Automation of Boiler Temperature and Water Level Control using Fuzzy Logic

Abdur Rohman, Bitopan Kakati, Riddhiman Saikia, Jamini Das, Amarjyoti Goswami, Anilesh Dey

***Abstract*—This paper analyses the feasibility of maintaining a constant temperature in the boiler using Fuzzy Logic. The boiler is an essential component of a thermal power plant and is used to heat water for generation of steam. Excessive heat may result in damage to the boiler. Therefore, maintaining a constant temperature in the boiler is a vital task. In this paper, we have anticipated a method of maintaining boiler temperature at an optimal point using Fuzzy Logic. The temperature and water are two important constraints of a boiler and hence given as two inputs to the fuzzy logic controller. Based on the values of these two parameters an output is generated to limit the temperature. If the temperature cannot be restricted over a specified period of time, then the boiler is switched OFF until a certain specified temperature is reached.**

***Index Terms*—Burner and Valve Control, Fuzzy Inference System, If-then rules, Nonlinearity and disturbances.**

I. INTRODUCTION

In a power plant, when steam is produced in the boiler, it is very necessary to control the temperature of the boiler so that its efficiency [1-3] and safety is not affected by the rise in temperature. As the temperature of the superheater of the boiler reaches the maximum operating temperature, it is very much essential to limit the temperature at a stable rate. The temperature should not be very low [4] also as it can decrease the efficiency of the plant. Steam temperature is one of the most challenging control loops in a power plant boiler because it is highly nonlinear and has a long dead time and time lag [5]. Adding to the challenge, steam temperature is affected by boiler load, rate of change of boiler load, air flow rate, the combination of burners [6] in service, and the amount of soot on the boiler tubes. Using automatic controller is much more convenient as labor-intensive controllers can be sometimes very time consuming. An automatic controller can work in a certain temperature limit. For instance, when the temperature exceeds the upper temperature limit, it will automatically reduce the temperature by switching off the boiler and when the temperature reaches the lower limit [7-9], it will automatically increase the temperature.

As seen in the power plants, the conventional control system uses PID controllers. These PID controllers have a lag and a large inertia [5-7] as a result of which controlling of temperature becomes challenging. So because of the nonlinearity, variation and disturbances [7] we would not be able to get satisfactory results using PID controllers. When it comes to the control of nonlinear and variable processes [9-13], the controller parameters have to be continually adjusted.

In this paper, we explore the possibility of achieving overheating protection in boilers of a power plant using Fuzzy logic. To attain this design, temperature sensor, water level sensor, DC motor for opening and closing of valves, LCD devices are employed. Many approaches have been already made. The only thing that makes our approach different is the use of the timer to set the time limit for the boiler to reach the optimum temperature. The primary intent of this paper is to control the temperature in the boiler when the nature is nonlinear and variable. Thus, designing a nonlinear controller, which is robust in terms of its performance for different operating conditions is crucial.

To present the stated objective this paper is outlined into 6 Sections, where Section II present the Methodology, the Merits is presented in Section III. Section IV outlines the obtained experimental results for the proposing approach. The concluding remarks are outlined in Section V.

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II. METHODOLOGY

A. Necessity of Temperature Control

A boiler is a closed vessel in which water in heated. If the water is not vaporized, the boiler is termed as a furnace. The energy source is combustion of fuels such as wood, coal, oil or natural gas. The heated or vaporized water is then used for various purposes. The steam, after conversion expands considerably higher than its initial volume and also travels at a very high flow rate [15]. Because of this, steam is a very efficient means to transfer energy. But without safety measures such as temperature and water level control, it can lead to erosion or scale formation and ultimately boiler failure [16].

Boiler failure in terms of the economy includes reduced performance and lower quality of steam at the outlet. But there are also damaging effects of boiler failures which are disastrous, including massive cost to industry and even death of workers. A ruptured boiler can lead to outbursts of pressurized steam, which, if sprayed on workmen can fatally injure them.

