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APPLICATION OF FUZZY LOGIC IN BOILER CONTROL

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Original scientific paper

Application of fuzzy logic for solving the control problems of boiler room shown on the examples of water level control in boiler drum and combustion quality control is presented. Fuzzy control rules were extracted from operator knowledge based on the relative relevance ruling criteria for existing boiler room. Proposed fuzzy control model was adjusted for given problem with simplification of output variables in order to speed up final calculation.

Key words: *boiler room, fuzzy logic, control*

Primjena neizrazite logike u vođenju kotla

Izvorni znanstveni članak

U radu je prikazana primjena neizrazite logike u rješavanju zadaća vođenja kotlovskog postrojenja, na primjeru regulacije razine vode u bubnju kotla i regulacije kvalitete izgaranja. Neizrazita pravila su nastala kao rezultat znanja korisnika sustava vođenja (operatera), pravila su odabrana na osnovu kriterija relativnog značaja postojećeg kotlovskog postrojenja. Predloženi neizraziti model prilagođen je danom problemu uz pojednostavljenje izračuna izlaznih varijabli u cilju ubrzanja.

Ključne riječi: *kotlovsko postrojenje, neizrazita logika, vođenje*

1 Introduction
Uvod

Fuzzy logic represents soft computing method for solving problems where classical logic cannot provide satisfying results. Fuzzy logic is multi-value logic derived from theory of fuzzy sets proposed by L. A. Zadeh (1965.). This kind of logic gained success because it makes use of the tolerance for imprecision and uncertainty to achieve tractability, robustness, and low cost solution [1]. The key quality of fuzzy logic standpoint is the possibility of giving a formal and procedural representation of linguistic terms used to state human-centred concepts. First basic concept underlying fuzzy logic is a linguistic variable, that is, a variable whose values are words rather than numbers. Fuzzy logic is a way of expanding classical logic because it allows values of variables to be different from simple true or false. Something is not always black or white; it can be any tone of grey also. Second basic concept is fuzzy if-than rule, that is, manner of dealing with consequents and antecedents in fuzzy world. There are several steps in fuzzy control systems design. The first ones have to be done is selection and definition of appropriate input and output systems variables. Those variables are subjected to quantification and normalization. Transformation in fuzzy domain by means of fuzzification is the next step (characterization of membership functions for every variable). Critical part is setup of rules definition in rules database based on collected expert knowledge. Next, rules are evaluated, based on selected reasoning model in if-than relations of inputs and outputs respectively. Finally, results of evaluation are defuzzified to output back to real world variable.

A membership function is a curve that defines how each point in the input space (universe of discourse) is mapped to a membership value (or degree of membership, or single quality of fuzzy variable) between zero and one. Several membership functions (on occasion called fuzzy numbers) are usually used to describe single fuzzy variable. This fuzzy numbers have different shapes like broken linear functions, sigmoid functions, Gaussian distribution functions, or quadratic and cubic polynomial functions.

Some criteria need to be taken into consideration in design process for variables and membership functions. Membership functions criterion: it is of less importance how membership function is shaped than it is how many of them there are and how they are distributed over the input/output space. Connected criterion is that the number of functions defined for one variable should be less than seven, plus or minus two. This principle is extracted from a psychological experiment reported [2] where the proof is given that the span of absolute judgment and the span of immediate memory impose a limitation on the amount of information that a human being is able to perceive, process and remember. These tests show that the number of entities a human can clearly remember for a short time is around seven, plus or minus two. Therefore, human brain can organize complex information into single granule of information. These granules of knowledge can then be treated as single entities. Next is the proper ordering criterion. The easiest way of getting it without interoperability analysis is by using specific shapes for fuzzy numbers (sets) and make them all same width [3].

Conventional control systems are built around mathematical models were with the help of one ore more differential equations response of systems will be described as result of changes in input variables. For the most part, implementation itself is conducted by usage of proportional-integral-derivation algorithm (PID algorithm) with several kinds of improvements that are the result of long-lasting development with overall satisfying results [4, 5]. Now, the following question can be asked; why even think of using something like fuzzy logic if there is adequate solution already? There are several reasons: many times the mathematical model of real process and systems does not exist or it is too hard for real implementation (a large amount of complex calculations and/or extensive memory demands). In these cases it is more productive to design a system on soft-computing and empirical rules to gain a more flexible model. Other soft-computing methods are successfully used for solving these and similar problems.

