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Design and Simulation of Fuzzy Logic Based Temperature Control for a Mixing Process in Therapeutic Pool

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Abstract. Stroke is one cause of the most deaths, in which one way of handling stroke can be done with hydrotherapy. Hydrotherapy is a therapy that is done in the therapeutic pool which is filled with warm water in temperature 31º-34º C. When in the warm water, body burden becomes lighter, so the stroke patients with impaired movement of the body can train the nerves and muscles in order to restore the function of these organs. However, the warm water that is used for the therapy is produced by the heater that requires much electrical energy. This research discussed how to use solar energy to produce hot water using Indirect Evacuated Tube Solar Water Heater systems and make the control system for controlling the mixing process between the hot and cold water by using the Fuzzy Logic Control of the Mamdani method. Therapeutic pool system will be modeled using Simulink. Modeling the mixing process is made on the basis of mass balance and energy balance equations. Then the system will be simulated with interrupted condition and gets set value changes in a particular time. The FLC is successfully reached and maintained steady to a set value. The results will be compared to the performance of the one with Proportional Integral Derivative controller.

1 Introduction

Stroke is the leading cause of death in Indonesia. In 2014, according to the Sample Registration Survey (SRS) conducted by Health Research and Development Agency, Ministry of Health shows, that stroke and heart attack becomes the first and second causes of death in Indonesia, with a percentage of 21.1% and 12.9% of 41,590 deaths nationwide throughout 2014. However, at this time the stroke treatment can be done in several ways, one of them is hydrotherapy. Hydrotherapy is an exercise therapy using warm water in the hydrotherapy pool (therapeutic pool). This therapy is one method of healing therapy against a stiff joint disease caused by stroke. The water used has a temperature between 31º-34º C, the temperature is quiet safe and provide a relaxing effect, can expedite the blood circulation, decrease pain and improve the ability of organ motion. The hot water used in

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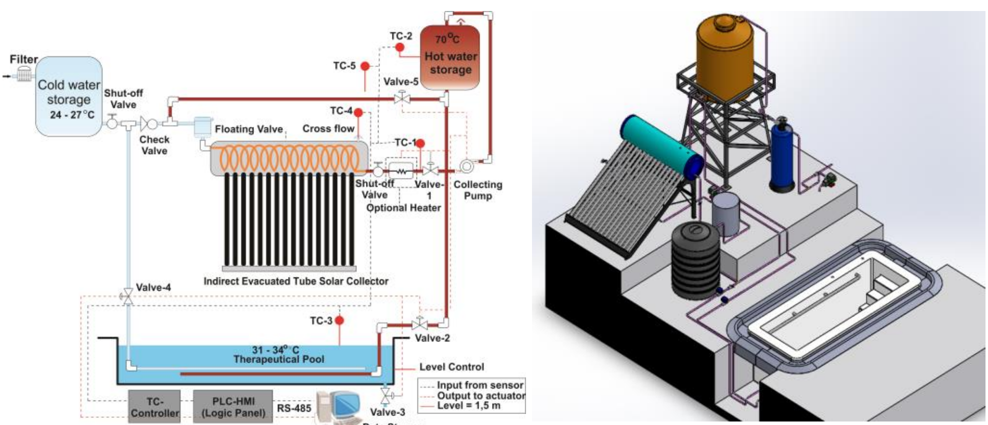
therapuetic pool is produced by Indirect Evacuated Tube Solar Water Heater (IETSWH) system. This system utilizes solar energy, thus it can save the electrical energy. But there is a problem, the existing therapeutic pools do not yet have the ability to control the temperature to be stable at temperatures therapy. Therefore, this study will design the control system that can control the temperature of the pool when the mixing process between hot and cold water. The control system is made using the Fuzzy Logic Control (FLC) with the help of software MATLAB/ Simulink, then the control is simulated and compared with the Proportional Integral Derivative (PID) controller. The result in [1] shows that FLC has better performance than the PID controller. We have also applied the DC motor because it is the most widely applied actuator in automation systems such as in the control position of an arm robot manipulator [2-4].

