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Development of Intelligent Secondary Circuit Cooling Using Fuzzy Logic Control for Test Bench Facility PT. PAL Indonesia

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Abstract

In Test Bench Facility of PT. PAL Indonesia, Secondary Circuit Cooling is used to keep the inlet temperature of water transferred from the main engine through a heat exchanger to the primary circuit in the standard condition of 32°C. Unfortunately, the secondary circuit cooling system cannot maintain the high temperature generated by the primary circuit. Therefore, controlling the water-cooling flow rate through a heat exchanger is important to obtain a standard temperature. This research developed an intelligent secondary circuit cooling system to control water flow rate using speed variation of pump impeller with Fuzzy Logic. The control methods were tested using a prototype in model scale at a ratio of 1:7. The system works due to the temperature difference between the inlet and outlet heat exchanger on the cold side, which improved with the application of fuzzy control. The error was reduced by 47.3% from the existing condition of 1.08. Furthermore, Fuzzy logic control contributes to keeping inlet temperature close to 32°C. This performance showed that this system can be used to improve the heat exchange from the main engine.

Keywords—Fuzzy Logic Control; Test Bench Facility; Model scale; Improvement

Introduction

Engine Commissioning is an activity used to obtain information on engine performance through different operating conditions based on load and velocity variations. Generally, the operating conditions are connected to the engine shaft using load variation generated from the water brake (W/B) dynamometer, with the application of load variation to measure and evaluate the engine performance [1] [2] [3] [4] [5]. This research focused on the cooling system domain and its relation to testing performance. The marine engine was embedded with a primary circuit, and as the load from W/B increased, the temperature from the main engine was raised. Furthermore, primary circuit cooling absorbs the heat and reduces its temperature, thereby preventing it from overheating. The primary circuit is a closed loop, hence, as the cooling media absorb heat from the main engine, the temperature increases. Therefore, additional devices, such as secondary circuits, are needed to overcome this error. This circuit type uses a cooling tower as the main device to emit heat from the cooling media. Figure 1 shows the flow diagram of the detailed information on the secondary circuit cooling system.

The high heat from the primary circuit flows out from the heat exchanger into the cooling system of the secondary circuit. This is followed by the transfer of warm water from the pump to the tower to reduce the cooling media's temperature, which is part of the second law of thermodynamics [6] [7] [8] [9] [10]. This research is used to investigate the detail of heat exchange for cooling.

The temperature of the cooling media in existing conditions was used to create the standard condition of the tower and performance efficiency [11] [12] [13] [14] [15]. This issue was identified by the test bench documents, where the highest temperature recorded is 40^0C, compared to the standard condition of 32^0C. Similarly, the temperature difference between exit and inlet water is narrow when load W/B is applied from 10% to 40%. In the initial condition, the high-water flow affected the cooling system performance due to its inability to maintain the standard temperature. Therefore, it is imperative to improve the cooling system to overcome these issues. In this study, the system was modeled to laboratory scale with the control system added to evaluate the enhancement.

Numerous studies related to this topic have been conducted, specifically for a wet counter-flow cooling tower [16] [17] [18] [19]. One of these studies was conducted using zone-specific Merkel numbers [20]. The result showed that the model is ideal for numerical optimization of cooling towers that need to meet stringent thermal performance and plume visibility requirements. A Novel model control on the cooling tower was also used to improve the efficiency of the industrial cooling tower, which increased the system's overall efficiency [21]. In addition, a novel model was designed to control the fan draft speed, and cooling tower pump flow rate based on climatic conditions. Both the model and control strategy were developed using Aspen Plus (V12.1), MATLAB (R2018b), and Simulink software. They were also validated and trained based on factory operating data. The model was tested in a pilot cooling tower facility with a capacity of 1 Ton Refrigeration and observed to obtain an energy consumption reduction rate of approximately 30% compared to traditional operations. A wet cooling tower system was used to enhance the thermal performance [22]. The model was proposed by exploiting the potential energy of water droplets to achieve the goal of forced ventilation. The results showed that the forced ventilation method can effectively reduce the unfavorable impact of the crosswind and the area under the wind. The research showed that the performance of the cooling tower was better with using four fans at a water discharge temperature of approximately 0.12°C and 0.34°C. The numerical study investigated the dynamic response of cooling towers under crosswind conditions [23]. This research used a 3D transient CFD model to simulate the natural draft cooling system. The results showed that the cooling tower characteristic parameters varied significantly with crosswind turbulence. The response period is easier for the tower to withstand crosswind disturbances at lower speeds. The smaller the crosswind speed changes for the cooling tower, the longer the response period of the emerging wind. Besides that, the chip muffler impacted the cooling performance of the natural draft wet cooling tower under crosswind [24]. This numerical research used a super large-scale natural draft wet cooling tower (S-NDWCT) to analyze the cooling performance. The result showed that the decrease in circulating water temperature increases with a decrease in angle, indicating little regularity with the distances between the mufflers and cooling towers. This research can provide a reference for optimizing layout patterns and muffler chip engineering applications.