Hence there is a need for proper control of both temperature and pressure (or water level) in the boiler. However the most efficient control can only be achieved by using the automated control rather than the manual type. Here is where our proposed system of fuzzy logic is put into use.

B. Proposed Fuzzy Inference System

Since the temperature and water in the boiler is variable between '0' to a maximum, therefore, for controlling these two parameters requires a system which can provide intermediate states and henceforth fuzzy logic has been found the most suitable practice as it can offer all the transitional states between '0' and '1'. The system proposed using Mamdani fuzzy control model using MATLAB & Simulink is represented in the fig below (Fig. 1).

Fig. 1. Proposed Fuzzy Inference System

To achieve the desired work three inputs are considered which are titled below:

- TEMPERATURE
- WATER LEVEL
- TIME

The temperature is taken from a temperature sensor which is positioned inside the boiler, water level is provided by level sensors located inside the boiler and a timer to detect the time for which the high temperature remains in the system.

For the implementation of fuzzy logic technique the inputs are divided into their membership values. For example, if the temperature is maximum then the membership value of the temperature is assigned as '1' and if the temperature is lowest then the membership value will be '0' and similarly for intermediate temperatures the membership will lie between '0' and '1'.

The first input is divided into three membership functions and are as follows (Fig. 2)

- LOW
- MEDIUM
- HIGH

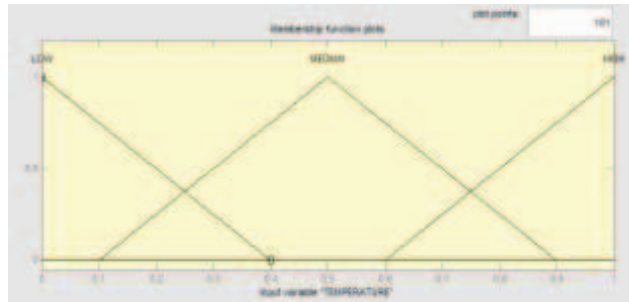

Fig. 2. Input Membership Function Temperature

The mf (membership function) 'LOW' is assigned at '0' point which means that the temperature is lowermost. The mf 'MEDIUM' which is placed in central position is given a 50% membership value representing that the temperature is medium inside the boiler. Similarly, for uppermost temperature the mf 'HIGH' is given the highest membership value.

For the second input, the membership functions are subdivided as follows (Fig. 3)

- LOW
- MEDIUM
- HIGH

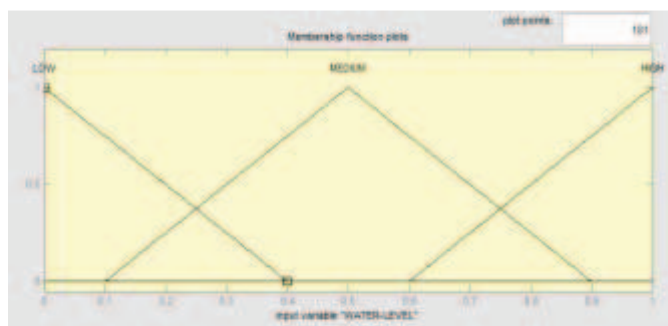

Fig. 3. Input Membership Function for Water Level

In this case the mf 'LOW', which is given the lowest membership value '0' indicates the lowest water level inside the boiler. The mf 'MEDIUM', having the membership value of 0.5 (50%) specifies the moderate water level and the last mf 'HIGH' having the highest membership value gives the highest level of water inside the boiler.

The third input TIME has a single membership function showing the maximum time counted by the timer when the temperature becomes very high (Fig. 4).

