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Feedback-feedforward fuzzy logic approach for temperature control in bioethanol vacuum distiller

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ABSTRACT

Energy conservation and diversification are becoming a major research issue. Awareness of the limited sources of energy from fossil fuels encourages research on renewable energy. Bioethanol is a promising fuel substitute for gasoline. Bioethanol processing includes sugar extraction, fermentation, distillation, and absorption. Temperature and pressure controls are essential in bioethanol processing. This paper presents a feedback-feedforward fuzzy logic approach for temperature control in a bioethanol vacuum distiller. In this study, vacuum pressure is employed as feedforward inputs for a fuzzy logic controller. The feedforward input directly modifies the main controller, i.e., fuzzy logic controller, through fuzzy rules. The controller is implemented using Arduino Mega 2560 microcontroller. The results show that the proposed feedback-feedforward fuzzy logic controller could successfully maintain the temperature at the desired setpoint value with small steady-state error (3.85%) and relatively shorter settling time compared to classical PID controller and fuzzy logic controller.

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1. INTRODUCTION

Energy is a fundamental need in modern life. According to the data from the International Energy Agency (IEA), the average world energy demand increase by 1.6% per year. This demand, was approximately 80% supplied from fossil fuels [1]. On the other hand, petroleum experts estimated that fossil fuels would run out in about 30 years [2]. Thus, it is an urgent need to explore alternative fuel sources as a substitute for fossil fuels. One of the promising candidates is bioethanol. Bioethanol is extracted from the rest of the crop which still contains sugar. The process of making bioethanol include sugar extraction, fermentation, distillation, and finally absorption process to purify the bioethanol in order to obtain fuel grade ethanol (FGE). Absorption process is done by using absorber that can take 2-3 days. Alternatively, it can be done in a vacuum distillation process that allows the formation of FGE in a relatively shorter time [3]. A concept of distillation in near vacuum condition is well explained in [4], while successful application of vacuum distillation is presented in [5] for biodiesel production and in [6] for crude lead refining. In vacuum distillation of bioethanol, the boiling point of water and pure bioethanol are very close. So, it is an urgent need to develop a strict temperature control for the distillation process.

Conventional controls, such as on-off control and PID control, are still widely used in temperature control. Examples of successful applications are reported in [7] for reducing return water temperature, in [8] for controlling domestic hot water and in [9] for controlling the fluid temperature in the heat exchanger. The use of the on-off controller and PID controller and their performances for vacuum distillation has been reported in [3]. Another widely use temperature control strategy is using fuzzy logic. Examples of successful application of fuzzy logic controller were reported in [10] for greenhouse application, in [11] for industrial roaster application, in [12] for furnace application, in [13] for an electric vehicle, in [14] for pantograph-catenary system, in [15] for swarm robotics and in [16] for the superheated steam application. Application of fuzzy logic controller (FLC) in vacuum distiller was reported in [17]. Two inputs, namely temperature error and difference of two consecutive errors, were used and its performance was compared to classical PID controller in [3]. The FLC outperform PID controller in term of overshoot and settling time of the response. This comparison result also complies with [18] comparing the performance of the on-off controller, PID controller, and fuzzy logic controller. Taking advantage of both PID controller and fuzzy logic controller, it is possible to employ a combination of fuzzy-PID control strategy such as in [19].

Dynamical characteristic of vacuum distiller can be studied from its model. The model can be derived analytically, such as in [20], or experimentally by system identification. Mathematical modeling through identification of vacuum distiller has been reported in [21]. Two approaches have been carried out, the first was based on extended least square (ELS) method and the later was based on adaptive neuro-fuzzy inference system (ANFIS). Experimental results suggest that a multi-input model approach should be used. Both methods suggest vacuum pressure as the candidate of additional input for the controller besides temperature error as in common approach. Since vacuum pressure tends to deviate the output temperature from its desired value, vacuum pressure should be treated as a disturbance to the process. This also complies with [22], suggesting to consider pressure in the dynamical model. Understanding the dynamic of vacuum pressure before it deviates the output would be beneficent, hence a feedforward control strategy would be a good candidate so alleviate the effect of variation in vacuum pressure.