Advantage of fuzzy logic over others is in the ability of developing systems based on fuzzy logic in the way close to the human operators' thinking. The implementation of the humans' experience and knowledge in systems design is possible. We can mechanize tasks already successfully done by human operators by means of knowledge transfer in fuzzy control model [6].

Modelling of boiler room and boiler turbine control systems is still of substantial interest, especially with new turbulences on fuels market, new energy field paradigms and direct influence on overall production. All this, move forwards with additional pressure on users for more effectiveness; fewer unplanned and deliberate shutdowns and greater ability to respond to rapid changes in production demands – more availability. Researchers developed several linear and nonlinear models representing the dynamics of boiler systems. Some of them are suitable for control design and have also been considered in papers; among them, the more recent ones are [7, 8, 9]. In literature [10, 11] dealing with application of fuzzy logic in boiler room control, problems are solved by using fuzzy logic as a helping tool for PID algorithm parameters determination in different observed situations. This approach asks for understanding of both process and mathematics behind PID algorithm from the source of fuzzy rules, something we cannot expect in case of common human operator. Some other approaches [8, 9] are based on different variant of adaptive auto-tuning controllers. In this paper, direct approach was selected with bypass to conventional control system and design of fuzzy control system only on the basis of rules set by human operator in hope of achieving satisfactory results. Some authors [11, 12] pointed out fuzzy logic based control system problems: much more resource demanding than PID and model-based controllers due to usage of implicit process model based on rules with benchmarked medium control performance compared to previous.

2
Boiler room control model
Model vođenja kotlovskog postrojenja

First, proposed boiler room control model is presented where the focus is on boiler water drum because of large number of boiler' emergency shutdowns, over 30 % of all recorded shutdowns is result of poor level control [3]. The second subject evolved is the burning quality control as representative of fuel consumption optimization. Figure 1 shows the observed boiler room with two identical boilers [6]. Boilers have shared feed-water tank, output steam header, secondary fuel preparation installation and stack. Every boiler has its own feeding for air, fuel and water. Both boilers are equipped with two burners in vertically parallel arrangement perpendicular to the furnace.

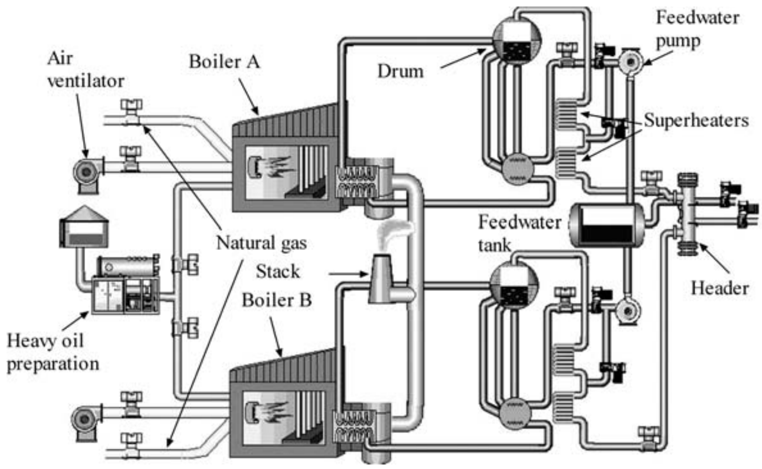

Figure 1 *Basic boiler room configuration*
Slika 1 *Osnovna shema kotlovskog postrojenja*

Heat input produced by burning of fuel in the presence of air causes boiling of water in boiler tubes. Real boilers are much more complicated than those shown in Fig. 1 and have complex geometry of risers and downcomers tubes [13], reheaters, preheaters, economisers. Water drum is critical component for drum type boilers because it maintains an adequate water level in the whole water-steam system and serves as steam separator for steam produced in risers. The second control loop observed was combustion control. From the angle of costs the burners control is most valued optimisation candidate. Even a small fuel consumption reduction produces significant saving especially if calculated on yearly basis [5, 6]. All conventional controllers used for boiler room controls were tuned according to the same criteria according to which the bandwidth was to be maximised without unnecessary wear of the drives and without introducing greater instability in control loops.

