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# Control of Boiler Temperature using PID, PD-PI and 2DOF Controllers

*Galal Ali Hassaan*

*Emeritus Professor, Department of Mechanical Design & Production, Faculty of Engineering, Cairo University, Egypt*

**A B S T R A C T**

This research paper investigates the control of a boiler temperature through its step time response to reference and disturbance inputs. The paper proposes three controllers: PID controller from the first generation and PD-PI and 2DOF controllers from the second generation. The three controllers are tuned using the MATLAB optimization toolbox and an ITAE performance index. The performance of the control system using the three controllers is compared with the performance using a fuzzy-PID controller. The comparison takes the form of graphical and quantitative form. The comparison reveals the best controller suitable to control the boiler temperature with the best performance characteristics.

Keywords: Boiler temperature control, PID controller, PD-PI controller, 2DOF controller, controller tuning, control system performance.

## Introduction

A water heating boiler was invented by Arabic scientists and engineers during the $9^{th}$ century AC through Banu Musa bin Shaker as documented in their book about ingenious devices (Hill, 1978). The boiler as an engineering unit has too many applications in facility heating, electrical generation, agricultural industry, pharmaceutical industry, chemical processing, textile industry, pulp and paper industry, petroleum and refineries industry, government and military applications, food and beverage industry and other applications (Industrial Boilers America, 2022, Cleaver Brooks, 2024). Because boilers work in multi-phase environment (water and steam) water level, steam temperature and pressure have vital importance in the safe operation of the boiler. Here comes the role of feedback control systems invented by Banu Musa bin Shaker (Hassaan, 2004).

This research paper deals with boiler temperature control as an starting effort by the author in the field of boiler control. The start is with introducing some of the efforts world-wise about boiler temperature control. Santoso, Nazaruddin and Machtadi, 2005 considered an approach to design a controller for the air-to-fuel ratio optimization in the combustion process of a power plant boiler. The used a fuzzy-logic controller developed for the combustion process comparing with a classical PI controller. Their comparison outlined 22 s settling time for the fuzzy logic controller compared with 46 s for the PI controller. The maximum overshoot was 26.7 % for the fuzzy-logic controller and 30 % for the PI controller. Kumar, 2010 outlined that the PID controller is widely used for steam temperature control in the boiler unit of thermal power plants. He presented a design method for a multi-objective PID controller to avoid the drawback of the conventional PID controller. He applied the adaptive-weighted PSO technique for parameters optimization of the controller. He showed that the application of the proposed technique improved the dynamic performance of the steam temperature control system with good robustness. Gu and Wang, 2012 used a PID controller based on BPNN in the temperature control system of an electrothermal boiler. The gain parameters of the PID controller were adjusted automatically. They used a mathematical model for the boiler based on least squares identification.

Aiswary, Akhil, Amal and Rajani, 2015 presented the control of water level in a steam boiler of a nuclear power plant by using a PID and a fuzzy-PID controllers. They presented the output step time response using both controllers for sake of comparison. Dhayale et al., 2016 presented some techniques used for boiler automation including monitoring temperature, pressure and water level. They investigated the use of PID, fuzzy-logic control for systems with uncertainty and nonlinearity and PLC and SCADA-based control. Lesewed, Khamis and Elzway, 2018 used a dynamic model for the water temperature in a biomass boiler (second-order model with delay time). They studied the use of a sliding mode control system for the boiler temperature and compared with using conventional PID controller with and without disturbance. Wang et al., 2019 used a multi-model switching control system based on heat transfer calculations to solve the problem of large inertia and delay of the steam temperature of the boiler. They presented the step time response of the boiler temperature under load conditions from 30 to 100 %.

