[1]Sonar (Limgaokar) Arun. D.

[2]Chile Rajan H.

[3]Mr. Vipul H. Kondekar

[4]Roshan Pushpan

[5]Somnath B. Thigale

[6] Vivek Rane

[7] Anup Vibhute

Dual Parameter Control of Drum Boiler using Formula-Based Fuzzy Controller

Abstract: - Formula-based fuzzy control has gained substantial importance over the last few decades in the precise control of complex processes. Such a control strategy achieves better control performance by revealing the underlying analytical structure of a fuzzy controller. Furthermore, in the design of industrial fuzzy logic controllers only triangular, trapezoidal membership functions are used extensively. This paper presents the design and implementation of a dual formula-based fuzzy PI controller used to control the pressure inside the drum boiler by regulating the level. The control structure derived here typically uses Gaussian membership functions as input variables and three singleton fuzzy sets as the output variables. When applied for real-time control of the pressure of a highly nonlinear drum boiler pilot plant, the proposed controller demonstrates the effectiveness of the controller. The drum boiler pressure control process efficiently responds to the proposed controller for both set-point tracking and load disturbances rejection mode.

Keywords: PI Controller, Fuzzy PI Controller (FPI), Formula Based Fuzzy Controller (FBFC), Gaussian Membership Functions (GMF).

I. INTRODUCTION

Drum boilers are widely used in power generation plants that convert heat energy into steam to generate electricity. Ever-changing steam demand necessitates a good operational boiler control system which requires in-depth process knowledge. Researchers and academicians are required to carry out ample experimentation on actual industrial boilers. This requirement demands a higher amount of cost involvement with time & safety of such systems can also be put at risk. A laboratory-level pilot plant development becomes the basic requirement. A well-developed boiler and heat exchanger setup at the COEP Technological University (formerly known as College of Engineering, Pune) is full of safety instrumented devices with flexible data acquisition via an OPC server. The primary aim of this system is to regulate the demand for quality steam to the heat exchanger while maintaining other input and output variables such as feed-water flow, steam flow rate, heat flow, drum pressure, steam temperature, drum water level, etc. within predefined nominal safety limits.

Nowadays fuzzy logic controllers have been successfully applied for the control of various non-linear processes, but the underlying mathematical structure of such fuzzy logic controllers has remained unidentified. Hence, creating a solid foundation for these controllers for better understanding, meaningful analysis, and more effective design of fuzzy control systems demands deriving the analytical structure of fuzzy controllers. H. Ying [1, 2] demonstrated one such technique of a fuzzy PID controller using trapezoidal, triangular membership functions. Kai [3] proposed an effective method of developing an analytical structure-based fuzzy PI controller for the batch sintering process.

Fuzzy models in general are more natural and easier to understand because fuzzy sets, fuzzy logic, and fuzzy rules are sensitive and meaningful. However, determining the controller structure, and parameters based on the given system model that meets the desired control performance is a real challenge [4]. An analytical structure for a fuzzy PID controller [5] by employing two fuzzy sets for each of the three input variables and four fuzzy sets

[1*]Sonar (Limgaokar) Arun. D.: Dr. D. Y. Patil Institute of Technology, Pimpri, Pune-18 e-mail: arundsonar21@gmail.com

2 S.G.G.S. Institute of Engineering & Technology, Nanded.e-mail: rhchile@sggs.ac.in

[3]Walchand Institute of Technology, Solapur. e-mail: meetroshan29@gmail.com

[4]N. K. Orchid College of Engineering and Technology, Solapur. e-mail: vhkondekar@witsolapur.org

[5] Shree Siddheshwar Women's College of Engineering, Solapur. e-mail: drsomnaththigale@gmail.com

[6,7]Dr. D. Y. Patil Institute of Technology, Pimpri, Pune-18

for the output variable derived using trapezoidal membership has demonstrated the effectiveness of the simplest fuzzy PID controller. Further, the analytical structures of the simplest fuzzy controllers using a modified rule base were developed and validated in [6,7,8] with a reduced number of controller tuning parameters having a rule base of only two rules.

The research presented in [9] deals with the simplest fuzzy PI controllers, using triangular membership functions where a comparative study of derived fuzzy PI controllers and conventional PI controllers proved the effectiveness of fuzzy PI controllers. Another research [10] reveals mathematical models for the fuzzy PID controllers employing three input variables with two fuzzy sets each and four fuzzy sets for the output variable. The nonlinear Takagi-Sugeno (TS) fuzzy PID controller with multiple fuzzy sets is explained in the paper [11]. This is a kind of variable gain/structure controller with a rule base of only four rules resulting in a reduced number of parameters to be tuned.

A classical PID controller is not always suitable for controlling nonlinear and complex systems though it is the most popular controller due to its simplicity and low cost as well [12]. It further explains the development of the classical PID controllers and their augmentation using fuzzy theory. The study [13] proposes a parallel fuzzy proportional plus fuzzy integral plus fuzzy derivative (FP + FI + FD) controller. The famous "small gain theorem" with bounded input and bounded output (BIBO) is used to address the stability issue of above-all fuzzy controllers. The proposed systems have shown much better set-point tracking, disturbance rejection, and noise suppression for nonlinear processes than conventional controllers. Hence, it becomes crucial to get the analytical structure of fuzzy controllers before one can exactly understand how fuzzy controllers work.

