A Novel Comparative Study on Modeling of Steam Condenser Using Fuzzy PID Controller

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Abstract - Shell-and-tube condenser is a heat exchanger for cooling steam with high temperature and pressure, which is one of the main kinds of heat exchange equipment in thermal, nuclear, and marine power plant. Based on the lumped parameter modeling method, the dynamic mathematical model of the simplified steam condenser is established. A dynamic model of a steam condenser is developed. The model is based on the assumptions of total condensation and constant liquid and vapour volumes. The operating condition is taken from the static balance of a power plant. Then, the pressure PID control system of steam condenser based on the Matlab/Simulink simulation platform is designed. A comparative study on modeling of a steam condenser with PID and Fuzzy PID are carried out and finally the results are compared.

Keywords- Shell-and-tube condenser, PID Controller, Fuzzy PID Controller, heat exchanger.

I. INTRODUCTION

The condenser is one of the important kinds of equipment in thermal power plant, nuclear power plants, and marine power plant. The reliability of condenser running directly affects the safety and economic operation of the entire power plant or power system. A steam condenser is a piece of machinery that turns steam into water. Many steam-based systems use a circuit of water to maximize their efficiency. Water is heated into steam, the steam provides motivation for a process, a steam condenser turns it back into water, and the cycle begins again. The failure of the condenser may cause the boiler or steam turbine unit to overheat, which endangers the safety of the whole generating unit or power plant. The power plant has strict requirements on the reliability and the tightness of the condenser. In addition to safety considerations, the condensation process of steam in the condenser is an important part of the system thermodynamic cycle, which greatly affects the economic performance of the system. Therefore, through the computer simulation experiments, the establishment of the dynamic model and understanding the dynamic characteristics of the condenser have a great significance on improving the safety and economic operation level of the steam condenser. Aiming at the steam condenser pressure control problem, based on the Matlab/Simulink simulation platform and the established mathematical model, a closed-loop condenser pressure control system is designed using Fuzzy PID Controller.

This paper is organized as follows. The literature survey that discusses on various methods used in optimizing shell tube exchangers are presented in Section II.The proposed methodology is presented in Section III and the mathematical formulation of the same given in Section IV.The simulation results are presented in Section V.Finally, conclusions are drawn in section VI.

II. LITERATURE SURVEY

The modeling of process engineering systems is still an open field because of its complexity. These processes have a highly non-linear behavior mainly due to the mutual interaction of severalphenomena of various kinds and the combination of technological components thatimplement the laws from different disciplines (mechanical, thermal,chemical). Even if these types of processes are present in a many industries with risk (nuclear, chemical, etc...), which require for their knowledge and control models moreprecise and usable.The Matlab-Simulink model of the steam generator has been developed by F.Betchine,et al.,[1].The aim of this work[1] is to create a model in Matlab-Simulink, of the steam generator situated at Lille 1 University, such a process occurred in many risky process, is characterized by multidomain energy. The global behavioral model is then simulated and the results are compared to the Bond graph model simulation results and Matlab -simulink library realization(that had been compared to experiments observation). The steam generator model shows acceptable coherence with the process behavior.

Sikos, et al.,[2] proposed a new methodology to use comprehensive up-to-date commercial software tools for heat exchanger network (HEN) reliability modeling and optimization. The idea behind this proposal is that to apply the combination of specific HEN optimization and reliability software packages has several advantages over the commonly used approach. There is a variety of features that need to be taken in to account to choose the right software tool. The HEN design[2] has a significant impact on reliability issues and this should be considered. There are many related issues and features – the robustness, the type of welding, the increment of maximum mechanical resistance, the impact on manufacturing costs, reduction of lost opportunity costs caused by exchanger outages, troubleshooting of heating exchanger problems by operators etc.

De Vasconcelos Segundo,et al.,[3] presents an optimization of shell-and-tube heat exchangers(STHEs) considering as objective function the minimization of the total annual cost by Differential Evolution (DE) and a novel Differential Evolution variant, denominated Tsallis Differential Evolution (TDE). Shell-and-tube heat exchangers are the most widely used heat exchanger in industrial processes and its design involves several steps, including the selection of geometrical and operating parameters. The variables used for the optimization were the shell internal diameter (Ds), the outside tube diameter (do)and the baffles spacing (B). Reductions of total annual cost about of 26.99% compared to the literature, and reductions of 14.50%, 11.50%, 6.90% and 1.15% compared to Genetic Algorithm (GA), Particle Swarm Optimization (PSO), Biogeography-Based Optimization (BBO) and Cuckoo-Search Algorithm (CSA) methods, respectively, were obtained for the case 1 and reduction of costs about 54.60%, 11.70% and 9.40%compared to the literature, GA and PSO, respectively, was obtained for the second case[3].