3
Boiler drum level control model
Model regulacije razine vode u bubnju kotla

Conventional control model usually consists of one-component for simpler and smaller boiler to tri-component control for medium to bigger drum type boilers [5]. From the control point of view, start-up problems of conventional tri-component control schema shown in Fig 2 can be solved by the use of a level controller in start-up and shutdown conditions and transfer to tri-component control when production of steam and flow of feed-water gets stable. In the presented expert fuzzy control model, same variables are used with the addition of an extra variable: steam demand. This variable is connected with pressure just before steam header and in normal work conditions; it is the same as the pressure at steam header. Drag force of boiler steam and fire demand is the change of pressure at steam header. When pressure is dropping consumers are spending more steam and the response of boiler is the following: fire is increasing with increased air and fuel input, more bubbles of steam are formed inside of boiler drum and false presentation of real situation if we look only at the level of water in drum. There is less water than is presented through level measurement. Inverse situation is when steam demand is dropping: decreased fire is producing less steam in steam tubes and drum is automatically showing lower level of water thant logically should be. In literature this described behaviour is called shrink-and-swell phenomenon [4, 5, 6]. In situations of large disturbances (e.g. dropping out or in of large consumers) conventional control system following capabilities drops and human operator has to control the situation and sometimes even take manual control over water level. Figure 3 shows the level and steam and feedwater flows measurements from observed system [5]. These types of situations were inspiration for evaluation of soft-computing in replacing human operators.

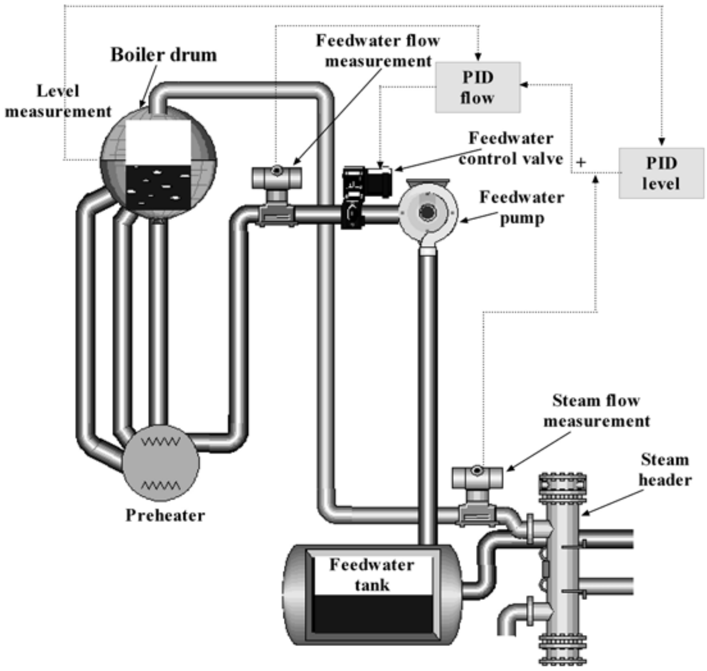

Figure 2 *Conventional tri-component control model*
Slika 2 *Konvencionalni tro-komponetni model regulacije*

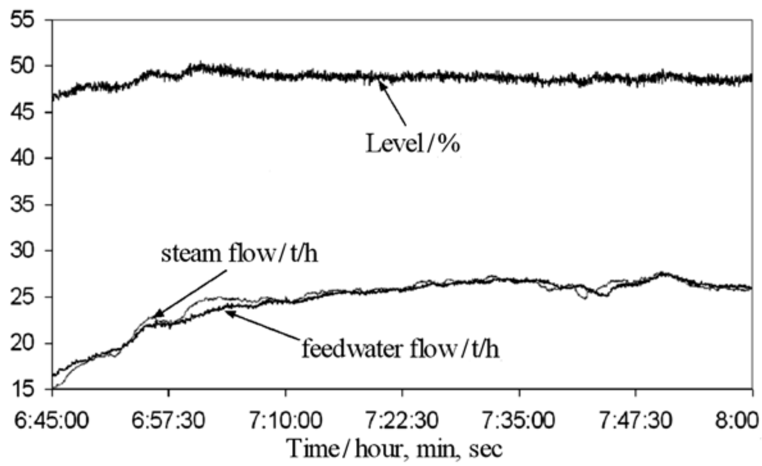

Figure 3 *Measurements of level and related steam and feedwater flows for conventional control* [6]
Slika 3 *Mjerenja razine te protoka pare i napojne vode za konvencionalni model vođenja* [6]