Feedforward control study already attracted many researchers. Amerongen, J [23] proposed model reference adaptive control principle to design a feedforward controller. A successful example of a feed forward control strategy for temperature control was reported in [24]. Combination of feedforward controller with another control strategy, in the form of feedback-feedforward controller, were reported in [25-28]. Chen, W. [25] generate fuzzy feedforward by decoupling concept such as in multivariable control approach. While Haifeng, S. et al. [26] used feedforward controller to modify a fuzzy PID controller. A common approach for feedback-feedforward controller was explained in [27] and [28], both threat disturbance input to modify the output of the feedback controller. In this study, vacuum pressure is proposed as feedforward inputs for a fuzzy logic controller. Differ from approaches in [25-28], the feedforward input is directly modify the main controller, i.e. fuzzy logic controller, through fuzzy rules. Using this feedback-feedforward fuzzy logic controller (FF FLC) approach, it is hoped to improve control performance in temperature control.

2. RESEARCH METHOD

Bioethanol vacuum distiller which have been developed in our earlier studies [17] is used in this study. As shown in Figure 1, the device consists of a distillation tube, control panels, heaters, condensation tube, cooling water container and a container for distillation product. The temperature sensor is located inside the distillation tube, while the vacuum pressure sensor is placed at the outlet of the distillation tube. In a distillation cycle, 25 liters of low concentrated bioethanol can be processed with this apparatus.

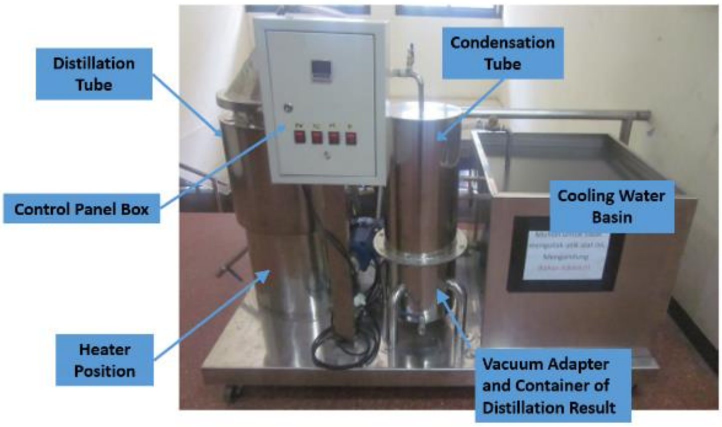

Figure 1. Bioethanol Vacuum Distilller Apparatus

Raw materials for the experiment is low concentrated bioethanol. This material is obtained by fermentation of the base material in the form of molasses. Fermentation results is low concentrated bioethanol with the maximum ethanol concentration is 30%. This concentration level would be increased in the distillation process. The basic principle of distillation is the separation of a mixture of two or more liquids through the process of evaporation. In order to be separated, the boiling point of constituent substances (in this study are bioethanol and water) must be different. Water boiling point is 100 degrees Celsius at a pressure of 1 Atm, while bioethanol is 77 degrees Celsius. Thus it is possible to separate these two liquids through a distillation process. On the condition of close to the vacuum, the boiling point of the liquid will decrease, so it is possible to get the distillation at a relatively lower temperature.

Bioethanol distillation procedures in this study follow:

1. Operate the vacuum pump until the pressure is around 0.5 Atm
2. Raise the temperature gradually until the temperature reached 62^{o}C (boiling point of ethanol at 0.5 Atm)
3. Maintain the temperature and pressure until the volume until the material (low concentrated bioethanol) is run out.

Figure 2 shows a diagram block of the proposed control scheme. Set point for the system is desired temperature of inner tube temperature. Since vacuum pressure is maintained at 0.5 Atm, the reference temperature is set at 62 ^{o}C. A fuzzy logic controller (FLC), embedded in an Arduino Mega 2560 microcontroller, is employed to provide PWM signal to drive heating elements. Fuzzy logic controller proposed in this research is the development of [17] using the classical approach of the fuzzy logic controller with two inputs, the error signal, and the difference signal error.

