

Comparative Study of Temperature Control in a Heat Exchanger Process

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ABSTRACT

In the present work the dynamic behavior of a plate heat exchanger (PHE) (single pass counter current consists of 24 plates) studied experimentally and theoretically to control the system. Different control strategies; conventional feedback control, classical fuzzy logic control, artificial neural network (NARMA-L2) control and PID fuzzy logic control were implemented to control the outlet cold water temperature. A step change was carried in the hot water flow rate which was considered as a manipulated variable. The experimental heat transfer measurements of the PHE showed that the overall heat transfer coefficient (U) is related to the hot water flow rate (m_h) by a correlation having the form:

$$U = 11045 m_h^{0.7158}$$

In this work the PHE model was found theoretically as a first order lead and second order overdamped lag while the experimental PHE represented dynamically (by PRC method) as a first order with negligible dead time value. A comparison between the experimental and the theoretical model is carried out and good agreement is obtained. The performance criteria used for different control modes are the integral square error (ISE) and integral time-weighted absolute error (ITAE) where the ITAE gave better performance. As well as the parameters of the step performance of the system such as overshoot value, settling time and rise time are used to evaluate the performance of different control strategies. The PID fuzzy controller gave better control results of temperature rather than PI, PID and artificial neural network controller since PID fuzzy controller combines the advantages of a fuzzy logic controller and a PID controller. MATLAB program version 7.10 was used as a tool of simulation for all the studies mentioned in this work.

Keywords: plate heat exchanger, dynamic behavior, model, PI controller, PID controller, fuzzy logic controller, artificial neural network controller.

دراسة مقارنة للسيطرة على درجة الحرارة في المبادل الحراري

الخلاصة

تم في هذا البحث دراسة السلوك الديناميكي لمبادل حراري صفانحي (ممر واحد ذي اتجاه متعاكس مؤلف من 24 صفيحة) عمليا ونظريا وتم تنفيذ السيطرة على المنظومة. تم استخدام استراتيجيات سيطرة مختلفة: المسيطر التقليدي والمسيطر الضبابي المنطقي التقليدي ومسيطر الشبكة العصبية الاصطناعية (NARMA-L2) ومسيطر fuzzy PID للسيطرة على درجة حرارة الماء البارد الخارج. وقد تم اعتماد التغير الخطوي لمعدل جريان الماء الحار كمتغير معالجة. تبين القياسات العملية لانتقال الحرارة في المنظومة PHE ان معامل انتقال الحرارة الكلي (U) يتناسب مع معدل جريان الماء الحار (m_h) حسب شكل العلاقة:

$$U = 11045 m_h^{0.7158}$$

تم في هذا العمل تمثيل المنظومة ديناميكيا كنموذج من مرتبة اولى من جهة التقدم الزمني (lead) وكنموذج ذو مرتبة ثانية مفرط المضائلة (overdamped) من جهة التأخير الزمني (lag) بينما وجد عمليا ان المنظومة يعبر عنها ديناميكيا كنموذج من مرتبة اولى مع اهمال قيمة الوقت الضائع (dead time). تمت المقارنة بين النموذج العملي والنظري وتم الحصول على توافق جيد. استعملت معايير الاداء لانواع السيطرة المختلفة وهو معيار تكامل الخطأ المربع (ISE) ومعيار التكامل الزمني للخطأ المطلق (ITAE) حيث ان المعيار (ITAE) اعطى اداء افضل. كذلك تم استعمال معاملات الاداء الخطوي للنظام مثل قيمة التطرف (overshoot) وزمن الاستقرار (settling time) وزمن الصعود (rise time) لتقييم الاداء لاستراتيجيات السيطرة المختلفة. اعطى المسيطر fuzzy PID افضل نتائج سيطرة على درجة الحرارة من بقية المسيطرات PI و PID والضبابي المنطقي التقليدي والشبكة العصبية الاصطناعية وذلك بسبب انه يجمع محاسن كلا المسيطرين PID والضبابي المنطقي. وتم استخدام لغة البرمجة MATLAB اصدار 7.10 كأداة لمحاكاة كل الدراسات المذكورة في هذا العمل.

List of Abbreviations

Symbol	Definition
ANN	Artificial Neural Network
APV	Aluminum Plant and Vessel
CI	Computational Intelligence
DAQ	Data Acquisition Board
de	Change of Error
e	Error
Er	Relative Error
FL	Fuzzy Logic
HE	Heat Exchanger
ISE	Integral Square Error
ITAE	Integral Time-weighted Absolute Error

MLBP	Multi-Layer Back Propagation
Symbol	Definition
MLP	Multi Layer Perceptron
MSE	Mean Square Error
NARMA-L2	Nonlinear Auto Regressive-Moving Average
NN	Neural Network
PHE	Plate Heat Exchanger
PI	Proportional-Integral
PID	Proportional-Integral-Derivative

Nomenclature

Symbol	Definition	Units
A	Area of heat transfer	m^2
C_p	Heat capacity	$J/kg \cdot ^\circ C$
G	Transfer function	–
G_c	Transfer function of controller	–
G_m	Transfer function of measurement	–
G_p	Transfer function of process	–
G_v	Transfer function of control valve	–
K	Steady-state gain of the process reaction curve method	$^\circ C$
K_c	Proportional gain	$Volt/^\circ C$
K_D	Derivative gain	$Volt/^\circ C$
K_I	Integral gain	$Volt/^\circ C$
m_c	Cold water flow rate	Kg/s
M_c	Cold water mass	Kg
m_h	Hot water flow rate	Kg/s
M_h	Hot water mass	Kg
s	Laplacian variable	s^{-1}
t	Time	s
T_{ci}	Inlet cold water temperature	$^\circ C$
T_{co}	Outlet cold water temperature	$^\circ C$
T_{hi}	Inlet hot water temperature	$^\circ C$
T_{ho}	Outlet hot water temperature	$^\circ C$
u	Control Action	–
U	Overall heat transfer coefficient	$W/m^2 \cdot ^\circ C$

Symbol

Symbol	Definition
'	Unsteady state
	Deviation
°	Steady state

INTRODUCTION

Heat exchangers (HEs) are devices that are used to transfer thermal energy between two fluid streams at different temperatures without mixing the two streams. They are one of the most important and frequently used processes in engineering, and one of the thermal components that present nonlinear behavior mainly due to complicated hydrodynamics and temperature dependence of fluid properties^[1-3]. There are several different types of HEs including shell-and-tube, double pipe, plate type and spiral tube. This study is concerned with plate heat exchanger (PHE), which is one of the most common type in practice.

