 (b) shows the basic block diagram of the FLC, which produces the output based on the fuzzy logic.

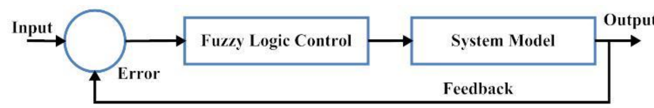

Fig 2(b). FLC controller

The suggested controlling strategies are not highly suitable for CSTH controlling, because it has the limitations of increased error value and settling time. To overcome these issues, this paper introduced an optimal control system, which provides the better performance compared than the other controlling techniques.

IV. Proposed Tri-Energy based Neural Network Controller

In this section, the clear description about the proposed methodology is presented with its clear flow illustration. The intention of this paper is to design the Continuous Stirred Tank Heater (CSTH) with an effective control system. For this purpose, a Tri-Energy based Neural Network Controller (TENNC) is designed for CSTH, which is shown in Fig 1. In CSTH, the variables such as rate of inlet flow and inlet temperature for both tank and jacket are given as the input. Then, it produces the output as temperature, volume, and flow of liquid. The major focuses of this design are to balance the material and energy around tank and jacket. Here, the steady state variables are determined during the steady state condition.

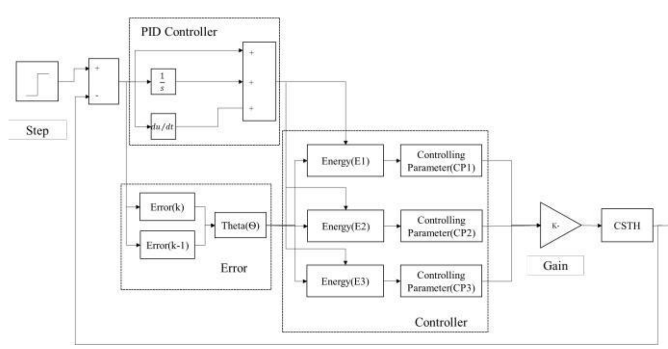

Fig 3. Controller design

A. *Continuous Stirred Tank Heater (CSTH)*

In this tank, the transmission rate from the jacket to the tank is calculated based on the following relation:

= . (−) (1)

Where, HT indicates the heat transmission rate, C_H is the coefficient of heat transmission, *j* indicates the jacket, *t* indicates the time, T is the temperature, and O defines the heat transfer area. The tank heater aims to maintain the tank fluid temperature at certain value. This model is developed based on the followings: material balancing and energy balancing around the tank and jacket. Here, the rate of accumulation is estimated based on the difference between the input flow rate and output flow rate. The material balance is estimated by using the following equations:

( ) = − (2)

( ) = − (3)

Then, the rate of energy accumulation is estimated based heat in and heat out with the summation of heat flow rate. Similarly, the energy balance around the tank and jacket are calculated as follows:

(4)

(5)

Moreover, the following models describes the stirred tank heater based on the following assumptions:

= (−) + . . (−) (6)

= (−) + . . (−) (7)

The variables used in these equations are defined in Table 1.

Table 1.Parameters and its description

Terms	*Description*
V	Volume
HT	Heat transmission rate
Cs	Capacity of specific heat
O	Area of heat transfer
RF	Reference value
i	Inlet
j	Jacket
Q	Rate of change of volume
a	Steady value
ji	Jacket inlet
C_H	Coefficient of heat transfer
	Density (mass/volume)
t	Time
T	Temperature in deg

The steady state variables are determined at the steady state condition based on the following parameters:

Table 2. Steady state variables and its values

Measure	*Value*
Qa	1 ft 3/min
	61.3 Btu/°F-ft3
	61.3 Btu/°F-ft3, Tis = 50°F
Ta	125°F, V = 10 ft 3
Tjs	150°F, Vj = 1 ft 3

In this model, the state variable equation is represented as follows:

= + (8.1)

= + (8.2)

Based on this, the state vector, input vector, and output vector are determined, which are illustrated as follows:

= [−] //State variables (9.1)

//Input variables (9.2)

= [ ] //Output variables (9.3)

At last, the state space variables are converted into the transfer function, which controls the tank temperature for maintenance.