In the design of a fuzzy logic controller, the shape of the membership function plays a vital role. The majority of the existing studies including the above ones about formula-based fuzzy controllers make use of triangular/trapezoidal membership functions due to their idealized properties [14]. The Conventional fuzzy controllers in real-time control often apply the Gaussian membership function (GMF) [15,16] as Gaussian membership functions are quite popular in the fuzzy literature due to their smooth and continuous derivatives which makes the mathematical analysis more traceable and simpler than any other membership function. Additionally, the representation of GMF is quite simple as it only needs two parameters, whereas any other membership function needs more parameters to represent it. This reduced number of parameters results in a lower degree of freedom (DOF) and can result in a robust fuzzy controller. Further, the GMFs guarantee a continuous control surface irrespective of the type-reduction and defuzzification method used. Experimental results also show that when the rule base is small fuzzy controllers using GMFs are faster [17,18]. People often portray their thought process as a normal distribution, the Gaussian membership function can better fit one's perception from the statistical point of view. Therefore, the proposed study on designing fuzzy controllers using the Gaussian membership function has got noticeable importance.

Hence, the important goal of this paper is to bring out the scientific model of a straightforward fuzzy PI controller designed using Gaussian membership functions and demonstrate its adequacy over the conventional PI controller and fuzzy PI controller designed using any other membership functions. The paper mainly focuses on performance testing of a formula-based fuzzy controller to control the steam pressure of the drum boiler of a heat exchanger pilot plant [19] whose basic flow sheet is shown in Fig.1.

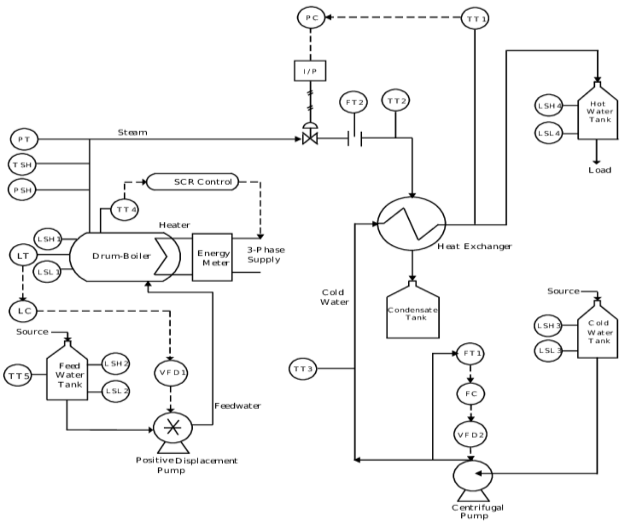

Fig 1. The flow sheet diagram of the drum-boiler system.

II. PROCESS DESCRIPTION

The drum-boiler pilot plant [19] used for carrying out real-time experimentation consists of an electrical boiler with a capacity of 30 kg\hr at 130^{0}C temperature and is well-equipped with all necessary instrumentation for measurement and control. The drum boiler consists of several process variables interacting with each other. The setup includes an electric boiler and a heat exchanger. The electrical boiler develops 4 bar pressure at 144^{0}C temperature and delivers steam of 30kg/hr, which is further utilized in the pipe-in-pipe type of heat exchanger.

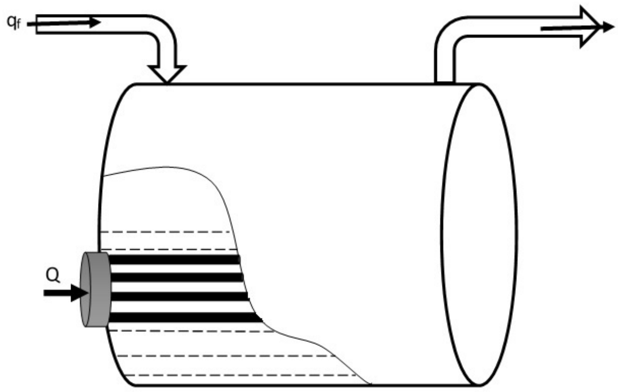

Fig 2. The Drum Boiler

The drum boiler shown in Fig. 2 is made up of SS304, where qf is the feed water flow rate, qs is the steam flow rate and q is the heat flow rate. The Drum boiler pilot plant is designed mainly for research purposes where the boiler plant acts as a utility unit for steam generation which is further cascaded with a steam-to-water heat exchanger. The key components of the boiler unit are the feed water tank, drum, and heater system. The feed water from the feed tank is pumped via a positive displacement pump into the boiler drum. The feed water is heated via the heater before it enters the drum, and the saturated steam is then taken out from the drum which passes to the heat exchanger via an equal percentage globe valve that controls the steam flow. The Silicon Controlled Rectifier (SCR) based firing system modulates heat energy to the boiler drum.

III. DESIGN OF FUZZY CONTROLLER

Fig.3 shows fuzzification, rule evaluation, and knowledge Base, defuzzification as necessary components of a general fuzzy logic controller. The two input variables are error, e$(nT)$and error rate r(nT) which are expressed as,

$$\left.\begin{aligned} e(nT) &= SP(nT) - y(nT) \\ r(nt) &= e(nT) - e(nT - T) \end{aligned}\right\} \qquad (1)$$

where; n, is a positive integer, T, is sampling period and SP, is the set point and $y(nT)$, is process output. Each input is first fuzzified into two fuzzy variables namely Positive Big (PB) and Negative Big (NB). The procedure to derive analytical structure of simplest Fuzzy PI controller is described below.

