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Original Article

A Novel Thermal Effect Minimization Method on Water Bath System Using F^2PID Controller

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Abstract *- The Water Bath System (WBS) may comprise a single or a mixture of substances used in clinical laboratories. Temperature is the most often varying parameter in the WBS that can affect the production of different products. Therefore, to deal with the temperature control of WBS, a Fuzzy Fractional Order Proportional Integral Derivative Controller (F^2PID) is proposed in this paper. The proposed F^2PID controller combines the advantage of a Fractional Order Proportional Integral Derivative (FOPID) controller and a Fuzzy Logic Controller (FLC). In the proposed F^2PID, the controlling parameters of FOPID are tuned by fuzzy logic that chooses optimum parameters of the proportional, integral, and derivative gains are 3, 0, and 1, respectively. The WBS is implemented in the MATLAB/Simulink platform, and the results are compared with existing controllers under different set points. The comparative analysis shows that the proposed controller is well suited for the application with different temperature set points.*

Keywords *- Water Bath System, Temperature, Set point, Transducer, Fuzzy rules, Heater, Error deviation.*

1. Introduction

Most industrial processes require a constant heating or uniform velocity temperature control mode [1]. The heating process in the industry takes place in a Water Bath System (WBS) in which there is a water tank and heating coils connected to a power supply through a thyristor, an outlet, and an inlet [2].

The inlet allows the fluid material to flow into the tank, in which a stirrer will stir the fluid so that it would be mixed up with the leftovers of the tank. This allows for lowering the heating value of the fluid already present in the tank. This causes further heating of the fluid, but the major problem is that the temperature value of the fluid at this point is unknown to the user. These data could be achieved by utilizing fluid sensors to measure temperature [3]. Moreover, the amount of heat fed to the fluid through the heating coil is unknown, which may lead to overheating or underheating fluid. Hence, a controller is used to control the heating induced by the heating coil.

The water bathing system could be used in clinical laboratories, research laboratories, food processing industries, and water plants. In this application, it is essential to have the desired temperature at a specific period of time so that errors in the work processes can be minimized. As the WBS is used in various temperature control applications. The normal temperature of natural gas is 25°C and should be maintained for transport through pipelines. However, sometimes, the temperature drops below the standard value when the pressure value decreases [4]. When preparing nanofibrils, the protein-isolated solution is heated to 80°C; hence, temperature control is required in this model [5]. In the synthesis of deep eutectic solvents (DESs), the temperature of WBS should be maintained at 90ºC.

During the synthesis, the p chlorophenol (2.58 g) was placed in a 10 mL screw-cap test tube kept at 70°C [6]. When preparing a non-eutectic SAT-urea mixture, the temperature in the WBS must be maintained at 60°C for 2 hours to melt the mix [7]. In the vitro digestion systems, the temperature is controlled using a heating lamp, a thermal sensor, and a water bath [8]. Humidity, atmospheric pressure, and dust are the main factors affecting the accuracy of the temperature in the WBS [9].

Hence, several sensors have been used to have better tracking capability. A thermometer circuit for a water bath system [10] was developed that uses the heating current without other measuring devices. In that approach, LED-LDR is adapted to isolate the transmitted high voltage with the output voltage indicator. The system was calibrated to have perfect mixing and data acquisition; hence, six K-type thermocouple sensors [9] were used. The readings of the sensor are displayed or stored on the personal computer. In the bio-oil recovery process [11], the percentage of aromatic and phenolic are analyzed using water bath temperature control.

Although many methods of temperature measurement have been used, the problem of temperature control in the tank is a crucial parameter. The control structure should be framed so that its liquid can be used efficiently for industrial purposes. The primary research requirement is to acquire constant temperature on any components used in industrial processes. This could be done by considering controller designs such as Proportional-Integral (PI), Proportional Integral Derivative (PID), and Proportional Derivative (PD) controllers [12].

A model predictive control with a PID [13] is used to control the temperature in the case of processing beverages and treatment for different diseases. Following this, some fuzzy-based approaches are formulated for the control of temperature. A self-learning-based sliding mode control [14] system that uses a rule modifier for the updation of firing strength weight is employed. The method proved the tracking stability performance, but that method did not compensate for sudden changes in input. Hence, an adaptive neuro-fuzzy interference system [15] aims to focus on the fuzzy logic problem by inhibiting the neural concept. Based on the parameters of the plant, the controller tuned itself through the backpropagation mechanism.

Feedback control of the temperature related to fuzzy logic is implemented by [16] using an air conditioner for overheating problems. The controller decides whether cooling a setpoint or heating is required. Then, on gas, the sensitive material analyzer, a temperature control system based on proportional integral derivative with long short-term memory, is reported by [17], which is trained by nonlinear dynamics of the Peltier system.

Here, the parameters in controllers are tuned by a hybrid approach of mean centre opposition-based learning particle swarm optimization. By considering the water bath system as an integer and non-integer system [18], a temperature control model is made concerning internal model control. In that method, a DC power source is used as a supply while a solid-state relay regulates the power flow.

