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Fuzzy Logic based Temperature Control of a Vacuum Distiller

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Abstract- This paper report design and implementation of a fuzzy logic based temperature controller in a vacuum distiller. The distiller is operated in nearly vacuum condition to improve capability of producing high concentrated bioethanol. Due to high heating power necessity, temperature control was performed manipulating AC voltage to heating elements. An Arduino based Fuzzy Logic control strategy was proposed, and its performance was compared to PID controller. Experimental results show that fuzzy logic controllers have better performance in controlling temperature of vacuum distiller.

Keywords: temperature control; vacuum distiller; fuzzy logic control; PID control.

Introduction

Recently, research for finding substitute of fossil fuels was getting more intensive [1]. One of prospective substitute to gasoline is bioethanol [1-4]. Bioethanol production starts from fermentation of sugar-contained crop residue, such as molasses. The result of this process is a low concentrate (7% -10%) bioethanol. Distillation process is then performed to produce bioethanol at higher concentration [5-8]. Due to azeotrope phenomenon [6][8], concentration of distilled bioethanol cannot reach near pure bioethanol. Purification is then usually done by dehydrating using water absorbent. This process takes up to 2-3 days [9]. On the other hand, distillation under nearly vacuum conditions can avoid azeotrope enable production of pure bioethanol [10]. However, reducing pressure will also reduce margin of boiling points between bioethanol and water. Hence, precise control of temperature is necessary for successful distillation.

This study want to provide precise control for vacuum distiller in bioethanol purification. Guideline for laboratory scale of vacuum distiller were reported in [11-13]. The main manipulated variable is temperature, controlled by regulating incoming voltage to the heater. Since it needs high heater power, DC voltage is not appropriate to be used. Given AC voltage as the input, it must be manipulated so that the temperature can be controlled. On-off control strategy has been used in our previous study [14], however the results were unsatisfactory. In this paper, a fuzzy logic based control is proposed for performance improvement. In the case of a vaccuum distiller, mathematical model is not completely known, so a fuzzy logic based control will be the most appropriate one. A TRIAC based dimming circuit is used as actuator. Although output of TRIAC has nonlinearity, what we need is actually a trigger signal, which is effectively provided by TRIAC. This paper is aimed as extension of our previous study in [15]. Design and experimental aspects will be highlighted in depth.

The rest of this paper is organized as follows. Section 2 describes experimental setup, control system design, and data acquisition. Experimental data, and its analysis describes in Section 3. And finally, Section 4 concludes the whole works.

Proposed System

A. Design of Fuzzy Logic based Control

A vacuum distiller apparatus developed in our previous study [14] was used throughout this study. As seen in Fig. 1, the apparatus comprises of a distillation tube, heater set, condensation tube and cooling water basin. A container for distillation product is located under the condensation tube. In once distillation cycle, 25 liter of raw material can be processed using this apparatus.

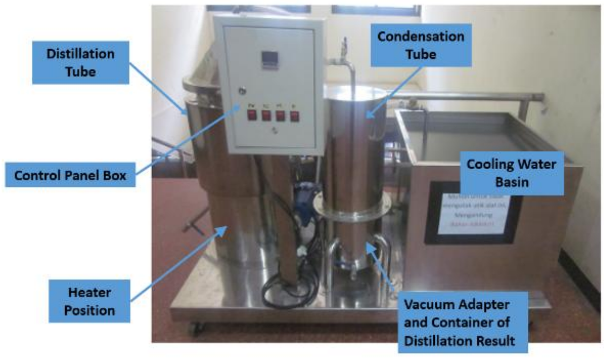

Fig.1. Vacuum distiller used in this study

Basic temperature control diagram of vacuum distiller is shown in Fig. 2. Temperature sensor (PT100) provide feedback signal refer to actual temperature inside distillation tube. Based on difference between desired temperature and actual temperature, the controller provides an appropriate control signal for dimming circuit. Furthermore, dimming circuit provides appropriate voltage to the heater. Detail explanation follows.

According to [16] and [17], fuzzy logic controller has superior performance, in the term of stability and effectiveness, to drive power electronics components. A Mamdami type Fuzzy logic controller is developed heuristically for this purpose. As shown in Fig.3. The fuzzy logic controller has 2 inputs, namely temperature error (error) and difference of error (delta error), and 1 output, i.e. dimming level command for the dimming circuit.