An PHE is a unit which transfers heat continuously from one media to another media without adding energy to the process^[4] and the PHE is widely recognized today as the most economical and efficient type of HE on the market^[5]. PHEs are important components of process and power industry today. Initially, use of the PHEs was limited to hygienic industries such as food processing, pharmaceuticals and dairy industries primarily due to their ease of cleaning. Nowadays they are finding increasing usage over wide variety of applications because of the advantages such as flexibility, higher heat transfer, ease of maintenance, compactness, lower rates of fouling, less effect of flow induced vibration and better controllability^[6]. The PHE consists of a pack of corrugated metal plates pressed together into a frame shown in Fig. (1). A gasket that seals around the plate prevents fluid mixing. It can also be used to create PHE flow configurations such as series, parallel, and multi-pass arrangements by closing and opening ports at the four plate corners^[8,9].

It is very important to know about the behavior of PHEs, when it is subjected transient flow, not only due to possible flow perturbation in the process loop but also to predict the flow variation required to impart control on the PHE when a transient temperature takes place. Dynamic analysis of HEs provides information about transient responses subjected to various disturbances. The dynamic process models can be used for simulation studies to get information about the process behavior; the models can also be used for control or optimization studies. The purpose of the HE is to maintain a specific temperature condition, which is achieved by controlling the exit temperature of one of the fluids in response to variations of the operating conditions.

The control of HE is complex due to its nonlinear dynamics. Traditional control methods have poor performances when applied to industrial processes whose models are strongly non-linear and multivariable -based. Better results can be obtained by applying modern control techniques^[10]. The computational intelligence (CI) techniques, such as FL and ANNs, have been successfully applied in many scientific researches and engineering practices^[11].

Alwan^[12] studied the dynamic behavior and conventional control in PHE. Baker^[13] studied the dynamic behavior and model in PHE. Khan, *et al.*^[14] carried out theoretical and experimental analyses of the dynamic of a counter current flow PHE. Diaz^[15] applied PID control and ANN control on HE. Skrjanc and Matko^[16] evaluated the fuzzy control on HE plant. Diaz, *et al.*^[2] investigated the use of adaptive ANNs to control of HE. Diaz, *et al.*^[17] designed PI, PID control and extended the ANN technique to control in HE. Al-Zobai^[18] conducted a simulation and experimental investigation to study the dynamic and feedback control of PHE while investigated temperature control using fuzzy control experimentally. Berto and JR.^[19] implemented and studied the efficiency of the PID feedback control in a PHE. Kharaajoo and Araabi^[20] designed ANN control of a HE pilot plant. Scariot, *et al.*^[21] studied the dynamic behavior of the PHE. Varshney and Panigrahi^[22] implemented the ANN based control and compared with the PID control on HE. Chen, *et al.*^[23] studied the fuzzy control of the HE. Farahani, *et al.*^[24] dealt with identification and control of ANN for an industrial HE. Mastacan, *et al.*^[25] implemented Fuzzy control in PHE. Mairi, *et al.*^[26] explained PI control and fuzzy control on HE. Kapustenko, *et al.*^[27] developed the simplified models for modeling of PHE. Vasickaninova, *et al.*^[28] studied PID and ANN for control of a HE.

This work is concerned with dynamic behavior of a PHE and the process control implemented using different control strategies through determining a correlation for the overall heat transfer coefficient of the PHE by finding the effect of the hot water flow rate (m_h) on the overall heat transfer coefficient (U) obtained from experimental work. Carrying out the experimental dynamic behavior by measuring the response of the outlet cold water temperature (T_{co}) under different step changes in hot water flow rate (m_h) is compared with the simulation results with MATLAB to implement the mathematical model. Selecting the best control parameters by carrying a tuning procedure using two performance criteria; the integral of the square error (ISE) and integral of the time-weighted absolute error (ITAE). Applying different control strategies such as conventional feedback control, fuzzy logic control and artificial neural network control as well as a comparison among them.

EXPERIMENTS

Experimental setup

The main part of the experimental rig is a PHE. It was manufactured by APV Company Ltd. England type (JHE) serial No. (1062) and the plates are made of stainless steel with gaskets. It contains 24 corrugated stainless steel plates assembled in counter-current configuration, single pass / single pass for both hot and cold streams. The specifications of the PHE are given in table (1). The PHE is arranged as U-type flow configuration. Two circuits: cold water circuit and hot water circuit as shown in Fig. (2) are made to circulate both the fluids through the heat exchanger. Cold fluid is supplied to the heat exchanger where it receives heat from the hot fluid across the plates. It is then sent to the cooling tower where the temperature comes down to the inlet condition. The hot fluid is sent to the PHE and fed back to the hot water tank which is kept at a constant temperature using a

temperature controller. The cold water valve and control valve of hot water are provided to obtain the required flow during the experiments. Hot water is obtained by using the submerged electrical heaters of 1.5 Kw and 3 Kw capacity provided to the hot water tank. The flow rates can be adjusted by the control valve. Flow rates are measured with the rotameters which are located before the fluids enter into the HE. Both hot and cold side rotameters have been calibrated. K-type thermocouples are connected at the entrance and exit pipelines of both cold and hot sides of the exchanger to measure the exchanger response for every one second. The responses are recorded with the help of the data acquisition system. All the thermocouples were calibrated before being used to measure the temperatures of the experimental. The computer control system required a computer and an interface unit. The interface unit consisted of Data Acquisition Board (NI USB-6009), signal conditioning card, relay, and power supply.

EXPERIMENTAL PROCEDURE

The system was calibrated before every experiment and the data collected from the experiments were of two types: steady - state data and dynamic response data.