The fuzzy logic provides multiple values on systems, for instance, it acts as a controller [25] [26] [27] [28] [29]. It is also an automatic guide for the vehicle industry [30]. This research increases line efficiency following automatic guide vehicles, specifically in accuracy and speed. The result showed that Fuzzy-PID has the ability to enhance the accuracy and speed by 28.6% compared to the use of a PID controller. Fuzzy logic is also for an unmanned aerial vehicle with vertical take-off and landing (VTOL) category [31]. A controller on SO (3) was presented to control the attitude of the quadrotor, using the angular velocity and rotation error as input as well as torque as output. The result showed that this system can control the attitude and maneuver smoothly with 0.02 rad steady-state error. Furthermore, research was carried out to investigate the fuzzy logic coefficient on the cooling system [32]. This research discussed the flexible operation of the Absorption Cooling System (ACS) using the Comprehensive Fuzzy Logic coefficient of performance (CFLCOP). The method used was based on energy and exergy efficiencies. The result indicated that this method has a longer ACS time obtainable than the last method. The continuity of ACS operation can also be achieved with a high degree based on the desired temperature. Fuzzy logic was also used to predict surface roughness in hard machining of EN31 steel using TiAlN coated cutting tool and MATLAB Software [33]. The result showed that the fuzzy logic model can estimate surface roughness with acceptable accuracy. High cutting speed and low feed rates deliver a good surface finish. This process is also used to enhance the efficiency of the cooling system [34] [35] [36] [37]. Fuzzy logic is also used to make hollow–curved metal surfaces using a die and punch capable of creating the hollow burrow in the process of sheet metal forming of deep drawing [38]. These experimental data were used to create a model using MATLAB software. The developed model is used to predict punch force and determine the optimized input parameters. The surface vessel used adaptive fuzzy logic to determine uncertainties of the dynamical model [39]. It uses a proportional derivative in conjunction with self-adjusting fuzzy logic compensation. The stability of the closed-loop system is investigated through novel Lyapunov-based arguments, and semi-global practical tracking is guaranteed.

Methods

Scaling and Components Selection

This section divides the system components into four, namely pump, cooling tower, heat exchanger, and hot water pool. Each component was scaled to obtain the complete design of the system on a model scale. Scaling components were developed using dimensional analysis. Equations (1), (2), and (3) were used to determine the Pump Head, Capacity, and Shaft power scaling, respectively.

$$Q_s = \frac{q}{n.D^3} \qquad (1)$$

$$\psi = \frac{H}{n^2.D^2} \qquad (2)$$

$$\hat{N}_s = \frac{N}{n^3.D^5.\rho} \qquad (3)$$

Where Q_s, ψ, $\hat{N}_s$, n, D, q, H, N, and ρ denote specific flow, coefficient of pump head, coefficient of power, impeller speed (rpm), Impeller Diameter (m), pump capacity (m^3/s), pump head specification (m), shaft power (Watt) and fluid density (kg/m^3), respectively. This study also includes capacity variations of a pump, using the affinity law as indicated in Equation (4).

$$\frac{q_1}{q_2} = \frac{n_1}{n_2} \qquad (4)$$

Herbert et al. [40] and Hill et al. [41] formulated the cooling tower scaling process scaling in Equations (5) and (6), while Worstell [42] formulated the geometric scaling using Equation (7). The fan cooling tower scaling process was determined using Equations (1) to (3).