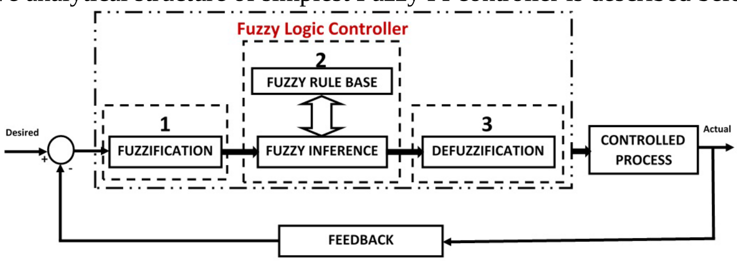

Fig 3. Basic Fuzzy Logic Controller

Table 1. Gaussian Membership Function Definition

-	Error	Error Rate
Negative	$e_{NB} = e^{-\left(\frac{(Ke+L)^2}{2(L/1.15)^2}\right)}$	$e_{NB} = e^{-\left(\frac{(Kr+L)^2}{2(L/1.15)^2}\right)}$
Positive	$e_{NB} = e^{-\left(\frac{(Ke-L)^2}{2(L/1.15)^2}\right)}$	$e_{NB} = e^{-\left(\frac{(Kr-L)^2}{2(L/1.15)^2}\right)}$

The discrete time structure of the classical PI controller is,

$$\Delta(nT) = Kp.r(nT) + Kr.e(nT) \quad (2)$$

where, $\Delta u_{PI}(nT)$ is the incremental control output.

The formula-based fuzzy PI controller is based on Eq.2, where; the error, $e(nT)$, error rate, $r(nT)$ are the two inputs to the fuzzy PI controller and $\Delta u_{PI}(nT)$ is the corresponding output.

The proposed formula based fuzzy PI controller uses two Gaussian membership functions at input and three singleton membership functions at output as shown in Fig.4 and Fig.5 respectively. The membership functions are defined over the interval $-L$ to L, which is known as the universe of discourse is given in Table 5. Fig.6 shows all possible input combinations (ICs) of scaled error and error rate for which a separate formula is to be derived.

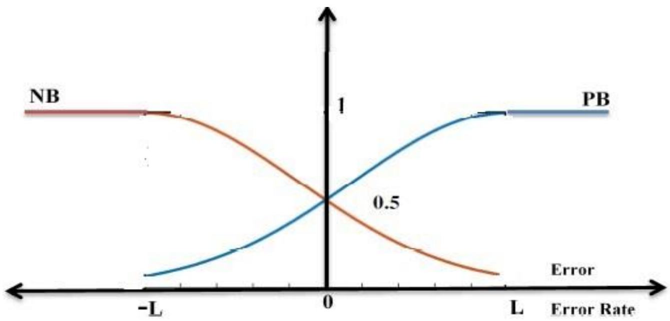

Fig 4. Gaussian Membership Function

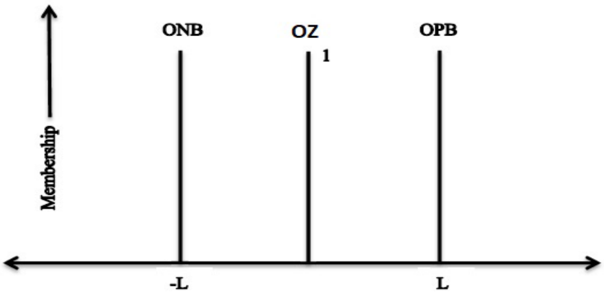

Fig 5. Output Membership Functions

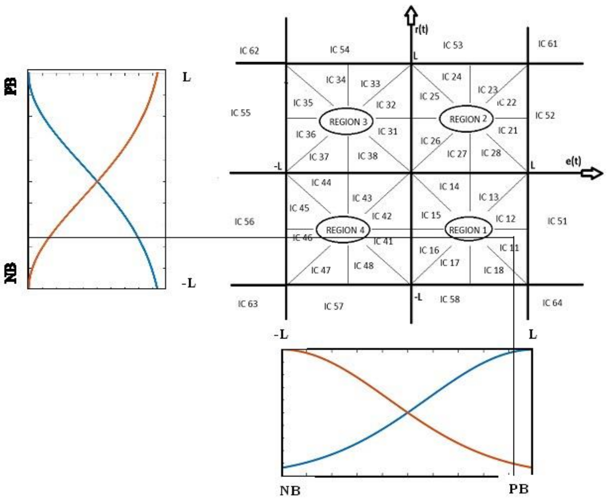

Fig 6. Distribution of regions with Gaussian Membership Functions

The mathematical expression for Gaussian membership function is given by equation 3,

$$f(x, c, \sigma) = exp^{-(x-c)^2/(2.\sigma^2)} \quad (3)$$

where, σ is a factor which determines the shape of the Gaussian curve i.e. curvature and c denotes the center of the curve. The two Gaussian membership functions have the centers at $-L$ and L. We have taken σ value to $L/1.15$ to achieve 50% overlap with neighboring membership function.

The fuzzy controller is derived using the FOUR control rules given below,

$$\boldsymbol{R1}: \; IF \; Error \; is \; \boldsymbol{NB} \; AND \; Error \; Rate \; is \; \boldsymbol{NB} \quad THEN \; \Delta u(nT) \; is \; \boldsymbol{ONB}$$

$$\boldsymbol{R2}: \; IF \; Error \; is \; \boldsymbol{NB} \; AND \; Error \; Rate \; is \; \boldsymbol{PB} \quad THEN \; \Delta u(nT) \; is \; OZ$$

$$\boldsymbol{R3}: \; IF \; Error \; is \; \boldsymbol{PB} \; AND \; Error \; Rate \; is \; \boldsymbol{NB} \quad THEN \; \Delta u(nT) \; is \; \boldsymbol{OZ}$$

$$\boldsymbol{R4}: \; IF \; Error \; is \; \boldsymbol{PB} \; AND \; Error \; Rate \; is \; \boldsymbol{NB} \quad THEN \; \Delta u(nT) \; is \; \boldsymbol{OPB}$$

further, the output of each execution is evaluated using Zadeh Fuzzy logic AND operator with Centroid Defuzzifier. The incremental control output is then given by equation 4 below,

$$\Delta u(nT) = \frac{\sum_{i=1}^{4} \Delta ui.\mu i}{\sum_{i=1}^{4} \mu i} \tag{4}$$

The new control output of the controller at $(n+1)T$ can be calculated by,

$$u(n+1)T = u(nT) + \Delta u(nT) \tag{5}$$

The steps to be followed in getting the formulae are,

Step 1: Define the Universe of Discourse (UoD) L.