Steady - State Data

1. The control valve was adjusted to give different flow rates, the hot water flow rate was varied from (0.0497 kg/sec - 0.1159 kg/sec) (laminar flow).
2. The cold water flow rate remained fixed at a constant value of (0.0414 kg/sec) and the thermostat set to 50 °C.

Dynamic Response Data

1. The control valve was adjusted in order to get the desired flow rate of hot water (0.0497 kg/sec).
2. Setting the cold water flow rate to remain fixed at a constant value of (0.0414 kg/sec) and set the thermostat to 50 °C.
3. A step change of (20%) was introduced in hot water flow rate after steady state is reached and the outlet cold water temperature was recorded each five seconds until the new steady state was reached.
4. The same procedure was repeated for different step changes in hot water flow rate (50%, 80%, 100%, 120%, and 135%).

MODEL ASSUMPTIONS

The following assumptions are frequently made in the modeling of PHEs:

1. The physical properties of the water are constant over the range of temperatures employed ^[15, 16, 20].
2. The heat losses to the surroundings are negligible and the two end plates of the exchanger serve as adiabatic walls ^[15, 16, 20].
3. The film coefficient for heat transfer is dependent principally upon the fluid velocity and is proportional to an exponential function of the flow rate ^[15, 16, 20].
4. The heat transfer within the water in any channel is by convection only ^[15, 16, 20].
5. The temperature distributions in all channels belonging to the same stream are identical ^[15, 16, 20].

6. The water will split equally between the parallel channels for each stream ^[15, 16, 20].
7. The thermal capacity of the plate wall is negligible compared with the thermal capacity of the water in the plate ^[15, 16, 20].
8. The plate can be considered as lumped system if the theoretical analysis depends upon inlet and outlet temperatures ^[15, 20].
9. The variation of temperature along the length is neglected ^[15, 20].

These assumptions are incorporated in the development of a lumped parameter model in which the system may be described by unsteady-state energy balances across any specific plate as indicated in Fig. (3). On considering that the overall heat transfer coefficient (U) is a function of the hot stream mass flow rate m_h which in turn is a function of time. Hence in the latter instance U is also a function of time, i.e. $U(t)$.

The steady state energy balance around cold plate gives:

$$m_c^o C_p T_{ci}^o + UA \left[\frac{T_{hi}^o + T_{ho}^o}{2} - \frac{T_{ci}^o + T_{co}^o}{2} \right] - m_c^o C_p T_{co}^o = M_c C_p \frac{dT_{co}^o}{dt} = 0 \quad \dots (1)$$

The steady state energy balance around hot plate gives:

$$m_h^o C_p T_{hi}^o - \left[m_h^o C_p T_{ho}^o + UA \left[\frac{T_{hi}^o + T_{ho}^o}{2} - \frac{T_{ci}^o + T_{co}^o}{2} \right] \right] = M_h C_p \frac{dT_{ho}^o}{dt} = 0 \quad \dots (2)$$

For dynamic studies the flow rate of hot water is chosen as an input variable while the inlet-temperature of cold and hot streams and flow rate of cold water are maintained constants. The overall heat transfer coefficient is a function of thermal resistance offered by hot and cold stream. As the flow rate of cold stream is considered constant, the overall heat transfer expression is given as:

$$U = a m_h^w \quad \dots (3)$$

Substituting equation (3) into equation (1) and(2) and simplification takes the shape as:

$$m_c^o C_p T_{ci}^o - m_c^o C_p T_{co}^o + Z m_h^{ow} T_{hi}^o + Z m_h^{ow} T_{ho}^o - Z m_h^{ow} T_{ci}^o - Z m_h^{ow} T_{co}^o = M_c C_p \frac{dT_{co}^o}{dt} = 0 \quad \dots (4)$$

$$m_h^o C_p T_{hi}^o - m_h^o C_p T_{ho}^o - Z m_h^{ow} T_{hi}^o - Z m_h^{ow} T_{ho}^o + Z m_h^{ow} T_{ci}^o + Z m_h^{ow} T_{co}^o = M_h C_p \frac{dT_{ho}^o}{dt} = 0 \quad \dots (5)$$

Where:

$$Z = \left(\frac{a A}{2} \right) \quad \dots (6)$$

The unsteady state energy balance around the cold plate gives:

$$m_c^o C_p T_{ci}^o - m_c^o C_p T_{co}^o + Z m_h^o T_{hi}^o + Z m_h^o T_{ho}^o - Z m_h^o T_{ci}^o - Z m_h^o T_{co}^o = M_c C_p \frac{dT_{co}'}{dt} \quad \dots (7)$$

The unsteady state energy balance around hot plate gives:

$$m_h^o C_p T_{hi}^o - m_h^o C_p T_{ho}^o - Z m_h^o T_{hi}^o - Z m_h^o T_{ho}^o + Z m_h^o T_{ci}^o + Z m_h^o T_{co}^o = M_h C_p \frac{dT_{ho}'}{dt} \quad \dots (8)$$

By linearizing non-linear terms, the introduction of deviation variables and the application of the Laplace transform, equations (7) and (8) may be simplified and solved simultaneously to give the transfer function [30]:

$$G_{(s)} = \frac{\bar{T}_{co(s)}}{\bar{m}_{h(s)}} = \frac{H (1 + t_a s)}{t_p^2 s^2 + 2 \gamma t_p s + 1} \quad \dots (9)$$

Thus if U is considered to be a function of t then the resulting transfer function $G_{(s)}$ between $\bar{T}_{co(s)}$ and $\bar{m}_{h(s)}$ represents a second-order lag with time constant τ_p and damping coefficient γ combined with a first order lead element having a time constant τ_a . The initial conditions used are listed in table (2).

CONTROL OF HEAT EXCHANGERS

A) Conventional PI and PID control

PI control is probably the most commonly used technique. PID control is one of the earlier control strategies and it's the most popular controller used in process control systems due to its remarkable effectiveness and simplicity of implementation [31]. Its actual signal of PI and PID control is related to the error by the equations [32]:

$$C(t) = K_c E(t) + \frac{K_c}{t_i} \int_0^t E(t) dt + C_s \quad \dots (10)$$

$$C(t) = K_c E(t) + \frac{K_c}{t_i} \int_0^t E(t) dt + K_c t_d \frac{dE}{dt} + C_s \quad \dots (11)$$

Where: $C(t)$: controller output, K_c : proportional gain of the controller, τ_i : integral time constant, τ_d : derivative time constant, C_s : initial value of controller, $E(t)$: error (difference between measured signal and set point).