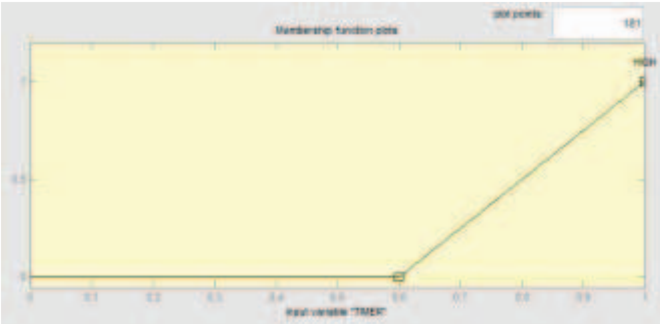

Fig. 4. Input membership Function for Time

Now, to obtain optimum action for keeping the boiler under safe and operating condition three outputs are defined viz.:

- BURNER
- VALVE
- SYSTEM SHUT

The first output controls the burner which is responsible to generate steam. Depending upon the temperature in the boiler the system will decide how much the burner flame is required. Burner flame is divided into three membership functions and given as (Fig. 5)

- OFF
- MIDDLE
- HIGH

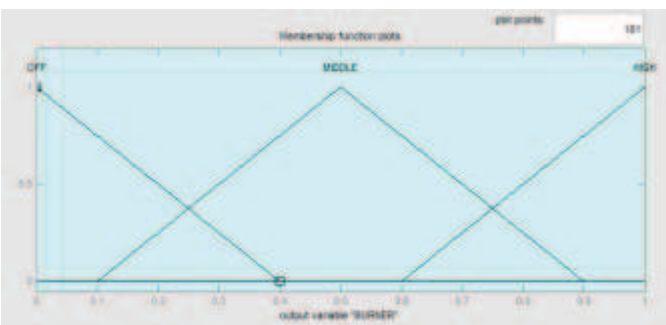

Fig. 5. Output Membership function for BURNER

In the above fig the mf 'OFF' has lowest membership value '0' showing the OFF position of the burner when the temperature is very high. The mf 'MIDDLE' is placed in the central position and given a 50% membership value to depict the intermediate level of the burner flame and the last mf 'HIGH' is given highest membership value to show the maximum flame in the boiler.

The second output VALVE is responsible for supplying the water to the boiler. It is also divided into three membership functions as represented in Fig. 6:

- OFF
- MIDDLE
- FULLY-ON

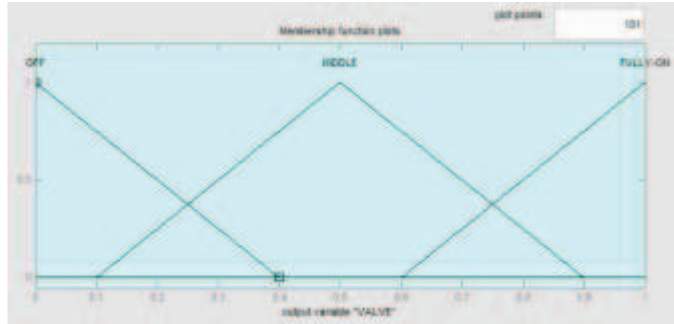

Fig. 6. Output Membership Function for VALVE

The first mf 'OFF' is given lowest membership value (i.e. 0) and depicts the OFF condition of the valve. The valve is operated through a DC motor. The second mf 'MIDDLE' is given a 50% membership value depicting the partially 'ON' position of the valve and moderate amount of water flowing through the valve. Again, the membership function 'FULLY-ON' is given highest membership value and depicts the maximum water flow through the valve.

The third output is SYSTEM SHUT and given a single membership value as shown in the fig below (Fig. 7)

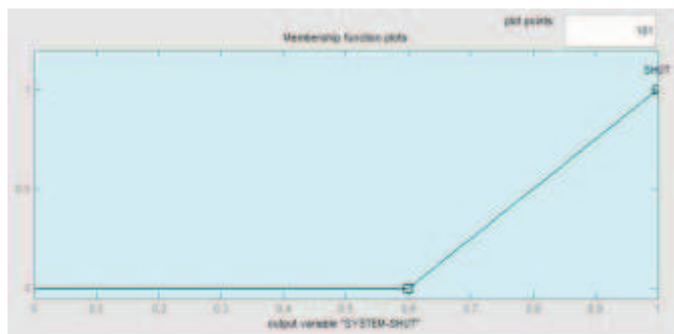

Fig. 7.Output Membership Function for SYSTEM SHUT

This output will only act when the temperature inside the boiler is very high and cannot be restricted.