In recent years, PID controllers have been used to control the temperature of nonlinear systems, which can also be used to control pressure and flow. In recent years, FOPID controllers have replaced PID controllers. Several complexities have arisen in temperature control in the industry. However, PID controllers lack nonlinear system control. At the same time, fractional calculus can be used for modelling with higher accuracy.

The fractional order calculus also faced some issues in the complex system [19]. Controllers are adopted in order to overcome the issues in fractional calculus. Moreover, the fuzzy logic is used to tune the control parameters of the controller. To bring the benefits of both these control approaches, the fuzzy-tuned FOPID controller is proposed in this work.

Prime contributions of this paper are given as follows,

- To design a WBS controller to limit the fluid temperature based on the application used.
- Model the Fractional Order Proportional Integral Derivative controller (FOPID) controller through fuzzy logic.
- To validate the performance of the control process with traditional methods.

The remaining part of this paper is organized as follows: Several recent works for temperature control in the WBS are discussed in section 2. The modelling of WBS, along with the proposed fuzzy-based FOPID (F^2PID) controller, is elaborated under section 3. The results of the proposed controller are evaluated in section 4, and the conclusion is given in section 5.

2. Literature Survey

Flavonoid is a bioactive compound found in plants used in medicinal, cosmetics, and pharmaceutical applications. Soursop leaf has the most antioxidant abilities. The extraction of flavonoids from the leaf was essential. Abdin et al. [20] proposed the extraction of flavonoids from plants using a water bath with a PID controller. The proportional integral derivative timer regulates the temperature for 45°C 20 minutes automatically. When an AC dimmer supplied the water bath, the stirring DC motor levelled the water temperature, which was incorporated in it, and then the sensor sensed the temperature.

The temperature of the used water was below the set point 45°C. So, the heater was ON to raise the temperature, and a proportional integral derivative controller was adopted in the control unit to bring the temperature as a particular value with the steady state error, overshoot less than 2% and 5% concerning Ziegler-Nichols method for tuning. After that, the ultrasonic device was turned ON when the temperature was 45°C to extract flavonoids from the plant for 20 minutes. The time was displayed on the LCD; after 20 minutes, the heater and stirrer motor. In addition, other tuning and controlling methods with less overshoot will be implemented to extract more flavonoids.

The efficiency of rotary evaporators mainly depended on the quality of the instrument, which cannot be controlled due to the absence of a relevant standard. Long Wang et al. [21] implemented a rotary evaporator’s water bath control system. Factors like water bath temperature, condensation efficiency, etc, influenced the sample recovery rate and solvent evaporation rate. In order to clarify the water bath temperature of the rotary evaporator, an accurate control technique was needed by using the recovery rate of Phthalate

Esters (PE). PE was an environmental compound, and the concentration rate was based on the temperature of the liquid. The temperature of the liquid was highly stable and controlled accurately when the system was modified. The recovery rate was developed by regulating the water bath temperature used in the rotary evaporator. The non-optimization-based control methods and the proportional integral derivative controller cannot handle the effective input and output constraints.

In order to rectify that, Aslam et al. [13] designed the temperature control of the water bath system using model predictive control. Model predictive control was an optimized control technique adopted to control the temperature in three cases without constraints, with input constraints, and with output constraints. Model predictive control was based on a system model and optimizer which regulates the temperature in the water bath without violating input and output constraints by reducing cost function for all three cases. By varying the inlet flow rate of water to the tank, the robustness of the model predictive control for temperature control was evaluated.

Even though model predictive control provides a better controlling process, it creates a high computational burden, and therefore, PLC was implemented with MPC for the industrial control process. Aslam et al. [22] proposed the real-time implementation of the Programmable Logic Controller (PLC) based model predictive control to regulate the tank's temperature and level of water in a bottle for industrial processes.

The resistive heating element heated the liquid in the tank, whereas a thermocouple and feedback-sensed temperature were given to PLC. The pulse width modulation-based flow control valve regulated the water flow of the bottle after reaching a particular temperature. Then, the water level was measured by weight cell and feedback to PLC, and it could be operated based on a scan cycle loop. Finally, MPC was implemented in real-time with PLC to regulate the temperature and level of water in the tank effectively.

Rybolt & Mebane [23] have implemented high-temperature water bath control and monitoring with sous vide cooking devices. It was a low-cost substitute to the normal scientific water bath and hot plate stirrer water bath in laboratories. The paper explained that raw food was sealed in a bag under a vacuum and then immersed in a water bath, which maintained a particular temperature to cook the food. The polycarbonate container was utilized as a hot water bath container.

The sous vide immersion circulator includes Bluetooth installed smartphone to turn the on and off the device and monitor the temperature an LED display. The precision cookers maintained the water at an exact temperature over a long period to cook the raw food and maintained the laboratory water bath $\pm 0.1°C$.

Wei et al. [24] suggested the smart bath assistive device for monitoring the temperature in WBS. In that model, six temperature sensors were affixed at different depths to get an optimum depth for measuring the temperature. Based on the experimental analysis, the mushroom-shaped device was modelled in which the stem part was immersed in water. The designed device can float in hot water and can monitor the variation in temperature over a long time. The performance of the suggested model was validated on a commercial analog bathing system.