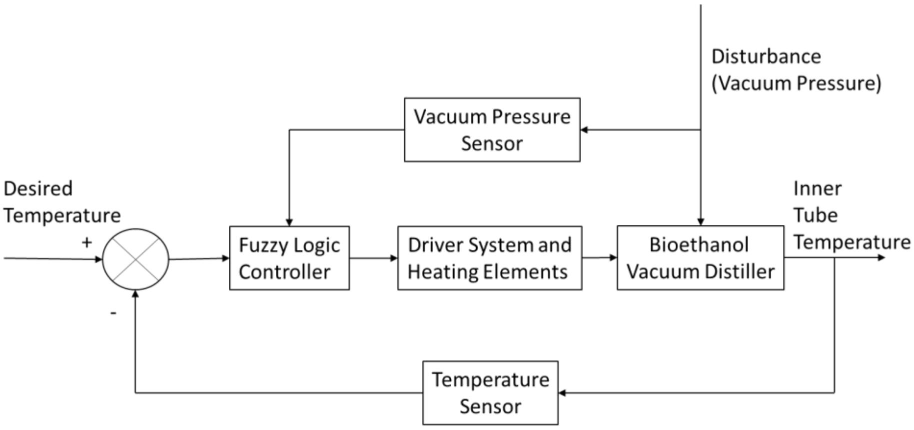

Figure 2. Proposed Control Scheme

Figure 2 shows a block diagram of a temperature control system is proposed. It is shown that the fuzzy logic controller has two pieces of feedback. Namely the difference between the reference temperature with the temperature in the tank (temperature error signal) and a pressure sensor readings MPX5100A. Figure 3, 4 and 5 respectively show the preliminary design of the fuzzy set of input I (temperature error), input II (vacuum pressure) and output, PWM signal form that will set the dimmer circuit which will distribute the heating element.

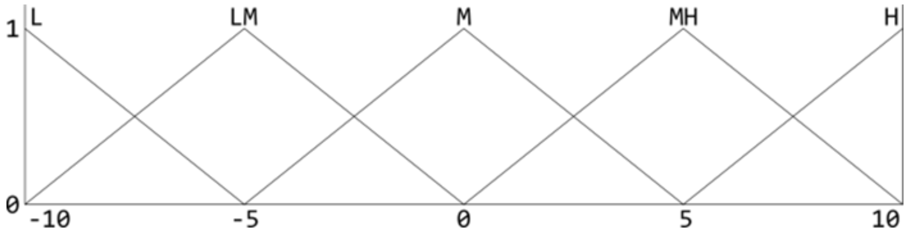

Figure 3. Initial fuzzy set of temperature error (^{o} C)

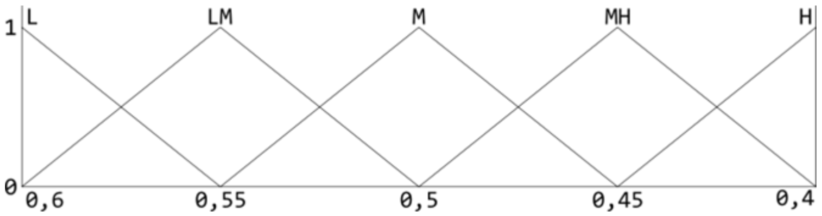

Figure 4. Fuzzy set of vacuum pressure (Atm)

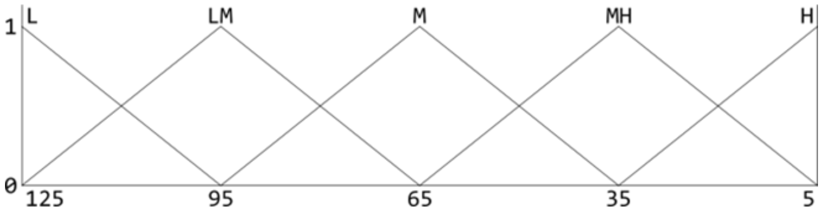

Figure 5. Fuzzy set of Output (Duty cycle of PWM Signal)

The labels of fuzzy sets in Figure 3-6 respectively are as follows: "L" is Low, "LM" is Low Medium, "M" for Medium, "MH" for Medium High, and "H" for High. Fuzzy rules have been prepared on the possible combinations of fuzzy input sets, bringing the total there are 25 fuzzy rules. Table 1 summarizes all the fuzzy rules used in this study. Premise 1 (Temperature Error) and Premise 2 (Vacuum Pressure) are connected with AND logic. An example of a fuzzy rule generated using Table 1 is IF Temperature Error is Medium AND Vacuum Pressure is Low THEN Duty Cycle of PWM is Low.

Table 1. Fuzzy Rules

Fuzzy Rule		Vacuum Pressure				
		L	LM	M	MH	H
Temperature Error	L	L	L	L	L	L
	LM	L	L	LM	M	M
	M	L	LM	M	M	MH
	MH	M	MH	MH	H	H
	H	H	H	H	H	H

The fuzzy rules and fuzzy sets definitions are programmed into the microcontroller Arduino Mega 2560. Then the experiments were performed to tune the fuzzy set that provides the best performance. In this study, without loss of generality, the procedures are simplified so that only fuzzy sets of first input (temperature error) are re-tuned. The tuning process is done heuristically, by redefining the range of error and error of fuzzy sets by taking into account the temperature which gives a dominant influence on the output response. Figure 6 shows the temperature error of fuzzy sets that give the best results. The best criterion is based on the specifications of the selected response, i.e. steady state error of less than 5 %, the maximum overshoot less than 10 % and settling time (time to reach steady state) is less than 2 hours.