Step 2: Calculate $e(nT)$ & $r(nT)$ at n^{th} sampling instant using equation 1.

Step 3: Multiply it with respective gains ke and ker, which becomes $Ke(nT)$, $Kr(nT)$ where, $Ke(nT) = ke.e(nT)$ and $Kr(nT) = ker.r(nT)$.

Step 4: Evaluate the respective membership values $e_{NB,}\, e_{PB}$ and $r_{NB,}\, r_{PB}$ for each of them using equations given in Table 5.

Step 5: Apply the rules from Control rule base given as defined above in the form of $\boldsymbol{If - Then - Else}$ and use Zadeh $\boldsymbol{MIN}$ operator.

Step 6: Evaluate the formula using Centroid Defuzzifier given by equation 4.

In this way, different 44 formulae for each IC region shown in Fig. 6, are obtained using above six step procedure. All such derived formulae are listed in Table 6 to Table 8 respectively.

Table 2. Formulae for Region 1, 2

Cell No	Region 1	Cell No	Region 2
11,12,13,14	$\frac{L \times (r_{PB} - e_{NB})}{(2(e_{NB}) + 1)}$	21,22,27,28	$\frac{L \times (r_{PB} - e_{NB})}{(2(e_{NB}) + 1)}$
15,16,17,18	$\frac{L \times (r_{PB} - e_{NB})}{2((r_{PB}) + 1)}$	23,24,25,26	$\frac{L \times (e_{PB} - r_{NB})}{(2(r_{NB}) + 1)}$

Table 3. Formulae for Region 3, 4

Cell No	Region 1	Cell No	Region 2
31,32,33,34	$\frac{L \times (e_{PB} - r_{NB})}{(2(r_{NB}) + 1)}$	41,42,47,48	$\frac{L \times (r_{PB} - e_{NB})}{(2(r_{PB}) + 1)}$
35,36,37,38	$\frac{L \times (e_{PB} - r_{NB})}{(2(e_{PB}) + 1)}$	43,44,45,46	$\frac{L \times (e_{PB} - r_{NB})}{(2(e_{PB}) + 1)}$

Table 4. Formulae for Region 5,6

Cell No	Region 5	Cell No.	Region 6
51.52	$L \times r_{PB}$	61	L
53,54	$L \times e_{PB}$	62	0
55,56	$-L \times r_{NB}$	63	$-L$
57.58	$-L \times e_{NB}$	64	0

IV. Stability Analysis

From the research stated by Kim and Tahk the relative stability of the controller can also be determined through computer simulations. In this study a block $K.e^{-sTd}$ is added prior to the actuator, in which K stands for gain multiplying factor and Td represents the time delay for system being unstable [20][21]. If the system shows

GM > 0, the close loop system is stable, GM > 6, we can double the gain without the system being unstable and PM > 30, the system is stable. Similarly based on simulations it was observed that the system under test started becoming unstable from K = 2.4 onward with nominal 2 samples delay, hence, the GM=20log10 (2.4) = 7.6 dB. Also, by taking K = 1, having a total of 7 samples delay @ 2.5 ms/sample, the system starts oscillating at (PM = 48 deg) from 5 seconds onwards. Thus Stability study shows minimum (GM, PM) is (7 dB, 39 deg) and the resultant (GCF, PCF) = (55rad/s, 113rad/s) and the results are reliable [22].

V. Implementation & Testing of Dual PARAMETER Fuzzy PI controller

To evaluate the control performance of the proposed formula-based fuzzy PI controller, software simulations on state-space model of the plant and real-time simulations on drum boiler were performed. Pressure control of the boiler drum was achieved by manipulating heat delivered by electrical heater. The heater is installed at a position where a minimum of 81% of the water level will always be maintained in the boiler drum throughout real-time as an important safety measure. This requires the drum boiler to be operated in a very narrow span of 81% to 99% of the water level. Keeping this in mind, the boiler drum level was kept constant at 86% using another independent Fuzzy PI controller during the real-time testing.

A complete third-order nonlinear model of boiler unit shown in Fig.1, which captures significant disturbances, shrink-and-swell effect, with the constraints on input and output was obtained. The state variables like volume of water $\mathrm{V_{wt}}$, pressure p, and volume of the steam V_{sd} in the drum were considered in deriving the boiler drum model. The manipulated variables to regulate pressure, p and level, l are the feed flowrate Q_f, steam flow rate q_s, and heat flow rate Q.