Mohanty, et al.,[4] proposed a new design optimization approach using the gravitational search algorithm is developed to obtain optimal configuration of a shell and tube heat exchanger from economic point of view. The objective function considered for the optimization process is the total annual cost including the investment cost and the operating cost. The Gravitational Search Algorithm(GSA)[4] is a heuristic search algorithm based on the law of gravity and mass interactions. Taking into account the importance of shell and tube heat exchangers in industrial applications and the complexity in their geometry, the GSA methodology is adopted to obtain an optimal geometric configuration.The comparison of the obtained results in [4] with other algorithms indicates that the GSA algorithm can be successfully applied for design optimization of a shell and tube heat exchanger from economic point of view.

A multi objective optimization of the heat transfer area and pumping power of a shell and tube heat exchanger is presented by Fettaka, et al.,[5] to provide the designer with multiple Pareto-optimal solutions which capture the trade-off between the two objectives. Nine decision variables were considered: tube layout pattern, number of tube passes, baffle spacing, baffle cut, tube-to-baffle diametrical clearance, shell-to baffle diametrical clearance, tube length, tube outer diameter, and tube wall thickness. The optimization was performed using the fast and elitist non-dominated sorting genetic algorithm (NSGA-II)[5] available in the multi objective genetic algorithm module of MATLAB. The algorithm was also used to determine the impact of using continuous values of the tube length, diameter and thickness rather than using discrete standard industrial values to obtain the optimal heat transfer area and pumping power. Results in [5] show that using continuous values of these three decision variables only leads to marginally improved performance compared to discrete values.

Computer-aided design has become extremely popular and its use in classroom can be very helpful, adding more analysis capabilities to all engineering areas. A free piece of educational software to teach transient analyses of shell-and-tube heat exchanger equipment to undergraduate students is presented by Cartaxo, et al.,[6]. The software was developed to provide unit operation courses with realistic exercises involving dynamic simulation of chemical processes. The use of the program[6] improves the efficiency of the course since it let students practice heat exchanger analysis while relieving them of tedious repetitive calculations.

Analyses to the equations, in addition to the theoretical developments of the proposed model are discussed by T. Tahir, et al.,[7].The physical process of condensation of the humid air in the condenser of seawater greenhouse that is located in Muscat, Oman was considered in [7]. A theoretical model was developed to describe the process of the condensation by using the heat and mass transfer equations. For this purpose, analyses to the equations and to the theoretical development of the proposed model were given in [7].

This paper[8] presents the modeling and experimental results of wire-and-tube condensers that are commonly used in vapor compression cycle based domestic refrigerators. A condenser was experimentally tested in a real refrigerator for some operating conditions. A simulation model was developed by P. K. Bansal, et al.,[8] using the finite element and variable conductance approach, along with a combination of thermodynamic correlations. The condenser capacity per unit weight was optimized using a variety of wire and tube pitches and diameters. An optimization factor, was defined as ratio of the condenser capacity per unit weight of the optimized design[8] and the present design. The application of this factor led toan improved design with 3% gain in capacity and 6% reduced condenser weight[8].

A Computational Fluid Dynamics (CFD) model is described by M. R. Malin,[9] for simulating flow and heat transfer in a condenser. A single-phase approach is used which predicts the flow of a steam air mixture within the condenser shell, and the heat and mass transfer processes are modeled using empirical correlations. The model in [9] is used to calculate the overall performance of an experimental marine condenser with a superheated steam supply.

A simplified hybrid dynamic model of a condenser has been developed by X.Ding, et al.,[10] and validated. The model is formulated from physical equations, but its parameters which are constants or can be considered as constants are determined using the experimental data by the least square method. This modeling approach[10] takes both advantages of empirical and theoretical modeling method. The merits of model include: 1) it balances the trade-offs Between complexityand accuracy; 2) the model order is very low; 3) all the state variables of the model are measurable. These make it very suitable for the design of advanced control systems for vapor refrigerant cycles. An experimental model[10] validation case is given and the results demonstrate that the model cans adequately predict the dynamic performance of the condenser.

