Dynamics and Control of Double-Pipe Heat Exchanger

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Abstract

Experimental investigation was conducted to study the dynamics of double-pipe heat exchanger using step change in flow rate of hot water and observe its effect on the temperature of cold water and it was found that the transfer function can be represented by first order system plus dead time (FOPDT).

$$G(s) = \frac{0.6 \, e^{-4s}}{20 \, s + 1}$$

MATLAB 7.4 simulation and programming was used to show the response of close-loop system using P, PI, PID and fuzzy logic control.
The Smith predictor was used to remove the effect of transport delay on the process and it was found that this method greatly improve the response of the system. The stability of the overall closed loop system was proved by using Bod plot diagram.

Introduction

Simple double pipe heat exchanger consist of concentric pipes. It is commonly used in applications involving relatively low flow rates and high temperature or pressure, for which they are well suited. other advantage include low installation cost, ease of maintenance, and flexibility [Robert ,2007]

[Gerard ,1974] formulated a model for a counter flow heat exchanger, which has taken into account variation of the heat transfer coefficient with respect to fluid flow rates and temperature. The approach used in this study to solve four nonlinear partial differential equations by linearization method . Experimental investigation using various test such as step function and sine wave was conducted. The results showed that the transfer function with variation of temperature in both stream could be approximated by the following forms:

$$G(s) = \frac{k e^{-\tau_D S}}{(\tau s + 1)} \qquad \boxed{1}$$

$$G(s) = \frac{K(\tau_3 s + 1)}{(\tau_1 s + 1)(\tau_2 s + 1)} e^{-\tau_D S} \qquad \boxed{2}$$

[Burn ,1981] used lead / lag approximation in modeling a double pipe heat exchanger system. The analysis involved extraction of successive real poles and zeros of the system transfer functions for temperature or flow forcing. [Shinsky,1967] formulated a model describing dimensionless temperature as function of flow rates.[Stephanopouls,1967] shown that the heat exchanger can be represented by a partial differential equation i. e distributed parameter system.[Timothy,2004] studied a double pipe helical heat exchanger numerically and experimentally for both heat transfer and hydrodynamic characteristics. Simulation were performed using various flow rates, his study involved the determination of uniformity of the residence time and temperature distribution as well as the heating-cooling uniformity.[Sudhir et al.,2006] used neural network for controlling temperature of double pipe heat exchanger .The results indicated that the feedback control system is suitable when the process detail are known completely. whereas neural network control is useful for the process with nonlinear and less knowledge about the process.[Anton et al.,2009] indicated that some parameters ,for example fluid density and heat capacity are not constant in operating temperature rang and this introduced anon-negligible nonlinearities in heat exchangers modeling.

The aim of this work is to find the transfer function of the double pipe heat exchanger experimentally and then using a MATLAB simulink to study the closed loop system via applying both conventional and advanced control methods.

Process Identification

Experimental identification of process dynamics has been an active area of search for many years by workers in several area of engineering.
A time domain fitting of step test data is the most direct way to obtaining an empirical linear dynamics model of process in order to find the parameter (dead time, time constant and process

gain) that fit the experimentally obtained step response data. The process is being identified is usually open loop, but experimental testing of close loop system is also possible. A step disturbance in hot water flow rate was introduced and record the temperature of could water . probably 80% of open loop process can be modeled by gain, a dead time, and one lag.

$$G(S) = k\frac{e^{-DS}}{\tau S + 1} \qquad 3$$

The steady state process gain (k) is equal to the ratio of the final steady state change in the output over the size of input, while the time constant estimated from the response by using several methods such as time takes (63.2) percent of the final steady state change and initial slop methods [Luyben,1997]. Bode plots is used to examine the stability of the system and evaluate the gain and phase margin. The gain margin is found by using the phase plot to find the frequency, where the

phase angle is 180. At this frequency look at the magnitude plot to determine the gain margin which is the gain required to raise the magnitude curve to 0 db. A positive gain margin mean that the system is stable, and negative gain margin mean that the system is unstable. [Luyben, 1997]
The phase margin is found by using the magnitude curve to find the frequency when the gain is 0 db. On the phase curve at that frequency, the phase margin is the difference between the phase value and 180.

Mathematical model of a heat exchanger

For double pipe heat exchanger, a liquid flows through the inner tube and it is being heated by another liquid that flows counter currently around the tube. The temperature of the inner liquid not only changes with time but also changes along the axial direction z, the energy balance equation is:-

$$\rho C_p A\Delta z[(T)|_{t+\Delta t} - (T)_t\ ] = \rho C_p\ VA(T)|_z\Delta t - \rho C_p\ VA(T)|_{z+\Delta z}\Delta t + Q\Delta\pi D\Delta Z \qquad 4$$

Dividing by $\Delta Z\Delta t$ and taking the limit of ΔZ and Δt go to zero yields

$$\rho C_p A\frac{\partial T}{\partial t} + \rho C_p\ VA\frac{\partial T}{\partial z} = \pi DQ \qquad 5$$

Where Q=U(T_{h_i}-T), substitute in Eq. (5) , yields:

$$\rho C_p A\frac{\partial T}{\partial t} + \rho C_p\ VA\frac{\partial T}{\partial z} = \pi DU(T_{h_i}\text{-T}) \qquad 6$$

Where
Q=amount of heat transferred from hot fluid to other per unit of time and unit of heat transfer area.
A=cross-sectional area of the inner tube.
V=average velocity of the inner liquid .
D=external diameter of the inner tube
U=overall heat transfer coefficient.

PID controller

The PID controller is widely used in industry. The transfer function is expressed as follows:-

$$Gc = Kc(1 + \frac{1}{\tau_i s} + \tau_D s) \qquad 7$$

It is very robust and can be used when we do not know the plant model very accurately. The design process involves finding values of K_c, τ_i and τ_D such that the design specifications are satisfied.
The PID gain search process is sometimes referred to as tuning. For certain plant type, The Ziegler-Nicolas method provides a structure tuning procedure, however not all plants are amenable to that type of tuning. One method relies on interactive computer simulation and analysis. Initial nominal gain values are choose , and then tune the controller parameters by simulating the response and verifying that the performance is acceptable. If the performance is not acceptable, update the gains and iterate the process. Naturally MATLAB is very helpful in this process. [Bishop,1977]

Smith predictor

A Smith predictor was used to design a controller to remove the effect of transport delay . The first step to design the controller $G_c(s)$ is to design a suitable controller $\hat{G}_{cs}$ (s) when the system has no dead time. J.M. Smith designed an

innovative controller scheme, to control the plant with dead time. The Smith predictor consist of $G_c(s)$, dead time e^{-DS}, and the plant transfer function $G(s)$.