B. *Tri-Energy based Neural Network Controller*

In this design, the output is compared with the input for identifying the error values, based on this, the controller controls the output parameter. Moreover, the time required for obtaining the desired temperature limit from the abnormal temperature limit should be minimum. It is known as settling time, so it must be reduced, because the increased settling time can affect the chemical reactions of the product inside the tank. Thus, this work intends to maintain the settling time with certain limit. This controlling technique is developed based on the neural network model, which is a kind of predictive controlling technique. In which, the controller determines the manipulated variable for optimizing the open loop performance within a time interval. At first, the ideal PID controller is designed with the control variable *r* and control error U.

( ) = ( ) + 1 ∫ ( ) + ( ) (1)

Where, indicates the gain of proportional, is the gain of integral, defines the gain of derivative, and *t* is the time.

$$= \sum \{ \quad \cong 0 \tag{2}$$

If the previous error value is not equal to 0, the error value is assigned; otherwise, it is assigned to 1. Similarly, the current error value is assigned to the temporary variable .

$$= \tag{3}$$

Consequently, the theta value θ is calculated with respect to the number of inputs, which is as follows:

$$\theta = \frac{* \ (\ )}{+ \ (\ )} \tag{4}$$

Based on the value of theta, the difference between the present θ and previous θ values are estimated, which is as follows:

$$\theta = \theta - \theta \tag{5}$$

After that, the weights of θ1, θ2θ3 are calculated as follows:

$$_1 = {}_1 + \theta' \tag{6}$$

$$_2 = {}_2 + \theta \tag{7}$$

$$= + (\theta_3 \quad _3 - 1)^2 \tag{8}$$

The controlling parameters such as CP_1, CP2 and CP_3 used for evaluating the gain of controller are estimated as follows:

$$_1 = 1 - \theta \tag{9}$$

$$_2 = 2 - \theta \tag{10}$$

$$_3 = 3 - \theta \tag{11}$$

Based on these parameters, the energy required for the controller is computed,

$$= {}_1(\ _1 + \quad _2) - {}_2(\ _2 + \quad _3) + {}_3(\ _3 + \quad _1) \tag{12}$$

Where, K_1, K_2 and K_3 indicates the saturation values. The major benefits of the proposed work are as follow:

- Reduced manpower and settling time
- Increased system performance
- It required minimum time
- It uses an optimization based controlling technique for reducing the error value
- Highly efficient compared than the existing controlling techniques.

V. Performance Analysis

In this simulation, the proposed optimal control system is evaluated and compared with the existing controlling techniques for proving the efficacy of the proposed system. Here, MATLACN/SIMULINK tool is utilized to test the control system based on the time and error. The measures that used to test the control system are amplitude, peak overshoot, settling time, rise time, ISE and IAE errors. Moreover, the different optimization techniques that used for controller design are analyzed for proving the superiority of the proposed optimal control system.

A. *Comparison between PI and TENNC controllers*

Fig 4 shows the amplitude of the existing PI and proposed TENNC controlling techniques with respect to varying time. Here, the blue colored line indicates the PI controller and red colored line indicates the TENNC controller. From the analysis, it is evident that the PI controller has high fluctuation, due to the increased oscillatory and rolling behavior. So, it must be reduced for maintaining the temperature of the tank at certain level. The proposed controller efficiently maintains the temperature by implementing the neural network logic.

