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Implementation of FUZZY Logic Based Temperature-Controlled Heat Exchanger

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Abstract:*A fuzzy Inference System toolbox developed with MATLAB is used in this paper to analyze the performance of a heat exchanger. Firstly, an analysis of a heat exchanger is conducted using a model which represents the heat exchanger based on a process reaction curve obtained from a pilot plant. Secondly, this research then compares the control performance of PID (Proportional Integral and Derivative) and fuzzy logic controllers. A comparison of PID (Proportional Integral and Derivative) and fuzzy logic controllers are then conducted. These control performances are used to draw conclusions. In the end, fuzzy controllers perform similarly to PID controllers in terms of control performance but give a better response when compared to PID controllers..*

Keywords:*Heat exchanger, Fuzzy logic controller, Proportional Integral and Derivative Control.*

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I. INTRODUCTION

In practice, heat energy is produced or absorbed during every chemical process [1].In the majority of engineering systems (boilers, gas turbines, chemical plants, oil refineries, turbofans), the heat exchanger plays a crucial thermal role. Heat exchangers are difficult to describe because they have uncertain mechanics, noncausalities, and nonlinearities [2-6].A heat exchanger system's complexity and nonlinear attitude, which are based on unidentified fluid properties such temperature-dependent qualities, contact resistance, leakages, and friction, make it challenging to control [7,8].Since heat exchanger is often employed in the process sector, researchers and engineers who work in modeling, sophisticated control strategy implementation, safe operation, or process integration are particularly interested in them. For instance, in [9] the authors examined and contrasted several heat exchanger mathematical models and heat exchanger controller types. To create safer heat exchanger network, authors employed risk assessment in [10]. Thermodynamic analysis of two improved ejector heat exchanger was conducted in [11]. An heat exchanger was developed by the authors to aid in regulating the bioclimatic device's temperature [12].At the same time, heat transfer processes account for more than 80% of all energy use in the globe [13,14]. Therefore, creating an appropriate control system may enhance both economic efficiency and heat transfer efficiency in addition to controlling the temperature of the heat exchanger output [15-17].

In the recent two decades, the use of artificial intelligence-based approaches in the control system has become a crucial topic [18-19]. A fuzzy logic approach is one that is frequently employed in the control system and is based on artificial intelligence [20]. The fundamental logic, which simply acknowledges "yes" or "no" as states, has evolved into fuzzy logic. It can distinguish grammatical variations like fairly large, large, extremely large, and so on thanks to fuzzy logic. So, using fuzzy logic will result in a system that is more adaptable [21].It has become popular to use fuzzy differential equations of integer and arbitrary order to evaluate the dynamics of mathematical models of physical processes [22]. The use of fuzzy theory in disease mathematical modeling helps to address problems related to quantifying uncertainty. In order to determine the fuzzy reproduction number and fuzzy equilibrium points, a model based on a particular population of people with a triangle membership function was used.

There are two fundamental types of heat exchangers: the solid wall heat exchanger and the direct contact heat exchanger. The solid wall heat exchanger transfers heat from one medium to another efficiently. In general, heat exchangers control fluid temperature. A predefined set point for the exchanger output temperature (leaving water) is controlled with fuzzy logic in this research. The use of fuzzy logic for the development of sophisticated control systems has become one of today's most successful technologies. Logic-based on fuzzy sets is perfect for applications since it resembles human decision-making and is capable of generating precise solutions from certain or approximate data. In the field of system design, it offers a useful alternative to purely mathematical approaches (e.g. linear control design) and purely logical approaches (e.g. expert systems). The ambiguities of human language and logic can be accommodated by fuzzy design, while other approaches require accurate equations to model real-world behaviors. In addition to providing an intuitive method for describing systems and automating the generation of effective models, it also provides a method for describing systems in human terms.

II. LITERATURE REVIEW

Using a test rig containing 90 thermosyphons arranged in six rows, Note [23] investigated the thermal performance of the heat exchanger. We altered the air velocity in the evaporator section as well as the inlet temperature. A computer program was developed to analyze the thermosyphon heat exchanger using the E - NTU method. By using the E - NTU method, a computer program was developed for analyzing thermosyphon heat exchangers. Simulation results were compared with experimental results to verify accuracy and conformity. There were differences in the temperature between the evaporator and condenser sections, with the evaporator section's temperature ranging from 100 to 250 EC, while the condenser section's temperature remained nearly constant at 25 EC. As a result of the experimental results, the thermodynamic model built with air moisture removal and total heat exchangers was found to be ineffective in estimating energy consumption. According to the results, 33% of primary energy could be saved through independent air moisture removal.

We propose solutions related to Heat Exchanger temperature control via conventional proportional integrals and derivatives (PID) to reduce overshoot, undershoot and non-linearity, as well as maintain the set temperature.