2 Research Method

2.1 Indirect Evacuated Tube Solar Water Heater System (IETSWH)

The IETSWH is a heater system which produces hot water using thermosyphon method. For the work principle of IETSWH, first the working fluid is heated by solar energy in evacuated tube, while the water will flow in the coiled tube. After the working fluid heated, then heat exchange will happen between the working fluid and the water through coiled tube as heat exchanger. The coiled tube in this research uses the stainless steel 304. By using this system, the output of hot water is more stable because it is operated by water pressure [5]. The reason for using stainless steel 304 in the coiled tube is manufacturing process. Because in the first experiment, we used copper material, but when the rolling process the coiled tube became torn. There are three processes that occur in the system of IETSWH is the collecting, circulating and mixing process. The scheme of these processes is shown in Figure 1 (a), and Figure 1 (b) for 3D.



(a) (b)

Fig. 1. Indirect evacuated tube solar water heater system.

Collecting is the process to collect the hot water and store it into the hot water storage. The collecting process begins with the cold water flow from Cold Water Storage (CWS) toward IETSWH and therapeutic pool. In the IETSWH, the cold water heated by working fluids (50% ethylene glycol + 50% water, this refers to [6, 7]) until its temperature reach certain value. After the thermocouple (TC) sensor detects the hot water reaching the setting value, then the solenoid valve opens and the water pump works to make the hot water flow toward Hot Water Storage (HWS). The HWS will save the temperature of hot water.

Circulating is the process to heat the water in hot water storage when the temperature of hot water drops under the setting value. It makes solenoid valve opened, and the hot water flows from HWS to IETSWH for reheating. In the heating process, the system is equipped with a heater, which works when the sun is dim or cloudy weather, so the heater is optional equipment that it can be turned on manually. The mixing process occurs in the therapeutic pool, it begins with cold water from CWS and hot water from HWS flow toward therapeutic pool through motorized valves and then these fluid mix to get temperature 31-34º C. There are several advantages of hydrotherapy systems that we use compared to existing ones, such as cheaper and more efficient electric power because utilizing solar energy to produce hot water. This study focused on the mixing process in the therapeutic pool. The temperature of therapeutic pool will set on 32º C. The position valve of hot water flow will be controlled, but the position valve of cold water flow is kept constant at fully opened.

2.2 Mathematical Model

To build mathematical model, the first thing to do is to make schematic diagram of therapeutic pool as shown in Figure 2. The differential equations is derived from Thermodynamics principle and mass balance equation. The empirical equation of convective heat transfer coefficient can be found in [8]. The therapeutic pool walls are assumed well insulated. The other assumptions to be made are constant properties of water such as specific heat and mass density.

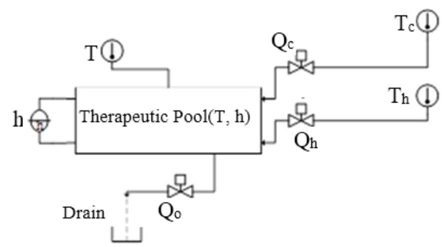


Fig. 2. Schematic diagram of therapeutic pool.

To build mathematical model of therapeutic pool, Thermodynamics principle and and mass balance equation, Equation (1), derived. The equations are written as follows.

$$\frac{dV}{dt} = Q_h + Q_c - Q_o \,; \; \frac{dE}{dt} = \rho c_p Q_c T_c + \rho c_p Q_h T_h - \rho c_p Q_o T_o - hA(T - T_\infty) \qquad (1)$$

To obtain the equation of water that changes over time, then the Equation (1) of thermodynamics principle is derived as Equation (2),

$$\frac{d(AH)}{dt} = Q_h + Q_c - Q_o \text{, then } \frac{dH}{dt} = \frac{1}{A}(Q_h + Q_c - Q_o) \qquad (2)$$

Equation (2) shows the water level changes the inlet and outlet water flow. We can derive the temperature rate of change from Equation (1) of mass balance equation, as shown,

$$\frac{d(\rho A H c_p T)}{dt} = \rho c_p Q_c T_c + \rho c_p Q_h T_h - \rho c_p Q_o T - hA(T - T_\infty) \qquad (3)$$

Assume that ρ and c_p have constant value, so we can get Equation (4), as shown,

$$\frac{d(AHT)}{dt} = Q_c T_c + Q_h T_h - Q_o T - \frac{hA}{\rho c_p}(T - T_\infty) \qquad (4)$$

T and H are the time-varying-variables, thus

$$AT\frac{dH}{dt} + AH\frac{dT}{dt} = Q_c T_c + Q_h T_h - Q_o T - \frac{hA}{\rho c_p}(T - T_\infty) \qquad (5)$$