Kativa et al. [25] suggested the Proportional Integral Derivative (PID) controller for temperature control in WBS. In that model, the parameters of the PID controller were tuned by the Zeigler-Nichols method. The simulation was carried out for the Proportional-Integral (PI) and Proportional Derivative (PD) controllers. The comparative analysis shows that the PID has provided a better outcome in terms of lower rise time and peak time.

Nasir et al. [18] suggested the Bat algorithm for fuzzy controller design for temperature control in WBS. In that paper, the suggested bat algorithm was adopted for generating the triangular membership functions. The initial population was generated based on real values of vectors. The suggested controller was validated on the WBS for varying set points such as 35ºC, 55ºC, and 75ºC. Moreover, the robustness of the controller was examined for the proposed control signals.

Mahmood et al. [26] suggested the use of a PID controller for temperature control of the water tank. The controller parameters of PID were tuned using the Ziegler-Nichols tuning method. The results obtained from the PID controller gains were compared with the other controllers tuning approaches. As it is shown that the Ziegler-Nichols tuning method has lower errors than the Tyreus-Luyben approach.

Tavoosi [27] suggested a type-2 fuzzy neural network controller for temperature control of WBS. Two fuzzy neural networks of type-2 have been used in that model; one was used as an identifier, and another one was used as a controller. The identifier was used to adjust the parameters, and the reverse model was used as the identifier.

Goel et al. [28] suggested the genetic algorithm-tuned neuro-fuzzy controller for temperature control in WBS. That suggested model does not require prior knowledge about the system and avoids the manual tuning of membership functions. The results of the suggested model were estimated under different operating points of 30ºC-40ºC-50ºC. Moreover, the results were verified using the disturbance rejection test and variable delay test.

2.1. Problem Definition

In a water bath system, the temperature of the fluid used in it has to be maintained for the user reference value. This is the main requirement in food processes and laboratories since, in those cases, the change in temperature of the medium used will impact the use of that material and make the whole system ineffective. Hence, the researchers employ several control structures, but the accuracy of the readings made by the sensor is poor. This is due to the unstable control generated by the controller. Some controllers have poor transient characteristics, while controllers like proportional integral controllers have the problem of vast steady-state error. The major issue in the existing controller, such as the PID and fuzzy, is the significant steady-state error. In the literature [20], the required temperature level is 45°C, and the PID controller produces large error values.

Moreover, the Zeigler Nichols method-based tuning method [25, 26] results in a more significant rise time and peak time. Temperature control is the key variable to be regulated in industrial scenarios; however, the least explorations are conducted on this topic. Moreover, it is observed that the set points are varied in different applications. Hence, this proposal aims to design a fuzzy-based FOPID controller to reduce inaccurate results in the water bath system under different scenarios.

3. Methodology

The temperature control on the water bath tank is essential since, for various industrial purposes, the fluid viscosity, temperature, and heating ratio vary. Hence, based on demand, the fluid temperature has to vary. To control the temperature of the liquid in the water bath system, a novel F^2PID controller is proposed in this paper. The proposed F^2PID controller works as the hybrid framework concerning Fuzzy rules and Fractional Order Proportional Integral Derivative (FOPID) controller. First, the temperature of the liquid is measured and fed into the controller, which examines the difference between the set point and the measured temperature. The fuzzy membership functions are generated based on the temperature error and error deviation values. Using the fuzzy rules, the controlling parameters of FOPID are tuned, and the temperature is controlled. The workflow of the proposed methodology is shown in Figure 1.

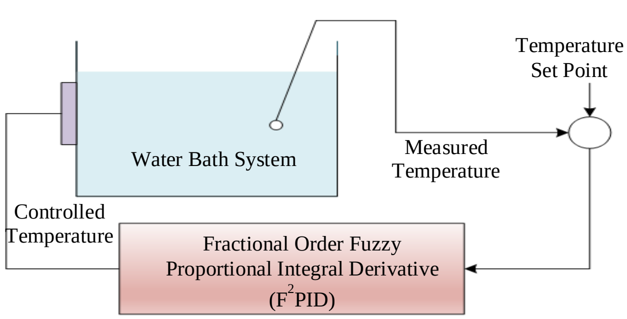


Fig. 1 Flow of the proposed methodology

3.1. Modelling of Water Bath System

The water tank, heater, sensor, and stirrer are essential components in a water bath system. The water bath consists of a suitable inlet and outlet that controls the tank's water level. The sensor in the tank measures process variables inside the water bath system. The value sensed by the sensor is fed into the controller for taking appropriate control actions. The Water Bath System (WBS) is modelled in this proposed work through transfer functions. Some assumptions are made for deriving the WBS that is given as follows.

- The heat capacity, density, and volume of the water tank are kept constant.
- The state of the tank is stable.

The balancing equations of material are given as follows,

$$M_{accumulate} = M_{incoming} - M_{leaving} \qquad (1)$$

Here, $M_{accumulate}$, $M_{incoming}$ and $M_{leaving}$ are the accumulated, entering and leaving the system's mass.

$$\frac{dM_{WB}}{dt} = M_{in} - M_{out} \qquad (2)$$

Here, M_{WB}, M_{in} and M_{out} are the mass of the water bath, incoming water, and outgoing water, respectively.