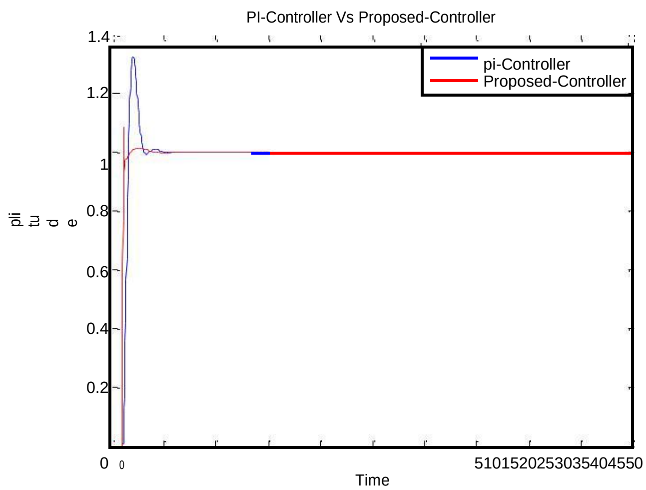

Fig 4. Comparative analysis between existing PI and proposed TENNC controller techniques

B. *Comparison between P and TENNC controllers*

Fig 5 shows the amplitude of the existing P and proposed TENNC controlling techniques with respect to varying time. Here, the blue colored line indicates the P controller and red colored line indicates the TENNC controller. Normally, the P controller has relatively maximum overshoot and long settling time, which affects the overall performance of controller.

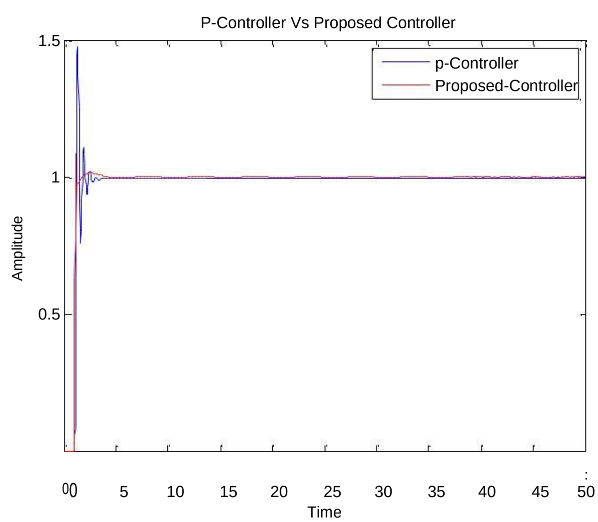

Fig 5. Comparative analysis between existing P and proposed TENNC controller techniques

Also, it has an increased steady state error, so it must be reduced for a better controller design. When compared to this controller, the proposed controller effectively solve these issues by increasing the overall performance with reduced error.

C. Comparison between PD and TENNC controllers

Fig 6 shows the amplitude of the existing PD and proposed TENNC controlling techniques with respect to varying time. Here, the blue colored line indicates the PD controller and red colored line indicates the TENNC controller. The major limitation of PD controller are, it requires a larger gain for performing the derivative action. Also, the maximum overshoot of this controller is small, and it has an increased steady state error. The proposed controller overcome these issues by calculating the gain based on the energy and controlling parameter. Thus, the TENNC outperforms the existing PD controller as shown in Fig 5.

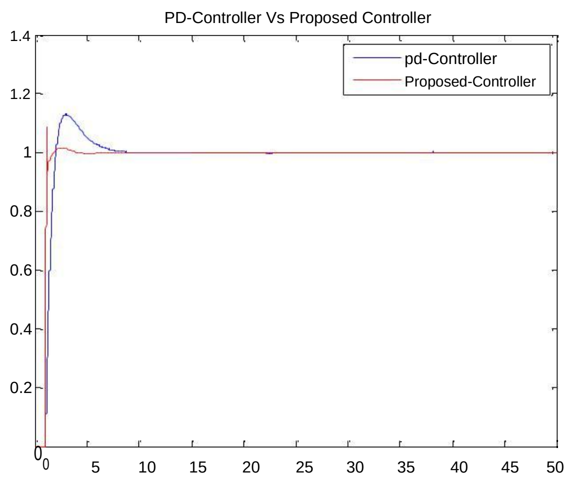

Fig 6. Comparative analysis between existing PD and proposed TENNC controller techniques