Tavoosi and Mohammadzadeh, 2021 presented a radial basis function network-based model predictive control to control the steam temperature of a power plant boiler. They used the Laguerre polynomials to obtain the local boiler model for different loads. They showed by simulation that the recurrent radial basis function based predictive model (RBFN-MPC) performed better than the multi-model based MPC. They presented the simulation results for RBFN-MPC and conventional MPC for the boiler temperature control. Cui et al., 2022 proposed a PID control strategy based on integral gain scheduling to solve the challenge of improving the control performance of a superheated steam temperature. They verified the effectiveness of the proposed technique under nominal and uncertain conditions for tracking and disturbance rejection performance. They presented the step time response of the temperature control system for 50, 75 and 100 % load using three controllers for comparison purposes. Wang, 2023 designed a fuzzy RBF neural network PID control method for steam temperature control. He used a first-order model for the steam temperature with time delay. He compared the step time response of the temperature control system using fuzzy-PID and a RBFfnn-PID controllers and compared the time based characteristics of the control system using both controllers.

**Nomenclature**

| | |
|---|---|
| $a_0,a_1,a_2$ | Process denominator parameters |
| $b_0,b_1$ | Process numerator parameters |
| C(s) | Laplace transform of the control system output |
| D(s) | Laplace transform of the disturbance input of the control system |
| $D_{R1}(s)$ | Denominator of $M_{R1}(s)$ |
| $D_{D1}(s)$ | Denominator of $M_{D1}(s)$ |
| $D_{R2}(s)$ | Denominator of $M_{R2}(s)$ |
| $D_{D2}(s)$ | Denominator of $M_{D2}(s)$ |
| $D_{R3}(s)$ | Denominator of $M_{R3}(s)$ |
| $D_{D3}(s)$ | Denominator of $M_{D3}(s)$ |
| e | Exponential |
| $G_c(s)$ | Controller transfer function |
| $G_{c1}(s)$ | PI mode transfer function of the 2DOF controller |
| $G_{c2}(s)$ | PID mode transfer function of the 2DOF controller |
| $G_p(s)$ | Process transfer function |
| $G_{PDPI}(s)$ | Transfer function of the PD-PI controller |
| $G_{PID}(s)$ | Transfer function of the PID controller |
| $K_d$ | Derivative gain parameter |
| $K_i$ | Integral gain parameter |
| $K_{pc}$ | Proportional gain parameter |
| $M_{D1}(s)$ | Transfer function of a PID controlled boiler temperature for a disturbance input |
| $M_{D2}(s)$ | Transfer function of a PD-PI controlled boiler temperature for a disturbance input |
| $M_{D3}(s)$ | Transfer function of a 2DOF controlled boiler temperature for a disturbance input |
| $M_{R1}(s)$ | Transfer function of a PID controlled boiler temperature for a reference input |
| $M_{R2}(s)$ | Transfer function of a PD-PI controlled boiler temperature for a reference input |
| $M_{R3}(s)$ | Transfer function of a 2DOF controlled boiler temperature for a reference input |
| $N_{D1}(s)$ | Numerator of $M_{D1}(s)$ |
| $N_{D2}(s)$ | Numerator of $M_{D2}(s)$ |
| $N_{D3}(s)$ | Numerator of $M_{D3}(s)$ |
| $N_{R1}(s)$ | Numerator of $M_{R1}(s)$ |
| $N_{R2}(s)$ | Numerator of $M_{R2}(s)$ |
| $N_{R3}(s)$ | Numerator of $M_{R3}(s)$ |
| PD-PI | Proportional Derivative – Proportional Integral controller |
| PID | Proportional Integral Derivative controller |
| R(s) | Laplace transform of the reference input of the control system |
| s | Laplace operator |
| U(s) | Laplace transform of the controller output |
| 2DOF | Two Degree of Freedom controller |

## Controlled Boiler Temperature

The structure and tuning of any control system depends of the type and complexity of the process model. For the process in hand, it has great varieties of mathematical models defining its dynamics. One of the dynamic models for the boiler steam was used by Wang, 2023 in his study of the PID control of the steam temperature of a boiler. The process, $G_p(s)$ model used by Wang is first-order one with time delay given by (Wang, 2023):

$$G_p(s) = 7e^{-42.8s}/(310s+1) \qquad (1)$$

The exponential term in Eq.1 can be replaced by a first-degree. Pade-polynomial approximation given by (Hanta & Prochazka, 2009):

$$e^{-42.8s} \approx (2-42.8s)/(2+42.8s) \qquad (2)$$

Combining Eqs.1 and 2 gives the process transfer function, $G_p(s)$ for boiler temperature control as:

$$G_p(s) = (-297.5s+14)/(13268s^2+662.8s+2) \qquad (3)$$

$= (b_0s+b_1)/(a_0s^2+a_1s+a_2)$

Where: $b_0$ =-297.5 ; $b_1$ = 14

$a_0$ = 13268 ; $a_1$ = 662.8; $a_2$ = 2 (4)

The step time response of this boiler steam temperature process reveals the dynamic characteristics of this process without any control. Its unit step time response is generated by the MATLAB command step (Mathworks, 2024) and shown in Fig.1.