Figure (1) shows the Smith predictor as a minor loop in the block diagram. The transfer function between v(s) and E(s) is

$$\frac{V(s)}{E(s)} = \frac{\hat{G}_c(s)}{1 + (1 - e^{-Ds})\hat{G}_c(s)G(s)} \qquad 8$$

Then the close-loop transfer function C(s)/R(s) can be given by

$$\frac{C(s)}{R(s)} = \frac{\hat{G}c(s)G(s)e^{-Ds}}{1 + (1 - e^{-Ds})\hat{G}c(s)G(s) + \hat{G}c(s)G(s)e^{-Ds}} \qquad 9$$

$$\frac{\hat{G}c(s)G(s)}{1 + \hat{G}c(s)G(s)}e^{-Ds} \qquad 10$$

Hence the block diagram of figure (1) can be modified to that of figure (2). The close-loop response of the system with dead time (e^{-DS}) is the same as the response of the system without dead time (e^{-DS}), [Ogata]
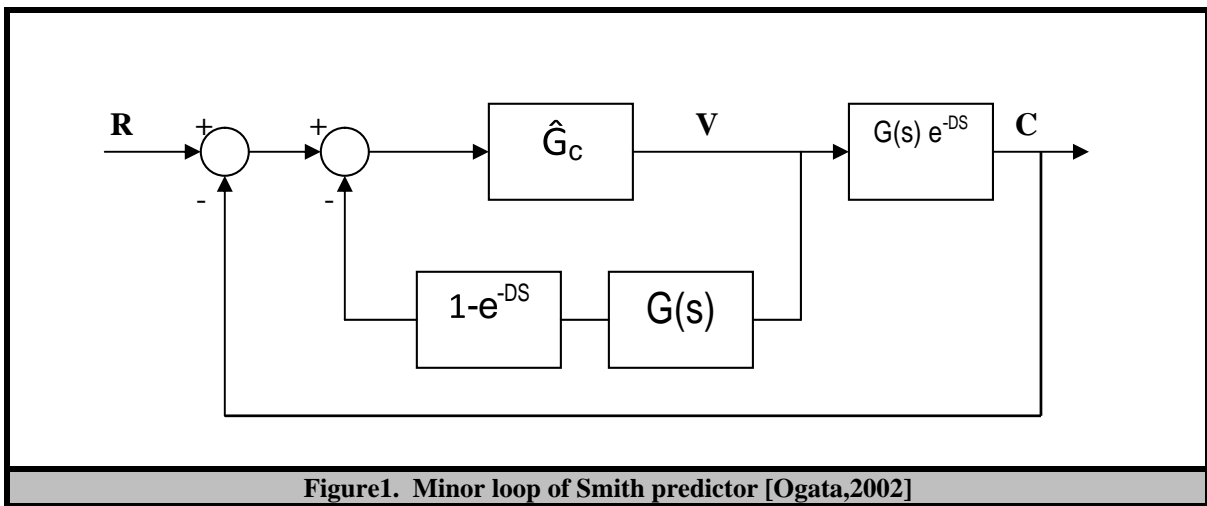
Figure1. Minor loop of Smith predictor [Ogata,2002]
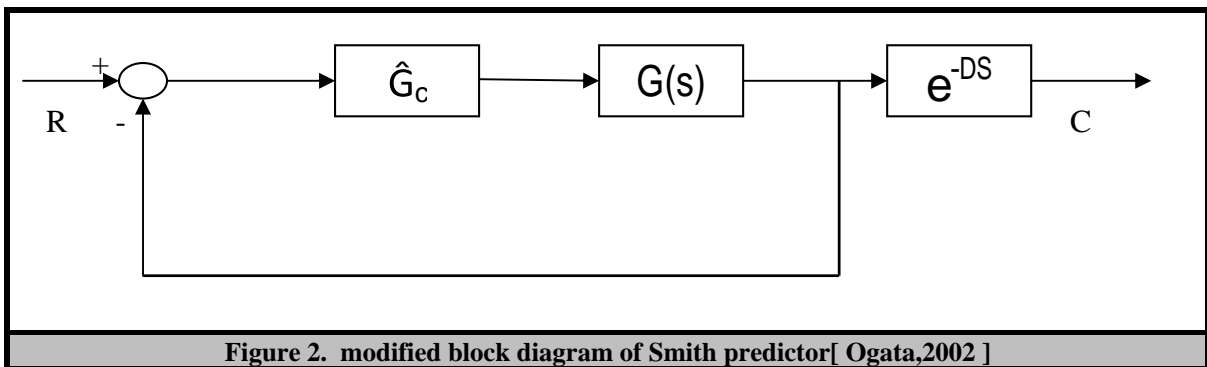
Figure 2. modified block diagram of Smith predictor[Ogata,2002]

3.10 Fuzzy Logic Control (FLC)

Fuzzy logic is a super set of traditional logic, according to [Zadeh,1989], who invented this concept in 1965. He said it is the logic of approximate reasoning and it is unlike other branches of artificial intelligence (AI) that use conventional logic. Since then, the theory of mathematics has gained more recognition from many researches in a wide range of scientific fields.

Fuzzy mathematics is attractive not only because it is based on the very intuitive idea of Fuzzy sets, but because it is capable of generating many structures that provide today's scientists and engineers with new insights into interesting, significant and often-debated problems in both science and engineering. [Zadeh L.A , 1989]

The theory of Fuzzy sets has one of its aims, the development of a methodology for the formulation and solution of problems that are too complex or too ill-defined to be analyzed by conventional techniques.

Hence the theory of Fuzzy sets is likely to be recognized as a natural development in the evaluation of scientific thinking [McCusker,1990].

The Fuzzy logic can be considered as a tool of promise for control. It can AL's sector, which ensures to enhance tomorrow's industrial control system [Zadeh ,1989].

Experimental work:-

The process involved a pilot plant of double pipe heat exchanger consisted mainly of two concentric pipes assembled in counter-current configuration single pass. The specification of double pipe are 37 mm outer diameter, 12 mm inner diameter and 1 m length was used.