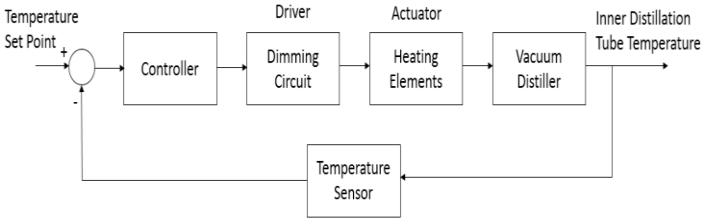

Fig. 2. General control schema

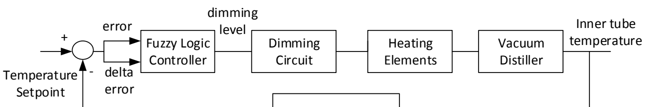

Fig. 3. Fuzzy logic control system

Fig. 4 and Fig. 5 show fuzzy set definition for the inputs. Initially, membership function of both input were set to uniform triangular. Non uniform shape of the triangular error fuzzy set (Fig. 5) was the results of fuzzy set parameter tuning. Very small portion of fuzzy set 'NM' and 'N' indicate that negative error signal is forced to close to 'Z'. Also it can be concluded that for positif value of error signal a coarse control is selected, while for negative value of error signal, a fine control is necesssary. On the other hand, fuzzy set of delta error has uniform shape. This is very natural decision, since for rapid changing system difference between two consequtive error becomes very small.

Membership function of fuzzy output (dimming value) was chosen as fuzzy singleton for simplicity, with the singleton values at 5, 20, 75, 110 and 125 (shown in Fig. 6). '125' was set for the biggest value of output voltage (±220 V), while '5' was set for the smallest value of output voltage (±0 V).

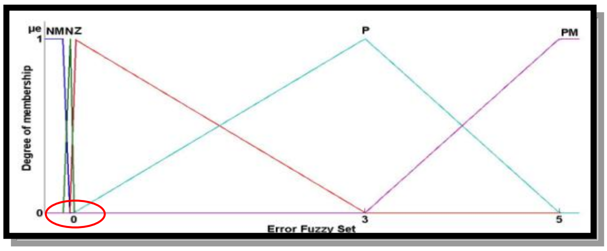

Fig. 4. Fuzzy Set of Temperature Error

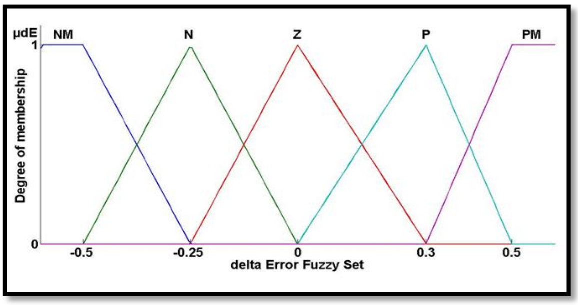

Fig. 5. Fuzzy Set of Difference of Error

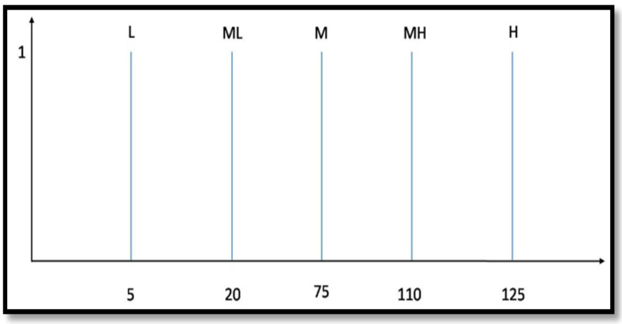

Fig. 6. Fuzzy Set of Dimming Level

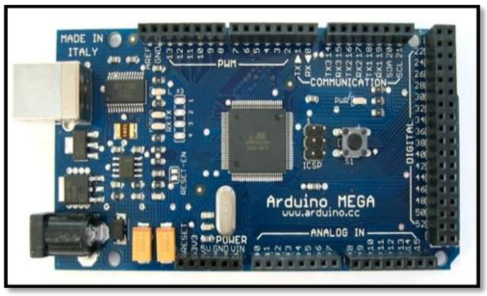

Fig. 7. Arduino Mega 2560 module

The most important part of a fuzzy system is fuzzy rule definition. In this study, fuzzy rules were determined experimentally using heuristic approach. Table 1 shows the complete fuzzy rules. In Table 1, e and de correspond to error signal and delta error signal, respectively. Contents of the table were refer to Figs. 4-6. Furthermore, Mini-Mamdani inference rule and weighted average defuzzyfication were employed in this study. An Arduino Mega 2560 board (Fig. 7) was used to implement the fuzzy system due to its simplicity.