The control procedure for controlling the temperature is obtained by defining some set of rules between input and output membership functions which are delineated in the following (Fig. 8). There will be 10 sets of rules for defining each combination.

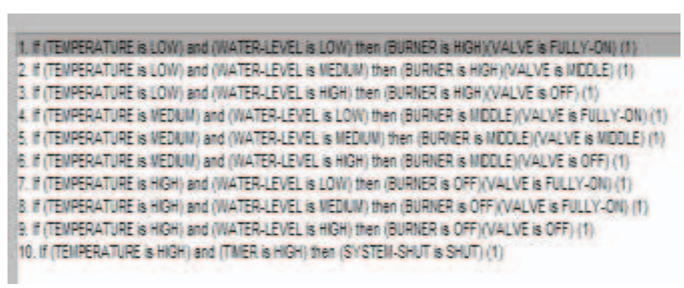
1. If (TEMPERATURE is LOW) and (WATER-LEVEL is LOW) then (BURNER is HIGH)(VALVE is FULLY-ON) (1)
2. If (TEMPERATURE is LOW) and (WATER-LEVEL is MEDIUM) then (BURNER is HIGH)(VALVE is MIDDLE) (1)
3. If (TEMPERATURE is LOW) and (WATER-LEVEL is HIGH) then (BURNER is HIGH)(VALVE is OFF) (1)
4. If (TEMPERATURE is MEDIUM) and (WATER-LEVEL is LOW) then (BURNER is MIDDLE)(VALVE is FULLY-ON) (1)
5. If (TEMPERATURE is MEDIUM) and (WATER-LEVEL is MEDIUM) then (BURNER is MIDDLE)(VALVE is MIDDLE) (1)
6. If (TEMPERATURE is MEDIUM) and (WATER-LEVEL is HIGH) then (BURNER is MIDDLE)(VALVE is OFF) (1)
7. If (TEMPERATURE is HIGH) and (WATER-LEVEL is LOW) then (BURNER is OFF)(VALVE is FULLY-ON) (1)
8. If (TEMPERATURE is HIGH) and (WATER-LEVEL is MEDIUM) then (BURNER is OFF)(VALVE is FULLY-ON) (1)
9. If (TEMPERATURE is HIGH) and (WATER-LEVEL is HIGH) then (BURNER is OFF)(VALVE is OFF) (1)
10. If (TEMPERATURE is HIGH) and (TIMER is HIGH) then (SYSTEM-SHUT is SHUT) (1)

Fig. 8. If-then rules for Controlling the Boiler Temperature

C. Proposed Control System

In the fuzzy logic control system we have proposed, temperature, water level and time are the three inputs. The two outputs are valve and burner. We are required to maintain the temperature of water and the water level at a certain optimum range to ensure prevention of failure of the boiler. The temperature and water level are calculated by sensors which are connected to the microcontroller.

In the flow chart given, the first column is of inputs (temperature, time and water level), the second column for conditions of inputs (High, Medium or Low) and the third column is for Output settings (High, Low and Off) given to the valve or burner. The nodes in the second column define the various combinations of input conditions and the corresponding horizontal line of the node leads to its output settings.

A few examples as shown in the chart are,

- If the temperature and water level are both set to HIGH, the burner and valve are both set to OFF.
- If the temperature is medium and water level is low, then the burner is set to low and valve is set to HIGH since we require more steam.
- If the temperature is LOW and water level is HIGH, then the burner is HIGH and the valve is OFF.

Additionally, there arises a special condition in the case where both inputs are set to HIGH. There is a possibility of failure of the boiler. If optimum condition is not reached within a certain time, even after both outputs switched to OFF, the whole system is SHUT DOWN.

So the fuzzy logic system has a grand total of 10 possible outputs.