$$T_{Win} - T_{Wout} = \frac{\dot{Q}}{\dot{m}_W.Cp} \qquad (5)$$

$$\frac{L}{G} = \frac{\rho_U.q_U}{\rho_A.q_A} \qquad (6)$$

$$\Pi = \frac{X_M}{X_P} = \frac{Y_M}{Y_P} = \frac{Z_M}{Z_P} \qquad (7)$$

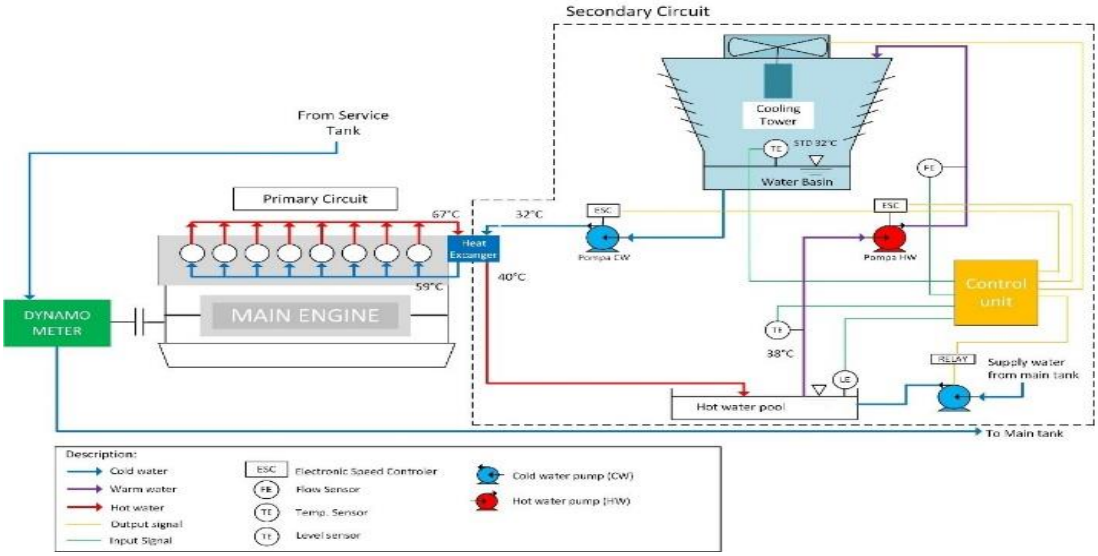

Fig. 1. *Secondary Circuit Cooling Arrangement (indicated with dashed line)*

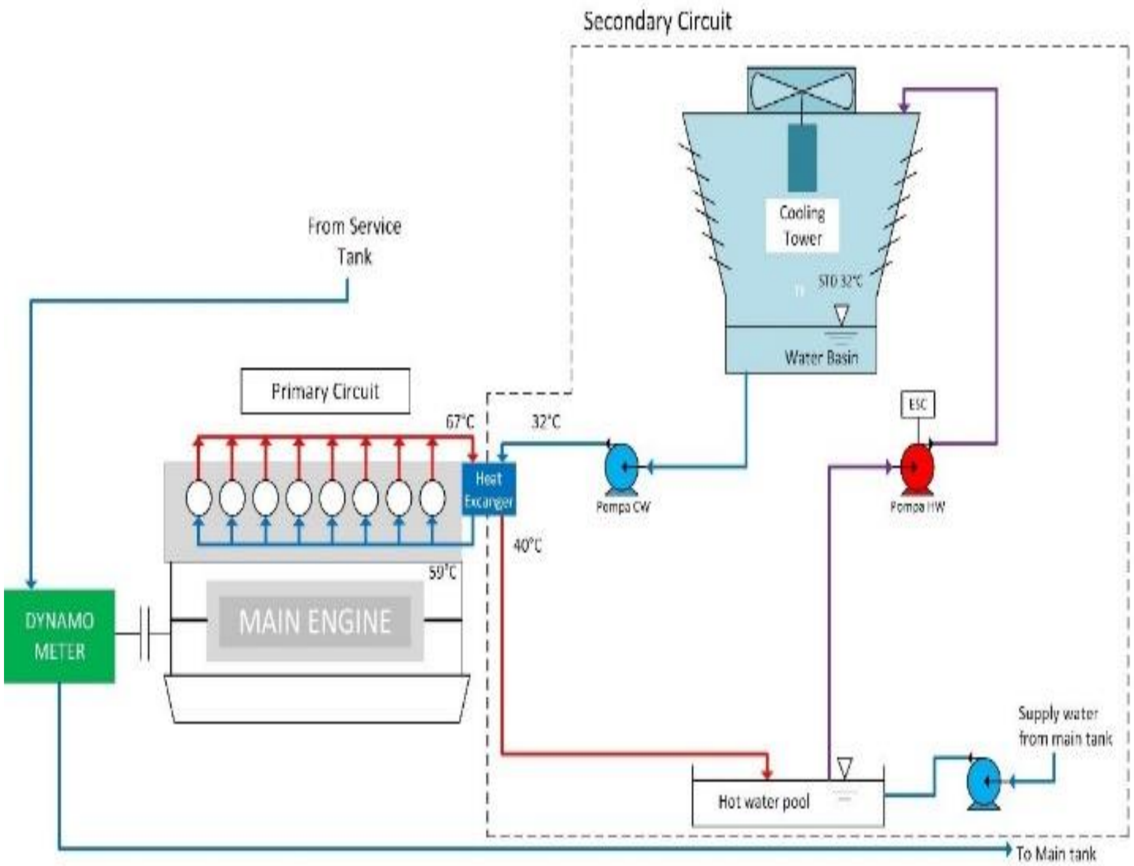

Fig. 2. *Cooling system with instrumentation*

Where $\dot{Q}$, $\dot{m}_w$, T_{Win}, T_{Wout}, C_P, ρ_U, ρ_A, q_U, Q_A, L, and G denote cooling capacity (Watt), water mass flow rate (kg/s), Water inlet temperature (°C), Water outlet temperature (°C), specific heat capacity of water (J/kg°C), air density (kg/m^3), water density (kg/m^3), air flow rate (m^3/s), water flow rate (m^3/s), liquid mass flow rate (kg/s), and gas mass flow rate (kg/s), respectively. Furthermore, Π, x, y, and z denote the pool's scaling factor, width, depth, and length. Subscript M indicates the model parameter, and Subscript P indicates the real scale parameter. In Equation (5), it is assumed that specific heat capacity in model and real scales were equivalent because both systems used identical water characteristics, hence, C_P is negligible.

Equation (8) was used to obtain heat generated from effectiveness.

$$\varepsilon = \frac{Q}{Q_{max}} \qquad (8)$$

Where ε is effectiveness PHE (dimensionless), Q is the actual heat flow (Watt), and Q_{max} is maximum heat flow (Watt).

Equation (7) was used to determine the geometric scaling for the hot water pool. This component is very simple, only geometric scaling when necessary, as shown in Fig. 2.

After scaling all components, the next step is the selection process, which is quite easy but can be difficult when available components do not meet the specifications.

Control System Design

Fig. 3. *Hot water pool*