TABLE. 1. Fuzzy rules

de \ e	**NM**	**N**	**Z**	**P**	**PM**
NM	H	H	H	MH	M
N	H	M	M	M	ML
Z	H	ML	M	MH	L
P	MH	M	ML	L	L
PM	M	ML	L	L	L

B. Design of PID Control

For PID controller, the parameters are determined based on open loop response of step input according to Ziegler Nichols I tuning rule[18], summarized in Table 2. Fig. 8 shows an experimental open loop respon of step input. Two parameters can be obtained from the response, namely delay time (L) and time constant (T). Next step is calculating controller parameters accoding to Table 2. Based on the experiments, the best PID parameters are Kp = 11.61, Ki = 0.01161 and Kd = 0.

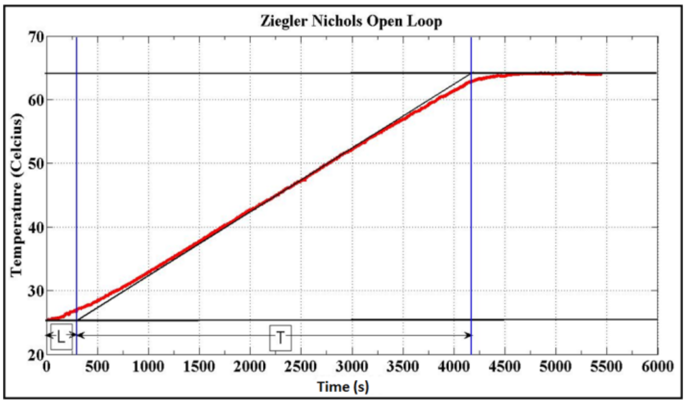

Fig. 8. Open loop response to step input

TABLE. 2. Determination of
PID controller parameters using Niegler Nichols I [18]

Controller	K_p	T_i	T_d
P	$\frac{T}{L}$	∞	0
PI	$0.9\frac{T}{L}$	$\frac{L}{0.3}$	0
PID	$1.2\frac{T}{L}$	$2L$	$0.5L$

C. Dimming Circuit

Fig. 9 shows dimming circuit used in this research. This circuitry contain zero cross detector circuit and TRIAC trigger circuit. The zero cross detector circuit has responsibility to detect when the sinusoidal pulse of 220 V AC voltage crossing 0 V. While TRIAC trigger circuit has responsibility to provide trigger voltage for both positive and negative pulse of AC voltage. Having this two parts, the dimming circuit will supply voltage continuously according to dimming level generated by controller.

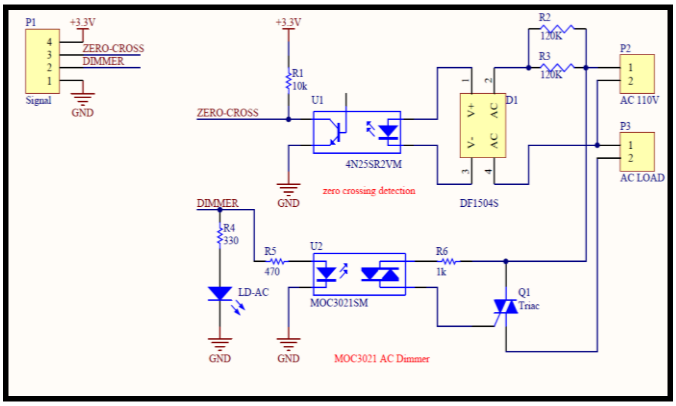

Fig. 9. Dimming Circuit

Experimental Results and Analysis

Control system in this research is aimed to provide an appropriate temperature for the vacuum distillation process. The distillation process are as follow:

a. Preparation of raw material (instead of using low concentrate bioethanol, 70% alcohol was used just to show the effectiveness of control methods).
b. Gradually increase the temperature set points, from 50°C, 57°C, 61°C, and 66°C to provide smooth temperature change. During this process, vaccum pressure was kept at 0.5 atm
c. Set the final temperature as 66°C while keep vaccuum pressure at 0.5 atm. This setting is according to experimental result of [10].
d. Maintain condition in c. for 2 hours

A. Experimental Results of Dimming circuit

Table 3 shows experimental result of TRIAC circuitry. It can be concluded that this circuitry has good performance with the average error rate of 4%. Fig. 10 shows an output example of dimming circuit with the TRIAC firing angle at 90° and dimming level of 64.