The linear time-invariant state space model of drum boiler pilot plant using [23,24] can be expressed via equation 6 given below, Appendix A.

$$\left.\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) + Du(k) \end{aligned}\right\} \qquad (6)$$

where the system matrices are given as,

$$A = \begin{bmatrix} 3.8807\mathrm{e}^{-007} & -8.8083\mathrm{e}^{-010} & 0 \\ -7.5682\mathrm{e}^{-004} & 4.3633\mathrm{e}^{-005} & 0 \\ -1.9321\mathrm{e}^{-005} & 2.9361\mathrm{e}^{-005} & -1.8933\mathrm{e}^{-005} \end{bmatrix} \qquad (7)$$

$$B = \begin{bmatrix} 1.4055\mathrm{e}^{-003} & 1.4055\mathrm{e}^{-003} & 4.2546\mathrm{e}^{-012} \\ -0.1610 & -0.6365 & 3.9380\mathrm{e}^{-007} \\ -1.4055\mathrm{e}^{-003} & 0.1454 & -8.9998\mathrm{e}^{-008} \end{bmatrix} \qquad (8)$$

$$C = \begin{bmatrix} 0 & 1 & 0 \\ 0.035201 & 0 & 0.0352010 \end{bmatrix} \qquad (9)$$

$$D = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \qquad (10)$$

The model thus obtained is used to carry out simulation studies as discussed earlier.

VI. Real time Boiler Performance Testing

The real time performance of the proposed formula-based fuzzy controller was tested for pressure control of the drum boiler in the system shown in Fig.7. The controller performance testing was done for step test, tracking and disturbance rejection (regulation) tests. During the step test, a step of 0.3 MPa was applied. While for the tracking test, step signal was varied from 0.15 to 0.20 MPa and the response was observed. further, during the disturbance rejection testing of the controller steam outlet valve opening was used as a disturbance signal once the pressure becomes constant. In the presence of steam valve disturbance also the controller was able to track desired pressure successfully.

Fig 7. Boiler Heat Exchanger Setup

The comparative analysis between the conventional PI controller and proposed fuzzy PI controller was carried out. The settings for conventional controller were set at $Kp = 160000$ and $Ki = 94$. Similarly for the proposed fuzzy PI controller, the parameters values were set as $Ker = 1.21$, $Kder = 1.1$, and $Kout = 30$.