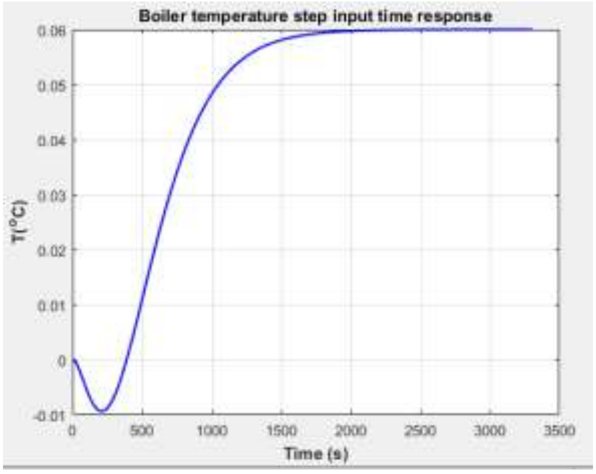


**Fig.1 Unit step time response of the boiler steam temperature.**

Comments:

- The boiler temperature process is stable.
- It shows undershoot due to the process delay time.
- It has no overshoot.
- It has 0.94 steady-state error.
- It has a settling time of about 1500 s.
- Any good proposed control system has to overcome the drawbacks undershoot, steady-state error and settling time.

## Controlling the Boiler Temperature using a Conventional PID Controller

Conventional PID controllers are still in use to control industrial boiler parameters (Tan, Lin, Fang & Chen, 2004, Kumar, 2010, Gu & Wang, 2012, Aiswary et al., 2015, Suthat & Wongvanich, 2021, Cue et al., 2022 and Wang, 2023). Therefore, for sake of comparison of the performance of the control system used to control the boiler steam temperature using two controllers from the second generation of PID controllers presented by the author in 2014 (Hassaan, 2021), the use of a conventional PID controller is presented first. A conventional PID controller has the transfer function, $G_{PID}(s)$ given by (Guo & Zhao, 2017):

$G_{PID}(s) = K_{pc}+ (K_i/s) +K_ds$ (5)

Where $K_{pc}$, $K_i$ and $K_d$ are the gain parameters of the PID controller.

The PID controller is cascaded with the controlled process with an error detector before it receiving the reference input and a feedback signal from the process with unit feedback. This is the structure of a simple block diagram incorporating the PID controller and the boiler temperature process. The transfer functions of the closed-loop control system for both reference and disturbance inputs are as follows:

- For a reference input R(s), $M_{R1}(s) = T(s)/R(s)$ is:

$M_{R1}(s) = N_{R1}(s)/D_{R1}(s)$ (6)

Where:

$N_{R1}(s) = b_0K_ds^3+(b_0K_{pc}+b_1K_d)s^2+(b_1K_{pc}+b_0K_i)s+b_1K_i$

And $D_{R1}(s) = (b_0K_d+a_0)s^3+(a_1+b_0K_{pc}+b_1K_d)s^2+(a_2+b_1K_{pc}+b_0K_i)s+b_1K_i$

- For a disturbance input D(s), $M_D(s) = T(s)/D(s)$ is:

$M_{D1}(s) = N_{D1}(s)/D_{D1}(s)$ (7)

Where:

$N_{D1}(s) = b_0s^2+b_1s$

And $D_{D1}(s) = D_{R1}(s)$

- *PID controller tuning:*

- The three PID controller parameters are tuned using the transfer function in Eq.6 and the MATLAB optimization toolbox (Lupez, 2014) to minimize the ITAE performance index.
- The tuned PID controller parameters are:

$K_{pc} = 2.003306$ ; $K_i = 0.018592$

$K_d = 30.49466$ (8)

- The unit step time responses of the boiler temperature for reference and disturbance inputs are plotted using Eqs.6,7 and 8 using the MATLAB command '*plot*' and shown in Fig.2.