Problems concerning different modes of operation during diverse operating conditions are covered by fuzzy control model shown in Figure 4. There are four input variables and one output variable. Four input variables: difference between flows of feedwater and produced steam, one single step variable concerning boilers load simply controlling if real load is over 20 % of full span and two variables for drum level – one for measurement of level error and second for rate of level change in both directions. As a standard, single setpoint for boiler drum water level is used and it is usually half of full level. There are practical reasons for that. When the level is significantly lower there is possibility of water deficit in water tubes, danger of their burning up. The opposite situation would be significantly higher water level and there is a danger of flooding of steam tubes and interruption of steam separation. In both cases the boiler would be useless for a longer period [4, 5, 6].

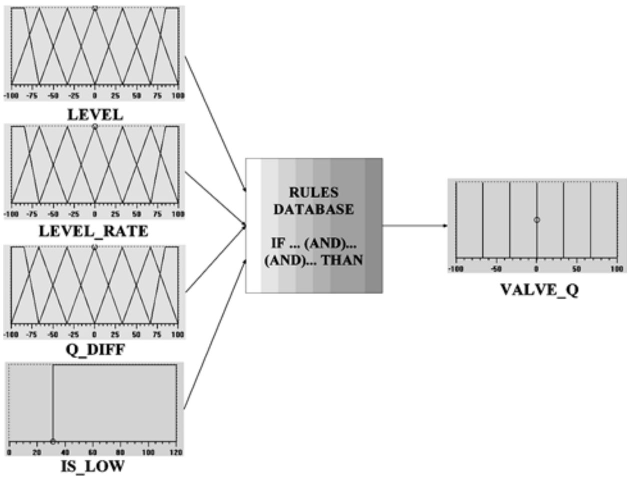

Figure 4 *Fuzzy level control model*
Slika 4 *Neizraziti model regulacije razine*

4 Combustion quality control model
Model regulacije kvalitete izgaranja

After consideration of the critical and most important sub-system from the overall security point of view, the focus is on cost control. Figure 5 presents conventional combustion control as it is found in the observed system. Distributor demands fire changes: increase, decrease or still. This demand is transferred through limiter and selector where proper quantity of air and fuel is determined in cross-limited fully metered oxygen trim manner [6]. Direct cost control point for boiler room is fuel spending. Therefore, oxygen sensor installed at exit of flue gas just before the stack for each boiler is used as source of input. Second useful information is the calculated efficiency of individual boiler. The measured air to fuel ratio is the third input variable and gives preview of the situation that follows. The selected output variable is the air to fuel ratio because of its direct impact on excess air and therefore the flame quality during combustion in the furnace. For safety reasons after defuzzification and normalization this output variable needs to be limited in the way that minimum value can never be below the calculated lowest value of excess air for the used fuel in the given situation. The lowest value is calculated for the present measured gas temperature and pressure in gas pipeline for natural gas and theoretical burning air/fuel ratio multiplied by 1,05 for loads over 30 percent of maximum. For lower loads, this constant is 1,10 for safety.

Time lag for oxygen trim is approximately 120 second for observed system and differs over load span. For fuzzy inputs additional selection was made with fuel flow, and intentionally neglected air flow (except in air/fuel ratio indirectly as calculated value) for the reason that fuel is more constant and better-measured variable of the two and it is also used as a measure of load for single boiler in distributors' calculus of demand. The model for fuzzy logic based combustion quality control is presented in Figure 6 where fuzzy variable air-fuel stands for measured ratio error, demand is fire demand from superior distributor controller, fuel is the measured fuel flow error, O_2 stands for measured residual oxygen in flue gas just before stack. In this example only natural gas as fuel was evaluated for simulation because no relevant data for heavy oil could be acquired during this work.