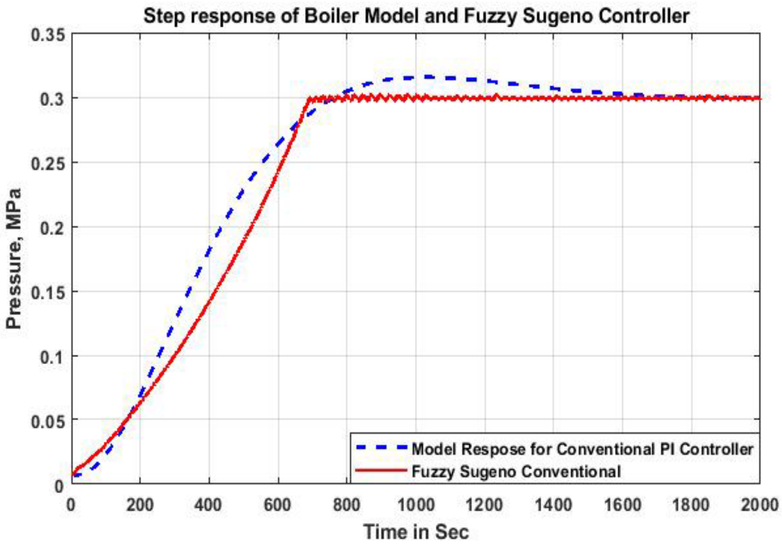

Fig 8. FBFC Sugeno and Model PI Controller Step Response

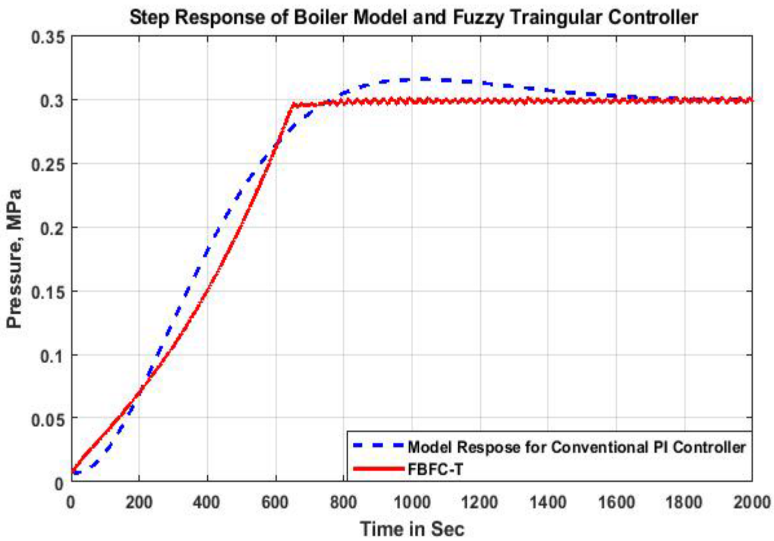

Fig 9. FBFC Triangular and Model PI Controller Step Response

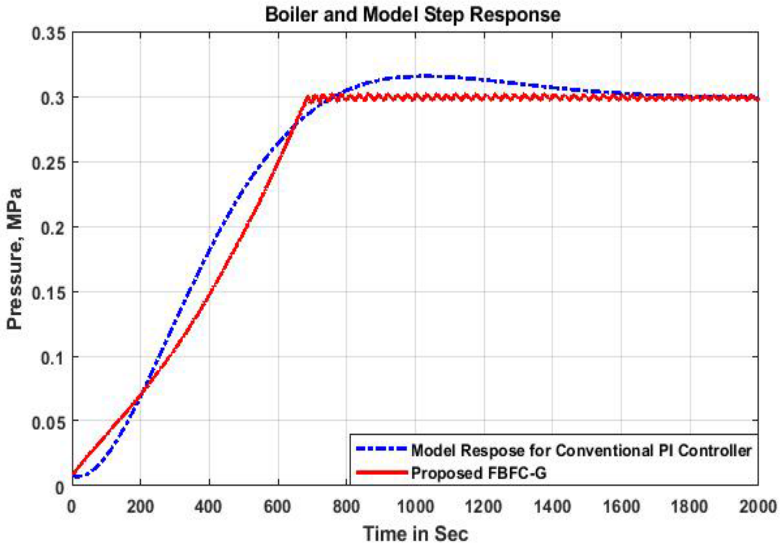

Fig 10. FBFC Gaussian and Model PI Controller Step Response

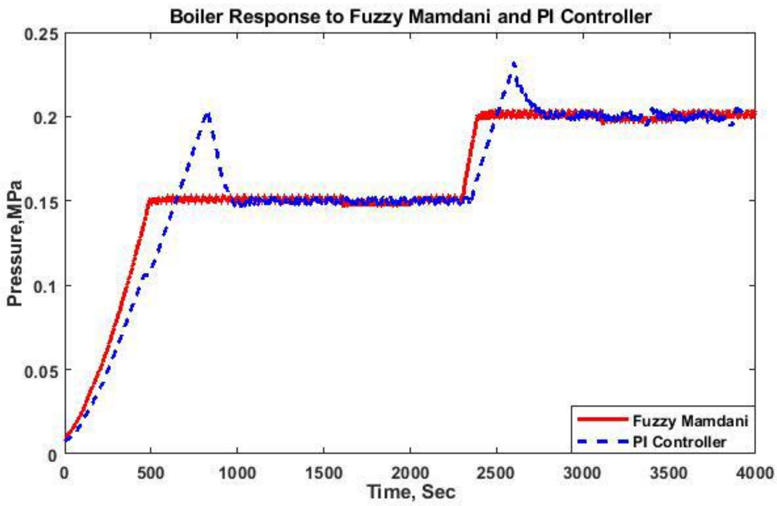

Fig 11. Fuzzy Mamdani and PI controller Tracking Response

Initially, the boiler model response to the PI controller was compared with the actual step response of boiler pressure on the application of step change in pressure. In Fig. 8, the standard fuzzy Sugeno type controller designed using the fuzzy toolbox of MATLAB was compared with the boiler model response to the conventional PI controller. Fig.9 and 10 show the comparison of the formula-based fuzzy controller designed using Triangular and Gaussian membership functions with boiler model response to conventional PI controller respectively.

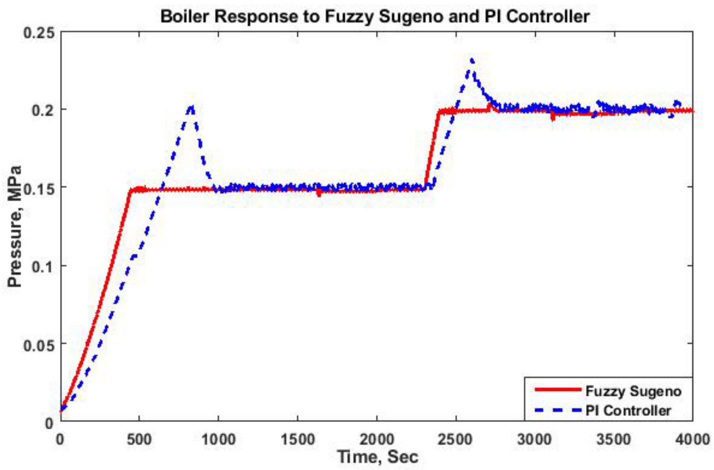

Fig 12. Fuzzy Sugeno and PI Controller Tracking Response

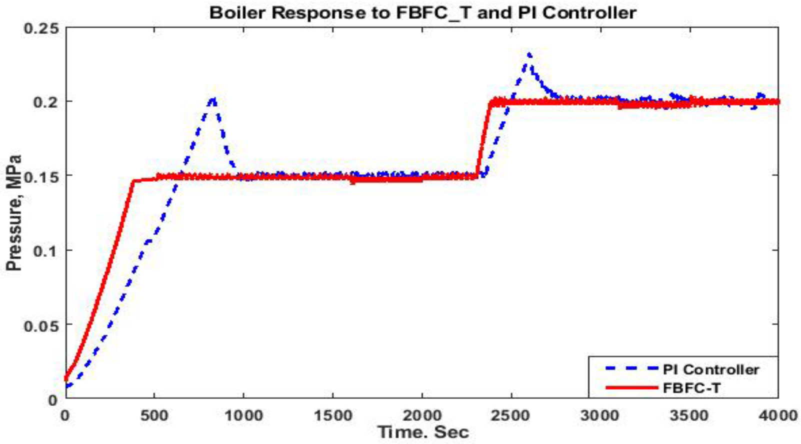

Fig 13. FBFC Triangular and PI Controller Tracking Response

Fig.11 and 12 shows tracking performance comparison between the conventional fuzzy controllers such as fuzzy Mamdani and fuzzy Sugeno developed using standard fuzzy controller design and the conventional PI controller Fig.13 and 14 reveals the comparative performance between formula-based Fuzzy Controller designed using Triangular membership functions and the proposed one designed using Gaussian membership functions with PI controller during tracking performance testing. Finally, Fig.15 shows the comparative performance of the formula-based fuzzy controller using Gaussian membership functions, PI Controller and the model performance in tracking mode.