Performance of feedback controllers depends on the values of their chosen parameters. process of choosing these parameters is known as controller tuning [33]. The following two methods are preferred here those of Cohen-Coon method [34] and Ziegler-Nichols method [35]. The main two methods of the time integral performance criteria used in the proposed work evaluated in terms of [33]:

✓ Integrated square error (ISE)

$$ISE = \int_0^{\infty} e^2 dt \quad \dots (12)$$

Integrated time-weighted absolute error (ITAE)

$$ITAE = \int_0^{\infty} t |e| dt \quad \dots (13)$$

B) Fuzzy logic (FL) control

FL is much closed in spirit to human thinking and natural language than classical logical systems. Nowadays FL is used in almost all sectors of industry and science [36-38]. The idea of FL controller was initially introduced by Zadeh (1973) and first applied by Mamdani (1974) in an attempt to control systems that are difficult to model mathematically [39]. FL Controller usually comprises of a fuzzification interface, data base, rule base, inference mechanism and a defuzzification interface [37, 40, 41]. A block diagram of FL control system is shown in Fig. (4).

C) Artificial neural network control

An ANN takes their name from the network of nerve cells in the brain [43] and it's a flexible mathematical structure, having strong similarity to the biological brain [44]. The most common for chemical engineering application is Multi Layer Perceptron (MLP), which is a feed forward neural network. It consists of multilayer structure, which apart from input and output layers, has at least one layer of processing units in between them. The layers between the input and output layers are termed "hidden"[45]. Feed their outputs to the next hidden nodes is shown in Fig. (5). The BP learning algorithm is currently the most popular learning rule for performing supervised learning tasks [46]. A learning algorithm of an MLP is called a Multi-Layer Back Propagation (MLBP) [11].

RESULTS AND DISCUSSION

The results obtained from the computer programs using MATLAB program version 7.10 for dynamic model and control. The first part shows the results of the open loop experimental and theoretical response for different magnitudes of step change in hot water flow rate. The second part shows the results of the control system using different control strategies.

Open Loop System**✓ Steady state results**

In Fig. (6) the values of overall heat transfer coefficient (U) are plotted against hot water flow rate (m_h), from which the correlation is:

$$U = 11045 m_h^{0.7158} \quad \dots (14)$$

The constant 1145 and 0.7158 were obtained experimentally, and the value of (R) the regression factor is 0.847.

✓ Dynamic behavior

The dynamic responses were studied for different step changes +ve (20%, 50%, 80%, 100%, 120% and 135%) in the manipulated variable (m_h) in order to study the effect of each change on the controlled variable (T_{co}). The theoretical results are compared with experimental results for different step changes. Fig. (7) represents the comparison between experimental and theoretical outlet cold water temperature response. It can be seen that the increase in (m_h) is directly proportional to (T_{co}) for different steps in (m_h) for theoretical and experimental work. Table (3) illustrates the relative error (Er), mean square error (MSE) between experimental and theoretical responses, the steady-state gain (K) and the time constant (τ) experimentally by using process reaction curve and shows that the theoretical results are in good agreement with experimental results. Also the analysis indicated that the process can be experimentally represented by first order.

Closed Loop System

Different control strategies are used: conventional feedback control, classical FL control, ANN control and PID fuzzy control. The value of hot water flow rate used in the control system is (0.0993) (kg/sec) and the value of cold water flow rate is (0.0414) (kg/sec).

A) Conventional Feedback Control

Conventional feedback control was applied using PI and PID modes to control the outlet cold water temperature. The tuning of the control parameters (proportional gain (k_c), time integral (τ_i) and time derivative (τ_d)) were applied. The optimum values of the controller parameters were tuned by using computer simulation programs based on minimum (ISE) and minimum (ITAE). The results of the control tuning parameters are given in table (4). Fig. (8) show the control response for PID mode for two different criteria. As shown in the Fig. (8) and table (4), it is clear that the overshoot and setting time of Ziegler-Nichols method are less than of the Cohen-Coon method for both PI and PID modes because Ziegler-Nichols method depends on closed loop system while Cohen-Coon method depends on open loop system. To evaluate the performance of the PI and PID controllers three parameters of the step response and the parameters (overshoot, settling time and rise time) have been considered and given in the table (5). Fig. (9), shows the comparison between two control modes. It is clear that PID mode gave better response that is clear through the lower values of the overshoot and response time. So PID controller is used in this work as a feedback mode of comparison with the other modes of a classical fuzzy, ANN and PID fuzzy controllers.

B) Fuzzy Logic Controller

The control tuning of the FL controller depends on the trial and error to find the scaled factors for each variable. The best values of the scaled factors were tuned using simulink program. The simulation model of PHE with classical FL controller is illustrated in Fig. (10). For the classical FL controller the input variable are error (e) and change of error (de), the output variable is the control action (u). The universe of discourse of error, delta error and output are [-1, 1], [-0.15, 0.15] and [-1, 1] respectively. The rule base that have been taken proposed by Mamdani fuzzy system.

The comparison between the transient response for PID and classical FL controller is shown in Fig. (11). Table (6) shows the performance criteria for classical FL and PID controllers. As shown in Fig. (11) and table (6), it's clear that the classical FL controller performs better compared to PID controller in terms of overshoot. But, on comparing the ISE, ITAE, settling time and rise time of both controller, the PID controller performs better because of the trial and error depending of FL controller tuning process.

C) Artificial Neural Network NARMA-L2 Controller

In order to evaluate the effectiveness of the NARMA-L2 control, the controller is implemented and applied to control PHE. NARMA-L2 control is one of the popular neural network architectures that have been implemented as simulink block in MATLAB software version 7.10 which contained in the neural network toolbox blockset. Fig. (12) illustrates the simulation model of PHE with ANN NARMA-L2 controller.