Hot and cold water were employed as circulating fluid. steady state values of cold and hot water flow rates are 300 and 600 l/min respectively. After reach the desired temperature of hot water tank (341K), and steady-state of cold water stream temperature (103K),a step change in hot water flow rate was introduced and record the outlet temperature of exit cold water each two second until a steady stat was reached and noting the apparent dead time.
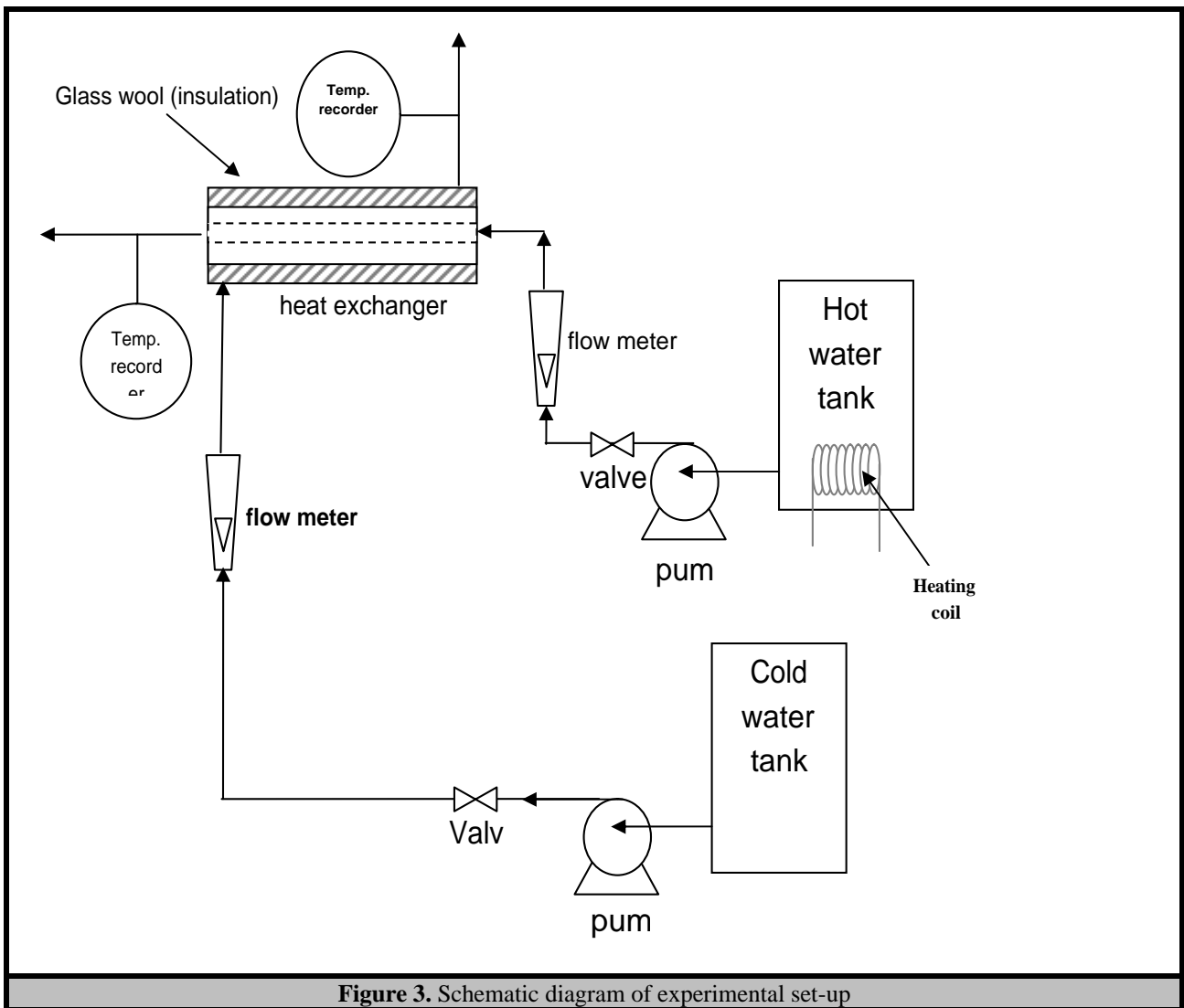

Figure 3. Schematic diagram of experimental set-up

Results and Discussion

- ### System identification

The actual response of the outlet could water temperature using step change in hot water flow rate is shown in figure 4. A process reaction curve was used to find the process parameters. From the shape of the response (using deviation variable), it is clearly that the system can be represented by first order system plus dead time (FOPDT)

$$G_p(s)=\frac{ke^{-DS}}{\tau s+1} \qquad 11$$

Where:

K is a process gain = 0.6 k/(k$_g$/s)
τ is the time constant =20 s
D is the transport delay = 4 s

A theoretical value of the sped of response (τ= m C$_p$ /h A) is 25s. The deviation between the theoretical and experimental value is due to a neglected the variation of heat transfer coefficient with respect to fluid flow rates and temperature. The transport delay involved the heat exchanger and all the accessories between the valve of hot water and temperature recorder.
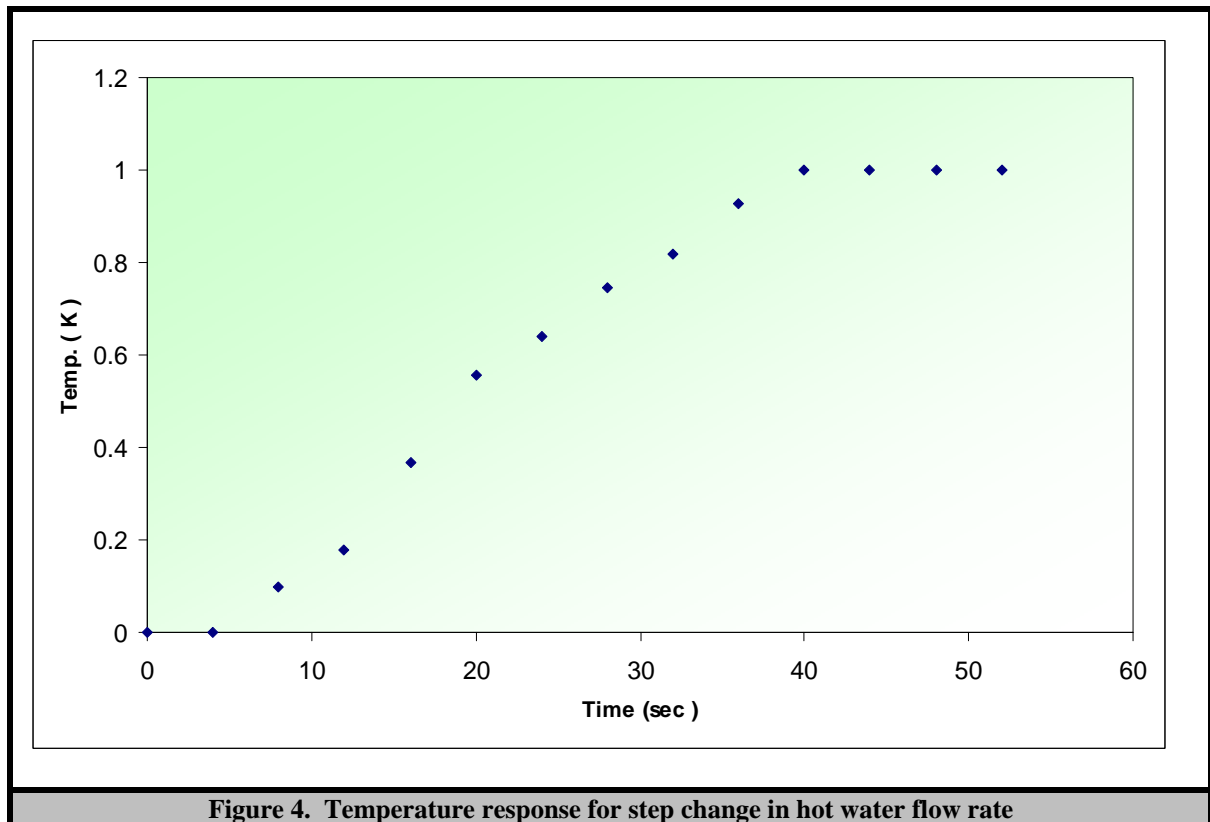
Figure 4. Temperature response for step change in hot water flow rate