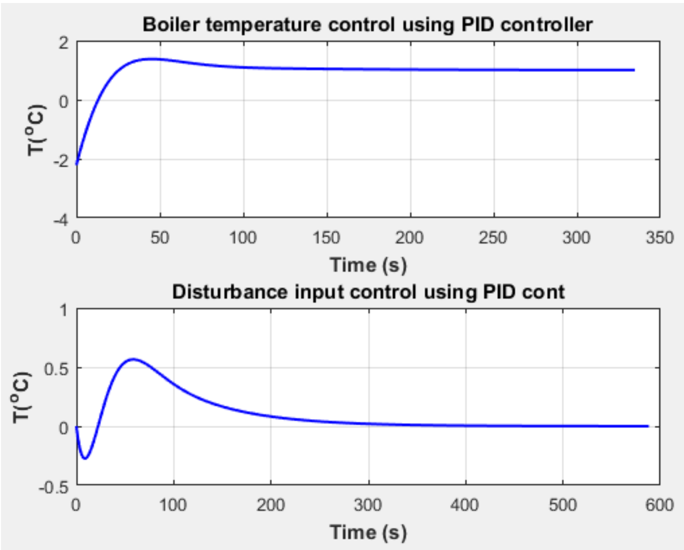


**Fig.2 Boiler temperature control using a PID controller.**

Comments:

- For a reference input tracking:
  - Maximum percentage overshoot: 36.8 %
  - Settling time: 204 s
  - Steady-state error: -0.0064
- For a disturbance input:
  - Maximum time response: 0.565 ºC
  - Minimum time response: -0.250 ºC
  - Time of maximum time response: 58 s
  - Settling time to zero: 400 s

## Controlling the Boiler Temperature using a PD-PI Controller

The PD-PI controller was introduced by the author as one of the second generation of PID controllers introduced by the author starting from 2014 to overcome the problems associated with the use of the conventional PID controller. The author used the PD-PI controller to control a number of processes having bad dynamics such as: first-order delayed processes (Hassaan, 2014), highly oscillating second-order process (Hassaan, 2014), integrating plus time delay process (Hassaan, 2014), delayed double integrating process (Hassaan, 2015), third-order process (Hassaan, 2020), greenhouse humidity (Hassaan,2023), boost-glide rocket control (Hassaan, 2023) and LNG tank level control (Hassaan, 2024). A PD-PI controller has the transfer function, $G_{PDPI}(s)$ given by (Hassaan, 2023):

$$G_{PDPI}(s) = [K_dK_{pc2}s^2 + (K_dK_i+K_{pc1}K_{pc2})\, s+K_{pc1}K_i]/s \qquad (9)$$

Where: $K_{pc1}$ and $K_d$ are the proportional and derivative gains of the PD-mode of the PD-PI controller

$K_{pc2}$ and $K_i$ are the proportional and integral gains of the PI-mode

The transfer functions of the closed-loop control system for both reference and disturbance inputs using the PD-PI controller are as follows:

- For a reference input R(s), $M_{R2}(s) = T(s)/R(s)$ is:

$$M_{R2}(s) = N_{R2}(s)/D_{R2}(s) \qquad (10)$$

Where:

$$N_{R2}(s) = K_{pc2}K_ds^3+(b_0K_{pc1}K_{pc2}+b_0K_dK_i+b_1K_{pc2}K_d)s^2+(b_0K_{pc1}K_i+b_1K_{pc1}K_{pc2}+b_1K_dK_i)s+b_1K_{pc1}K_i$$

and

$$D_{R2}(s) = (b_0K_{pc2}K_d+a_0)s^3+(a_1+b_0K_{pc1}K_{pc2}+b_0K_dK_i+b_1K_{pc2}K_d)s^2+(a_2+b_0K_{pc1}K_i+b_1K_{pc1}K_{pc2}+b_1K_dK_i)s+b_1K_{pc1}K_i$$