To test robustness of the proposed controller the comparative performance analysis between proposed formula based fuzzy controller using Gaussian membership function and conventional PI controller in presence of disturbance through the steam valve was studied. As a prerequisite for this test, the time required to completely open and close the valve (One Cycle) was measured noted as 8 Sec. Then, the steam outlet valve was opened between 45% to 55% opening with the delay of 8 Sec. Thus, From Fig 16, it can be established that the proposed controller successfully maintains the desired pressure in presence of the disturbance also.

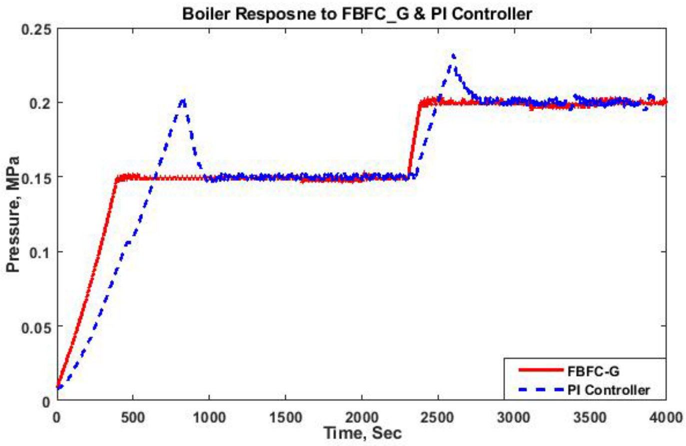

Fig 14. FBFC Gaussian and PI Controller Tracking Response

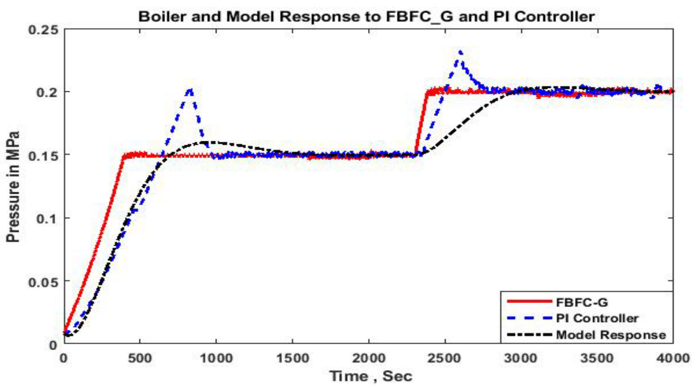

Fig 15. FBFC Gaussian, PI and Model PI Controller Tracking Response

From the responses, it is perceived that the proposed controller tracks the set point very well and does not give any overshot. Table's 8 and 9 give the parametric comparison between various fuzzy controllers and he proposed Formula based fuzzy controller with PI controllers respectively. From this, FBFC using Gaussian membership function shows 2.88% improvement in rise time and 25\% betterment in overshoot when compared with other types of Fuzzy Controllers. It can further be noticed that the FBFC using Gaussian membership functions shows betterment of 73% in rise time, 9.25% in settling time, 86\% in overshoot when compared with conventional PI controller.

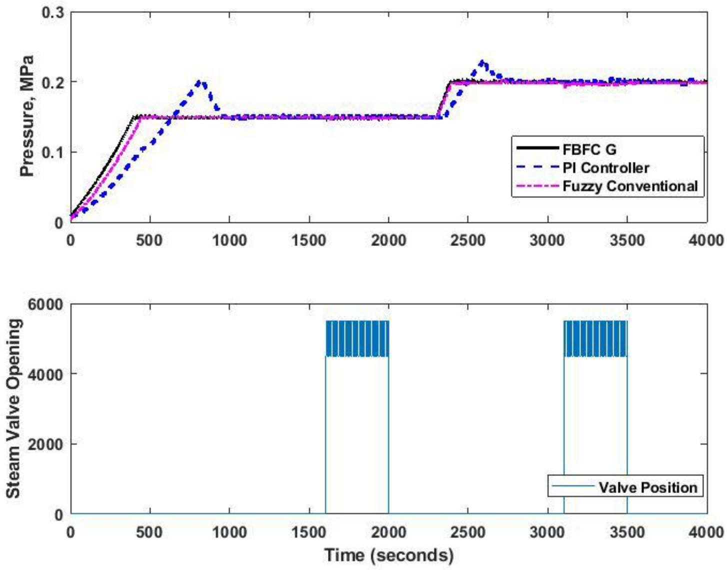

Fig 16. Pressure Comparison with Steam Disturbance

VII. CONCLUSION

The work presented here is mainly focused on, the performance evaluation of a formula-based fuzzy PI controller developed using Gaussian membership functions as the fuzzy controller performance is highly sensitive to membership function. The drum boiler pressure was successfully maintained at the desired level in the presence of disturbance using the proposed controller. The controller demonstrated its effectiveness in controlling complex dynamics drum-boiler heat exchanger plants. It can be further noticed that the proposed controller can capture complex shrink and swell effects of boiler drum level also. Further, from the simulation results, the proposed controller performed well for set-point tracking as well as load disturbances without violating the input and output constraints. The proposed formula-based fuzzy controller performs exceedingly well as compared to the conventional PI controller. From Tables 9 and 10 the fuzzy controllers do not show any overshot. The formula-based fuzzy PI controller using Gaussian membership function surpasses conventional fuzzy controllers using triangular membership functions and the conventional PI controller in real-time boiler pressure control.

ACKNOWLEDGMENT

We express gratitude to the Department of Instrumentation Engineering, College of Engineering, Wellesly Road, Shivaji Nagar, Pune-411005, and all the people who supported us during the work.