If the system is first order, then the output response curve has anon-zero slope at the initial time. The response of the system with a relative order greater than one has zero slope at initial time. [wayne Bequette ,1998]

Closed loop

For simplicity we assume that the transfer function of close-loop system involved only the transfer function of process and controller due to small time constant of valve and transmitter compared with process and controller.
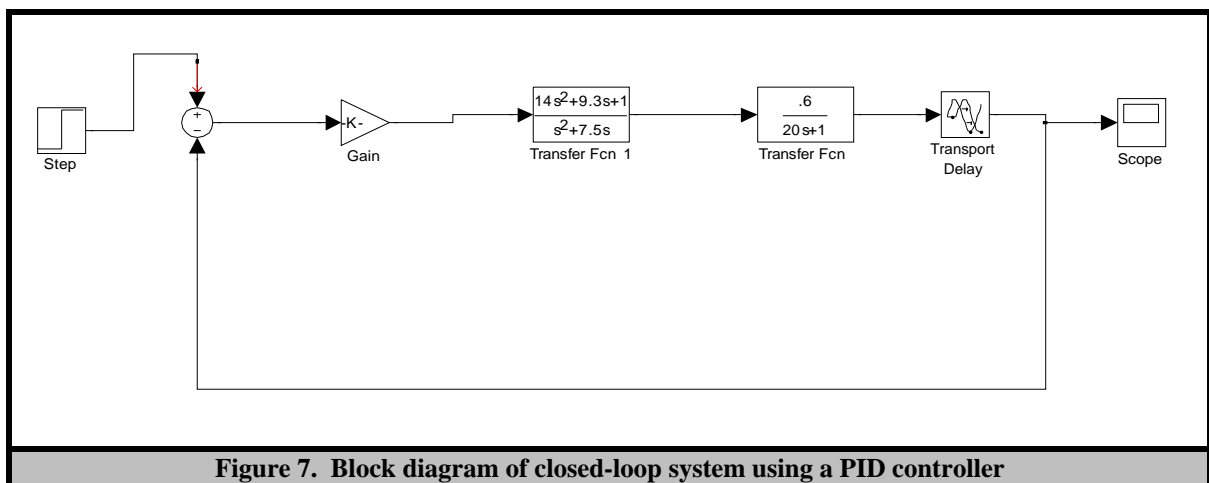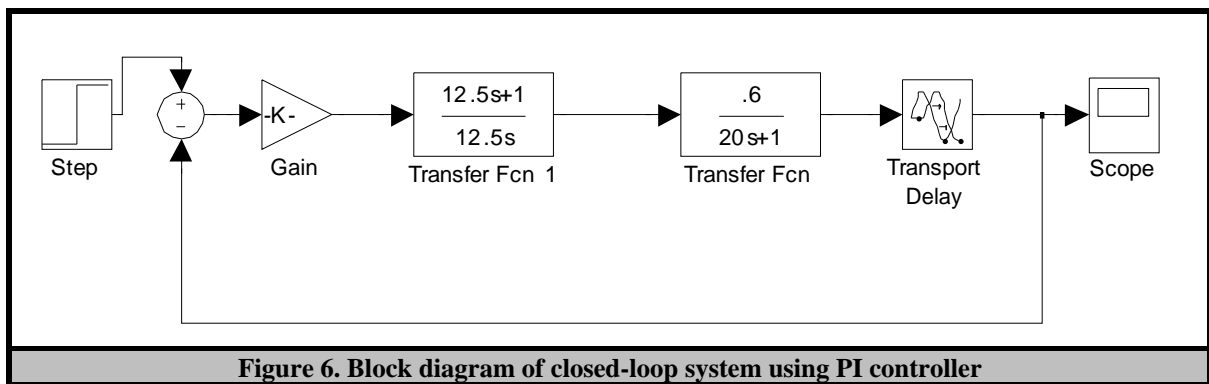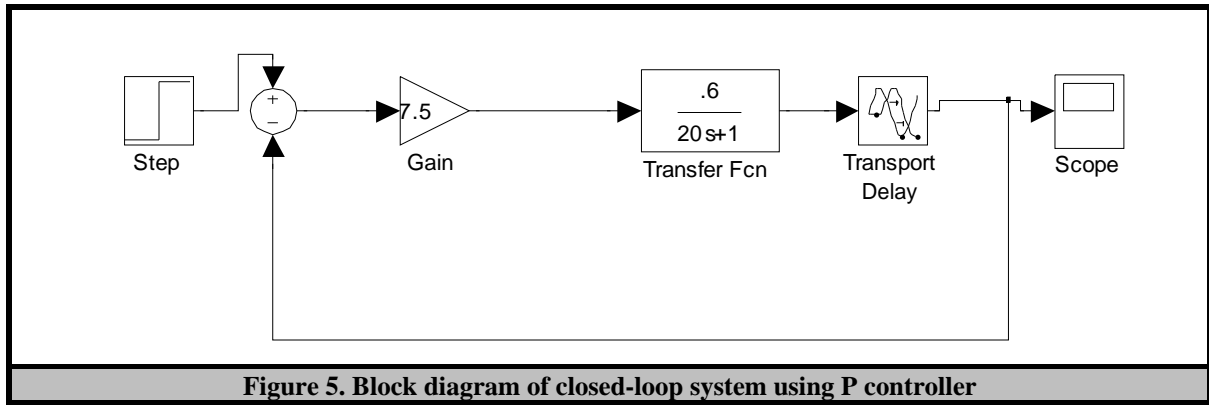
A servo problem was considered using MATLAB simulink via unit step change in set point of controlled variable which is the outlet
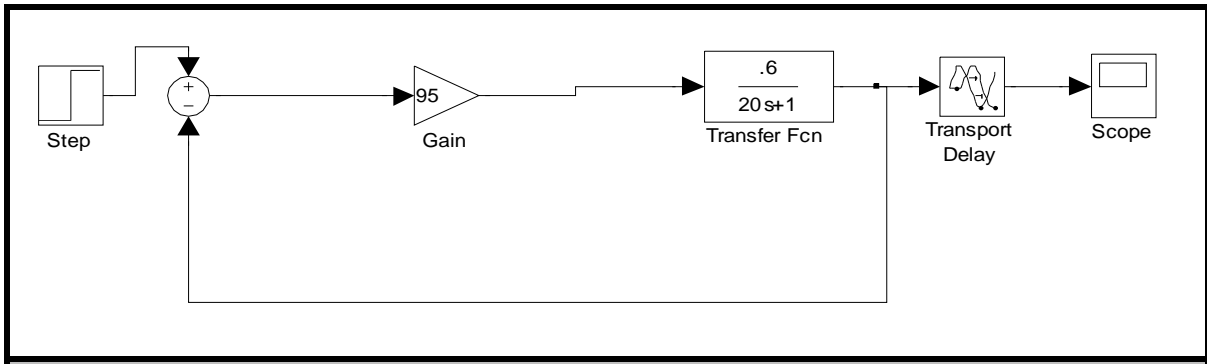
temperature of cold water stream .The initial tuning constants(proportional gain (K$_c$), time integral (τ_I) and time derivative (τ_D))for P, PI and PID controller were found using empirical model