III.PROPOSED METHODOLOGY

3.1 Structure Characteristics

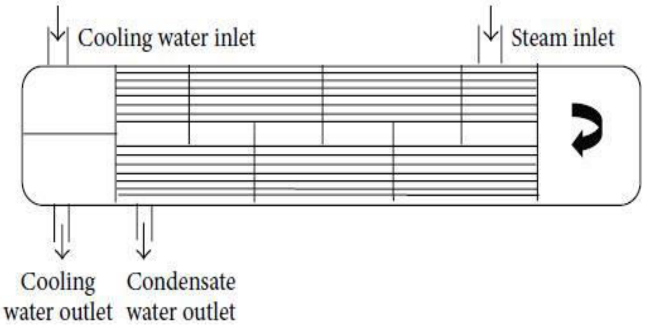

Figure 1: Structure diagram of shell-and-tube condenser

The shell of shell-and-tube type condenser is usually cylindrical or elliptical as shown in Figure 1, which is connected with end closures for constituting the water chambers. Between the end closures and the shells, a perforated tube plate is fixed, in which a lot of cooling water pipes are arranged hierarchically. The entrance pipe of steam is located in the upper part of the condenser shell, which is directly connected with the exhaust equipment through the compensator. In the lower part of the shell, there is a gathering tank (or a hot well water tank) of the condensed water. The air out let port is positioned at the lower part of shell and the air is drawn through this nozzle.

3.2 Working Principle

The working principle of the steam condenser is shown in Figure 2.

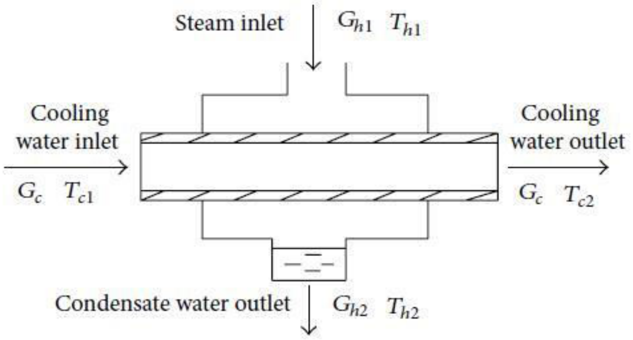

Figure 2: Schematic diagram of condenser.

Steam goes into steam field of the condenser through steam admission pipe. Steam gets in touch with the condenser tube wall to begin the radiate condensation; at the same time, the latent heat is transferred to the cooling water through the surface of the cooling water pipe. Cooling water with inlet temperature is fed into water chamber through the cooling water pipe, where the cooling water is assigned to all pipes of the first procedure in the lower part of the condenser shell. The cooling water flows into another water chamber along the first six cooling water pipes and then enters the next flow pipes and carries through heat exchange with the steam. Through such several procedures in return, the cooling water with the outlet temperature is discharged from the outlet pipes. Due to the lack of system sealing property, the air is drawn out from the condenser constantly to ensure the requirements of the system's vacuum degree. The drawing as contains the air and steam. In the beginning of the condensation, the air volume is very smaller than the total amount of steam. With the steam and air flowing toward the exhaust port, steam is continuously condensed down. Then ,the steam quality in the mixture gradually decreases. On the contrary, the relative content of the air increases gradually. Until the relative content of air fed into the cooling zone air has reached a great numerical extent, the steam condensation process terminates.

IV.MATHEMATICAL FORMULATION

4.1 Dynamic Model

The dynamic model of the steam condenser described here is based on energy balance and cooling water mass balance.

4.1.1 Energy Balance

Energy balance is based on the assumption of total condensation, i.e. the inlet steam and outlet condensate are both saturated. Hence, the heat transferred from steam to cooling water is equal to the latent heat of steam:

$Q = F_c\lambda$ --(1)

where, Q is the condenser heat duty [kW], Fc condensate mass flowrate, [kg/s] andthe specific latent heat of steam at the saturated condition.