5 Fuzzy control system design
Oblikovanje sustava neizrazite logike

In this work, fuzzy logic controllers are for the most part composed of the membership functions of a triangular shape and the rule base that has the Takagi-Sugeno rule type [6, 11]. The simplified Takagi-Sugeno rule can be presented

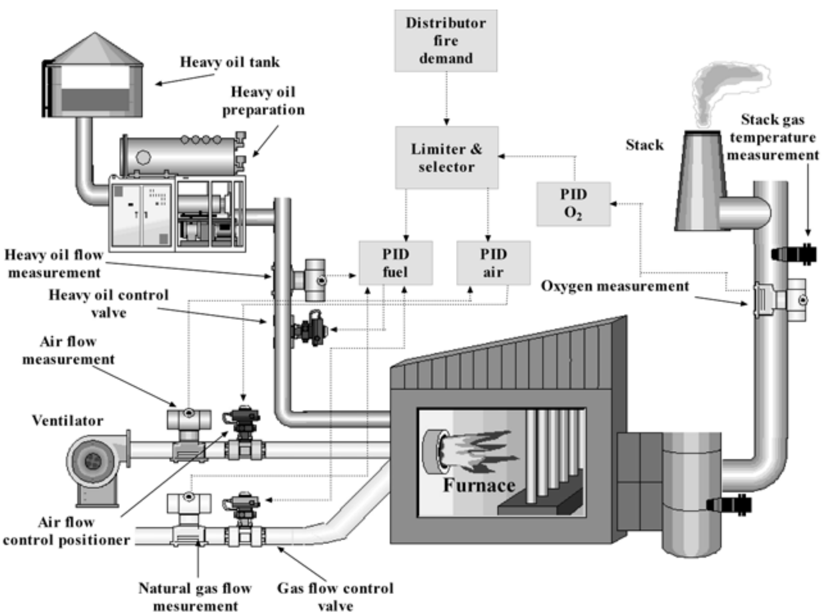

Figure 5 *Conventional combustion control*
Slika 5 *Konvencionalna regulacija izgaranja*

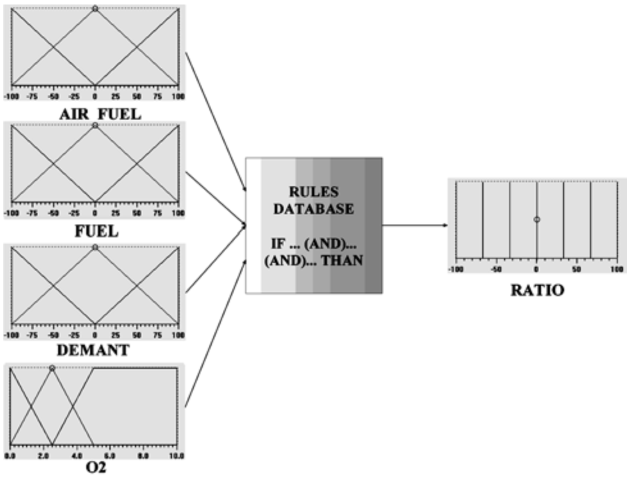

***Figure 6** Combustion quality fuzzy control model*
***Slika 6** Neizraziti model regulacije kvalitete izgaranja*

in the following way:

IF x_1 is MF_{i1} ..... **AND** x_m is MF_{im}, **THAN** y is w_i, (1)
(for $i = 1$ ..... n).

Where:
$x^T = (x_1, \dots, x_m)$ is the input vector of fuzzy variables,
MF_{ij} is the membership function for the j-th input of the i-th fuzzy rule,
y is the output of the i-th rule,
w_i is the real value of the consequent,
n stands for number of rules and
m is the total number of input variables.

In Eq. (1), IF parts of the rule statement are called antecedent and the statements in the THAN part are called the consequent. The membership function MF_{ij} for the case is mostly triangle membership function with symmetrical characteristics, with mathematical expression:

$$MF_{ij}(x_j) = \begin{cases} 1 - \dfrac{2\left|x_j - a_{ij}\right|}{b_{ij}}, & \text{where } \left|x_j - a_{ij}\right| \le \dfrac{b_{ij}}{2} \\ 0, & \text{otherwise} \end{cases} \quad (2)$$

Graphically, a_{ij} represents the central point and b_{ij} the width of the symmetrical triangular membership function. Simplification is in interference were AND operator is defined by plain multiplication. Therefore, membership value for any rule can be calculated as:

$$\mu_i(x) = \prod_{j=1}^{m} MF_{ij}(x_j) \quad (3)$$

Finally, output y of the fuzzy controller can be calculated by different calculation methods [3, 6, 13], for this case centroid method was used and expressed as:

$$y = \frac{\sum_{i=1}^{n} \mu_i \cdot w_i}{\sum_{i=1}^{n} \mu_i}. \quad (4)$$

Input were real word values (input vector), calculated, then returned real value y. In fuzzy words: fuzzification, rules evaluation and defuzzification by means of centroid method.