(Ziegler-Nicolas) ,and attest for closed loop control system and fine-tuning was conducted using a MATLAB simulik . Figures (5,6,7,8 and 9) show the block diagram of P, PI , PID, fuzzy logic control and Smith predictor, while figures (10,11,12,13 and 14) show the response of these block diagram respectively. The results indicate that the smith predictor is greatly improved the response or controlled variable. A PI and PID removed the offset but the settling time response is large compared with that in using smith predictor which only ten second. From figures (11 and 12) one can see that the time required for response curve to reach and stay within rang about the final value of specified by absolute percentage of the final value usually 2% or 5% (a settling time) equal 50 second when using PI controller and 40 second when using PID controller while only 5 second in using Smith predictor .The controlled variable in P ,PI ,and

PID control methods overshoots its set point while dos not in using Smith predictor and fuzzy logic control

A stability of open loop and closed loop using smith predictor was stated using first order pade approximation via Bode diagram. Figure (15) indicate that the system is stable because gain and phase margin are positive.
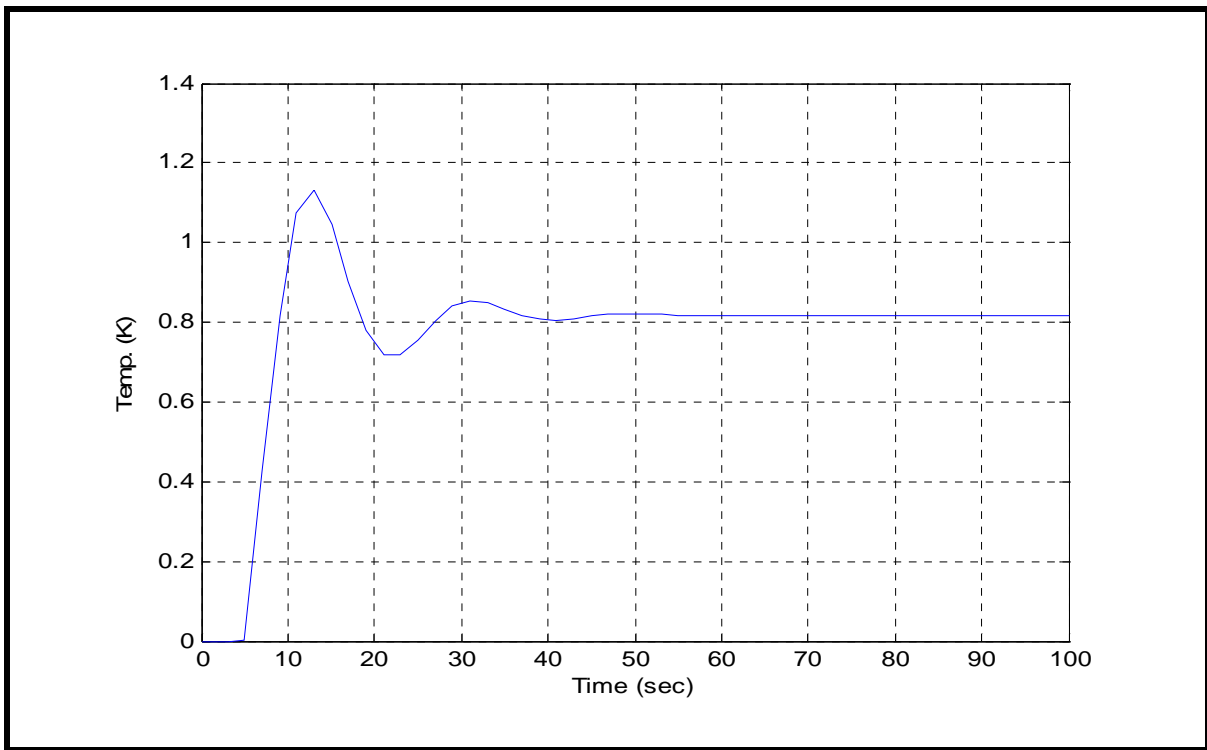

Figure 5. Block diagram of closed-loop system using P controller

Figure 6. Block diagram of closed-loop system using PI controller

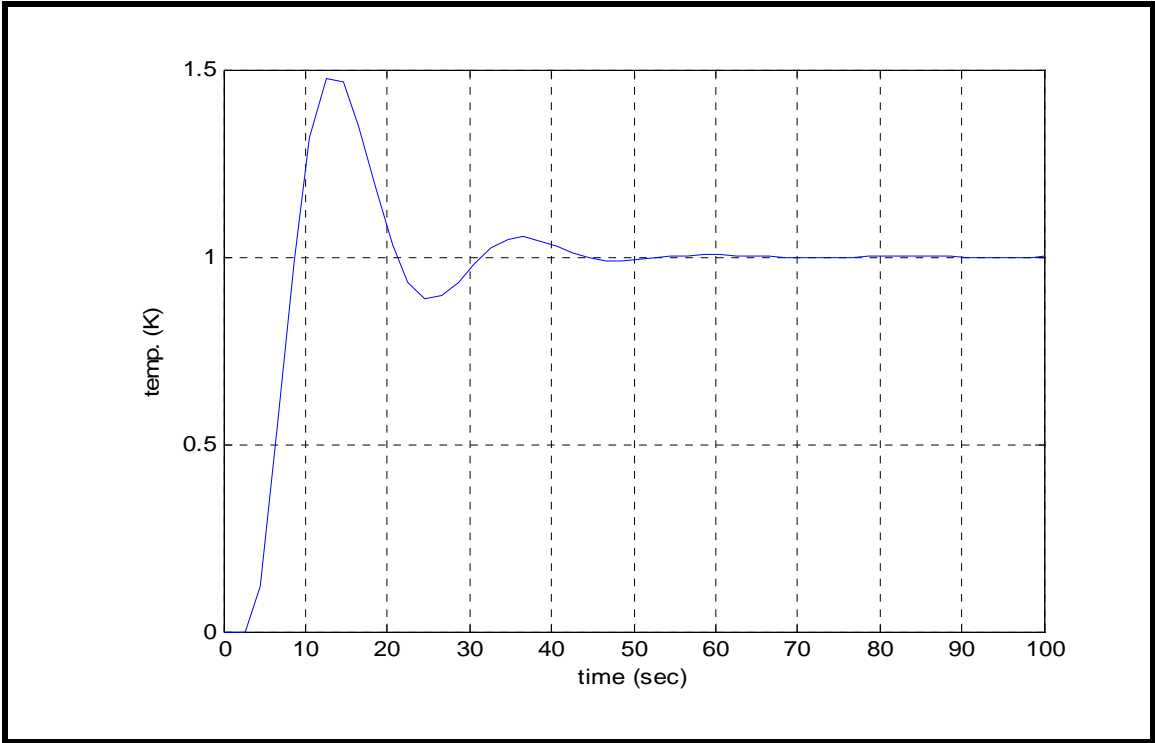**Figure 7. Block diagram of closed-loop system using a PID controller**