The equation of mass can be reframed in terms of flow rate, and density is given as follows.

$$\frac{dM_{\rho}}{dt} = F_i\rho - F\rho \qquad (3)$$

Here, ρ is the mass density, V is the liquid volume, $F_i$and F are the inflow and outflow of the liquid, respectively. If the tank volume is constant, the following condition will occur.

$$F_i\rho - F\rho = 0 \qquad (4)$$

The WBS works based on the liquid flow; thus, the material concept is required for generating the energy model.

The energy balancing equations of WBS are given as follows,

$$E_{accumulate} = E_{in} - E_{out} \qquad (5)$$

Here, $E_{accumulate}$ is the accumulated energy in the system, E_{in} and E_{out} are the energy entering and leaving the system, respectively.

$$VU_p\rho\frac{dT}{dt} = FU_p\rho(T_i - T) + Q \qquad (6)$$

The above equation can be written as follows,

$$\frac{dT}{dt} = \frac{F}{V}(T_i - T) + \frac{Q}{VU_p\rho} \quad (7)$$

Here, U_p is the heat capacity of the tank (J/Kg°C), ρ is the fluid density of the tank (Kg/m^3), V is the tank volume (m^3), Q is the heat energy supplied by the base heater (J/sec), T and T_i are the time constant and integral, respectively. The generalized form of the above equation is given by,

$$\frac{V}{F}\frac{dT}{dt} + T = \frac{1}{FU_p\rho}QT_i \quad (8)$$

Here, $\frac{V}{F} = \tau$ is the time constant of the system, $\frac{1}{FU_p\rho} = k$ is the system gain. Based on these equations, the first-order equation is represented as,

$$\tau\frac{dT}{dt} + T = KQ + T_i \quad (9)$$

The transfer function of the water bath system is given as follows,

$$G_p(s) = \frac{K}{\tau s+1} = \frac{T(s)}{Q(s)} \quad (10)$$

By applying the specification of WBS, the transfer function is obtained as,

$$G_p(s) = \frac{60}{720s+1} \quad (11)$$

By applying the dead time as the 30s, the transfer function is obtained as,

$$G_d(s) = \frac{1}{30s+1} \quad (12)$$

The overall transfer function of the WBS is written as follows.

$$G(s) = G_d(s).G_p(s) \quad (13)$$

$$G_p(s) = \frac{60}{720s+1}.\frac{1}{30s+1} \quad (14)$$

$$G(s) = \frac{60}{21600s^2+720s+1} \quad (15)$$

$$G(s) = \frac{0.0029}{(s+0.0014).(s+0.033)} \quad (16)$$

Equation (13) is the overall transfer function of WBS while applying the dead time 30s in this equation; the final model of WBS is obtained as Equation (16), which is used in the Simulink model to represent the WBS.

3.2. Temperature Control in WBS

The process control system is nonlinear; thus, it is difficult to obtain an accurate system model. Thus, several controllers have been developed for first and second-order systems to control the process variables. The WBS consists of different components, such as a water tank, controller and heater. In practical applications, the temperature in WBS is measured with sensors. The user sets the reference temperature value based on the applications. In this work, different temperature set points are given to the controller to examine its performance efficacy.

3.2.1. Proposed F^{2}PID Controller for Temperature Control in WBS

In this proposed work, F^{2}PID is designed by considering the nonlinear dynamics of the WBS. Thus, the controlling parameters of the F^{2}PID controller need to be modified to minimize the error and improve the system stability. The F^{2}PID controller combines the benefits of Fuzzy Logic and Fractional Order PID (FO-PID) controller.

The FOPID controller has more degrees of freedom than the traditional PID controller. The FOPID controller has an integer and differentiator in the order of [29] and [30]. In F^{2}PID, fuzzy rules are added before the FOPID controller to tune the gain parameters. Fuzzy rules are generated to the error and deviation in error. The working of the proposed F^{2}PID controller is shown in Figure 2.

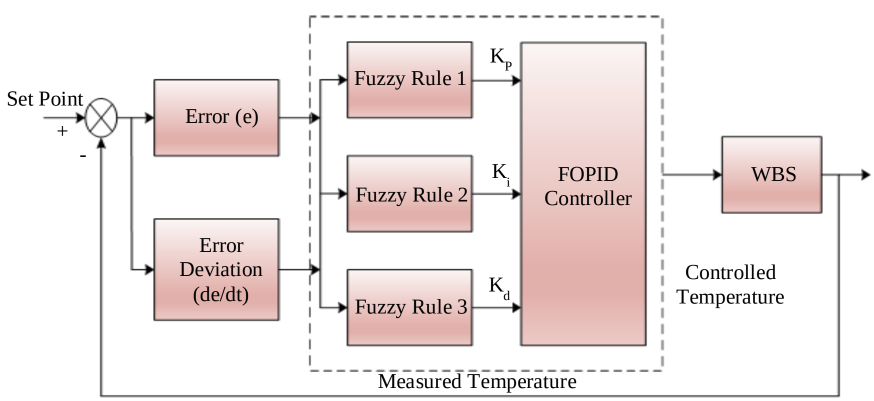


Fig. 2 Proposed F^{2}PID based temperature control

Table 1. Fuzzy rule-1 for parameters tuning of Kp

de/dt (Kp) / e (Kp)	-L	-M	-S	Z	+S	+M	+B
-L	-L	-L	-S	-S	+S	Z	Z
-M	-L	-L	-M	-S	-S	Z	+S
-S	-L	-M	-S	-S	Z	+S	+S
Z	-M	-M	-S	Z	+S	+M	+B
+S	-S	-S	Z	+S	+S	+M	+S
+M	-S	Z	+S	+M	+M	+M	+B
+B	Z	Z	-S	-S	-S	+B	+B