III. ANALYSIS OF PROPORTIONAL INTEGRAL DERIVATIVE CONTROLLER

A controller with a proportional, integral, and derivative mode is among its most powerful but most complex modes. Standard PID controllers have the following analytical expression:

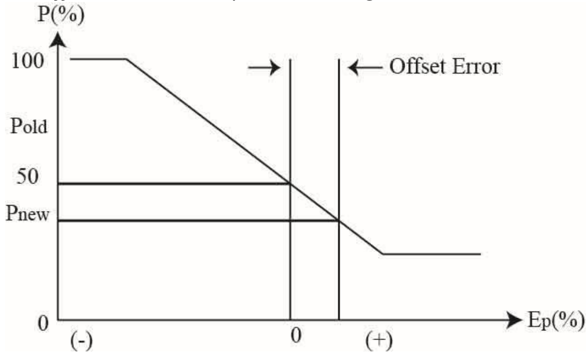
$$U = K_P + K_D \frac{de}{dt} + K_I \int e(t)dt + P_0 \quad (1)$$

where,
U = The controller output (0-100%)
K_P= Proportional gain constant
K_D = Derivative gain constant
K_I = Integral gain constant
$e(t)$ = Error i.e.$PV - SP$or $SP - PV$,
depending on whether it is a direct acting or reverse acting controller thermosyphon took place at $C_h = C_c$.A condenser and evaporator should not have the same air face velocity.$P = i_{as}$ or feed forward.

An example of an enclosed heat exchanger system with chilled ceilings and desiccant cooling was studied by Niu et al. [24] to maintain indoor air humidity within a comfort zone and reduce the risk of water condensation on chilled panels. As compared to an all-air system using constant volume, the chilled ceiling system can conserve up to 44% of primary energy. Based on the controller output, Zhang et al. [25] determined that the error was linearly related to the output of the controller. A one-to-one correspondence exists between each value of error and its corresponding controller output over a certain range of errors above the set point. A controller's output rate is related to error rates by the integral constant K_I. The higher the value of K_I, the larger the change in output caused by a small error. As the valve opens, the error value of the controller decreases and displays the rate of valve opening, such as in the case of a heat exchanger.

K_D is a derivative constant that measures how fast the error changes, rather than how much it changes. Also known as the anticipating control rate, derivative action is the rate at which a decision is anticipated. This mode of control produces a permanent residual error when a change in load occurs, and this is an important characteristic of proportional integral and derivative control. Offset [26] refers to this error. In addition to reducing the proportional band, a large constant K_P can minimize it. 0 % and 100% are the proportional bands for positive and negative errors, respectively. In Figure 1, the controller is set at 50% with no nominal load and the errors are as shown.

Figure 1: Offset Error in a Proportional Integral and Derivate Controller



Lags in control and process systems are visible in simple delays in controller output changes, as well as in the reduction of errors when a controller action is performed.

Integral actions overshoot the error and output to the operation point if the lags in the process are too large. There is also the possibility of the error oscillating around zero or even being cyclic. Figure 2 shows a dashed band representing the proportional band. A shift in the whole proportional band [26] can be explained by the integral action.

Other PID weaknesses include the presence of strong disturbances (non-linearity), time-varying parameters of the process, and the presence of dead times. Another problem with PIDs is the nonlinearity of the process, the presence of time-varying parameters, and dead periods. These issues are caused by the assumption that the process behaves in a linear way. It is possible to simplify this process in a stable situation, but strong disturbances can take it far from the set point. A process' parameters can also change over time if they are changed.

Figure 2: Overshoot and Cycling in PID Controller

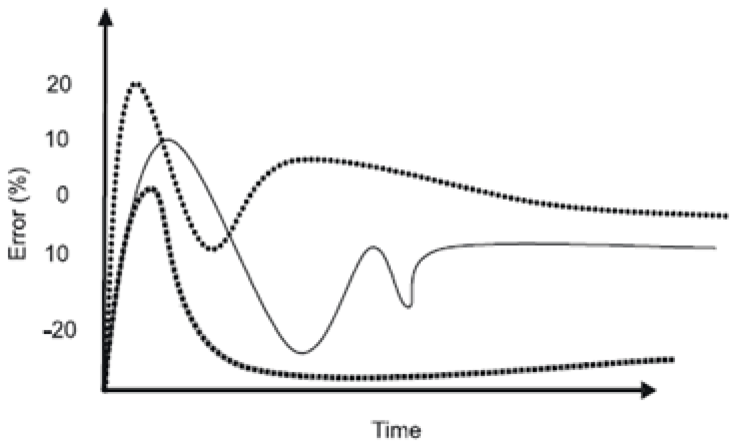
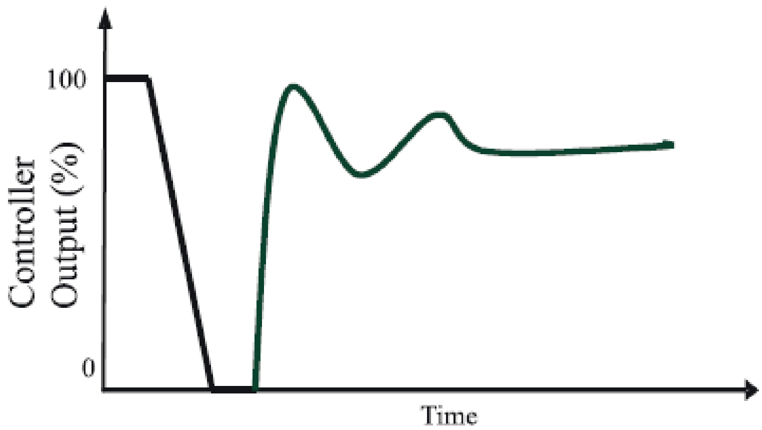