D. Comparison between PID and TENNC controllers

Fig 7 shows the amplitude of the existing P and proposed TENNC controlling techniques with respect to varying time. Here, the blue colored line indicates the P controller and red colored line indicates the TENNC controller. The PID controller integrates the benefits of both I and D controllers, but the limitations behind this controller are, reduced maximum overshoot and increased error value. But in the proposed controlling technique, the value of theta is estimated based on the previous and present error values, which efficiently reduces the error value. So, the TENNC maintains the voltage and temperature at a certain limit.

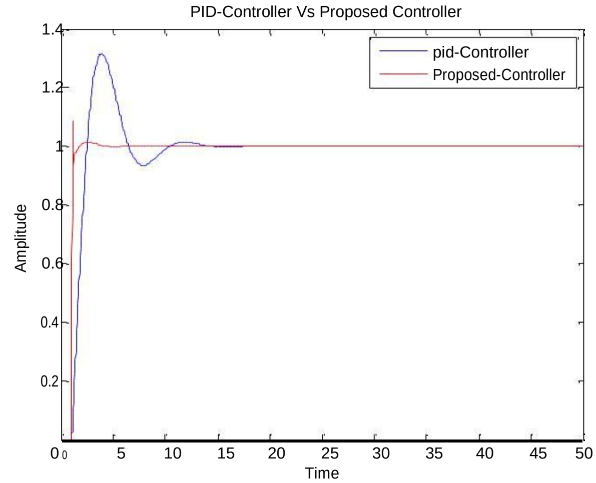

Fig 7. Comparative analysis between existing PID and proposed TENNC controller techniques

E. Comparison between Existing and Proposed controllers

Fig 8 shows the amplitude of the existing P, PI, PD, PID and proposed TENNC controlling techniques with respect to varying time. The proposed controlling technique incorporates the benefits of the traditional PID controller, so it has the ability to reduce the steady state error with increased system stability and reduced settling time. Thus, the TENNC provides the better performance results, when compared to the existing controlling techniques. In this evaluation, it is stated the proposed controller is highly suitable for controlling the CSTH.

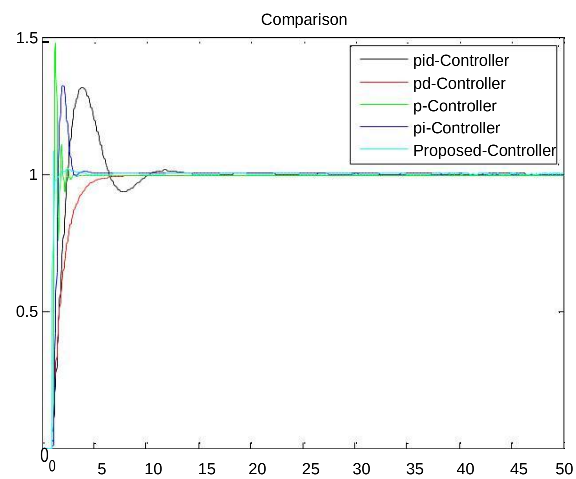

Fig 8. Comparative analysis between existing P and proposed TENNC controller techniques

F. Analysis of Controllers

Table 3 compares the existing and proposed soft computing techniques that used for designing the controller with respect to the measures of peak overshoot, settling time, and rising time. The techniques considered in this evaluation are Z-N, Genetic Algorithm (GA), Particle Swarm Optimization (PSO), and GA + PSO. These are all the optimization techniques, which gives the optimal solution during the controller design. From the results, it is evident that the proposed TENNC provides the better results, when compared to the other techniques.