$Q = UA\Delta T_m \quad Q = F_c\lambda$ --(2)

where, UA is the overall heat transfer coefficient times the heat **transfer area and ΔTm is the logarithmic mean temperature** difference defined as:

$$\Delta T_m = \frac{T - T_{cw}}{\ln\left(\frac{T_c - T_{cw}}{T_c - T}\right)}$$ --(3)

where, Tc is condensate temperature, Tcw the cooling water inlet temperature and T the outlet temperature of cooling water. Hence, a cooling water energy balance yields

$$\frac{dT}{dt} = \frac{F_{cw}}{M_{cw}}(T_{cw} - T) + \frac{Q}{M_{cw}C_P}$$ ---------------------------------- (4)

where, Fcw is the mass of rate of cooling water, [kg/s], M cw the cooling water hold up, [kg], and CP the heat capacity of the cooling water [kJ/(kgK)].

According to the Wilson Plot, the product of overall heat transfer co efficient and area can be approximated by the following empirical equation:

$$\frac{1}{UA} = a_1 F_{cw}^{-0.8} + a_2$$ ---(5)

where a1and a2 are constant. a2 is determined by UA when Fcw= 1. In this case, UA is dominated by the heat transfer rate between the steam and tube wall, as wellas the heat resistance of the tube wall. By assume the ultimate outlet temperature of coolant, a2 can be determined.

Parameter	Value	Unit
R	0.461526	kJ/(kgK)
V	3	m^3
λ	2265.65	kJ/kg
UA	356.972	kW/K
M_{cw}	6500	kg
C_P	4.2	kJ/(kgK)
α	0.3162	K/kPa
β	68.0958	°C
a_1	8.7292e-2	
a_2	7.3787e-4	

Table I.Condenser Parameters

Variable	Value	Unit	Description
F_s	4	kg/s	steam flowrate
F_c	4	kg/s	condensate flowrate
F_{cw}	107.8881	kg/s	cooling water flowrate
P	90	kPa	condenser pressure
T	80	°C	cooling water outlet temperature
T_{cw}	60	°C	cooling water inlet temperature
T_c	96.5538	°C	condensate temperature
Q	9062.6	kW	heat duty

Table II.Condenser Variables

4.1.2 Mass Balance

Mass balances of steam and condensate are based on the assumption of constant volumes, i.e. the steam volume and condensate volume are constant, or, the outlet flow rate of condensate is controlled to maintain the condensate level is constant with in the condenser. To simplify the model, it is also assumed that steam inlet and condensate outlet both are saturated. Therefore, according to ideal gas equation,

$$\frac{dP}{dt} = \frac{RT_c}{V}(F_s - F_c)$$ --(6)

Where P is the pressure of condenser, [kPa], R the specific gas constant, V condenser volume, [m3] and Fs the steam mass flow rate, [kg/s].Condensate temperature and pressure have a unique relationship. For implicitly, it is linearly approximated as follows:

$T_c = \alpha P + \beta$ --
(7)

V.IMPLEMENTATION AND SIMULATION RESULTS

The steam condenser model described in chapter IV, has five equations, two of them are dynamic. There are eight variables, Fs, Fc, Fcw, P, T, Tcw, Tc and Q, and seven parameters R, V ,λ, **UA, Mcw, CP , αa nd β . The parameter values are given in** Table 1, where parameters, a1 and 2 is determined by **assuming T = 90 [0C] when Fcw= ∞.The steady**-state values of eight variables at the nominal operating point are shown in Table 2.

A Simulink model based on the above description has been created as shown in Figure 3.

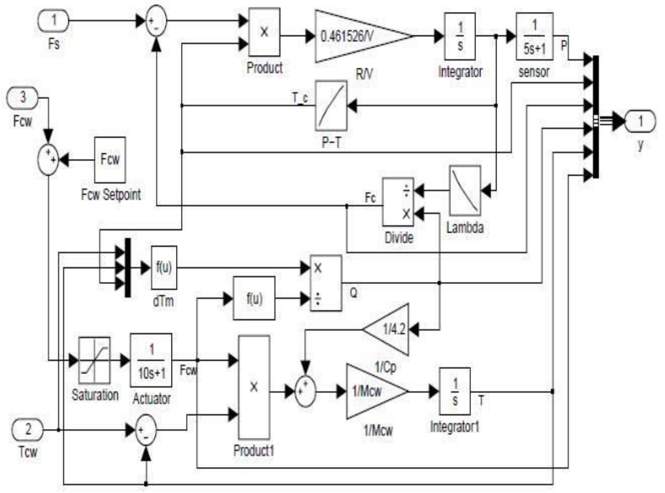

Figure 3.Steam Condenser Simulink Model

The closed-loop model with heat duty,pressure, temperature, and cooling water flow using PID controller is shown in Figure 4.