Figure 3: Cycling in PID Controller

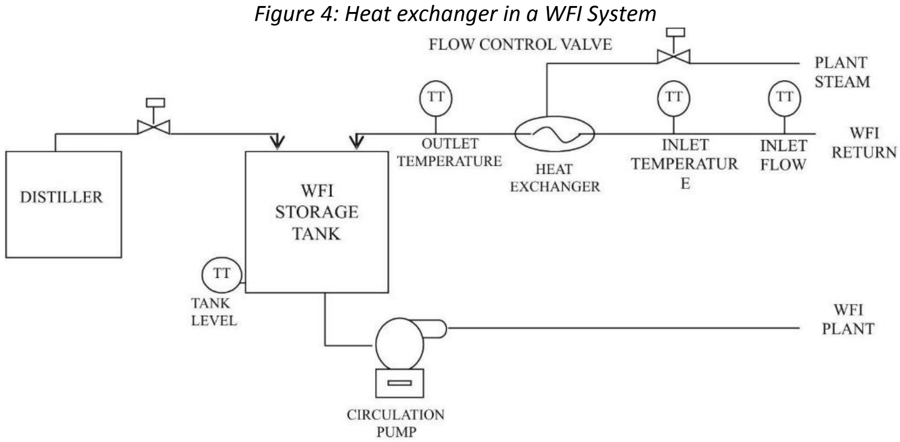


IV. LITERATURE REVIEW

For the purpose of studying the response and control activities of fuzzy logic controllers, the Heat Exchanger for Water for Injection (WFI) system was selected. As shown in Figure 4, the WFI system uses a wireless network. It is composed of a distiller, a tank for storing and distributing WFI, a circulation pump, and a heat exchanger. In addition to generating distilled water, the distiller also maintains the acceptable production limits of the WFI storage tank. WFI is circulated throughout the plant continuously by the circulation pump.

A Heat Exchanger returns unused distilled water to the storage tank. This heat exchanger is primarily responsible for maintaining the set point of the return WFI temperature. With the help of a steam flow control valve, the amount of steam being pumped into the heat exchanger can be regulated. By controlling the steam flow control valve position, the heat exchanger controls the process variable, namely temperature.

Figure 4: Heat exchanger in a WFI System



4.1 **Design Steps**

Step 1: *System Functional Requirements*

By controlling the return WFI temperature, the system minimizes the effects of process upsets, such as set point or load changes causing overshoots or undershoots.

Step 2: *System Parameters*

A single process variable, water temperature, governs the heat-exchange process. In effect, the PID controller controls steam flow into the heater by reading the outlet water temperature and applying a mathematical algorithm to produce a control variable.

Step 3: *System Parameters in terms of fuzzy sets*

A single process variable, water temperature, governs the heat-exchange process. In effect, the PID controller controls steam flow into the heater by reading the outlet water temperature and applying a mathematical algorithm to produce a control variable.

$$Error = Set\ point - Process\ variable \quad (2)$$

The next step was to decide which fuzzification function should be used. Selecting the fuzzification function, the next step was to determine which fuzzification function to use. A temperature loop tends to be a slow-acting loop as opposed to a pressure loop or pH loop, so trapezoidal and triangular functions are used for temperature loops. There is the possibility of implementing more complex functions, but the computing overhead is greater. Through the use of MATLAB, "Temperature Error" is decomposed into fuzzy regions. Each region within the variable's domain was given a unique name known as a label.

Labels indicate how accurate a control action needs to be for a variable. Labels should be used in greater numbers the tighter the control action. It is also recommended that each label overlaps slightly with its neighbor. Fuzzy controllers are characterized by smooth, stable control surfaces due to their overlap. In order to identify the 'Temperature fuzzy' regions, these labels were used:

$pb =$ Error is positive and big
$ps =$Error is positive and small
$z =$ Error is zero
$ns =$ Error is negative and small
$nb =$Error is negative and big

For the 'Error Rate', the labels usedare:

$p =$ Rate is Positive,$ze =$ Rate is zero
$n =$ Rate is negative

For the 'control output', the following were used:

Vh = Control output is very high
$High$= Control output is high
med = Control output is medium
low = Control output is low
vlControl output is very low