Table 3. Comparison between the existing and proposed controllers based on its characteristics

Algorithm	Peak Overshoot	Settle Time	Rise Time
Z-N	7.306	7.5196	2.888
GA	28.21	11.494	1.549
PSO	0.015	7.3931	2.711
GA+PSO	0.016	3.6119	1.022
TENNC	0.085	1.053	1.0093

G. Error of Existing and Proposed Controllers

Table 4 illustrates the error value of the existing and proposed controlling techniques. The proposed controlling technique finds the error value by estimating the difference between the output value and input value of the system. Based on this value, the controller maintains the temperature at certain level. Moreover, the previous and present error values are calculated in the proposed design for estimating the energy and controlling parameter. So, it efficiently reduced the ISE and IAE error values, when compared to the existing controllers.

Table 4. Analysis of error value

Controllers	ISE	IAE
PID	0.6359	1.626
PD	0.4939	1.359
I	0.1238	0.6321
PI	0.305	0.5942
TENNC	0.02965	0.1088

VI. Conclusion and Future Work

This paper presented a new controlling technique, namely, TENNC for controlling the CSTH. The intention of this paper is to design an optimal control system for controlling and maintaining the CSTH. Traditionally, the PI, PD, P, PID and FLC controlling techniques are available for CSTH. Due to its increased error rate, which has a reduced accuracy. The proposed controlling techniques intends to control the tank based on its temperature level. It reduces the settling time for analyzing chemical reactions inside the tank. In this work, the material balance and energy balance of the tank and jacket are considered in CSTH. Moreover, the error value is determined by finding the difference between the output of system and the input of system. Moreover, the energy and controlling parameters are estimated in TENNC for calculating the gain given to CSTH. During experiments, the traditional controlling strategies and the optimization techniques used for design a controller are analyzed based on the measures of peak overshoot, settling time, rise time, IAE and ISE errors. From the results, it is analyzed that the proposed controller outperforms the existing techniques by efficiently reducing the error value with increased system performance.

REFERENCES

[1] F. S. Santos and L. B. da Silva Lima, "Analysis of Data reconciliation techniques applied to a continuous stirred tank heater," *Semina: Ciências Exatas e Tecnológicas,* vol. 36, pp. 97-106, 2015.

[2] J. Zheng, *et al.*, "A using of just-in-time learning based data driven method in continuous stirred tank heater," in *Intelligent Control and Information Processing (ICICIP), 2016 Seventh International Conference on*, 2016, pp. 98-104.

[3] V. Kabila and G. G. Devadhas, "Comparative analysis of PID and fuzzy PID controller performance for continuous stirred tank heater," *Indian Journal of Science and Technology,* vol. 8, 2015.

[4] Y. Zhang, *et al.*, "Data-driven design and optimization of feedback control systems for industrial applications," *IEEE Transactions on Industrial Electronics,* vol. 61, pp. 6409-6417, 2014.

[5] J. A. Levinson, *et al.*, "Automated process control laboratory experience: Simultaneous temperature and level control in a continuously stirred tank reactor system," 2014.

[6] Y. Wang, *et al.*, "Improved fuzzy PID controller design using predictive functional control structure," *ISA transactions,* vol. 71, pp. 354-363, 2017.

[7] P. Kumar, *et al.*, "Optimal Design of PID Controller for a CSTR System Using Human Dynamic Opinion Algorithm," *Imperial Journal of Interdisciplinary Research,* vol. 2, 2016.

[8] S. Sehgal and V. Acharya, "Design of PI controller for Continuous Stirred Tank Heater process," in *Electrical, Electronics and Computer Science (SCEECS), 2014 IEEE Students' Conference on*, 2014, pp. 1-5.

[9] R. Singh, *et al.*, "Implementation and evaluation of heating system using PID with genetic algorithm," *Indian Journal of Science and Technology,* vol. 8, pp. 413-418, 2015.

[10] S. Tripathi, *et al.*, "Design of Intelligent controller for Isothermal Continuous Stirred Tank Reactor System," 2017.