In this research, the system is modified by adding an instrumentation component used to obtain sensor data and a control unit to regulate water inlet temperature. The components are illustrated in Fig. 3, with the control system analyzed using a fuzzy logic toolbox in MATLAB®. The pump was regulated using a relay module with a certain setpoint value for other system control, such as water level and supply. The limitation to simplifying the problem focused on flow regulation with a variation of water temperatures, as shown in Fig. 3. Input for this fuzzy logic control is the temperature of the water entering the heat exchanger, with output variations of pump capacity regulated using PWM.

Fuzzy modeling was carried out in this study using knowledge based on real test parameters in the Test bench facility, PT. PAL Indonesia. Meanwhile, for the system inference, Mamdani and defuzzification methods with Centre of Area (CoA), derived by Hooda et al. [44].

3D Modelling and Prototyping

This part focused on 3D modeling the system and its realization using SolidWorks.

Testing

This step is intended to determine the system performance using a variation of inlet water temperature from data. The system is set to a point temperature of 32°C, with the inlet temperature measured to compare the actual error value. After testing, the result is analyzed with the cooling capacity based on data comparing the existing and new conditions.

Result and Discussion

Pump Scaling

The model scale depends on the scale factor ($\Pi = I_M/I_P$) with a ratio of 1:10 to maintain model accuracy [45]. In this case, the scale factor is determined using the ratio of pump impeller diameter available (D_M) and pump impeller existing (D_P) at an average of 36 mm. Therefore, the scale factor (Π) in this case is 1:7, determined using Equations (1) to 3 and listed in Table 1.

Table 1. *Pump Selection*

Parameter	Specification
Impeller Diameter	0.036 m
Impeller Rotation	150 rpm
Pump Capacity	216 L/H (max)
Heat Pump	3 m
Power Shaft	4.2 W

The pump in the test bench facility is selected based on its capacity value. Table 1 shows that the suitable type of specification is pump DC30A – 1230 with a maximum capacity of 240 L/H.