D) PID Fuzzy Controller

The FL controller structure can be classified into different types, and the most popular one is PID fuzzy controller. The control tuning of the PID fuzzy controller depends on the trial and error to find the scaled factors for each variable^[47]. The best values of the scaled factors were tuned using simulink program. The simulation model of PHE with PID fuzzy controller is illustrated in Fig. (13). The inputs of PID fuzzy control are defined as the proportional gain (K_c), integral gain (K_i) and derivative gain (K_d). The output variable, is called the control action (u). By trial and error the proportional gain has a range of [0, 1.25], integral gain has a range of [-2, 2], derivative gain has a range of [0.1, 1.25] and control action has a range of [0, 1.25].

E) Comparison Among PID, ANN And PID Fuzzy Controllers

A comparison among different control strategies of the transient response for the PHE with PID, ANN and PID fuzzy controllers as shown in Fig. (14). To evaluate the performance of different controllers parameters of the step response of the system have been considered. In all the three controllers the performance indices of different controllers are the ISE and ITAE as well as the parameters are evaluated and comparative studies of their performance are tabulated in the table (7).

From Fig. (14) and table (7), the simulation results clearly show that the PID fuzzy controller gives better control of temperature rather than PID controller and ANN controller. It has been seen that more accurate results were obtained using ANN controller over PID controller, further better results obtained by using PID fuzzy controller. From the above observations it is clear that the PID controller produces high values of overshoot and settling time. To compensate this kind of high values, ANN controller has been implemented. By implementing this method the system overshoot and settling time were reduced. For further reduction requirements, the PID fuzzy controller was suggested. ISE and ITAE of PID fuzzy controller show lower values compared to other modes which indicates the robust control of this controller. Although PID fuzzy mode gave better performance, but the high value of the rise time shows one of its disadvantages. The reason for that high value is the significant time investment needed to correctly tune membership

functions and adjust rules to obtain a good solution. The more rules suggested, the increasing difficulty obtained. The results required more system memory and processing time ^[47]. The results showed that the PID fuzzy controller is slightly better than ANN controller. From these observations it is clear that PID fuzzy controller is a much better option for control rather than PID and ANN controller because PID fuzzy controller combines the advantages of a fuzzy logic controller and a PID mode.

CONCLUSIONS

Based on this study of dynamics and control of a PHE, the following conclusions can be derived:

1. The experimental heat transfer measurements of the PHE show that the overall heat transfer coefficient (U) is related to the hot water flow rate (m_h) by a correlation having the form:

$$U = 11045 m_h^{0.7158} \quad \dots (15)$$

2. The PHE model is found theoretically as a first order lead and second order overdamped lag while the experimental PHE (using PRC method) represented dynamically as first order with a negligible dead time value.
3. PID feedback controller is better than PI feedback controller because it gives smaller ITAE, ISE, overshoot, settling time and rise time values.
4. PID controller performs better when it is compared to classical fuzzy logic controller because of the trial and error depending of fuzzy logic controller tuning process.
5. Artificial neural network controller is better than feedback and classical fuzzy logic controllers because the artificial neural network controller learns system and it has got generalization capabilities.
6. The PID fuzzy controller gives a much better control performance of temperature rather than PID controller and artificial neural network controller because PID fuzzy controller combines the advantages of fuzzy logic controller and a PID controller.

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Table (1) Plate heat exchanger specifications ^[29].

Plate length (cm)	58.0
Plate width (cm)	7.0
Plate thickness (mm)	1.0
Equivalent diameter of channel (mm)	4.0
Channel flow area (m ²)	1.4*10 ⁻⁴
Plate pitch (mm)	3.0
Mean flow channel gap (mm)	2.0

Table (2) System and operating conditions.

Cold water flow rate	m_c	0.0414 (kg/sec)
Hot water flow rate	m_h	0.0497 (kg/sec)
Temperature of initial cold water	T_{ci}	20 (°C)
Temperature of initial hot water	T_{hi}	50 (°C)
Specific heat capacity	C_p	4174 (J/kg.°C)
Water density	R_o	993 (kg/m ³)
Length of plate heat exchanger	L	0.58 (m)
Width of plate heat exchanger	E	0.07 (m)
Thickness of one plate heat exchanger	S	0.001 (m)
Length of fluid in plate heat exchanger	L_{fluid}	0.50 (m)
Width of fluid in plate heat exchanger	E_{fluid}	0.065 (m)
Thickness of fluid in plate heat exchanger	S_{fluid}	0.046 (m)

Table (3) the relative error (Er), mean square error (MSE) between experimental and theoretical (T_{co}) response and system parameters for different step changes.

m_h	Er	MSE	k	τ (sec)
20%	0.1110	3.3329e-004	103.62	36.45
50%	2986.5	0.7588	96.58	35.71
80%	0.9694	0.0254	95.82	32.78
100%	0.8960	0.0217	94.96	30.53
120%	5.8441	0.9231	93.9	30
135%	1.8257	0.0901	93.3	29.2

Table (4) Control parameters of PI and PID controllers.

Control tuning methods	Controller parameters			ITAE	ISE
	K_c	τ_I	τ_D		
Ziegler-Nichols tuning (PI)	10.6614	0.1587	—	0.2163	0.2517
Cohen-Coon tuning (PI)	10.8959	0.1596	—	0.2795	0.2804
Ziegler-Nichols tuning (PID)	13.7972	0.0952	0.0238	0.0298	0.1236
Cohen-Coon tuning (PID)	16.1441	0.1181	0.0175	0.1871	0.2705

Table (5) Comparison of different parameters of PI and PID controllers.

Parameters	PI controller	PID controller
Overshoot %	2.177	2.12
Settling time	1.61	0.73
Rise time	0.086	0.077

Table (6) Comparison between the performance of classical FL controller and PID controller.

Parameters	Classical FL controller	PID controller
ISE	0.4655	0.1236
ITAE	0.2187	0.0298
Overshoot %	1.006	2.12
Settling time	2.575	0.73
Rise time	2.715	0.077

Table (7) Comparison of different performance indices and different parameters in controllers.