Substitute Equation (2) to above equation, then we get Equation (7)

$$AH\frac{dT}{dt} = Q_c(T_c - T) + Q_h(T_h - T) - \frac{hA}{\rho c_p}(T - T_\infty) \qquad (6)$$

$$\frac{dT}{dt} = \frac{1}{AH}\left[Q_c(T_c - T) + Q_h(T_h - T) - \frac{hA}{\rho c_p}(T - T_\infty) \right] \quad (7)$$

Equation (7) shows the relationship between the temperatures changes with the energy carried with the inlet water. In order to get the convective heat transfer coefficient, we assume the heat transfer over flat plate, written as in the following equations [6].

$$h = \frac{k}{A/P} N_u \;\; ; \;\; N_U = Ra_L^{1/4} \; ; \; Ra_L = \frac{g\beta(T - T_\infty)(A/P)^3}{\nu^2} P_r \quad (8)$$

In this simulation, the values of parameters for the therapeutic pool are defined in Table 1.

Table 1. Therapeutic pool parameters and value.

Parameter	Value	Parameter	Value
Hot water temperature	$T_h = 70^o C$	Nusselt number	Nu
Cold water temperature	$T_c = 27^o C$	Rayleigh number	Ra_L
Environment temperature	$T_\infty = 31^o C$	Prandtl number	P_r
Cold water flow rate	$Q_c = 0.0008\ m^3/s$	Gravitational acc.	$g = 9.81\ m/s^2$
Hot water flow rate	$Q_h = 0.0008\ m^3/s$	Volumetric expansion coeff	$\beta = 1/^0 C$
Drainage flow rate	$Q_o = 0.0008\ m^3/s$		
Bottom area	$A = 3\ m^2$	Kinematic viscosity	v, m^2/s
Pool perimeter	$A = 3\ m^2$	Pool Temperature	T, $^0 C$
Air thermal conductivity	k, $W/m^0 C$	Pool Height	H, m

3 Design of Fuzzy Logic Control

First thing in the design of Fuzzy Logic Control (FLC), it is necessary to determine how the number of inputs and outputs to be used [9]. Next, the system will be designed to use one input of a temperature error and the output of the valve opening value. The FLC has decision-making mechanisms, among others.

3.1 Fuzzification

Fuzzification is a process of change crisp values into fuzzy values, here in the form of fuzzy value is linguistic form. Fuzzification process depends on the design of membership functions created. In this study of input membership function is designed with five members, namely NL (Negative Large), NM (Negative Medium), Z (Zero), PM (Positive Medium) and PL (Positive Large). The fifth member is designed to use members of the triangle. Table 2 shows the input parameters of membership function. So that the membership function input can be seen in Figure 3.

Table 2. Membership function input

Error (Input)	Parameter
NL (Negative Large)	(-inf) - (-0.1)
NM (Negative Medium)	(-0.2) – 0
Z (Zero)	(-0.02) – 0.02
PM Positive Medium)	0 – 0.2
PL (Positive Large)	0.1 – inf

On the output membership function is determined limits the desired output value is 0 to 1, because the output generated is used to adjust the valve opening. Membership output function is designed to use the type of bell member and a triangle. In the ouput membership design, there is MOpen which has the meaning the value of valve position between open and half open. While the MShut means between closed and half open. They are shown in Table 3 and the results are shown in Figure 4.

Table 3. Membership function output

Error (Input)	Parameter
Shut	(-inf) - (-0.9)
MShut	[0.25 2.5 -0.5]
Modulating	[0.25 2.5 0]
MOpen	[0.25 2.5 0.5]
Open	0.9 - inf

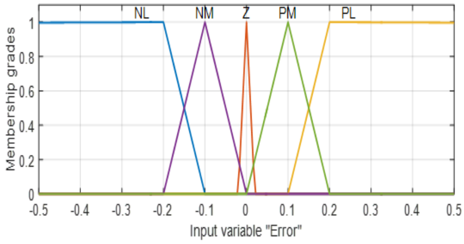


Fig. 3. Membership function input.

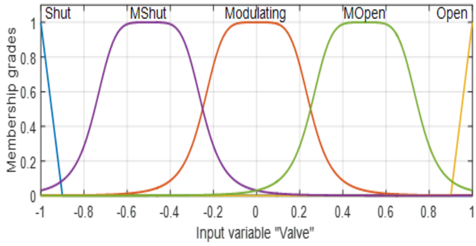


Fig. 4. Membership function output.