Heat exchangers require more steam when the actual temperature varies from the set point, and the more positive the "Error" the more steam is needed. A temperature rate of change of error based on input variable temperature is also used indirectly.
Where

$$Temperature\ rate = Previous\ Error - Current\ Error \quad (3)$$

PID controllers are analogous to PID controllers based on the derivative action generated by the p, ze, and n labels. A fuzzy region has been defined for the variable "Temperature Rate". Fuzzy regions are also defined for the output variable "Control".
Step 4: *Formulation of Control Rules*
Below are some intuitive rules for how heat exchanger applications should be made. Contrary to conventional control methods, which yield mathematical models, the rules are formulated as IF-THEN statements. 'Temperature Error', three labels, one label in each direction, and a zero for 'Temperature Rate' are represented by the five labels in this model. Two labels represent the positive direction and two represent the negative direction. This section explains the rules for controlling temperature error and temperature rate in each combination by taking control variables.
Here

$$Error = Derived\ set\ point - Actual\ temperature\ at\ the\ outlet\ of\ the\ heat\ exchanger$$
$$= SP - PV(out) \quad (4)$$

Table 1: Rule Base 1

Rule	Antecedent Block	Consequent Block
Rule 1.1	IfError is nb and Rate is n	THEN output to valve is high
Rule 1.2	IfError is nb and Rate is ze	THEN output to valve is vh
Rule 1.3	IfError is nb and Rate is p	THEN output to valve is vh
Rule 1.4	IfError is ns and Rate is n	THEN output to valve is high
Rule 1.5	IfError is ns and Rate is ze	THEN output to valve is high
Rule 2.1	IfError is ns and Rate is p	THEN output to valve is med
Rule 2.2	IfError is z and Rate is n	THEN output to valve is med
Rule 2.3	IfError is z and Rate is ze	THEN output to valve is med
Rule 2.4	IfError is z and Rate is p	THEN output to valve is med
Rule 2.5	IfError is ps and Rate is n	THEN output to valve is med
Rule 3.1	IfError is ps and Rate is ze	THEN output to valve is low
Rule 3.2	IfError is ps and Rate is p	THEN output to valve is low
Rule 3.3	IfError is pb and Rate is n	THEN output to valve is low
Rule 3.4	IfError is pb and Rate is ze	THEN output to valve is vl
Rule 3.5	IfError is pb and Rate is p	THEN output to valve is vl

In Table 1, 15 rules are defined for each possible state of the defined process variables. "Rule r.c" is the name of the rule whose number is calculated based on rows and columns when tabulated in rule matrix form. In Table 2, you can see the Rule - Matrix 1.

$$Rate = Previous - Current \quad (6)$$

Table 2: Rule Matrix

	nvb	nb	z	ps	pb
n	high	Vh	Vh	High	High
ze	med	Med	med	Med	Med
p	low	Low	Low	Vl	Vl

Step 5: *Selection of a Method of Defuzzification*

Defuzzification using the "center of gravity" or "centroid" method addresses the weighting of input variables on output calculations [27]. Using fuzzy sets and rules as inputs, the output fuzzy sets are created before being converted to crisp outputs to control steam valves. The output fuzzy set represents the steam valve control variable, so all the rules with truth in them will fire. Defuzzification involves the following steps:

An error rate is calculated by determining the "Error" and the "Error Rating" of the system sensor at a particular time. A rule that fires determines the degree of fulfillment. To create a single system output, the rules must be combined somehow. How to do this is shown in the following three-step procedure [27].

1. As the true level of a premise, take the minimum of the truth levels of all premise expressions connected by an AND.
2. At the truth level of the premise, truncate the output fuzzy set.
3. In the output variable's fuzzy set, copy the newly modified fuzzy set. At each point in the domain (along the horizontal axis), combine the new fuzzy region with the current contents. OR the outputs together if the region is not empty.

MATLAB is used to simplify and illustrate this. It is determined what value to use for the control output. Steam control valves are adjusted using this value. This will result in new measurements from the temperature sensor, thereby re-starting the gain cycle.

V. SYSTEM SIMULATION

The Membership Functions were generated using MATLAB. With the help of MATLAB, the control outputs were calculated for given ‘Temperature errors’ and ‘Temperature Rates’.Figure 6 illustrates the results of running the Temperature Rate Membership Functions.Figure 7 shows the output of the 'Product Current Membership Functions'.