Parameters	PID controller	ANN controller	PID fuzzy controller
ISE	0.1236	0.0601	0.0547
ITAE	0.0298	0.0091	0.0031
Overshoot %	2.12	1.049	1
Settling time	0.73	0.462	0.432
Rise time	0.077	0.5	0.599

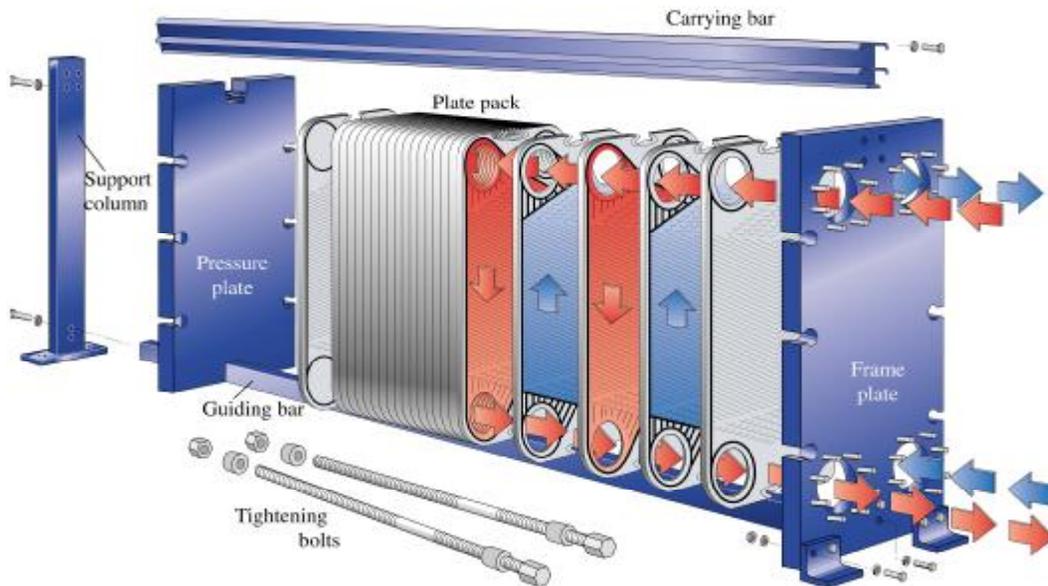


Figure (1) Gasketed plate-and-frame heat exchanger [7].

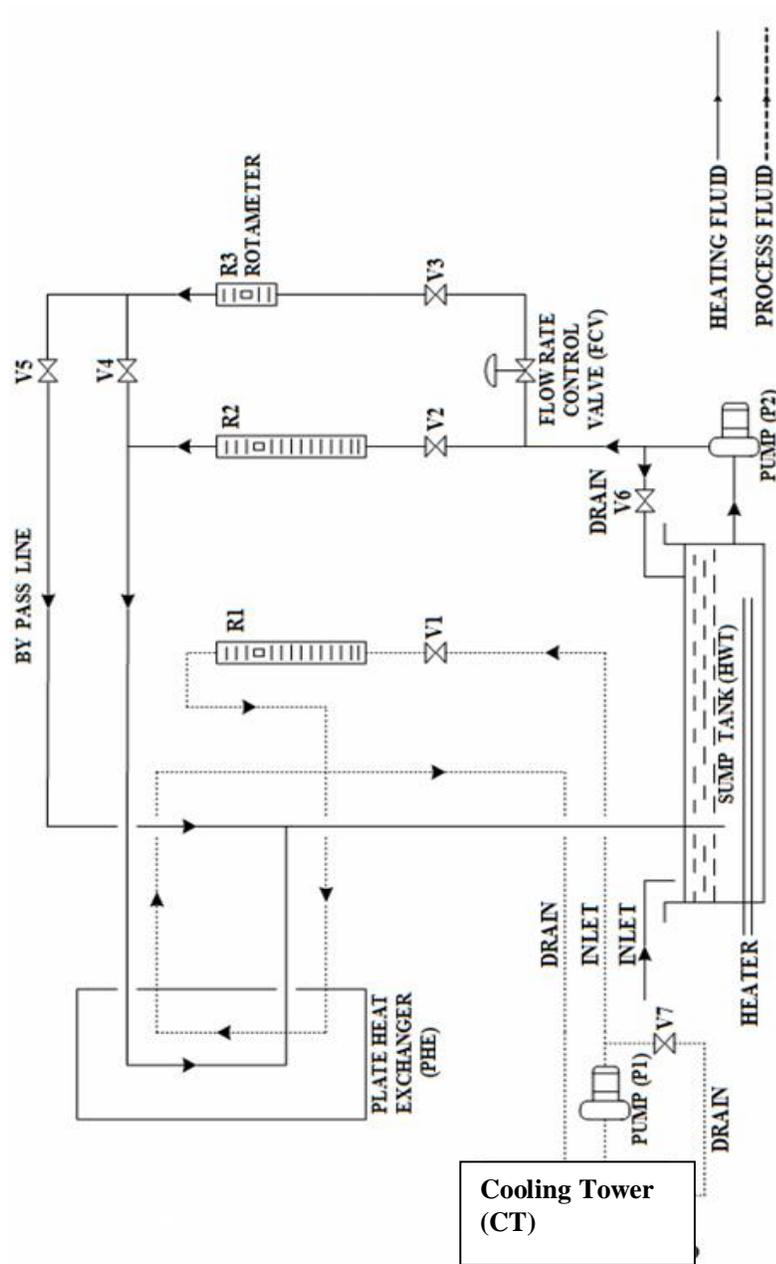


Figure (2) Schematic diagram of the experimental rig.

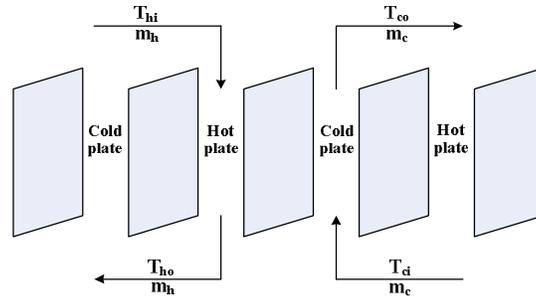


Figure (3) Arrangement of cold and hot streams for PHE(as lumped system).