Table 2. Fuzzy rule-2 for parameters tuning of Ki

de/dt (Ki) / e (Ki)	-L	-M	-S	Z	+S	+M	+B
-L	+B	+B	+M	+M	+S	Z	Z
-M	+B	+B	+M	+S	+S	Z	Z
-S	+B	+M	+S	+S	Z	-S	-S
Z	+M	+M	+S	Z	-S	-M	-M
+S	+M	+S	Z	-S	-S	-M	-L
+M	Z	Z	-S	-S	-M	-L	-L
+B	Z	Z	-S	-M	-M	-L	-L

Table 3. Fuzzy rule-3 for parameters tuning of Kd

de/dt (Kd) / e (Kd)	-L	-M	-S	Z	+S	+M	+B
-L	-S	+S	+B	+B	+B	+M	-S
-M	+S	+S	+B	+M	+M	+S	Z
-S	Z	+S	+M	+M	+S	+S	Z
Z	Z	+S	+S	+S	+S	+S	Z
+S	Z	Z	Z	Z	Z	Z	Z
+M	-L	-S	-S	-S	-S	-S	-L
+B	-L	-M	-M	-M	-S	-S	-L

The fuzzy membership functions examine the proportional, integral and derivative gains. The fuzzy rules generated for optimum parameter tuning are given in Tables 1, 2 and 3. Here, the control parameters are optimized between the ranges of -3 to 3. Here, the membership functions are represented as large negative (-N), negative medium (-M), negative small (-S), zero (Z), small positive (+S), positive minimum (+M) and positive big (+B). The fuzzy rules are generated based on the membership functions of errors and error deviations of temperature. This work, three different rules are generated for the proportional, integral and derivative gains.

4. Result and Analysis

The Simulink model of the proposed work for constant set point is depicted in Figure 3, in which the transfer function equation denotes the WBS. The proposed controller is validated under two different cases.

- Case 1: Constant temperature set point (40ºC).
- Case 2: Varied temperature set points (40ºC-50ºC-60ºC) and (30ºC-40ºC-50ºC).

The required range of temperature varies in terms of different applications, as mentioned in sections 1 and 2. Hence, two different cases are considered for validating the performance of the controller.

One of the cases is considered for a constant level of temperature, and another case is taken for varying levels of temperature. Here, the temperature level varies between 40˚C and 70ºC. In order to check the efficacy of the proposed controller, these points are randomly taken.

In case 2, the set points of the temperature variations in time; thus, 3 different set points are given to the WBS model. The Simulink model of the proposed work under case 2 is shown in Figure 4. In this case, the fuzzy rules generate optimum values for the FOPID controller; thus, it controls the WBS temperature based on the set points.

Figure 5 shows the temperature curves of the WBS while using the proposed controller under case-1 and case-2. Figure 5(a) shows the controlled temperature of the WBS during 40°C. Moreover, the temperature set point varies from 40°C, 50°C, and 60°C up to 20s, 60s, and 100s, respectively. These results verify that the proposed controller has a lower settling time of 10s under case 1. In case 2, the settling point of the proposed controller is 10s, 25s and 65s for varying set points. The actual temperature of the liquid in the WBS is 38°C in case-1, and the temperature under case-2 ranges between 0-58°C after using the proposed controller. The range of controlled temperature is raised to the set points in different cases, indicating the proposed controller's performance efficacy under varying set points.