- For a disturbance input D(s), $M_{D2}(s) = T(s)/D(s)$ is:

$$M_{D2}(s) = N_{D2}(s)/D_{D2}(s) \qquad (11)$$

Where:

$N_{D2}(s) = N_{D1}(s)$ without filter after D(s)

and $D_{D2}(s) = D_{R2}(s)$ without filter after D(s)

- *PD-PI controller tuning:*

- The four PD-PI controller parameters are tuned using the transfer function in Eq.10 and the MATLAB optimization toolbox (Lupez, 2014) to minimize the ITAE performance index.
- The tuned PD-PI controller parameters are:

$K_{pc1} = -2.88685$ ; $K_d = -198.91468$

$K_{pc2} = 1.44258$ ; $K_i = 46.17055$ (12)

- The unit step time responses of the boiler temperature for reference and disturbance inputs using the PD-PI controller are plotted using Eqs.10, 11 and 12 using the MATLAB command '*plot*' and shown in Fig.3.

Comments:

- For a reference input tracking:
  - Maximum percentage overshoot: zero
  - Settling time: 0.0691 s
  - Steady-state error: zero
- For a disturbance input (to improve the performance of the control system regarding the rejection of the disturbance, a high pass filter of gain 100 is added after D(s) .. Kejm, 2019):
  - Minimum time response: $-1.845\times10^{-5}$ ºC
  - Time of minimum time response: 0.018 s
  - Settling time to zero: 0.200 s

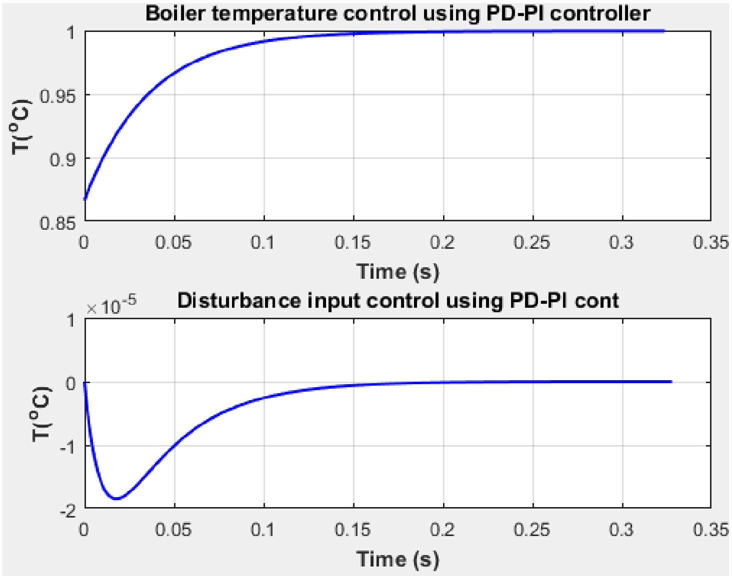


**Fig.3 Boiler temperature control using a PD-PI controller.**

## Controlling the Boiler Temperature using a 2DOF Controller

Several 2DOF controllers were introduced by the author as members of the second generation of PID controllers introduced by him starting from 2014 to overcome the problems associated with the use of the conventional PID controller. The author used the 2DOF controllers to control a number of processes having bad dynamics such as: highly oscillating second-order process (Hassaan, 2015), delayed double integrating process (Hassaan, 2015), second-order-like processes Hassaan, 2018), gas turbine speed control (Hassaan, 2022), boost-glide rocket control (Hassaan, 2023), greenhouse temperature (Hassaan, 2023) and liquefied natural gas tank level control (Hassaan, 2024). The structure of the 2DOF controller in the block diagram of a control system controlling a process is shown in Fig. 4 (Hassaan, 2022). It comprises two sub-controllers: PID-control mode in the feedforward path receiving the error signal and a PD-control mode in a feedforward loop receiving the reference input of the control system as an input to this sub-controller mode. The transfer functions of the two control modes are as follows:

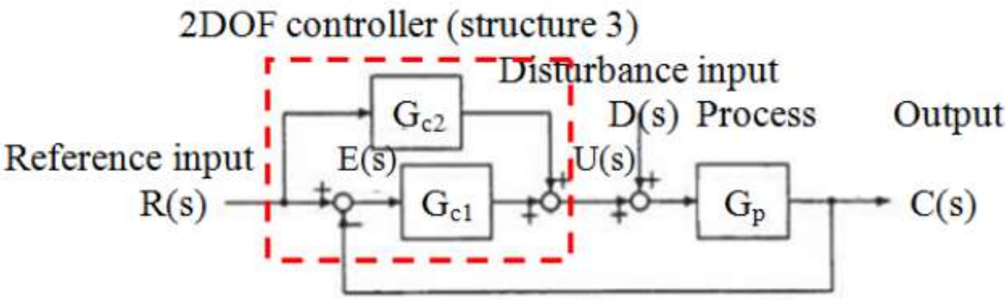


**Fig. 4 Control system of boiler temperature control using a 2DOF controller.**

$G_{c1}(s) = (K_{pc1}s+K_{i1})/s$

and (13)

$G_{c2}(s) = (K_d s^2+K_{pc2}s+K_{i2})/s$

Where: $K_{pc1}$ and $K_{i1}$ are the proportional and integral gains of the PI-mode of the 2DOF controller

$K_{pc2}$, $K_{i2}$ and $K_d$ are the proportional, integral and derivative gains of the PID-mode

The transfer functions of the closed-loop control system for both reference and disturbance inputs using the 2DOF controller are as follows:

- For a reference input R(s), $M_{R3}(s) = T(s)/R(s)$ is:

$M_{R3}(s) = N_{R3}(s)/D_{R3}(s)$ (14)

Where:

$N_{R3}(s) = b_0K_ds^3+(b_0K_{pc1}+b_0K_{pc2}+b_1K_d)s^2+(b_0K_{i1}+b_0K_{i2}+b_1K_{pc1}K_i+b_1K_{pc2})s+b_1K_{i1}+b_1K_{i2}$

and

$D_{R3}(s) = (a_0+b_0K_d)s^3+(a_1+b_0K_{pc2}+b_1K_d)s^2+(a_2+b_1K_{pc2}+b_0K_{i2})s+b_1K_{i2}$

- For a disturbance input D(s), $M_{D3}(s) = T(s)/D(s)$ is:

$M_{D3}(s) = N_{D3}(s)/D_{D3}(s)$ (15)

Where:

$N_{D3}(s) = N_{D1}(s)$ without filter after D(s)

and $D_{D3}(s) = D_{R3}(s)$ without filter after D(s)

- *2DOF controller tuning:*

- The 2DOF controller structure proposed in the present work has five gain parameters. Investigating the transfer function of the control system for the reference input reveals the fact that to attain a zero steady-state error for the closed loop control system of the boiler temperature using the 2DOF controller $K_{i1}$ has to be set to zero.
- The remaining four 2DOF controller parameters are tuned using the transfer function in Eq.14 and the MATLAB optimization toolbox (Lupez, 2014) to minimize the ITAE performance index.
- The tuned 2DOF controller parameters are:

$K_{pc1}$ = 1.00164 ; $K_{pc2}$ = -190.000

$K_{i2}$ = -11.72394; $K_d$ = 11.73243 (16)

- The unit step time responses of the boiler temperature for reference and disturbance inputs using the 2DOF controller are plotted using Eqs.14, 15 and 16 using the MATLAB command '*plot*' and shown in Fig.5.