Figure 5: Temperature Error Membership Functions

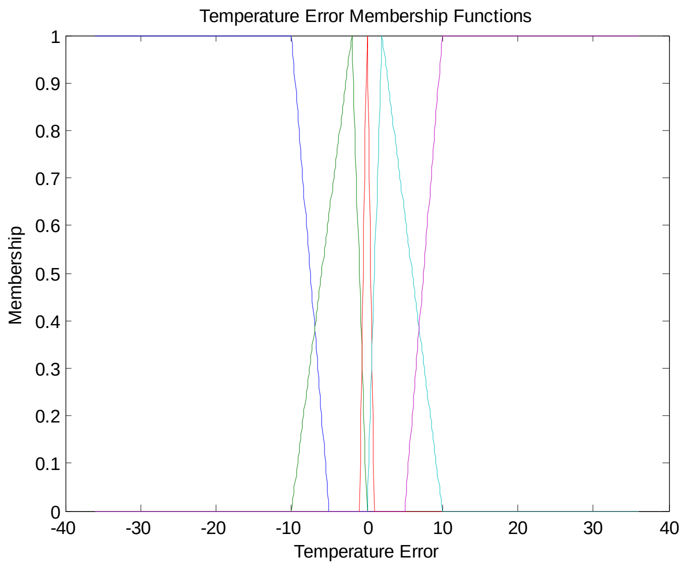


Figure 6: Temperature Rate Membership Functions

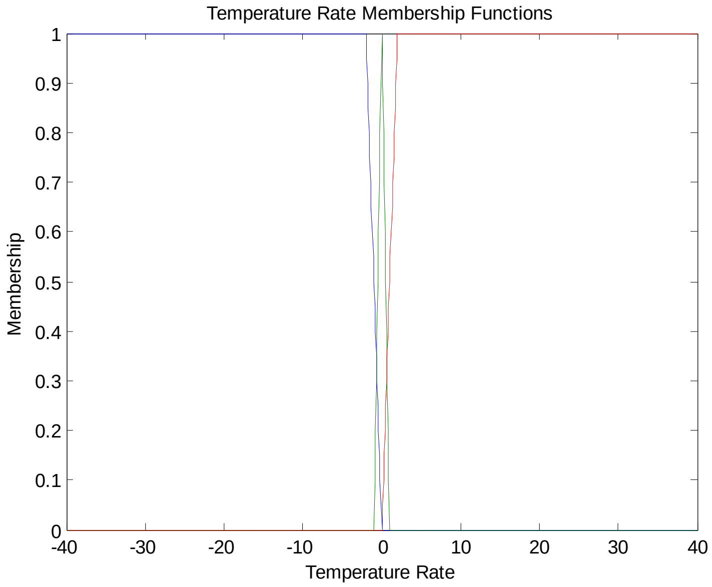
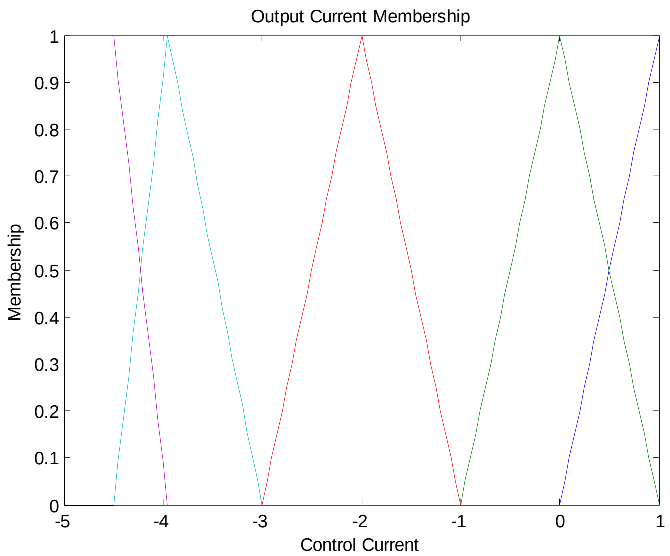


Figure 7: Output Current Membership Functions



5.1 Centroid Defuzzification

The next step was to create a Mamdani fuzzy system that uses centroid defuzzification. After creating the Mamdani fuzzy system, this was followed by the Centroid defuzzification process. For instance, suppose that the fuzzy controller is given a temperature error of -8.1 degrees Celsius and a temperature rate of 0.3 degrees Celsius per minute. Firstly, antecedent membership functions are calculated and their fulfillment assessed.

After the 15 rules were analyzed, fuzziness relation operations were performed. Based on the results of the MATLAB RUN in the 'Sequence of Fuzzy Rules', shown in Figure 8, the results are as follows. This figure shows that the fuzzy output sets have been aggregated to create a single fuzzy output set, which is not a single fuzzy set.

As can be seen in Figure 9 when the 'Aggregation of Fuzzy Rule Outputs' is run.After finding the crisp value, we move on to the next step. A MATLAB program output current, the fuzzy set to find the crisp output current:

In figure 11, we can see the current 'Crisp Output Value'. The control valve would receive a current of –3.402mA for these inputs. Steam control valves are adjusted based on this value. This is followed by a new set of measurements by the temperature sensor, which starts the cycle over again. Using one pair of inputs at a time, six more cases of 'Temperature Errors' and 'Temperature Rates' were entered into the fuzzy controller.