In this research, flow variation is regulated by affinity law with classified based on the highest efficiency of the pump. From Equation (4), the resulting variation pump capacity with PWM as an output variable is shown in Table 2.

Table 2. *Pump Capacity Related To Pwm*

Capacity (L/H)	PWM
144	153
180	191
216	216

Cooling Tower Scaling

The type of cooling tower used in the test bench facility is induced draught, where heat rejected through contact between the water droplet and the air was retracted using a fan cooling tower [41]. Equations (5) through (7) were used to determine the geometric and process scaling. Table 3 is the outcome of the cooling tower specifications in model scale.

Table 3. *Cooling Tower Specification*

Parameter	Specification
Fan speed	1800 rpm
Fan Diameter	0.28 m
Cooling capacity	160 W
Airflow	72 L/H
Water flow	108 L/H
Length (x)	0.42 m
Width (y)	0.42 m
Height (z)	0.42 m
Parameter	Specification

The relevant component for those specifications is unavailable in model scale, except the fan cooling tower determined based on the airflow specification. Therefore, this component must be manufactured to determine the specification.

Heat Exchanger

Heat exchanger allows cooling media to exchange heat from higher to lower source using the Heat Sink. The water block is a heating element consisting of a circular pipe through which heat is absorbed in the cooling media. This experiment only provides process scaling with a proportional relationship between heat and effectiveness. Equation (8) was used to determine the model scale value, and the available component was selected. However, the correct value for the heating element does not exist, indicating the only solution is applying the nearest heat specification of 100 W and setting its correct value using the dimmer.

Hot Water Pool

Table 4 illustrates the parameters for scaling a hot water pool, which is quite easy and geometrically simple. Using similar law from Equation (7), the size of the hot water pool can be obtained.

Table 4. *Hot Water Pool Specification*

Parameter	Specification
width (x)	0.28 meter
length (y)	0.21 meter
depth (z)	0.70 meter

Fuzzy Logic Control

The variable linguistic in this fuzzy logic modeling is associated with several forms of membership function by Rahmat et al. [46], as shown in Figure 4. The source of temperature membership is obtained from test bench data information. Another membership function is the value of PWM of the pump motor, which was generated from Table 2.

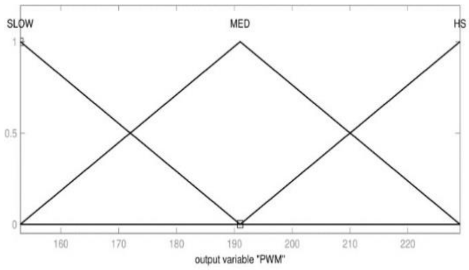

Fig. 4: *Membership Functions of the Output (Pulse Width Modulation)*

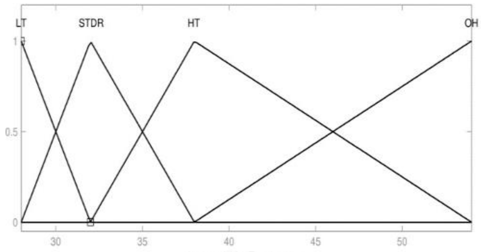

Fig. 5: *Membership Function of Input (Temperature)*

Figs. 4 and 5 represent the membership and PWM of the temperature sensor as the input and output. Therefore, the fuzzy logic can be completely generated, as shown in Table 5.

Table 5. *Rules Table*

Temperature Read	PWM OUTPUT
LT	SLOW
STAR	MED
HT	HIGH
OH	HIGH

The rules of fuzzy control acquired from Table 5 with the help of MATLAB software using a surface menu were used to decide on the control system. The yield plotted graph is shown in Fig. 6.

The plotted diagram represents the pattern of decision-making of the control system. For instance, the temperature read from the sensor at 38°C depicted by a vertical straight blue line was maintained to a standard of 32°C using a PWM of 213.