After selection and definition of fuzzy variables and construction of core model, build-up of rule database was performed. Rules are built in two ways: observation of operator's reactions during work and response of operators to given questions. Normally, responses and observations need to be taken into consideration before implementation in model. Sometimes surveyed operator has difficulties articulating his response or misinterpreting what is really going on, in this situations choice had to be made: either neglect or appropriately modify the rule in question. Some of stated rules were not considered not for the reason that they were not valid but because they did not fit in proposed model (usage of non-defined variables, non-defined relations or obviously not connected relations).

As example of regular rule, operator stated the following sentence: "If water level in boiler drum is at desired level and we have big steam demand and pressure drop at steam header and steam flow with constantly big input of fresh water in boiler drum, water flow level should be almost fully opened."

For this case of statement the following fuzzy rule was defined:

IF *level* is null **AND** *q_water* is p_big **AND** *q_steam* is p_big **AND** *p_header* in null
THEN *water flow valve* is p_big

Where: null stands for no change or fixed value depending on variable definition, p_big for positive big flow of water/steam/position of water valve.

Example of irregular rule: operator stated the following: "If demand is less than 40 percent and water level is very high then pressure on header is slowly lowering and oxygen then falls down to less than 1,80 percent."

This shows one big problem of soft-computing especially fuzzy logic in pure form. The system is again human dependant: our imperfection as designers and imperfection of human objects used as etalon for systems behaviour. Operators tend to think only in frame of their present system of working and reacting, and not how maybe it should be done, which is normal, but can be a barrier for getting things done. Some further work needed to be done for better knowledge extraction, more extensive research of things already done by others, or developing faster and better method for the rules database creation and evaluation.

The resulting fuzzy rules database for level control includes 141 rules. Less than one third is the product of expert knowledge and the rest is interpolation and partly pure guessing. Fuzzy rules database for burning quality control included 60 rules and even smaller percentage of rules extracted from operators than in the case of level control. This could be partially the result of common sense: from the operators' point of view if the safety demand is satisfied (e.g. in the case of combustion to have air rich mixture and never to drop below one percent in stack gas) they are not very much concerned with present burning quality but more in the sense of the whole shift or in the best case on hour to hour basis.

6 Results
Rezultati

In simulations for level control model, two experiments were performed. To identify tracking performance of controller, the level setpoint is initially varied for 30 percent

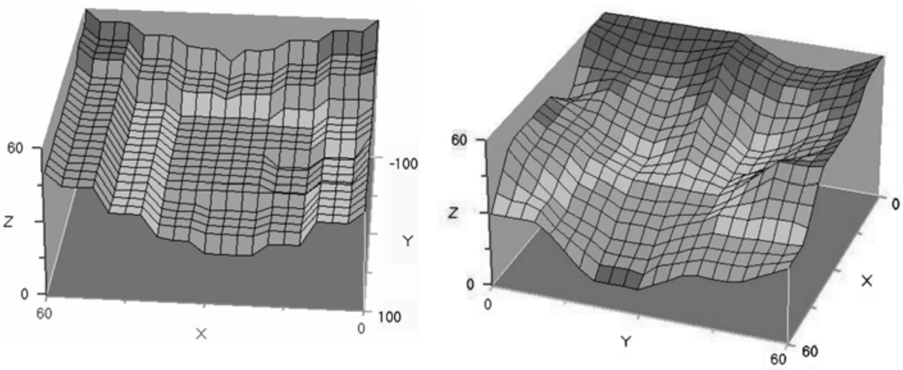

***Figure** 7 Static 3D function of level control model (left: load under 30 percent; right: load over 80 percent)*
***Slika** 7 3D prikaz statičke funkcije modela vođenja razine (lijevo: opterećenje ispod 30 %; desno: opterećenje iznad 80 %)*