Figure 8: Consequent of Fuzzy Rules

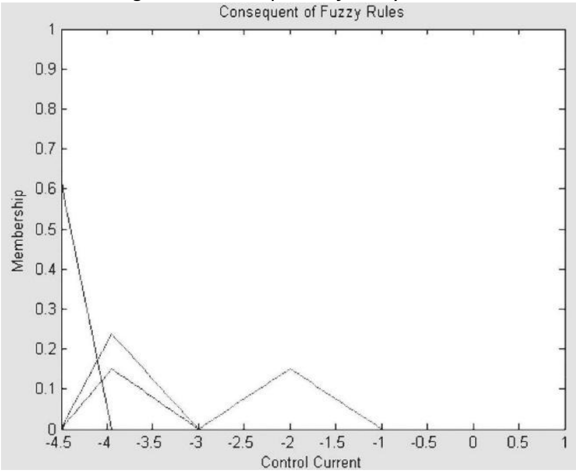
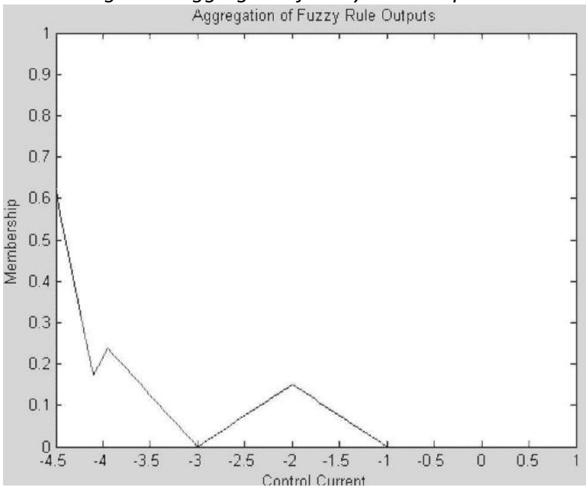


Figure 9: Aggregate of Fuzzy Rule Outputs



According to Table 3, the various Crisp outputs were computed using MATLAB's Centroid Deffuzzification program, and the results were recorded accordingly. All cases have the same 'Temperature Rate'. For purposes of illustration, this was assumed to happen in a real system.

VI. RESULTS

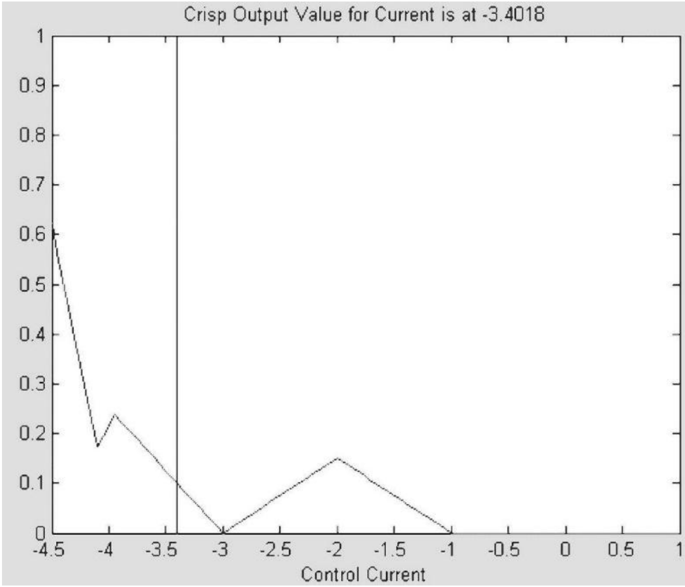
In Table 3, we present the results of our simulation.

Table 3: Simulation results

Error(^{O}C)	Rate (^{O}C/min)	Control Output
-8.1	0.3	-3.402
-5.0	0.3	-2.143
-3.0	0.3	-0.839
0	0.3	0.000
3.0	0.3	1.039
5.0	0.3	2.239
8	0.3	2.613

A user-configurable block for testing PID control was used to test the standard PID instruction. In order to calculate output, we used the independent gains equation.

Figure 10: Crisp output current



In order to adjust the loop tuning constants, Kp, Ki, and Kd, the loop tuning constants, Kp, Ki, and Kd, were adjusted. In order to achieve fuzzy control, ladder logic software was used to create fuzzy rules under Base 1 and insert values. Authors have Rule Base 1 Data as shown in Table 4:

Table 4: Rule Base 1 Data

	nvb	nb	z	ps	pb
n	0	1	1	0	0
ze	-2	-2	-2	-2	-2
p	-3.95	-3.95	-3.95	-4.5	-4.5

A set point of 90OC is shown in Figure 11 and Figure 12, respectively, in the response of the PID Controller, Rule Base 1.