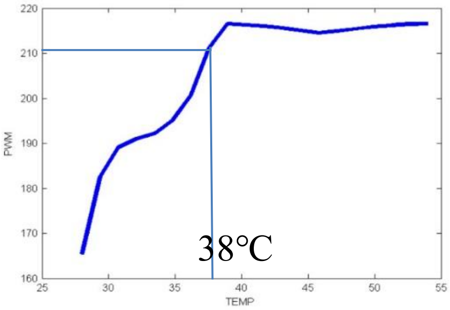

Fig. 6. *Control System Decision Making*

This research was conducted by applying various heating elements, which increased the water temperature leaving the heating element. Outlet water temperature is the input of the cooling control system. According to Fig. 5, the temperature axes are the input, which was increased gradually using the same pattern from the test bench facility PT. PAL Indonesia. After applying the input, the control system was used to guide the water temperature entering the heating element by adjusting the pump rotor speed through PWM (Pulse Width Modulation). The initial input temperature of the fuzzy logic controller was set to 28°C and the PWM to 168, which increased the water temperature to the standard condition. The water temperature in the heating element goes under the standard condition because generally, water increases its temperature with a rise in heat load, which usually takes approximately 7 minutes. Subsequently, the water temperature leaving the heating element (T.out.HE) increases until it reaches 38°C. When the maximum specification of a cooling system is reached, the temperature decreases to 36°C, which is high, hence, the result is unsatisfactory.

3D Model and Realization

This section shows the system model in 3D, its parts, and the prototype made using the component numbering in Fig. 5a and Table 6.

Table 6. *Part List*

Parameter	Qty.	Specification
Cooling Tower	2	Induced Draft Cooling Tower
Hot Water Pump	1	Centrifugal Pump (DC30A – 1230)
Cold Water Pump	1	Centrifugal Pump (DC30A – 1230)
Hot Water Pool	1	Water basin
Heat Exchanger	1	Plate Heating Element

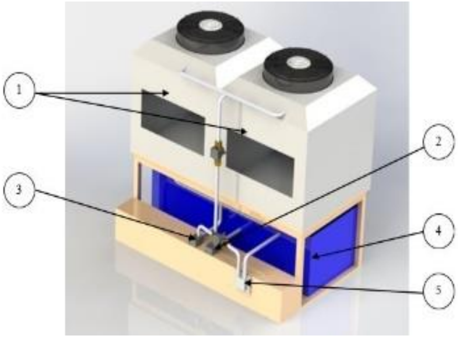

Fig. 7. *3D model of the Intelligent Secondary Circuit Cooling*

Testing

The testing results using a variation of entrance water temperature and heat exchanger (T.in.HE) with a set point adjusted to 32°C are shown in Tables 7 and 8. However, before conducting this process, the temperature sensor was tested to obtain real data of measurement using the pump flow characteristic as an output.

Table 7. *System Testing Results In The Existing Condition*

T.in.HE$_{Act}$ (°C)	**Set Point (°C)**	**T.in.HE$_{Result}$ (°C)**	**Error Temp.**
33	32	32	0
33.1	32	32.9	-0.9
34.8	32	33.12	-1.12
36.1	32	34.45	-2.45
37.5	32	35.80	-3.8
38.6	32	36.05	-4.05
Average temperature error (°C)			±2.05

Table 8. *System Testing Result Using Fuzzy Logic Control*

T.in.HE Act (°C)	**Set Point (°C)**	**T.in.HE Result (°C)**	**Error Temp.**
33	32	31.8	0.2
33.1	32	31.1	0.9
34.8	32	29.6	2.4
36.1	32	30.4	1.6
37.5	32	31.8	0.2
38.6	32	33.2	-1.2
Average temperature error (°C)			±1.08

From the tables, the new condition needed to reduce error temperature from setpoint, with an error value of 1.08°C. Although the value obtained is insignificant, it can slightly reduce the error temperature to achieve standard conditions accurately. Error reduction can be calculated using Equation (9).

$$\%error\ reduction = \frac{2.05 - 1.08}{2.05} \times 100\% = \mathbf{47.3\%} \qquad (9)$$

Fig. 8. *System Realization*

Conclusion

This research compared system performance between the existing and new conditions using fuzzy logic control. It includes inlet water control using a variation of pump capacity in the secondary circuit used to support the cooling system in the primary system to keep the temperature at standard condition during the engine testing process. The following conclusions were obtained:

1. The model scale prototype was determined based on dimensionless equations applied to each cooling secondary circuit component. The scale factor for this model prototype is 1:7, determined based on pump impeller diameter available (D_M) and divided using the existing impeller diameter (D_P).
2. Fuzzy logic control contributes to the inlet temperature near the setpoint value of 32°C using an error reduction of **47.3%**.

Further research is recommended to use model predictive control (MPC) with fuzzy logic control to maintain the setpoint value in Industrial sectors. Furthermore, dynamic modeling is necessary to overcome the optimal design and reduce the time to the trial error of the prototype.

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