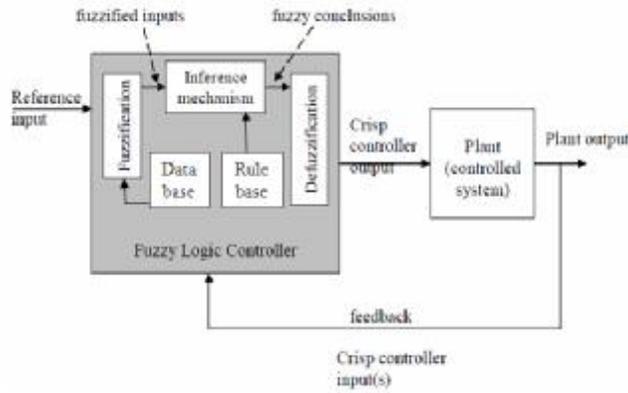


Figure (4) Fuzzy logic control system [42].

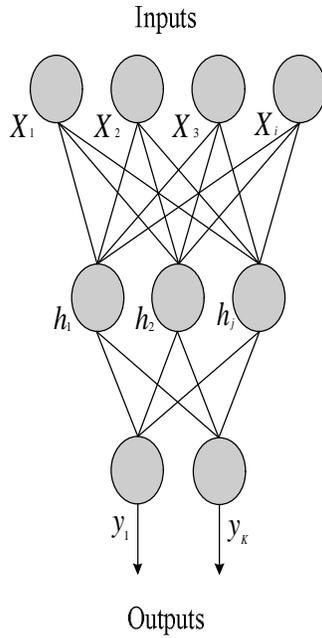


Figure (5) The multi-layer perceptron neural network arrangement.

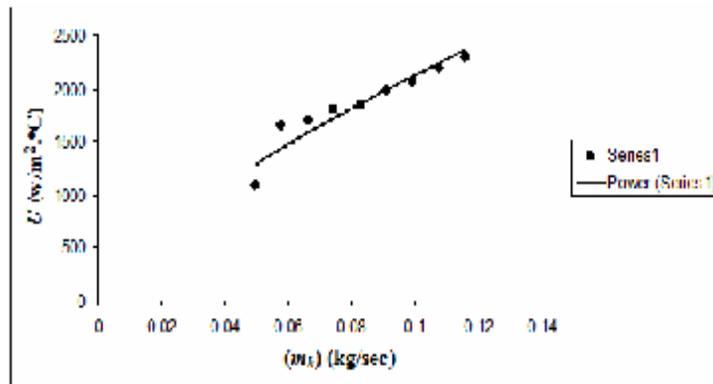


Figure (6) The relation between overall heat transfer coefficient (U) and hot water flow rate (m_h).

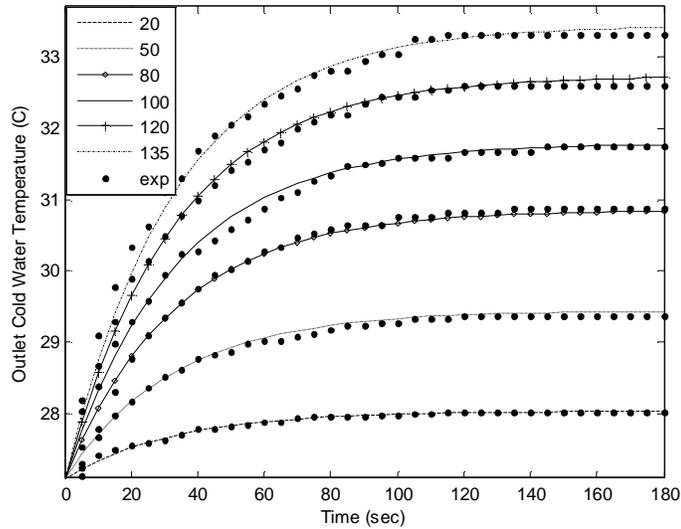


Figure (7) Comparison between experimental and theoretical (T_{co}) response for +ve different step changes in (m_h).

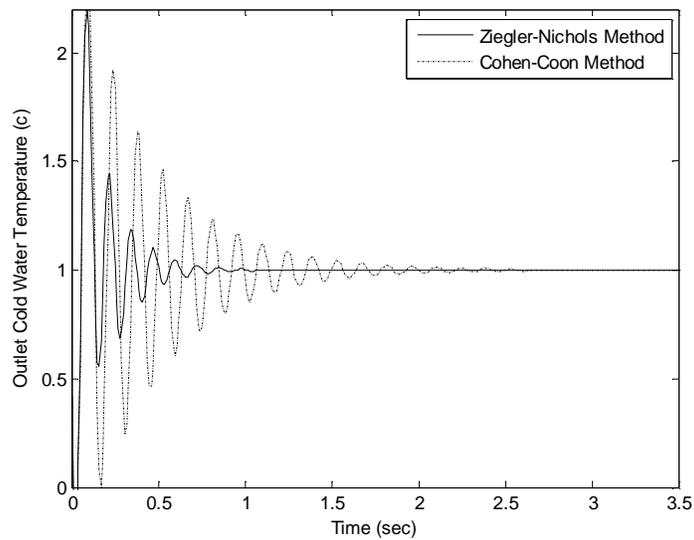


Figure (8) Transient response of the PHE with PID controller mode (unit step change).

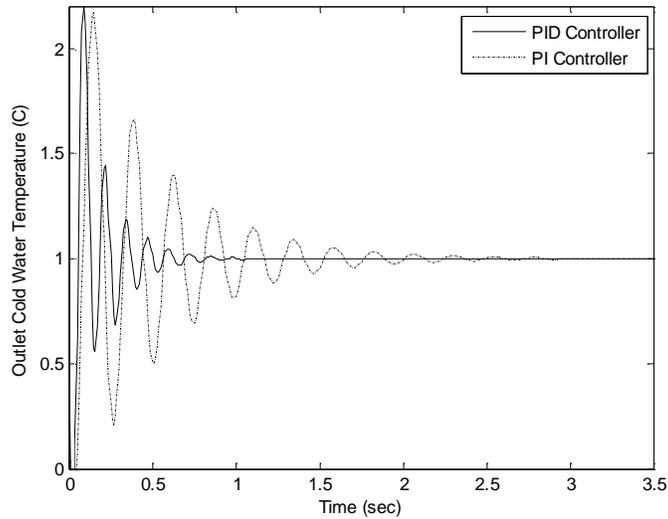


Figure (9) The comparison between the transient response for PI and PID controllers (unit step change).