REFERENCES

[1] Hao Ying. A general technique for deriving analytical structure of fuzzy controllers using arbitrary trapezoidal input fuzzy sets and Zadeh AND operator. Automatica, 39(7):1171–1184, July 2003.

[2] Hao Ying. General Analytical Structure of Typical Fuzzy Controllers and Their Limiting Structure Theorems *. Automatica., 29(4):1139–1143, DOI:10.1109/nafips.1996.534716, 1993.

[3] Liang Kai, Fang Kangling, and Huang Weihua. Design and application of fuzzy PI controller based on analytical structure. Proc. - 3rd Int. Conf. Intell. Networks Intell. Syst. ICINIS 2010, 0:331–333, 2010.

[4] Hao Ying. Fuzzy Control and Modeling: Analytical Foundations and Applications (IEEE Press Series on Biomedical Engineering). 2000.

[5] B. M. Mohan and Arpita Sinha. Analytical structure and stability analysis of a fuzzy PID controller. Applied Soft Computing Journal, 8(1):749–758, jan 2008.

[6] Ritu Raj and B.M. Mohan. Analytical structures and stability analysis of the simplest Takagi-Sugeno fuzzy two-term controllers. International Journal of Process Systems Engineering, 5(1):67–92, DOI:10.1504/ijpse.2019.096674, 2019.

[7] Ritu Raj and B. M. Mohan. An Analytical Structure of the Simplest Takagi-Sugeno TITO PI/PD Controller. IFACPapersOnLine, 51(1):19–24, 2018.

[8] Murali Bosukonda and Naresh Kelothu. Mathematical Models of the Simplest Fuzzy Two-Term (PI/PD) Controllers Using Algebraic Product Inference. Modelling and Simulation in Engineering, 2011:1–7, DOI:10.1155/2011/573715, nov 2011.

[9] B M Mohan and A V Patel. Analytical structures and analysis of the simplest fuzzy PI controllers. Automatica, 38(2):981 – 993, 2002.

[10] B. M. Mohan and Arpita Sinha. The simplest fuzzy PID controllers: Mathematical models and stability analysis. Soft Computing, 10(10):961–975, DOI:10.1007/s00500–005–0023–9, 2006.

[11] Murali Bosukonda and Ritu Raj. Takagi-sugeno fuzzy pid controllers: mathematical models and stability analysis with multiple fuzzy sets. International Journal of Fuzzy Computation and Modelling, 3:33, 01 2020.

[12] Vineet Kumar, BC Nakra, and AP Mittal. A review of classical and fuzzy PID controllers. Int. J. Intell. Control Syst., 16(3):170–181, DOI:10.1007/s11633–010–0528–2, 2011.

[13] Vineet Kumar, A. P. Mittal, and R. Singh. Stability analysis of parallel fuzzy P + fuzzy I + fuzzy D control systems. International Journal of Automation and Computing, 10(2):91–98, 2013.

[14] Ching Chang Wong, Chih Hsun Chou, and Don Lin Mon. Studies on the output of fuzzy controller with multiple inputs. Fuzzy Sets Syst., 57(2):149–158, DOI:10.1016/0165– 0114(93)90154–A, 1993.

[15] Hyun Mun Kim and Jerry M Mendel. Fuzzy basis functions: comparisons with other basis functions. IEEE transactions on fuzzy systems, 3(2):158–168, DOI:10.1109/91.388171, 1995.

[16] Georg F Mauer. A Fuzzy Logic Controller for an ABS Braking System. IEEE transactions on fuzzy systems, 3(4):381–388, DOI:10.1109/91.481947, 1995.

[17] S. Dima, C. Antonopoulos, J. Gialelis, and S. Koubias. A network reliability-oriented event detection scheme for Wireless Sensors and Actors Networks. IEEE International Conference on Industrial Technology, Athens,, pages 362–367, 2012. DOI:10.1109/ICIT.2012.6209964.

[18] Xiang-Jie Liu and Xiao-Xin Zhou. Structural analysis of fuzzy controller with gaussian membership function. IFAC Proc. Vol., 32(2):5368–5373, 1999.

[19] I. Siddiqui, D. Ingole, S. Agashe and D. Sonawane, "Hands-On Experience with Implementation of Classical Control for Process Plant," 2018 Fourth International Conference on Computing Communication Control and Automation (ICCUBEA), Pune, India, 2018, pp. 1-6, doi: 10.1109/ICCUBEA.2018.8697474.

[20] Kim S-H and Tahk M-J. Missile acceleration controller design using proportional–integral and non-linear dynamic control design method. Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering, 226(8): 882–897, DOI:10.1177/0954410011417510, 2012.

[21] R. Padhi, Chv Sirisha, Achintya Sarkar, P Kar, and T. Srinivasan. Nonlinear and linear autopilot performance comparison of tactical flight vehicle. AIAA Guidance, Navigation, and Control Conference 2012, pages 1–24, DOI:10.2514/6.2012– 4683, 08 2012.

[22] R.H.Chile A.D.Sonar (Limgaokar) and B.M.Patre. Design, analysis and performance evaluation of f-pi controller based on analytical structure developed using gaussian membership functions. International Journal of Information Technology and Electrical Engineering, pages 1–7, 08 2020.

[23] J. Astrom, K. and D. Bell, R. Drum-boiler dynamics. Automatica, 36:363–378, 2000.

[24] K. Mrunalini, P. Kundu, and K.K. Dutta. State space model for drum boiler system. Journal of Institution of Engineers India , Ele., 86( ):260-267, 2006