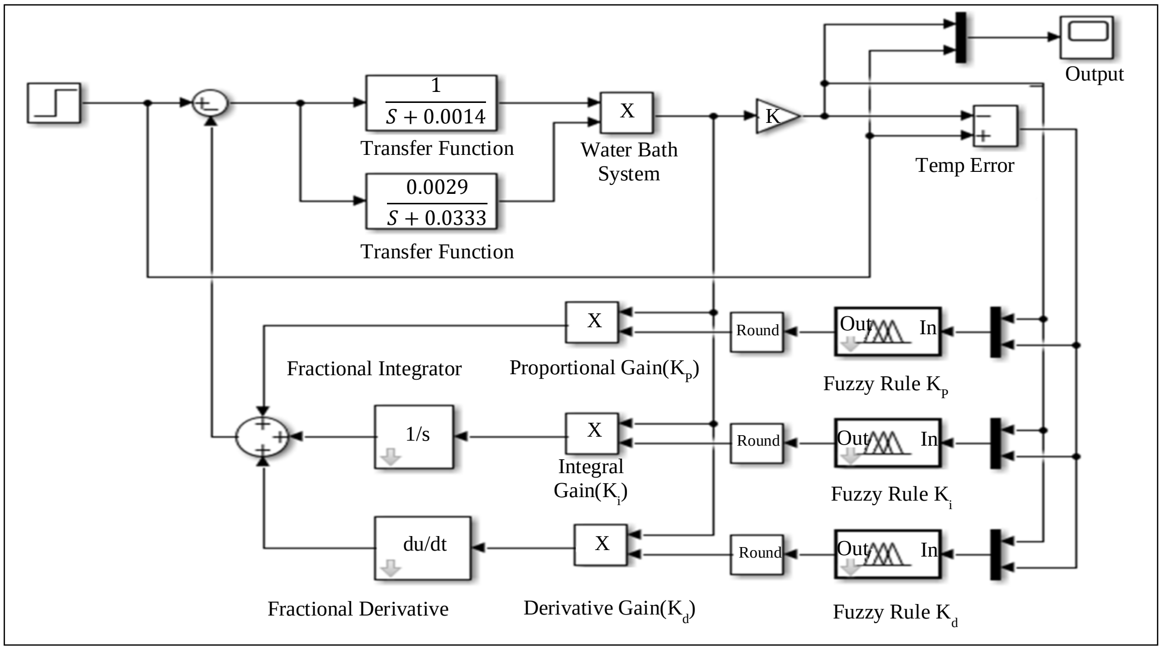


Fig. 3 Simulink model of the proposed work for case 1

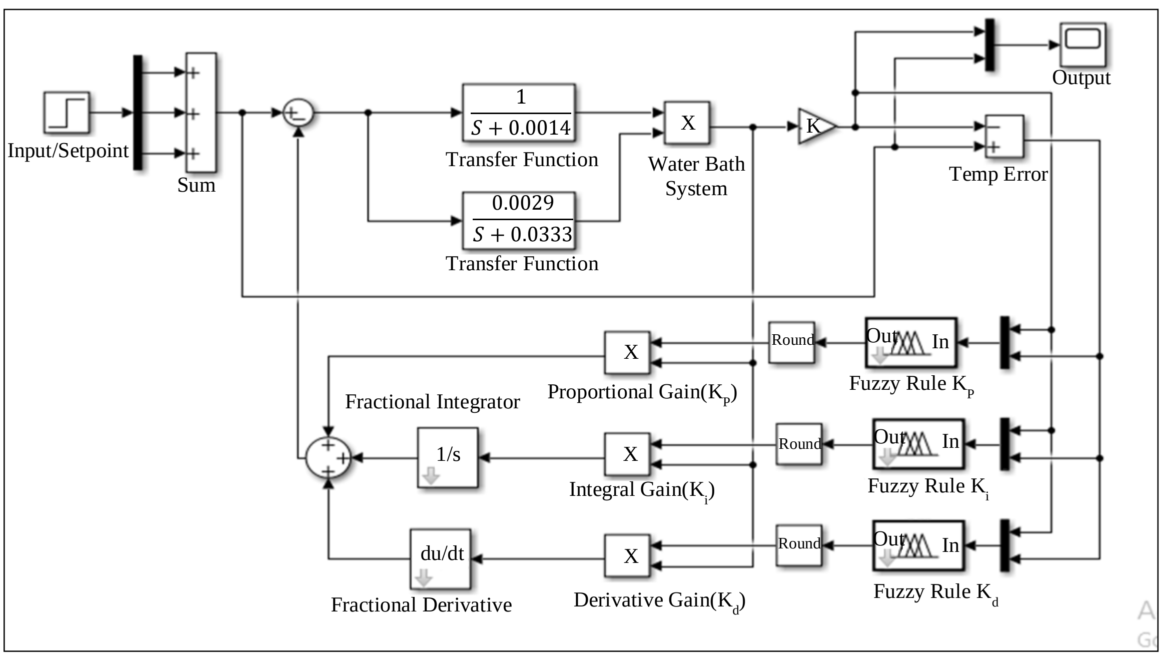


Fig. 4 Simulink model of the proposed work for case 2

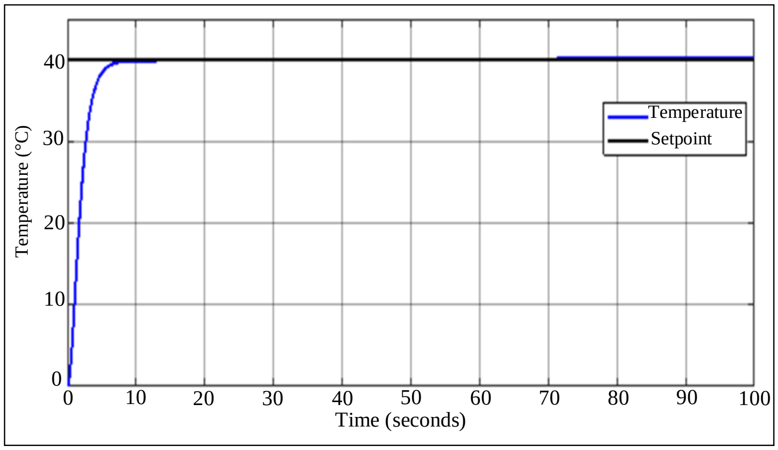
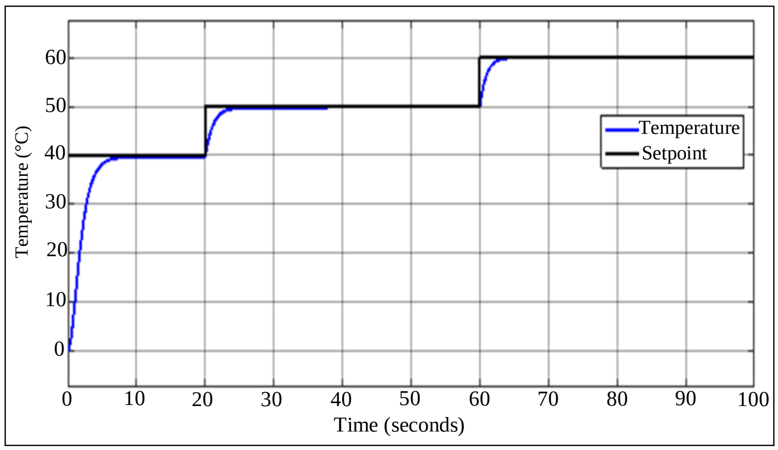
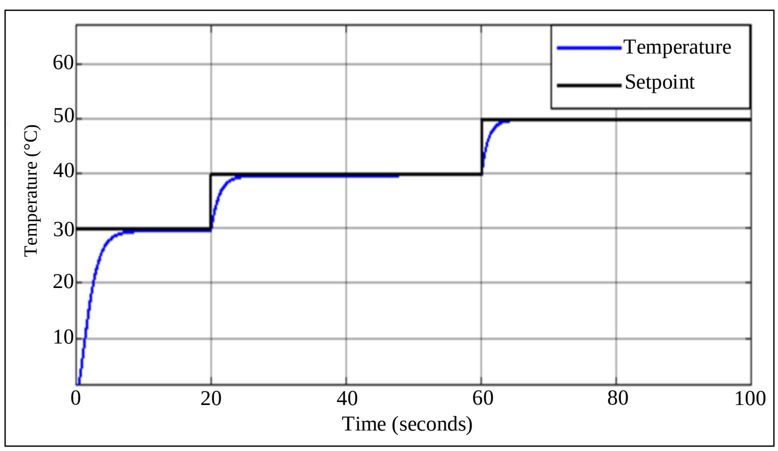


Fig. 5 Temperature variation in WBS over time under case-1



(a)



(b)

Fig. 6 Temperature variation in WBS over time under case-2: (a) 40°C-50°C-60°C, and (b) 30°C-40°C-50°C.

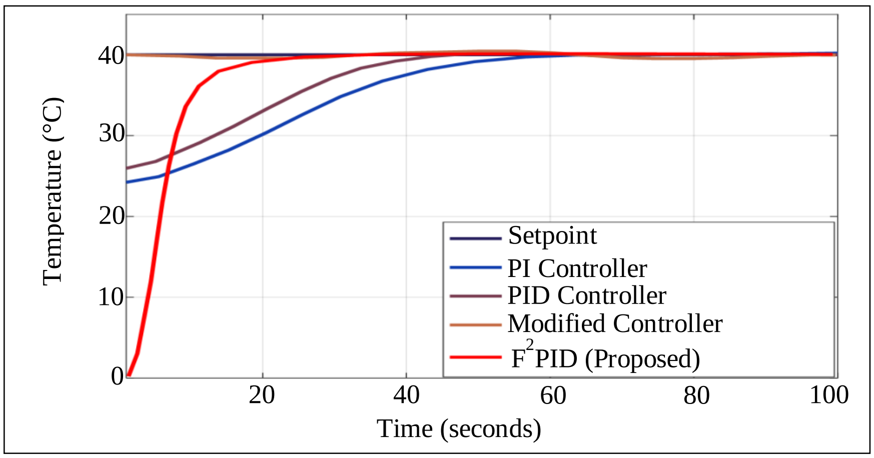
The values of the FOPID controller tuned by fuzzy rules are shown in Table 4. The comparative analysis of temperature control by the F^2PID controller is depicted in Figure 7. Here, the performance of the proposed controller is validated with existing controllers such as PI [20], PID [20], modified controller [21] and PLC-predictive controller [22]. Here, the existing controllers are compared to the proposed controller under two cases. In Figure 7(a), the set point of temperature is given as 40°C for all the controllers. As shown, the proposed model's temperature is raised from 0°C, whereas the controllers, such as PI and PID, are raised from 25°C based on their application. The different ranges of temperatures are reached at the set point while using the controllers. Moreover, the modified controller controls the temperature near the set point but has a more considerable settling time. The results imply that the proposed controller has a lower settling time when compared with existing controllers.