3.2 Inference Fuzzy

After the input value fuzzified, then FLC proceeds to the next phase of "decision-making" to bring the temperature according to the temperature set value. In the process of decision making, fuzzy rules are very important because it is the decision-making based on the logic set forth in fuzzy rules. Logic is in fuzzy logic rule is "IF ... THEN ...”. IF rule describes the circumstances that have been designed. While THEN elicits responses that will occur in that state [10]. When designing fuzzy rules are very flexible, this meant the rule-making depends on the ability and understanding of the designer for the system [11]. In this study, the fuzzy rules designed consists of five rules. The fuzzy rules in this study are shown as follow: Rule No 1, IF Error is NL, THEN Valve is Shut; Rule No 2, IF Error is NM, THEN Valve is MShut; Rule No 3, IF Error is Z, THEN Valve is Modulating; Rule No 4, IF Error is PM, THEN Valve is MOpen; Rule No 5, IF Error is PL, THEN Valve is Open.

3.3 Defuzzification

Defuzzification is the process of translating the results of the decision-making output signal in the form of linguistic forms into crisp values. Translating it back into a crisp shape is because the hardware can only read signals in the form of crisp signals and can not read the form linguistic input signal. The defuzzification method used is the centroid method.

4 Simulation Results

Simulation results show the FLC performance when controlling the system. To make sure the ability of the FLC, the output response of both the FLC and PID were compared for main parameters and changed parameters as disturbance. The changed parameters would be done to the inputs, cold and hot water temperature. The changed parameters as disturbance cold and hot water temperature to the systems as shown in Figure 5 and Figure 6 respectively. The response systems of the FLC and PID with changed parameters is shown in Figure 7.

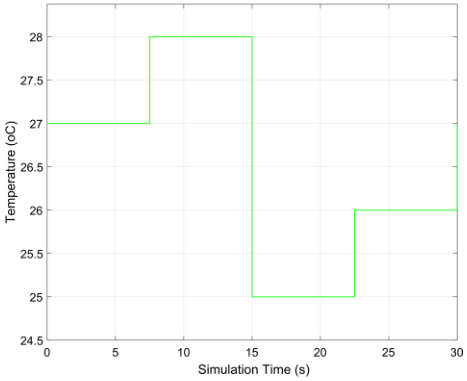


Fig. 5. Cold water temperature as disturbance

The comparison results show that the rise time is 0.23 s for PID and 0.12 s for FLC; overshoot is 3.82 % for PID and there is no overshoot for FLC; settling time is 4.51 for PID and 1.15 for FLC; steady state error is 0.004 s for PID and 0.034 for FLC.

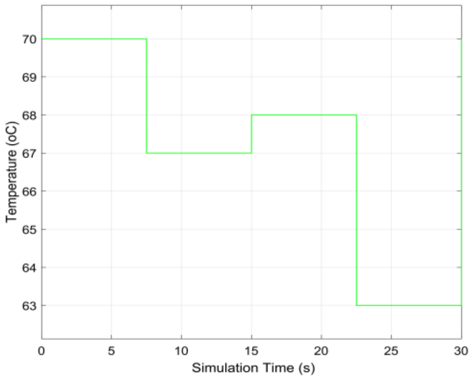


Fig. 6. Hot water temperature as disturbance.

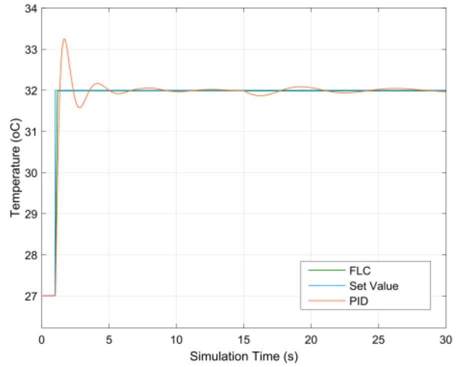


Fig. 7. The response systems of FLC and PID with changed parameters.

5 Conclusion

Simulation results show that Fuzzy Logic Control method has better performance than the conventional PID. The FLC has better adaptation than PID for varying disturbance due to cold and hot water temperature variation. For future work, it will be valuable to implement the FLC to the system, associated with a microprocessor capable of supporting and installation of the actuator.

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