Comments:

- For a reference input tracking:
  - Maximum percentage overshoot: 0.0181 %
  - Settling time: 0.8120 s
  - Steady-state error: zero
- For a disturbance input (to improve the performance of the control system regarding the rejection of the disturbance, a high pass filter of gain 100 is added after D(s) .. (Kejm, 2019):
  - Minimum time response: $-2.6\times10^{-4}$ °C
  - Time of minimum time response: 0.030 s
  - Settling time to zero: 1.000 s

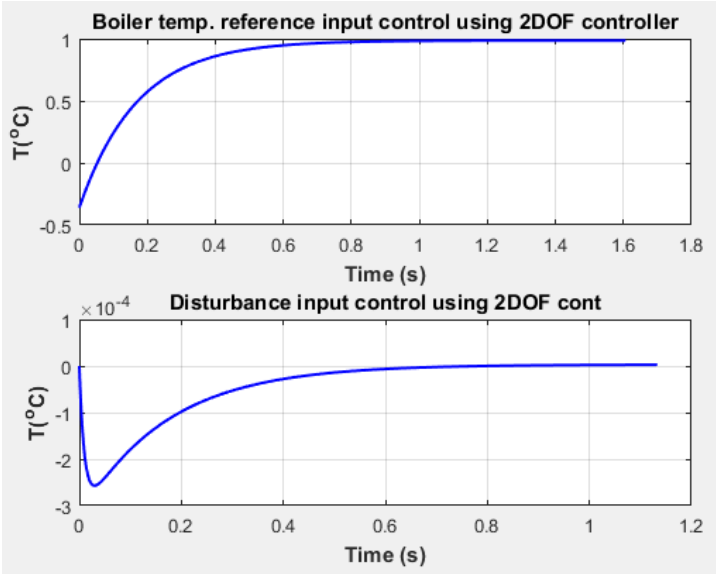


**Fig.5 Boiler temperature control using a 2DOF controller.**

## Comparison with Other Controllers

The performance of the control system used for the boiler temperature control is compared graphically and numerically when using the proposed three controllers, a fuzzy-PID controller (Wang, 2023). A graphical comparison of the performance of the control system with the four controllers is shown in Fig. 6 for the reference input of the control system.

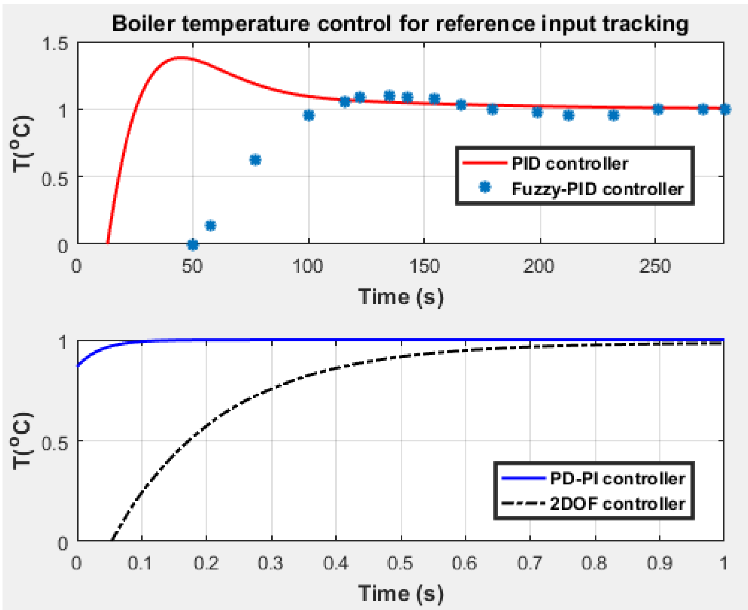


**Fig. 6 Comparison of reference input step time response using four controllers.**

A quantitative comparison for the time-based specifications of the boiler temperature control system is shown in Table 1 for reference input of the control system.

**Table 1 – Time-based characteristics for reference input.**

| Controller | Maximum overshoot (%) | Settling time (s) |
|---|---|---|
| Fuzzy-PID (Wang, 2023) | 9.2 | 240 |
| PID (present work) | 36.8 | 204 |
| PD-PI (present work) | 0 | 0.069 |
| 2DOF (present work) | 0.0181 | 0.812 |

A graphical comparison of the performance of the control system with three controllers (excluding the fuzzy-PID controller) is shown in Fig. 7 for the disturbance input of the control system.