Figure8. Block diagram of closed-loop system using smith predictor
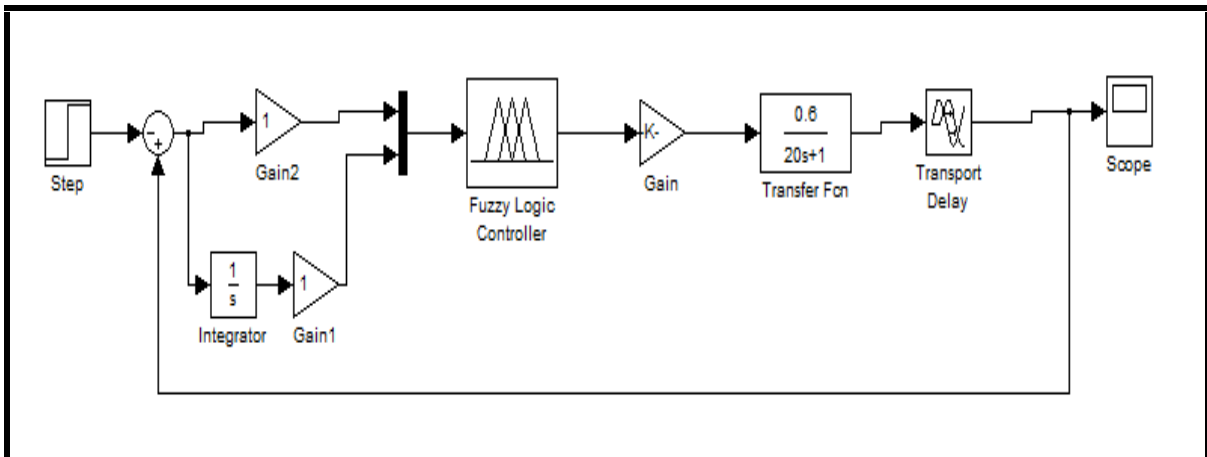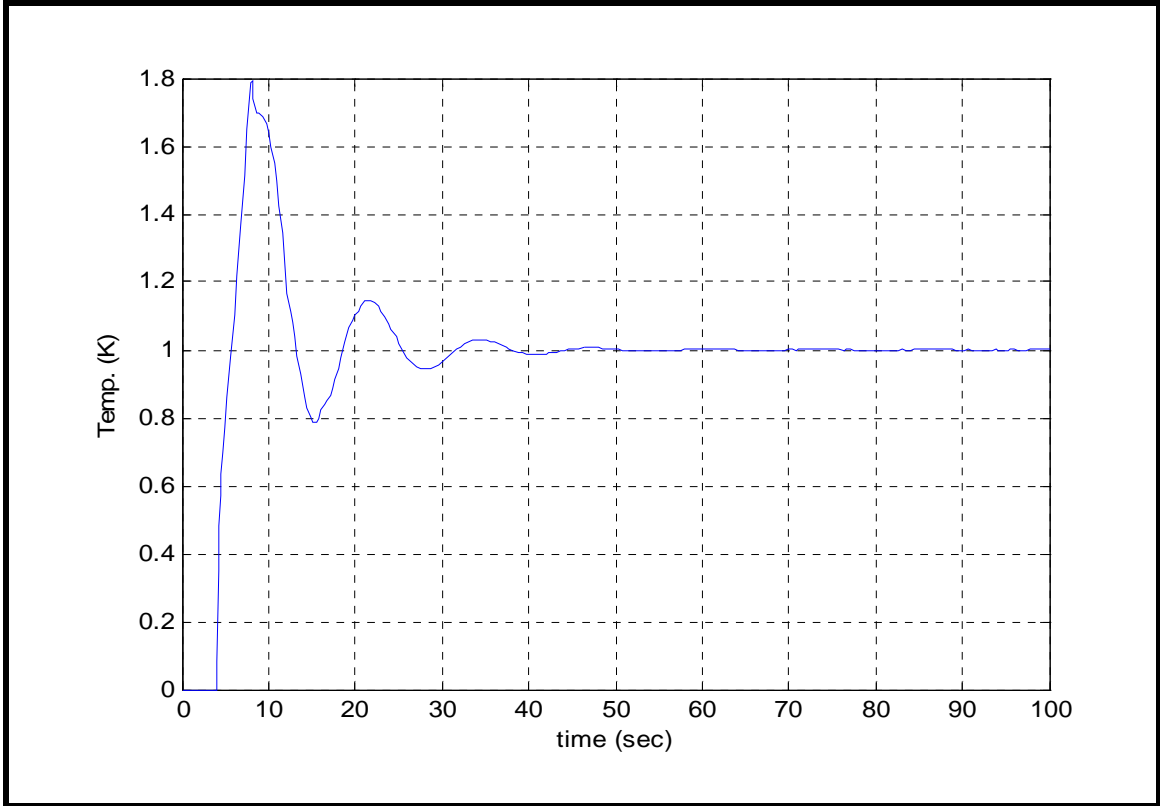