Figure 11: Response of PID Controller

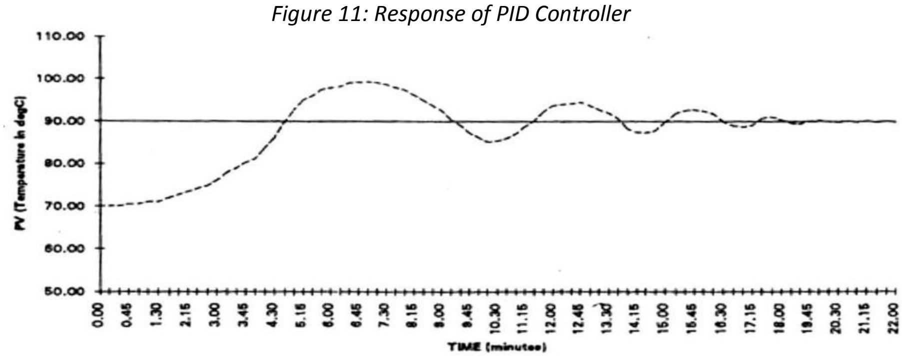
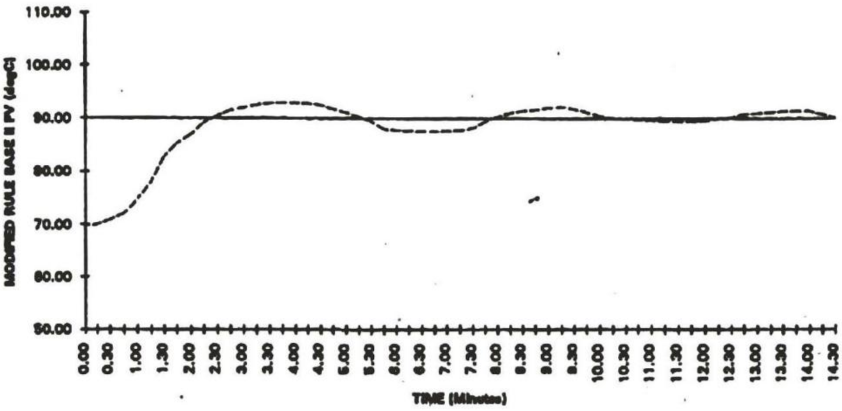


Figure 12: Response of Rule Base 1



The rules were modified using a heuristic approach. Table 5 shows how Rule Base 1 has been modified based on experience. When 'Error' was large, the steam control valve was controlled by a large signal due to a slow response rate. Here is Table 5 with the modified data.

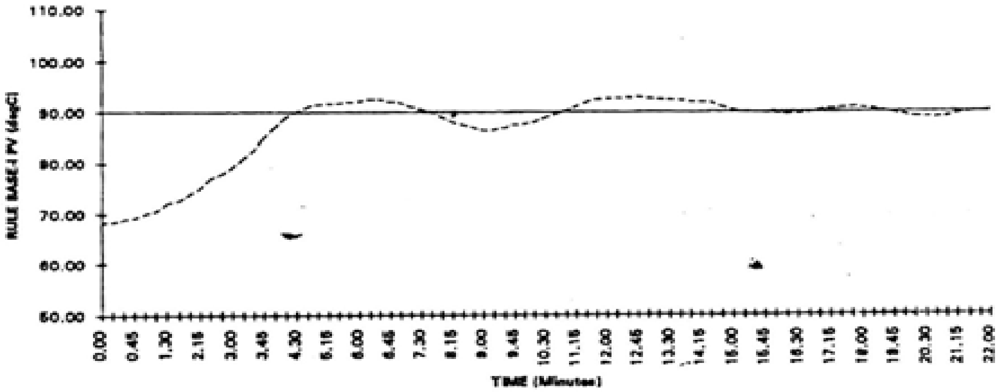
Table 5: Modified Rule Base 1 Data for a faster response

Nvbnb z ps pb

n	1	1	1	1	1
ze	-1	-1	-1	-1	-1
p	-3.95	-3.95	-3.0	-3.0	-3.0

According to Figure 13, the modified Rule Base 1 response looks like this: In contrast to PID Control, the modified Rule Base 1 response is much better. In table 6, we compare three fuzzy strategies with the PID controller. We consider the following factors when evaluating a response.

Figure 13: Traditional PID with settling point.



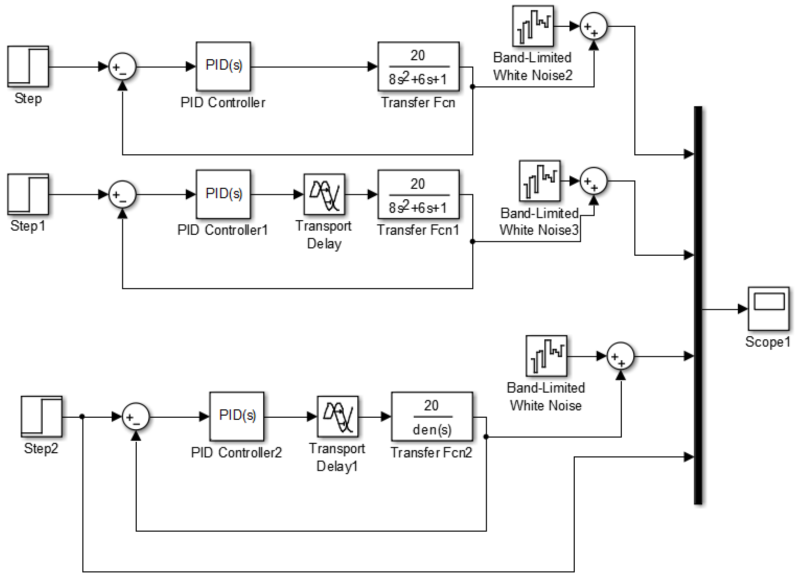
1. *Time Constant:* The time constant is defined as time required to complete 63.2% of the total response.
2. *Peak Error:* It is the maximum deviation of the process variable from the set point.
3. *Settling Time:* In the event of a transient input or a change in set point, the settling time is the time required for the process control loop to bring the process variable back to within the allowable set point range.