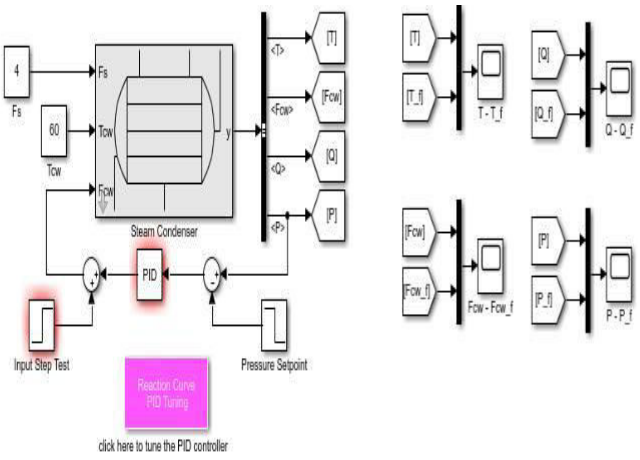

Figure 4.Steam Condenser Simulink Model with PID Controller

The closed-loop model with heat duty,pressure, temperature, and cooling water flow using Fuzzy PID controller is shown in Figure 5.

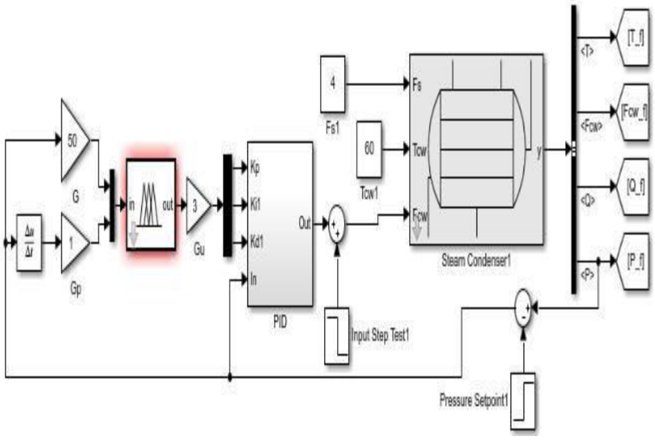

Figure 5.Steam Condenser Closed-Loop Model Using PID Controller and Fuzzy

The Simulink model includes a first order delay with time constant of 10 [s] to represent the actuator and another first order lag of 5 [s] for the pressure sensor. By applying the closed-loop tuning method, the ultimate gain, Ku = 24 and ultimate period, Pu= 3.08 [s] have been detected. Thus, parameters of the PI controller are: Kc= 0.45 *Ku = 10:8 and TI = Pu/1.2 = 2.56 [s]. The closed-loop response with PID and fuzzy PID Controller based on the parameters in table II are taken and the following simulation results for heat duty, temperature, pressure and cooling water flow rate are obtained

in Figure 6a, Figure 6b, Figure 6c, and Figure 6d respectively.

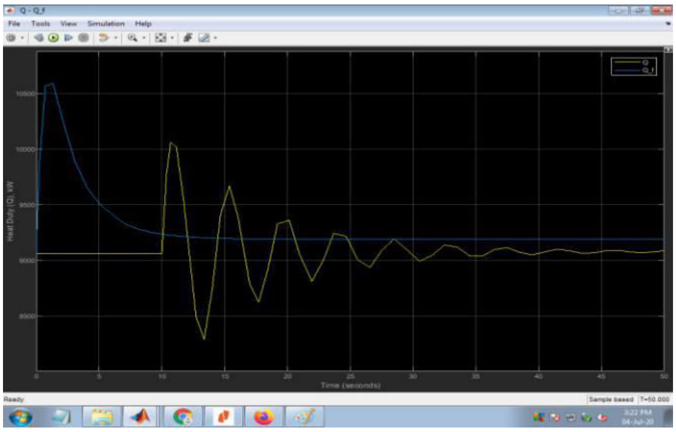

Figure 6a.Closed-Loop Response to a Step Change in Heat duty Setpoint with PID and fuzzy PID Controller