Figure9. Block diagram of closed-loop system using fuzzy logic control

Figure. 10 response of closed loop using P controller

Figure. 11 response of closed loop using PI controller

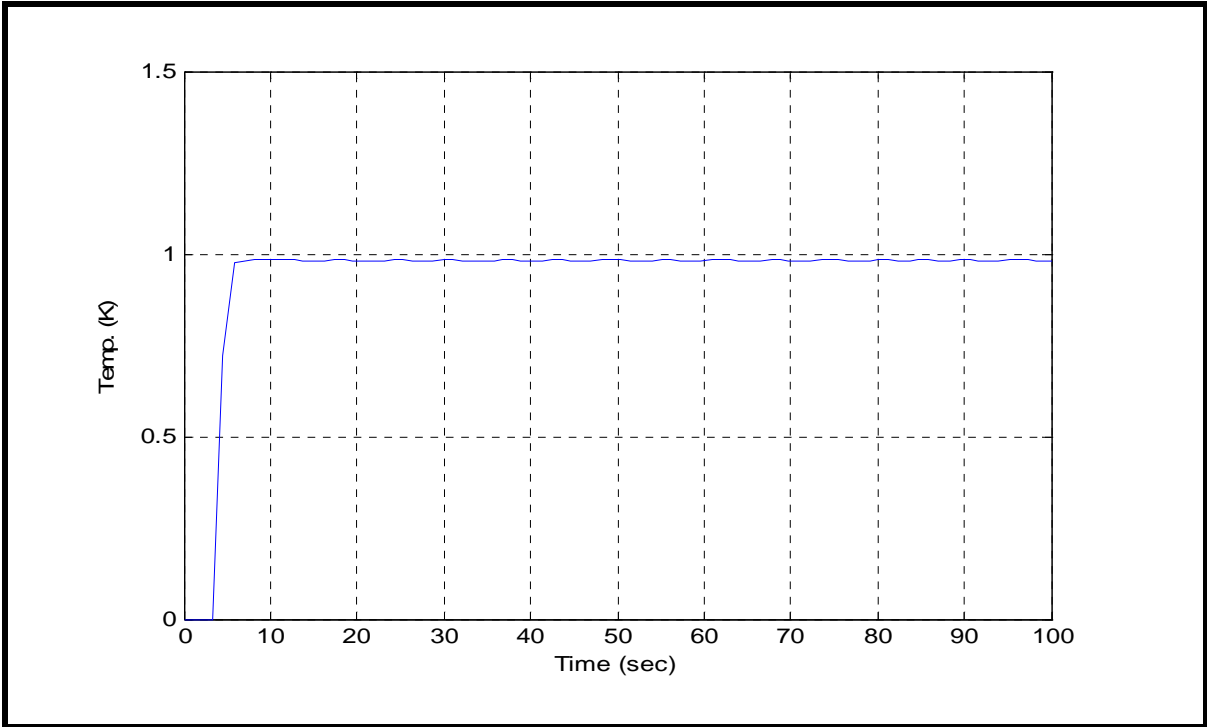**Figure. 12** response of closed loop using PID controller

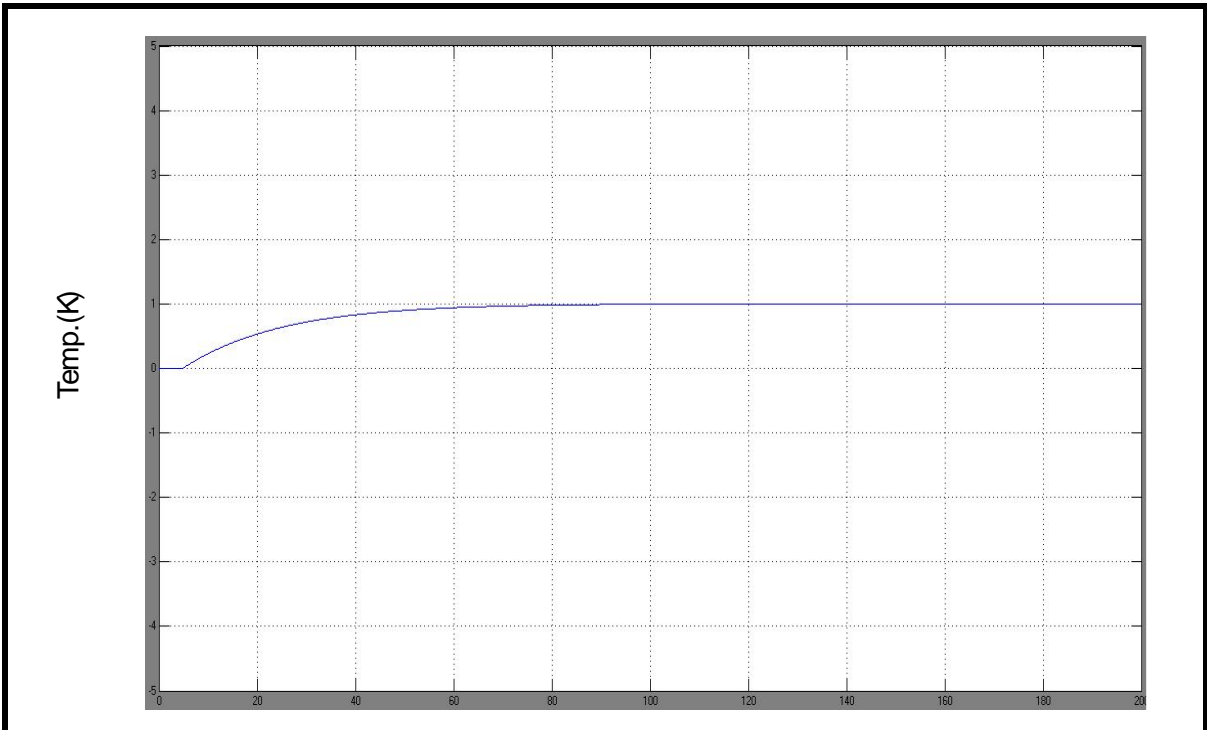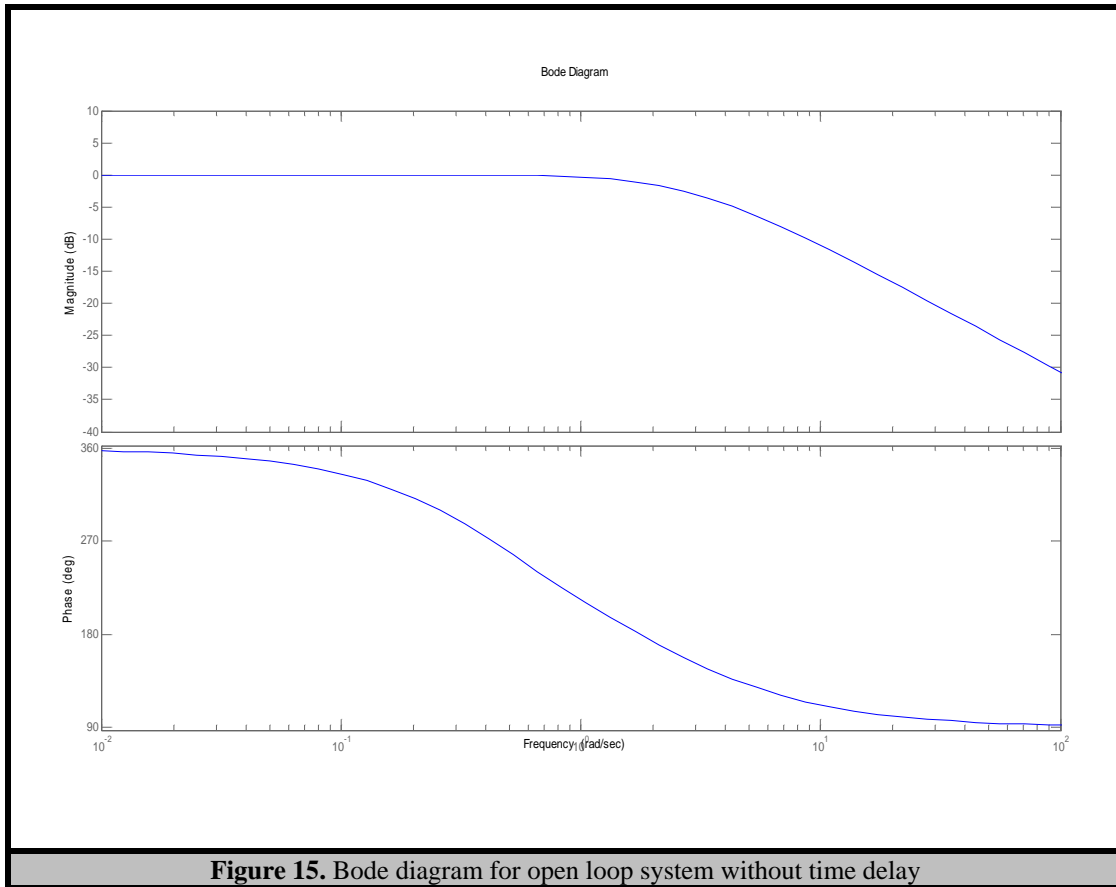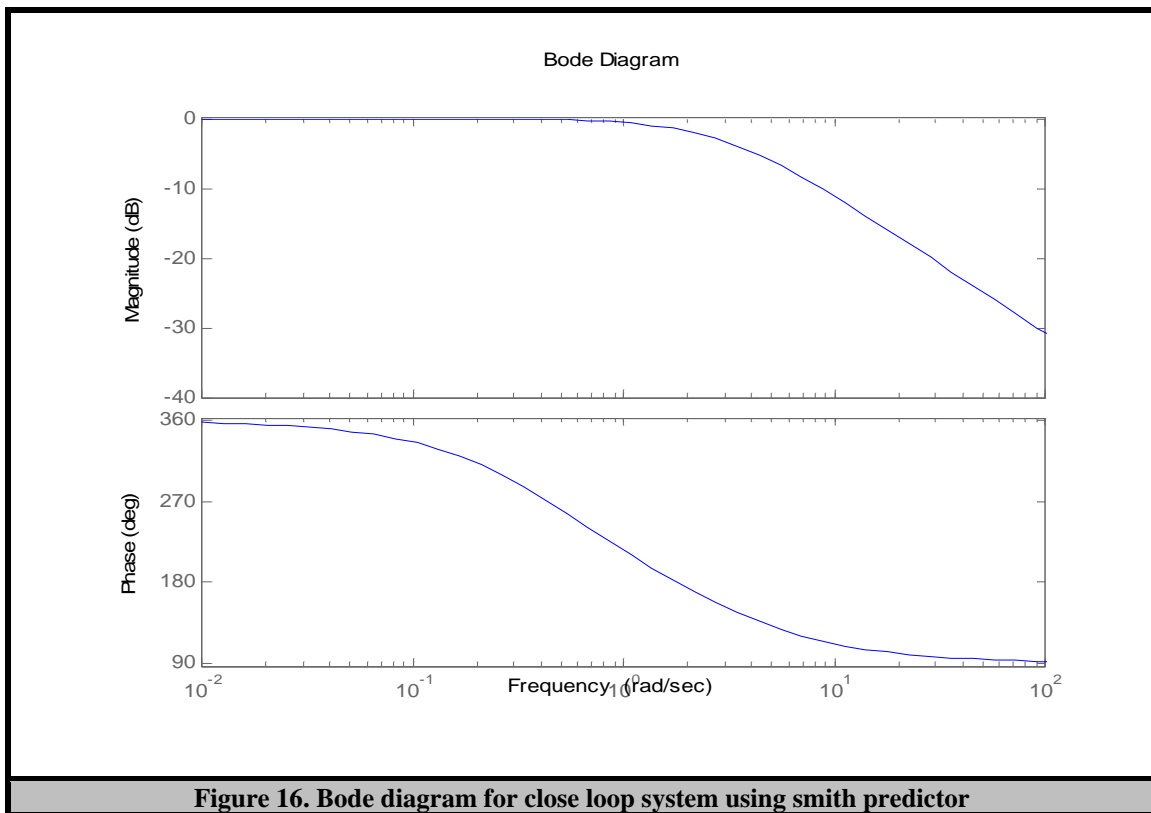**Figure 13.** Response of closed loop using smith predictor