[11] J. Poovarasan, *et al.*, "Design of Fractional Order PID controller for a CSTR process," *Int. Ref. J. Eng. Sci,* vol. 3, pp. 8-14, 2014.

[12] J. Jin, *et al.*, "An intelligent control system for traffic lights with simulation-based evaluation," *Control Engineering Practice,* vol. 58, pp. 24-33, 2017.

[13] L. C. Mendoza, *et al.*, "Testing and modelling of a novel oil-free co-rotating scroll machine with water injection," *Applied Energy,* vol. 185, pp. 201-213, 2017.

[14] N. Abdullah, *et al.*, "Design and simulation of hierarchical control of two continuous stirred tank heater in series," *Indian Journal of Science and Technology,* vol. 9, 2016.

[15] S. Lu, *et al.*, "Rotating machine fault diagnosis through enhanced stochastic resonance by full-wave signal construction," *Mechanical Systems and Signal Processing,* vol. 85, pp. 82-97, 2017.

[16] M. Niederer, *et al.*, "Nonlinear model predictive control of the strip temperature in an annealing furnace," *Journal of Process Control*, vol. 48, pp. 1-13, 2016.

[17] V. Léchappé, *et al.*, "Delay estimation and predictive control of uncertain systems with input delay: Application to a DC motor," *IEEE Transactions on Industrial Electronics*, vol. 63, pp. 5849-5857, 2016.

[18] K. Hashimoto, *et al.*, "Self-triggered model predictive control for nonlinear input-affine dynamical systems via adaptive control samples selection," *IEEE Transactions on Automatic Control*, vol. 62, pp. 177-189, 2017.

[19] A. S. Kantha, *et al.*, "Hybrid genetic algorithm-swarm intelligence based tuning of continuously stirred tank reactor," in *Industrial and Information Systems (ICIIS), 2014 9th International Conference on*, 2014, pp. 1-6.

[20] A. Rabiee, *et al.*, "Nonlinear model predictive control of a continuous stirred tank heater based on multiple neural networks," *Journal of Basic Applied and Scientific Research*, vol. 3, pp. 893-1000, 2013.

[21] A. Albagul, *et al.*, "Design and Implementation of PI and PIFL Controllers for Continuous Stirred Tank Reactor System," *International Journal of Computer Science and Electronics Engineering (IJCSEE) 130*, vol. 2, 2014.

[22] P. Laszczyk, *et al.*, "Modelling of hybrid CSTR plant: Heat transfer considerations," in *Process Control (PC), 2017 21st International Conference on*, 2017, pp. 228-233.

[23] H. Ameur, "Energy efficiency of different impellers in stirred tank reactors," *Energy*, vol. 93, pp. 1980-1988, 2015/12/15/ 2015.

[24] S. N. Deepa and I. Baranilingesan, "Optimized deep learning neural network predictive controller for continuous stirred tank reactor," *Computers & Electrical Engineering*, 2017/07/08/ 2017.

[25] A. Abdelkader, *et al.*, "A nonlinear high gain observer for an olive oil waste esterification in a Continuous Stirred Tank Reactor," in *Sciences and Techniques of Automatic Control and Computer Engineering (STA), 2014 15th International Conference on*, 2014, pp. 1049-1054.

[26] A. Khapre and B. Munshi, "Computational study of entropy generation minimisation in continuous stirred tank reactor," *International Journal of Exergy*, vol. 19, pp. 15-40, 2016.

[27] P. Scholar, "Analysis of Conventional controllers for high pressure rated modified CSTR system," *Analysis*, vol. 3, 2016.

[28] N. M. Ramli and M. S. Mohamad, "Modelling for Temperature Non-Isothermal Continuous Stirred Tank Reactor Using Fuzzy Logic," *World Academy of Science, Engineering and Technology, International Journal of Environmental, Chemical, Ecological, Geological and Geophysical Engineering*, vol. 11, pp. 145-151, 2017.