In Figure 7(b), the comparative analysis of temperature control is carried out based on three different set points in proposed and existing controllers. In this case, the performance of controllers is taken for the same set points. In the existing controller, the set points are given as 50ºC-60 ºC-70ºC for varying times. When changing the set points, the settling time of the existing PLC controller takes 15 seconds to reach the set point of 50ºC; at the same time, the settling time of the proposed controller takes 7 seconds to reach the set point of 50ºC.

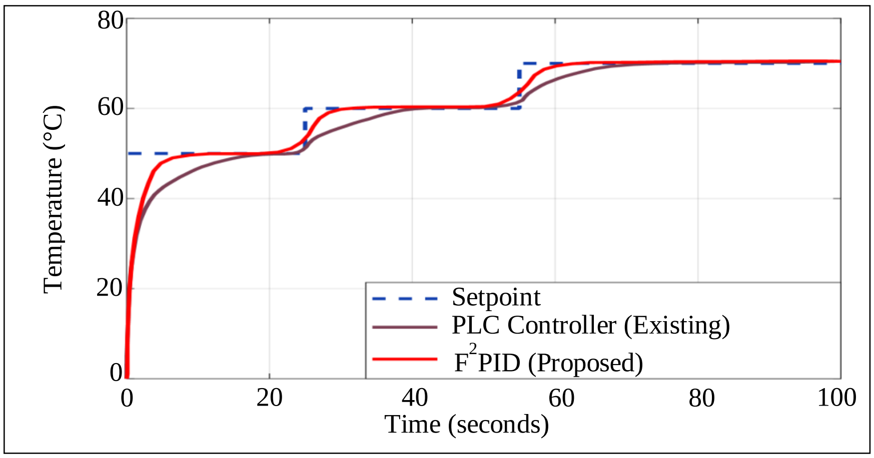
The comparative analysis shows that the proposed controller is efficient for the WBS for different applications. The hardware model of WBS consists of a sensor, water tank and coil heater. The WBS is supplied with a coil heater with power 2500W. The specifications of WBS used in the experimental model are shown in Table 5.

Table 4. Control parameters tuned by fuzzy rules

Parameters	Values
P	2
I	2
D	2
λ	1
μ	1



(a)



(b)

Fig. 7 Comparative analysis of temperature control in WBS: (a) Case-1, and (b) Case-2.

Table 5. Specifications of the experimental model

Parameters	Values
Water Tank Capacity	12 litres
Temperature of Inlet Water	25°C
Flow Rate	1 litre/min
Sampling Period	30s

Table 6. Experimental results

Performance Criteria			PID Controller (Existing)	F^2PID Controller (Proposed)
Time to Reach 30°C	Time to Reach the Set Point 30°C		150s	120s
	Overshoot	Maximum(°C)	5.89	2.16
		Minimum (°C)	0.29	0.25
	Undershoot	Maximum(°C)	0.61	0.68
		Minimum (°C)	-	0.47
Time to Reach 40°C	Time to Reach the Set Point 40°C		330s	240s
	Overshoot	Maximum(°C)	3.68	1.82
		Minimum (°C)	0.78	0.28
	Undershoot	Maximum(°C)	1.12	0.72
		Minimum (°C)	-	0.28
Time to Reach 50°C	Time to Reach the Set Point 50°C		300	270s
	Overshoot	Maximum(°C)	4.93	2.32
		Minimum (°C)	0.13	0.02
	Undershoot	Maximum(°C)	0.57	0.41
		Minimum (°C)	0.37	0.24

Table 7. Comparative analysis of error metrics

Controllers	PI Using Ziegler-Nicholas Tuning (Mahmood et al. 2018)	PID Using Ziegler-Nicholas Tuning (Mahmood et al. 2018)	PI Using Tyreus-Luyben Tuning (Mahmood et al. 2018)	PID Using Tyreus-Luyben Tuning (Mahmood et al. 2018)	Proposed Controller
Integral Absolute Error (IAE)	70.2	60.1	68.6	59.5	48.92 (case 1) 33.41 (case 2)
Integral Square Error (ISE)	186.48	144.6	180.93	142.1	138.9 (case 1) 121.5 (case 2)

The results measured from the experimental model are illustrated in Table 6. The comparative analysis of error metrics is shown in Table 7.

5. Conclusion

In this work, the F^2PID controller is proposed for temperature control of the WBS in different set points. Initially, the mathematical equations for WBS are presented in this paper, and the final transfer function equation is used in the Simulink model to represent the WBS. The measured temperature from WBS is fed into the F^2PID along with the set point. The F^2PID controller combines both the FOPID controller and the FLC, in which different fuzzy rules choose the controlling parameters of the FOPID.

The performance of the proposed model is implemented on MATLAB/Simulink, and the results are taken in terms of two cases of constant and varying set points. Moreover, the IAE and ISE values for the proposed controller under case-1 are 48.92 and 138.9, respectively. Meanwhile, the IAE and ISE values for the proposed controller under case 2 are 33.41 and 121.5, respectively. From this analysis, it is concluded that the proposed controller has better performance in terms of varying operating conditions. Moreover, the results imply that the proposed controller has a lower settling time than existing controllers. In future work, intelligent controllers will be used for temperature control in WBS under different test cases.

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