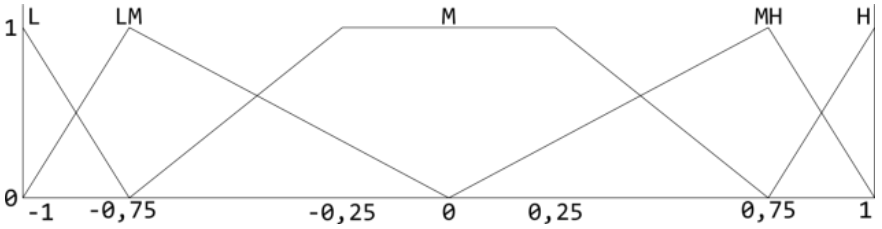

Figure 6. Fuzzy set of temperature error (after tuning)

3. RESULTS AND ANALYSIS

Following the procedure in section 2, the experiments were carried out. Figure 7 shows the experimental results. In this figure, the temperature was set to 62 °C. The response was the first time to reach the set point in about 4000 seconds. Table 2 provides a summary and comparison of the performance of the proposed control scheme with another approach in [3, 17]. The response of our proposed feed-forward fuzzy logic controller has small overshoot and error steady state. However, the values are still below the design specification, i.e., 10% and 5% overshoot and error steady state, respectively. In term of settling time, the performance of the proposed approach is better than in [17]. This value is particularly important since time to reach a steady state condition will determine the speed of bioethanol purification.

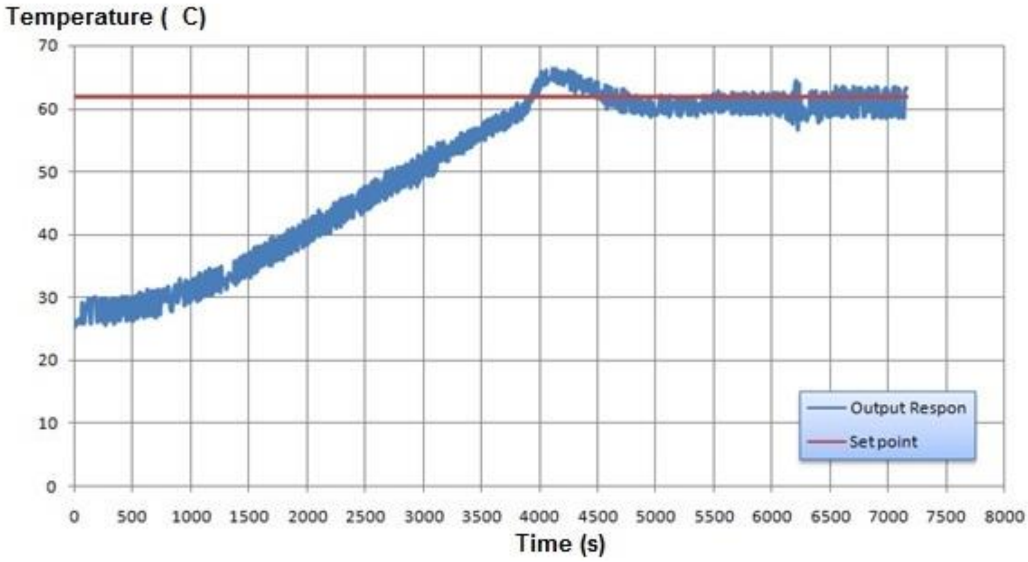

Figure 7. Distillation response

Table 2. Performance Comparison of Several Controllers

Control Strategy	Overshoot (%)	Settling time (sec)
PID Control [3]	2.63	6000
Fuzzy Logic Control [17]	0	5400
FF Fuzzy Logic Control	3.85	4270

4. CONCLUSION

This paper presents a feedback-feedforward fuzzy logic controller is proposed. Vacuum pressure is employed as feedforward inputs for a fuzzy logic controller. The feedforward input directly modifies the main controller, i.e., fuzzy logic controller, through fuzzy rules. Experimental results show that the response of feedforward fuzzy logic controller has small overshoot and error steady state. However, the values are still below the design specification, i.e., 10% and 5% overshoot and error steady state, respectively. In term of settling time, the performance of the proposed approach is better than our previous study. This value is particularly important since time to reach a steady state condition will determine the speed of bioethanol purification.

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