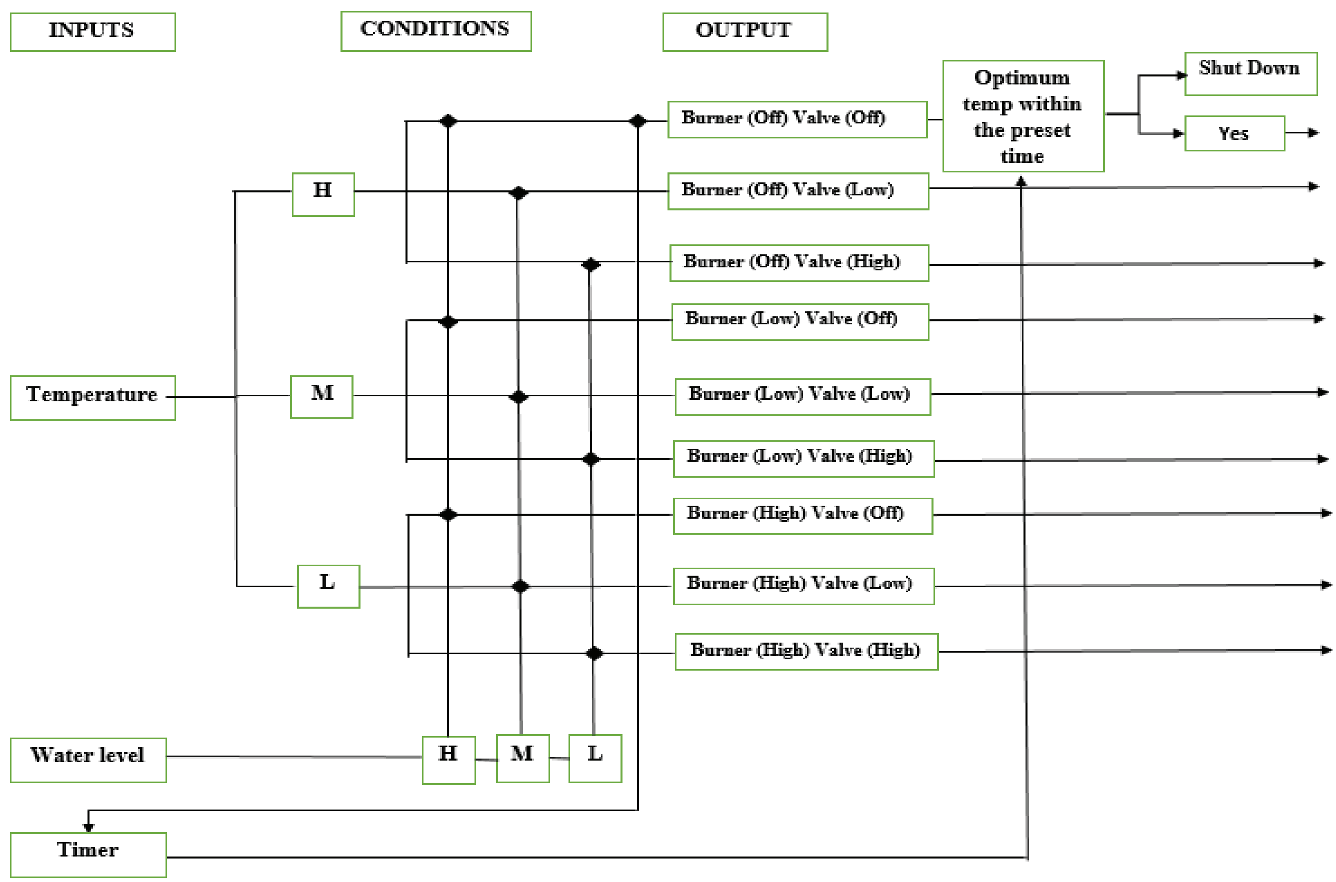

Fig. 9. Representation of proposed control system

III. MERITS

While PID controllers are widely used due to its simplicity and feasibility, it is the most basic system of control. Therefore their use is limited when complex processes are required to perform a task. Moreover, PID controllers are only capable of measuring varying inputs and calculating difference between them. If differences estimated are less precise, the output correction is not accurate.