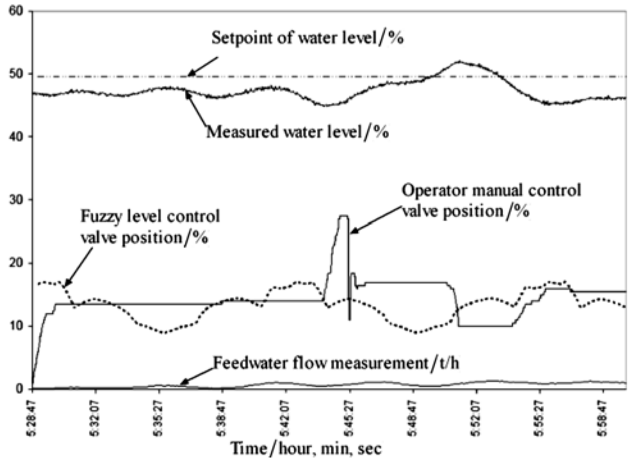

***Figure** 8 Fuzzy level control compared with operator manual control in startup situation with false feedwater and steam flow measurement*
***Slika** 8 Usporedba regulacije neizrazitom logikom s ručnim upravljanjem operatera u polaznoj situaciji s netočnim očitanjem protoka napojne vode i pare*

of full span of level. For identification of regulation performance, the difference in flow rates for water and produced steam was varied rapidly in a triangular steps fashion as the load disturbance. Figure 7 shows two different static responses of fuzzy control model. Left picture presents situation for level control and load under 30 percent and the right one for load above 80 percent correspondingly. The sampling time of the controller was 500 ms.

In Figure 8, main goal of level control is illustrated where for the same situation fuzzy logic and human operator in startup situations are compared. Specificity of this situation is that with low loads, flow measurements are not representative and the situation is not controllable by conventional control. Measured feedwater flow is below actual values; comparison was made with actual water consumption values obtained from feedwater tank [14].

Simulation of combustion quality control focus was in following the performance over the normal operating span of load for one boiler during everyday oscillations of demand (Figure 9). Load was oscillated in near triangular steps from 65 to 75 percent of load to get the appropriate following air/fuel ratio in span from 10,05 to 13,00 with 1,8 percent and 2,9 percent respectively of oxygen in stack gas. Sampling time of this controller was 5 seconds.

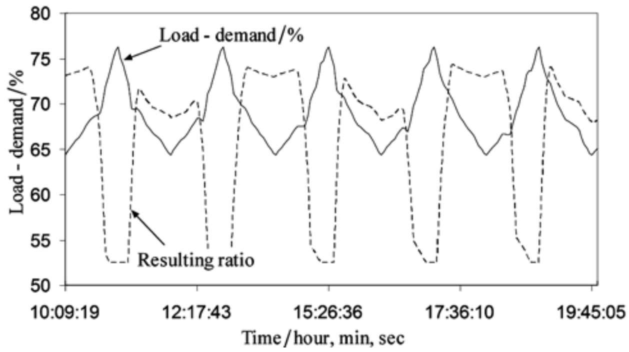

***Figure** 9 Simulation results for altering load demand and resulting air to fuel ratio (triangular steps of load variation from 65 to 75 percent of full span)*
***Slika** 9 Rezultati simulacije promjene opterećenja i ostvareni odnos zrak-gorivo (pilasti koraci promjene opterećenja od 65 do 75 % od cijelog opsega)*

7 Discussion and Conclusion
Rasprava i zaključak

Two control sub-systems of boiler room control were analyzed, and boiler water drum level and burning quality control nonlinear dynamic fuzzy models are presented as well. The errors due to variation of the load and different regimes of work have been eliminated or reduced by the use of fuzzy model for level control model. Combustion quality control model did not produce satisfactory results (equal or better than present control system) and should be further revised and improved.

In direct approach used in fuzzy control design fully completed rules sets are sometimes hard to get from operators alone without designers rules post-tuning. Interpolation of missing rules was made to fulfil criteria of completeness by trial and error method. Fuzzy logic based control can be good choice if the controller designer has a sufficient amount of operational knowledge. Downside is that this method does not produce solutions that are more general so consequently this controller cannot be used on any other even similar system and uncovered work conditions of this system. This fact stands and remains for further study on generalization of lessons learned.

One possible direction is usage of customize neural networks and genetic algorithm. For adjustment of fuzzy rules in training of supposed neural-fuzzy model genetic algorithm could be used to select rules for different working conditions (start-up, shutdown, normal) and enhance usage of direct human knowledge. Membership functions parameters in that case could be tuned in back-propagation manner and grab hold of real systems behaviour. Further analysis is needed to answer if soft computing could provide control that is more general in case of boiler room.

8
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