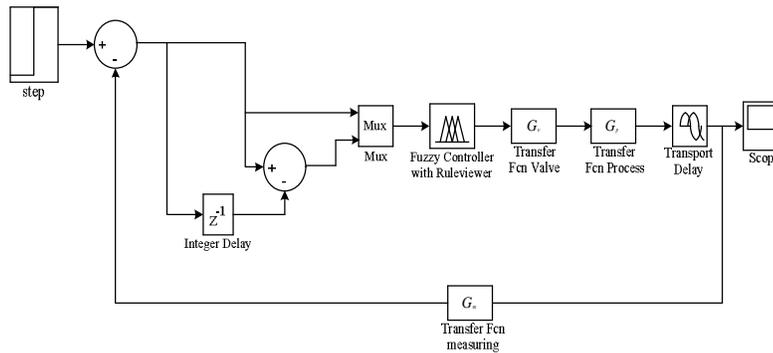


Figure (10) Simulation model of PHE with classical FL controller.

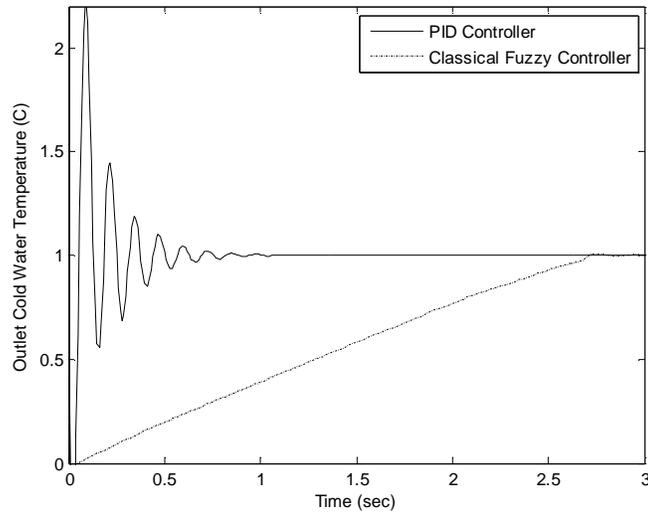


Figure (11) The comparison between the transient response for PID and classical FL controllers.

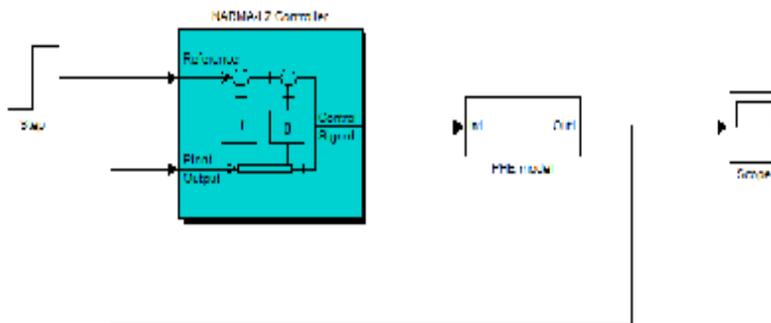


Figure (12) Simulation model of PHE with ANN NARMA-L2 controller.

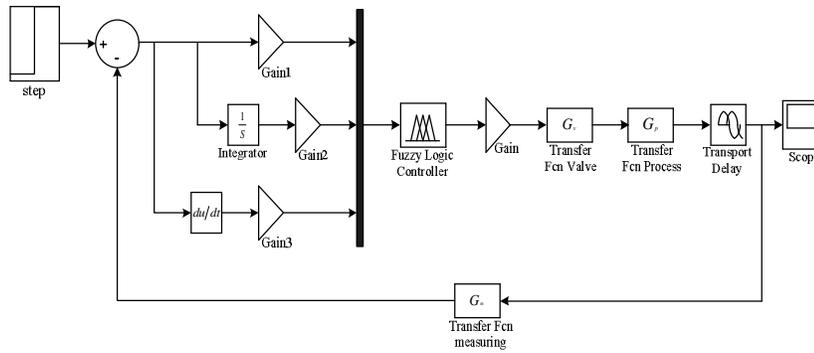


Figure (13) Simulation model of PHE with PID fuzzy controller.

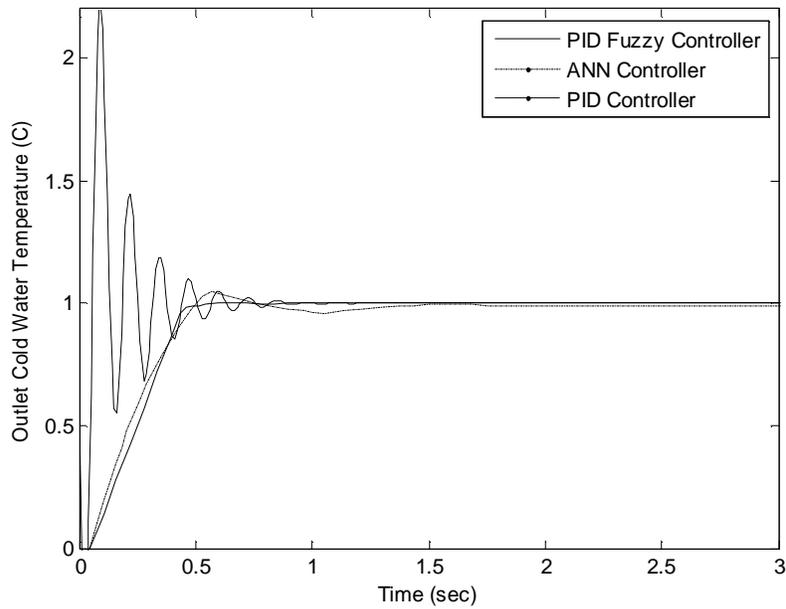


Figure (14) The comparison among the transient response for PID, ANN and PID fuzzy controllers.