Comparatively the fuzzy logic system is more accurate when it comes to detection of disturbances even if the estimated differences are less precise. Also the response of fuzzy logic is faster and robust than other conventional systems. The complex processes are also easily handled by fuzzy logic. The fuzzy logic system does not require a fast processor to operate.

IV. RESULTS AND DISCUSSION

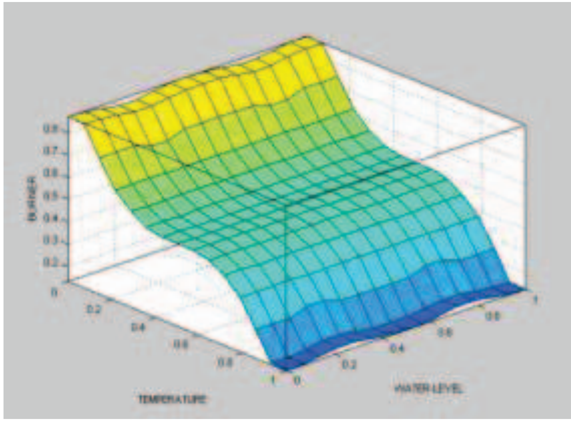

Fig. 10(a). Surface between temperature and water-level with respect to Burner

Fig. 10(a) demonstrates the surface between temperature and water level with respect to burner. (0, 1, 0) point indicates that when the temperature is high and water level is zero the burner flame needs to be decreased so as to cool down the temperature. The point (0, 0, 1) indicates that both the temperature and water level is low and therefore we need to increase the burner flame. The point (1, 0, 1) indicates that when the water level is high and there is a low temperature in the boiler, so we definitely need to increase the burner flame to increase the temperature. Again (1, 1, 0) shows that if both the temperature and water level is high, then we need to decrease the burner temperature. The equation for this surface will be:

F(x, y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2 + p30*x^3 + p21*x^2*y + p12*x*y^2 + p03*y^3 (1)

Coefficients (with 95% confidence bounds):

p00 = 0.9115 (0.8781, 0.945)
p10 = -1.809 (-1.988, -1.631)
p01 = -0.03168 (-0.21, 0.1467)
p20 = 2.959 (2.603, 3.314)
p11 = 0.06336 (-0.2158, 0.3426)
p02 = 0.03168 (-0.3241, 0.3875)
p30 = -1.972 (-2.197, -1.748)
p21 = -5.807e-016 (-0.1938, 0.1938)
p12 = -0.06336 (-0.2572, 0.1305)
p03 = 2.013e-015 (-0.2247, 0.2247)

Fig. 10(b) shows the surface between temperature and water-level with respect to the valve. (1, 0, 0) indicates that when the temperature is low and the water level is high the valve needs to be shut down. (1, 1, 0) also indicates that the valve should be off when both the temperature and water level is high

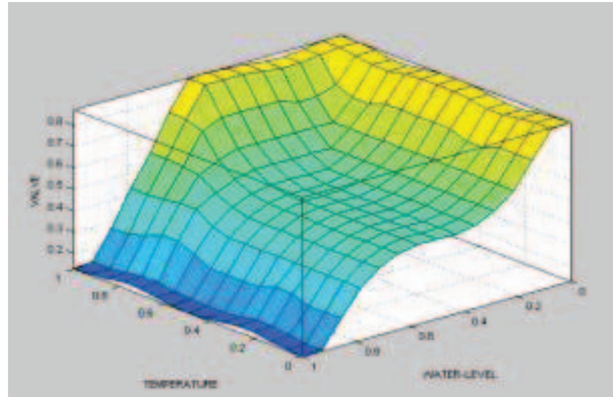

Fig. 10(b). Surface between temperature and water-level with respect to Valve

Again (0, 0, 1) shows that when there is a low amount of water in the boiler the valve needs to be opened for efficient performance. Point (0, 1, 1) shows that the valve should be opened when the temperature is high, but the water level is low so as to reduce the temperature. The equation of this surface will be:

F(x, y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2 + p30*x^3 + p21*x^2*y + p12*x*y^2 + p03*y^3 + p40*x^4 + p31*x^3*y + p22*x^2*y^2+ p13*x*y^3 + p04*y^4 + p50*x^5 + p41*x^4*y + p32*x^3*y^2+ p23*x^2*y^3 + p14*x*y^4 + p05*y^5 (2)

Coefficients (with 95% confidence bounds):
p00 = 0.8494 (0.8152, 0.8837)
p10 = -0.4392 (-0.8693, -0.009127)
p01 = 1.195 (0.7644, 1.625)
p20 = 4.687 (2.447, 6.928)
p11 = -2.856 (-4.514, -1.198)
p02 = -18.37 (-20.61, -16.13)
p30 = -13.12 (-18.35, -7.897)
p21 = -3.437 (-7.076, 0.2022)
p12 = 13.82 (10.18, 17.46)
p03 = 53.36 (48.14, 58.59)
p40 = 14.29 (8.753, 19.83)
p31 = 9.51 (5.521, 13.5)
p22 = -2.937 (-6.568, 0.6942)
p13 = -18.33 (-22.32, -14.34)
p04 = -60.13 (-65.68, -54.59)
p50 = -5.43 (-7.606, -3.254)
p41 = -3.098 (-4.888, -1.308)
p32 = -4.14 (-5.839, -2.442)
p23 = 3.707 (2.009, 5.406)
p14 = 7.72 (5.931, 9.51)
p05 = 23.22 (21.04, 25.4)

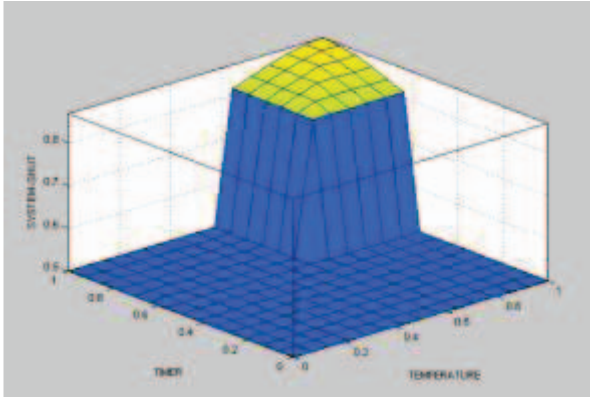

Fig. 10(c). Surface between Timer and temperature w.r.t. System Shut

Fig. 10(c) depicts the scenario when temperature and water level is very high and the burner flame is not decreasing as to control the temperature within the given time preset in the timer. The point (1, 1, 1) shows that when the temperature is very high and the timer passes the preset value then, to prevent the damage to the boiler, the system needs to be shut down. When the timer value passes beyond the limit and the temperature is not within the working range, then the microcontroller directs a signal to the switch to shut down the boiler. The equation of this surface will be:

$$F(x, y) = p00 + p10*x + p01*y + p20*x^2 + p11*x*y + p02*y^2 + p30*x^3 + p21*x^2*y + p12*x*y^2 + p03*y^3 + p40*x^4 + p31*x^3*y + p22*x^2*y^2 + p13*x*y^3 + p04*y^4 \quad (3)$$

Coefficients (with 95% confidence bounds):

p00 = 0.4226 (0.3623, 0.4829)
p10 = 0.9689 (0.4587, 1.479)
p01 = 0.9689 (0.4587, 1.479)
p20 = -3.692 (-5.432, -1.951)
p11 = -2.644 (-3.966, -1.322)
p02 = -3.692 (-5.432, -1.951)
p30 = 5.179 (2.744, 7.613)
p21 = 3.412 (1.613, 5.212)
p12 = 3.412 (1.613, 5.212)
p03 = 5.179 (2.744, 7.613)
p40 = -2.351 (-3.533, -1.17)
p31 = -2.367 (-3.363, -1.371)
p22 = 0.8051 (-0.162, 1.772)
p13 = -2.367 (-3.363, -1.371)
p04 = -2.351 (-3.533, -1.17)