Table 6: Comparison of PID and Fuzzy Strategies

	Time constant	Peak Error	Settling time
PID Control	4.15 mins.	9.3EC	12.15 mins
Rule base 1	3.30 mins	2.5EC	12.30 mins

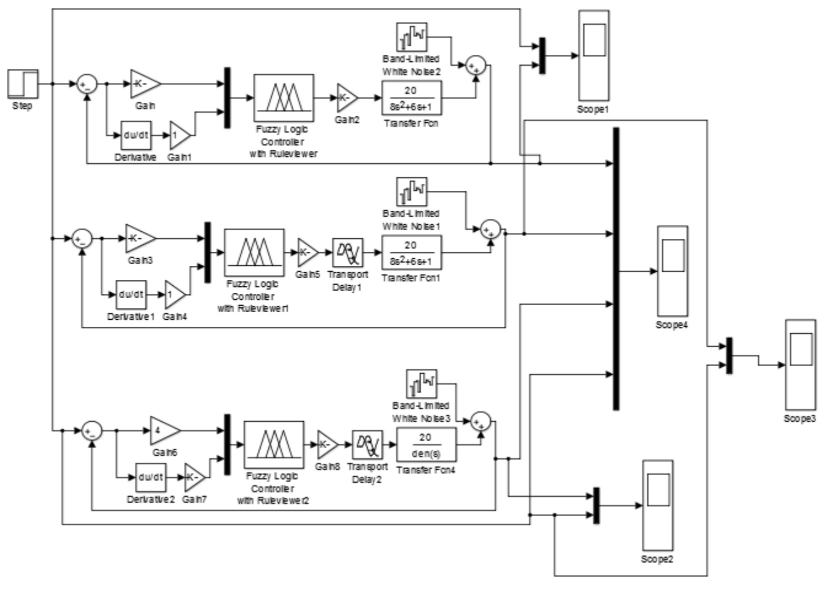
Modified Rule Base I	3.15 mins	2.3EC	5.30 mins

Figure 14: PID Architecture in Simulink



As shown in Figure 14, the transfer function is controlled by a PID controller. There are four blocks in this diagram: the PID module, the step function, the Band limited white Gaussian noise, the transfer function, and the scope for displaying the results. Fuzzy logic controller with band-limited white Gaussian noise is shown in figure 15, along with the step signal, transfer function, and output scope.

Figure 15: Fuzzy system Architecture in Simulink



6.1 Analysis of Results

In Table 6, the control output changes in sympathy with the error values as they increase from negative to zero and then finally to positive, as predicted. The 'Crisp output' of -3.402mA implies that the actual heat exchanger temperature is higher than desired. Therefore, the controller closes the steam valve to lower the temperature when the 'Crisp output' shows a negative current. A positive output current indicates that the heat exchanger's actual temperature is below the designed. The controller is opening the steam control valve to let in more steam, which increases the heat exchanger's temperature.

There is no change in output direction at zero control output. Figures 10-13 show that Rule Base 1 reduced the overshoot by a significant amount, despite no significant changes in the time to reach the set point. The PID response also showed a considerable reduction in cycling around the set point when Rule Base 1 was applied. Similar results were obtained when Rule Base 1 was modified. Neither the set point nor the time required for it to be reached changed significantly. Compared to Rule Base 1, there was a further reduction in overshoot. Because Rule Base 1 had been modified, this occurred. The process variable lingered above the set point despite practically no cycling around it. The centroid method is used to derive rules.

VII. CONCLUSION

Heat Exchangers in a WFI system were studied and their problems associated with conventional PID controllers were identified. Multiple variables affecting the stability of the controller were found to be the main problem causing the inconsistent behavior. Inconsistent behavior was found to be caused by multiple variables affecting the controller's stability. Our strategy was based on rules. To calculate the FLC, rule base 1 uses the rate of change of the temperature error at the heat exchanger outlet. In comparison with a PID controller, the overshoot was drastically reduced, even though there was no significant improvement in the time needed to reach the set point. Further modifications were made to rule base 1 in order to speed up the response time. To speed up the response time. The proposed algorithm was verified in the simulation section.

Conflict of interest

There is no conflict to disclose.

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