TABLE. 3. Experimental Result of TRIAC Firing Angle

Firing angle (°)	Theoritical delay time (ms)	Experimental delay time (ms)	Error (%)
90	5,00	5,4	8,00%
105	5,83	6,2	6,29%
120	6,67	7	5,00%
135	7,50	7,6	1,33%
150	8,33	8,2	1,60%
165	9,17	9	1,82%
Average error (%)			4,01%

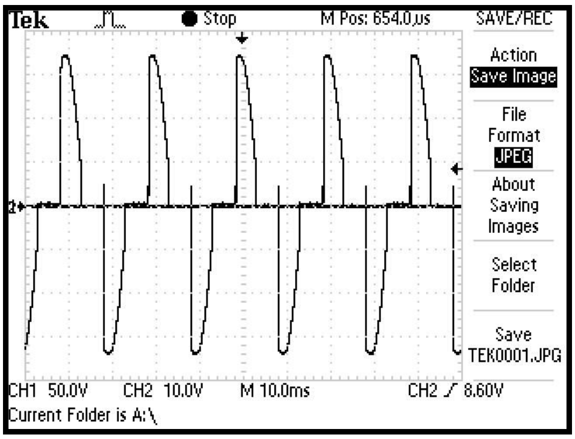

Fig. 10. Output Example of Dimming Circuit

B. Experimental Results using PID Controller

Fig.11 shows system performance using the selected parameters of PID controller. Our concern are on 3 performance indicators, maximum overshoot, settling time and error steady state. According to Fig. 11, maximum overshoot was small enough (2.63%), settling time was relatively big (around 6000 seconds) and no steady state error was perceived.

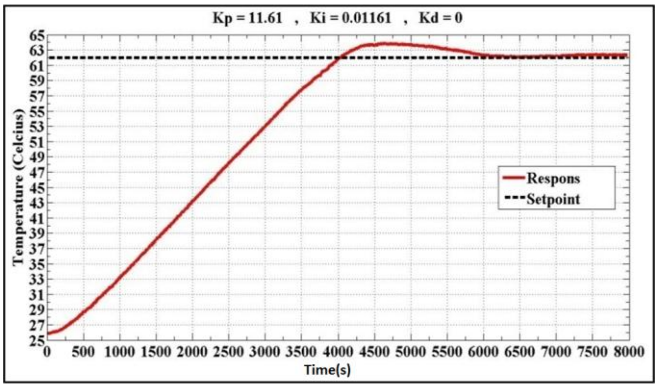

Fig. 11. Response of vacuum distiller using PID controller

C. Experimental Results using Fuzzy Logic Controller

Fig. 12 shows inner temperature of distillation tube by using designed fuzzy logic controller. There is no overshoot perceived and settling time is relatively shorter (5400 seconds) comparing to that of PID controller.

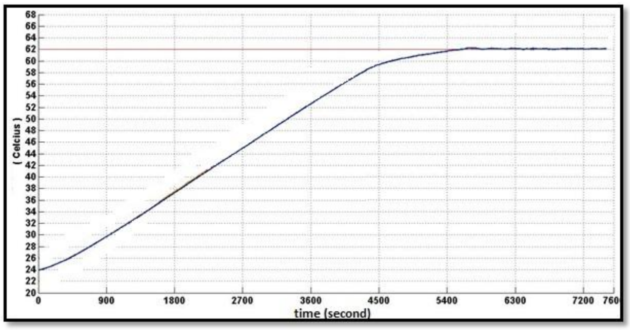

Fig. 12. Control performance of fuzzy logic controller

From the control point of view, since control purpose is to provide certain temperature without overshoot, these result are very good. But unfortunately, distillation results are still out of expectation. The maximum bioethanol concentration is 88%, which is still far from our expectation of producing pure (100%) bioethanol. Table 4 summarized the best result from series of experiments.

TABLE 4. Performance Summary

Control Stategy	**% Overshoot**	**Settling time (sec)**	**% Bioethanol**
PID	2.63%	6000	88%
Fuzzy Logic	0%	5400	88%

Concerning to the bioethanol concentration issue, we argue that since temperature and pressure are two dependent variables, control strategy should be made for temperature and vaccuum pressure in integrated manner. This will left for further study.

Conclusion

In this paper, temperature control system for a vacuum distiller has been developed. Two control strategies has been proposed and compared, namely PID controller and fuzzy logic controller. These control strategis were implemented using Arduino Mega 2560 board. Output of the controllers then provide dimming level/value to a dimmer circuit. This circuit then supplied corresponding signal to the heater as an actuator for the system. From the performace comparison of output temperature (temperature inside the distillation tube), fuzzy logic controller has superior results in the sense of overshoot and settling time.

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