V. CONCLUSION

The suggested control model for temperature and water level control of a boiler is expected to improve the operation of the boiler. The 10 combination of the rules is expected to facilitate the optimum operation of the boiler without failure. The surface graphs obtained from the combinations depicts the achievement of the desired operation. This advancement by providing intermediate states for maintaining a constant temperature with respect to water level using fuzzy logic is a unique model at lower cost. Such implementation can offer flexibility in the control strategy for providing optimum operation. In further studies more flexibility in the operation can be implemented.

REFERENCES

[1] M. E. Flynn and M. J. 0' Malley," *A Drum Boiler Model for Long Term Power System Dynamic Simulation," IEEE Transactions on Power Systems*, Vol. 14, No. 1, February 1999.

[2] G. Irwin, M. Brown,, B. Hogg, and E. Swidenbank, " *Neural network modelling of a 200MW boiler system*," *IEEE proceedings-Control theory and Applications,* 1995, 142(6), pp. 529-536.

[3] Anabik Shome, Denis Ashok. S. (2012). Fuzzy Logic Approach for Boiler Temperature & Water Level Control. *International Journal of Scientific & Engineering Research*, 3(6).

[4] Astrom. K, Hang. C.C, Persson. P. and Ho.W.K. (1992). Towards intelligent PID control. Automatica, 28(1): 1-9.

[5] Astrom. K. J. and Hagglund. T. (1995).PID Controllers: Theory, Design, and Tuning, 2nd Edition, Instrument Society of America, USA.

[6] Franksen, O. I. (1978). Group representation of finite polyvalent logic, in A. Niemi (ed.). Proceedings of 7th Triennial World Congress, International federation of automatic Control, Pergamon, Helsinki.

[7] Junran Jin, Hengshuo Huang, Junman Sun, Yongchao Pang. (2013). Study on Fuzzy Self-Adaptive PID Control System of Biomass Boiler Drum Water. *Journal of Sustainable Bioenergy Systems*, 3:93-98.

[8] Mamdani. E. H. (1977). Application of fuzzy logic to approximate reasoning using linguistic synthesis. *IEEE Transactions on Computers*, 26(12):1182-1191.

[9] WU Mingliang, WU Mingyong, HUANG Jiankang, SHAO Ling. (2011). Intelligent Control System of Water Level for Boiler Drum Based on OPC and MATLAB. Proceedings of the 30th Chinese Control Conference, July 22-24, 2011, Yantai, China.

[10] Zadeh, L. A. Soft computing and fuzzy logic. // *IEEE Software* 11 6 (1994) str. 48 56.

[11] Goto, S.; Nakamura, M.; Matsumura, S. Automatic realization of human experience for controlling variable pressure boilers. // Control Engineering Practice 10 (2002)str. 15 22

[12] Alobaida, F.; Postler, R., Ströhle, J.; Epple, B.; Hyun-Gee, K. Modeling and investigation start-up procedures of a combined cycle power plant. // Applied Energy 85 (2008) str. 1173 1189

[13] Tan,W.; Fang, F.; Tian, L.; Fu, C.; Liu, J. Linear control of a boiler–turbine unit: Analysis and design. // ISATransactions 47 (2008) str. 189 197.

[14] Frederick M. Steingress (2001). *Low Pressure Boilers* (4th ed.). American Technical Publishers. ISBN 0-8269-4417-5.

[15] Frederick M. Steingress, Harold J. Frost and Darryl R. Walker (2003). *High Pressure Boilers* (3rd ed.). American Technical Publishers. ISBN 0-8269-4300-4.

[16] ASME Boiler and Pressure Vessel Code, Section I, PG-5.5, *American Society of Mechanical Engineers* (2010)

[17] B. Widrow, J. McCool, and B Medoff, "*Adaptive control by inverse modelling*," 12th Asimolar conference on Circuits, Systems and Computers, 1978.