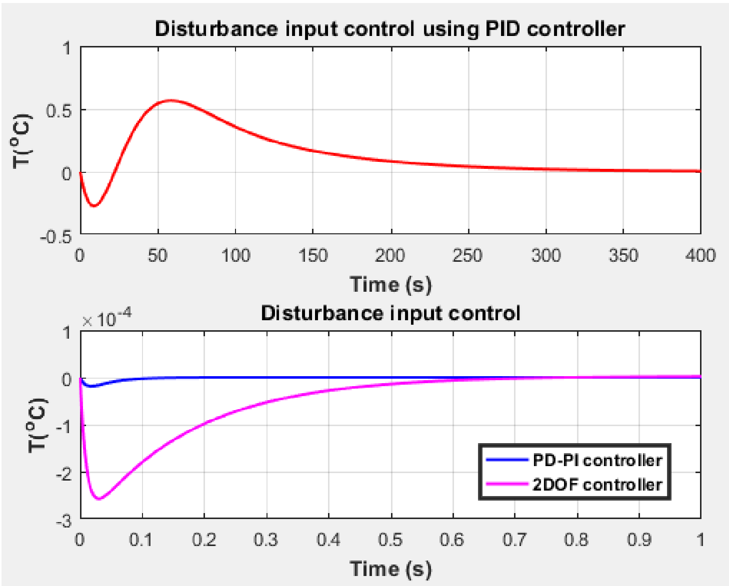


**Fig. 7 Comparison of disturbance input step time response using four controllers.**

The time-based characteristics of the disturbance step time response are compared in Table 2.

**Table 2 – Time-based characteristics for unit disturbance input.**

| Controller (present work) | Maximum (minimum) time response (°C) | Settling time (s) |
|---|---|---|
| PID | 0.565 | 400 |
| PD-PI | $-1.845\times10^{-4}$ | 0.20 |
| 2DOF | $-2.60\times10^{-4}$ | 1.0 |

**Conclusions**

- The paper investigated the control of the boiler temperature using three controllers two of them from the second generation of PID controllers.
- The controllers proposed for this purpose was the PID (from the first generation) , PD-PI and 2DOF (from the second generation).
- The three controllers were tuned using the MATLAB optimization toolbox and an ITAE error-based performance index.
- The performance of the control system was evaluated through the maximum percentage overshoot and the settling time for reference input tracking.
- For the disturbance input, the control system was evaluated through the maximum (or minimum) value of the boiler temperature step time response and its settling time to its steady-state value.
- The three proposed controllers were compared with a fuzzy-PID controller from previous research work.
- The controlled boiler temperature as a process to be controlled had bad dynamics when excited by a step input in terms of a large steady-state error (0.94 °C) and large settling time (1500 s).

- The PD-PI controller could compete with all the presented controllers in this study. It resulted in a control system without any overshoot or steady-state error and a settling time of only 0.069 s compared with 240 s for the fuzzy-PID controller. It could suppress the disturbance input unit step time response to zero with minimum time response of 0.1845 m$^o$C compared with 0.565 $^o$C for the PID controller. The disturbance step time response settled to zero in about 0.2 s compared with 400 s with the PID controller.
- The 2DOF controller could generate a reference input tracking unit step response with 0.0181 % maximum overshoot compared with 9.2 % with the fuzzy PID controller and a settling time of 0.812 s compared with 240 s for the fuzzy-PID controller. It could suppress the disturbance step time response to a minimum step time response of 0.26 m$^o$C compared with 0.25 $^o$C for the PID controller and one s settling time to zero compared with 400 s for the PID controller.
- The MATLAB optimization toolbox has proven through applications in the field of controller tuning that it is a reliable technique for controller tuning purposes.

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## DEDICATION

**Banu Musa bin Shakir:**

- I dedicate this work to the designer of the first boiler in the 9th century AC.

Banu Musa bin Shakir (three brothers) [Hassaan, 2004].

- They lived during the era of Abbasid Caliphs Alma'mun, Almutasim,

Alwathiq and Almutawakkil (813-861 AC).

- They were pioneer scientists in the fields of mathematics, physics,

astronomy, politics and mechanical engineering.

- They wrote 20 books.
- They were the founder of feedback automatic control systems.
- They were the founder of automatic dynamic fountains.
- The image shown here is a *hot water boiler* from their design (Hill, 1979).
- This is why I dedicate them this work about boiler temperature control.