Figure14. Fuzzy logic control

Figure 15. Bode diagram for open loop system without time delay

Figure 16. Bode diagram for close loop system using smith predictor

Conclusion :

There are a few points which must be emphasized:

1) The system Can be represented by FOPDT with process gain (K_p=0.6) and time constant of 20s

2) Smith predictor greatly improved the response of closed-loop, a settling time only 5 second in using Smith predictor

3) The open and closed-loop systems are stable due to positive gain margin

4) Fuzzy logic controller is recommended due to low cost ,easy to implement and it does not required an accurate mathematical model.

Abbreviatin

p	*proportional control*
PI	*proportional integral control*
PID	*proportional integral derivative*

Notation

A	Surface area of heat transfer, (m^2)
C	Control variable (temperature), (k)
C_p	Heat capacity of water, $kjkg^{-1}.k^{-1}$
D	Transport delay, (s)
G	Transfer function, ($k.s.kg^{-1}$)
G_c	Transfer function of controller
h	Heat transfer coefficient ($KJ.m^{-2}.s^{-1}$)
K_p	Process gain, ($k.s.kg^{-1}$)
K_c	Controller gain
R	Input variable
m	mass of water in heat exchanger, (kg)
τ	Time constant, (s)
τi	Integral time of controller
τ_d	derivative time of controller

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دراسة ديناميكية المبادل الحراري دو الانبوب المزدوج والسيطرة علية

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الخلاصة

لقد تم اجراء تجارب عملية لايجاد ديناميكية المبادل الحراري من نوع الانبوب المزدوج عن طريق اجراء اضطراب تدريجي في معدل جريان الماء الحار و ملاحظة التغير الحاصل في درجة حرارة الماء البارد الخارج للمبادل الحراري وقد وجد بانه يمكن تمثيل النظام بدالة تحويل من الدرجة الاولى مع تعويق زمني.

تم محاكات النظام عن طريق استخدام برنامج MATLAB لغرض دراسة السيطرة على المبادل الحراري وباستخدام طرق مختلفة مثل التناسبي والتناسبي التكاملي والتناسبي التكاملي التفاضلي و السيطرة الضبابية.

وقد تم ازالة تاثير التعويق الزمني عن طريق استخدام Smith predictor وظهر تحسن كبير في سلوكية النظام اخيرا تم دراسة استقرارية النظام ووجد بان النظام مستقر.