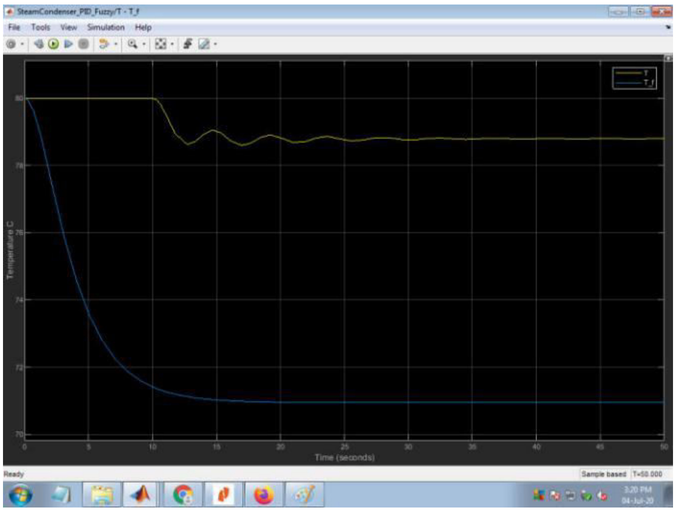

Figure 6b.Closed-Loop Response to a Step Change in Temperature Setpoint with PID and fuzzy PID Controller

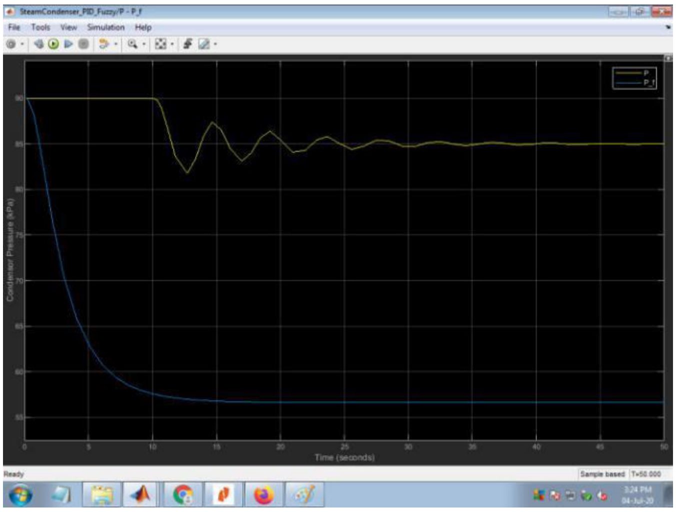

Figure 6c.Closed-Loop Response to a Step Change in Pressure

Setpoint with PID and fuzzy PID Controller

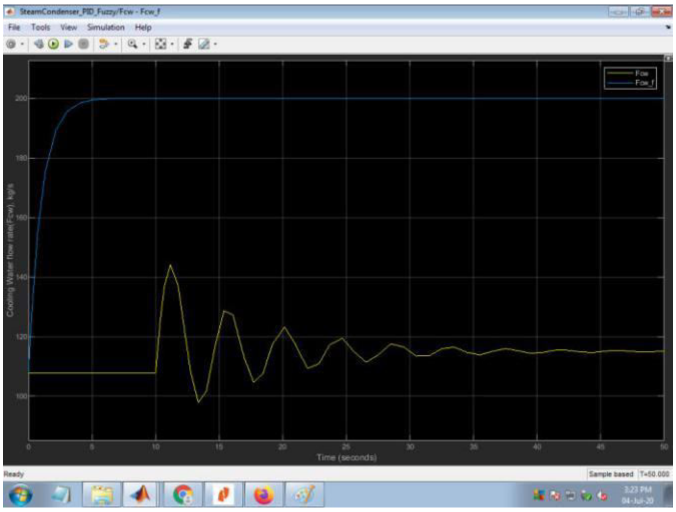

Figure 6d.Closed-Loop Response to a Step Change in Cooling water flow rate Setpoint with PID and fuzzy PID Controller

VI. CONCLUSION

One of demerits of FLC is disability in self-tuning which contribute to contingent on knowledge of experts or expert system. PID could identify the almost optimum parameters of FLC that tuning output membership functions for achieving to the best performance. PID-Fuzzy controller is one of the most effective methods in term of conditions that designing FLC is so problematic. In this paper, PID Fuzzy controller controls steam condenser pressure,temperature,heat duy and cooling water flow rate with high accuracy. In the final analysis, the PID could demonstrate its capability to tune up FLC parameters promptly with uppermost level of accuracy.Thus our comparative study concludes that PID-Fuzzy controller outperforms with better accuracy than PID controller.

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