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Research paper

Modeling and control of a real time shell and tube heat exchanger

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Abstract

Process industries generate large amount of heat that needs to be transferred. Shell and tube heat exchangers are extensively used in industries for utilization of the heat energy generated from different processes. For definite utilization of this energy, the temperatures of the hot and cold fluids passing through the heat exchanger should be monitored and controlled efficiently. A proper model of heat exchanger is required for the purpose of monitoring and control. The objective of the paper is to mathematically model the heat exchanger using system identification methods and experimentally evaluate the effectiveness of two PID controller tuning methods such as Internal Model Control (IMC) and relay auto-tuning for temperature control. The Auto Regressive–Moving-Average model with eXogenous inputs (ARMAX) model of the heat exchanger is obtained from the Pseudo Random Binary Signal (PRBS) experiment performed on the heat exchanger system. The outlet temperature of the cold fluid is considered as the controlled variable. Based on the obtained model, PID settings are designed using the two tuning methods, and the closed loop responses such as servo and regulatory are compared experimentally. It is seen from the experimental results that the IMC based controller shows better results than the relay auto tuning method in terms of time integral error (i.e., ISE and ITAE).

Keywords: Shell and tube heat exchanger; Autoregressive–moving-average model with exogenous inputs (ARMAX) model; Internal Model Control (IMC); Relay auto-tuning

1. Introduction

Heat transfer equipment are an integral part of the process industries as large quantity of heat is being generated on daily basis and it needs to be utilized efficiently to save energy costs. The challenge is to use it as effectively as possible to reduce energy losses. Shell and tube heat exchanger is extensively used in process industries which derived its name from the construction; which has round tubes mounted inside a cylindrical shell. Temperature control is imperative for efficacious use of a heat exchanger. Designing controllers for heat exchanger is a challenging task because of the non-linearity present in the system. Many researchers have implemented proportional integral derivative (PID) controller in heat exchanger for better servo and regulatory responses. Internal model control (IMC) based PID controller is used for temperature control by Khare & Singh and Padhee [1,2], and they implemented three conventional controllers for temperature control. Advanced controller like adaptive predictive control is applied to a laboratory heat exchanger by Bobál et al. and Raul et al. [3,4], and they compared the model based controllers to a conventional PI controller.

The ARMAX model is an extension of Auto Regressive model with eXogenous inputs (ARX) model and belongs to the equation error family. The ARMAX model structure is widely used for the modeling and control purpose not only in the process industries but in various other fields. The ARMAX model is used for steam distillation essential oil extraction system [5]. The auto-tuning procedure for PID controllers based on ARMAX model of naphtha treatment unit is discussed [6]. Hence, the ARMAX model is used in the present work to model the heat exchanger.

The use of relay feedback test for generating a sustained oscillation instead of using the conventional methods is suggested [7]. The method is simple to use and effective. In the present work relay auto tuning is used for controlling the cold fluid outlet temperature. The results are then compared with

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Nomenclature

$A(q^{-1})$	characterizes the dynamics present in the plant and noise subsystems
$A(z)$	characterizes the dynamics present in the plant and noise subsystems in discrete time
a	amplitude of the limit cycle
$B(q^{-1})$	represents how input reacts with the system
$B(z)$	represents how input reacts with the system in discrete time
$C(q^{-1})$	represents the noise model
$C(z)$	represents the noise model in discrete time
$D(q^{-1})$	characterizes the auto regressive behavior
d	disturbance
$e(k)$	random signal
F_h	hot fluid flow rate
$F(q^{-1})$	characterizes the dynamics of the plant that are unique to it
$G(q^{-1})$	transfer function representing the plant
$G(s)$	transfer function representing the plant in 's' domain
G	the process model in 's' domain
G_p	process transfer function in 's' domain
$H(q^{-1})$	transfer function representing the noise
h	is the magnitude of the relay
K_u	ultimate gain of the system
k_c	proportional gain
n_a,n_b,n_c	order of the model
n_k	delay in the system
P_u	ultimate period of the system
r	set point
Q_c	the IMC controller transfer function
T_{co}	outlet temperature of the cold fluid
T_d	derivative time
T_i	integral time
$u(k)$	input or probe signal
$V[k]$	random process
$y(k)$	output or observed response
ω_u	ultimate frequency of the system
λ	tuning parameter
θ	time delay

Abbreviations and acronyms

ARMAX	Auto Regressive–Moving-Average model with eXogenous inputs
ARX	Auto Regressive model with eXogenous inputs
DPT	Differential Pressure Transmitter
IMC	Internal Model Control
I/P	Current to Pressure
ISE	Integral Squared Error
ITAE	Integral Time-weighted Absolute Error
LPH	Liters per Hour
PID	Proportional Integral Derivative
PRBS	Pseudo Random Binary Signal
RTD	Resistance Temperature Detector
Z-N	Ziegler-Nichols method

IMC based PID tuning method. The internal model control (IMC)-PID tuning method is first proposed by Rivera et al. [8] and then by Morari and Zafirou [9]. In the present work, tuning rules proposed by Paul et al. [10] is used to derive controller setting for the given system.

Heat exchangers are abundantly used in industries. For this purpose, a robust control action must be implemented. The objective of the present work is to obtain a suitable mathematical model from the experimental data which can be used to design an efficient PID controller for the control of temperature of the shell and tube heat exchanger. Two sets of controllers are designed by the relay auto tuning method and IMC method, and the performances of these two controllers are evaluated experimentally and compared. The efficacy of the two controllers is investigated by the Integral Squared Error (ISE) and the Integral Time-weighted Absolute Error (ITAE) performance criteria.

2. Heat exchanger system

The shell and tube heat exchanger system as shown in Fig. 1 is a single pass shell and tube type, used to heat the cold fluid passing through tube to a desired temperature. The hot fluid passes through the tube side and cold fluid through shell side. Two heating tanks that are fitted with stirrers are used to generate hot water. The PID controller is installed in the system to control the heaters so that hot water is generated at constant temperature. Centrifugal pumps are installed in the set up to pump hot and cold fluids. The flow rates of hot and cold fluid are controlled by two separate pneumatic control valves. Four RTD sensors are installed in the heat exchanger to measure the inlet and outlet temperatures of both hot and cold fluid. Two more RTD sensors are installed in the heating tanks. Four solenoid valves are installed in the system that act as on–off valves. Four rotameters and a differential pressure transmitter (DPT) are installed to measure the flow rate of hot and cold fluid. Two

Fig. 1. Photograph of shell and tube heat exchanger system.

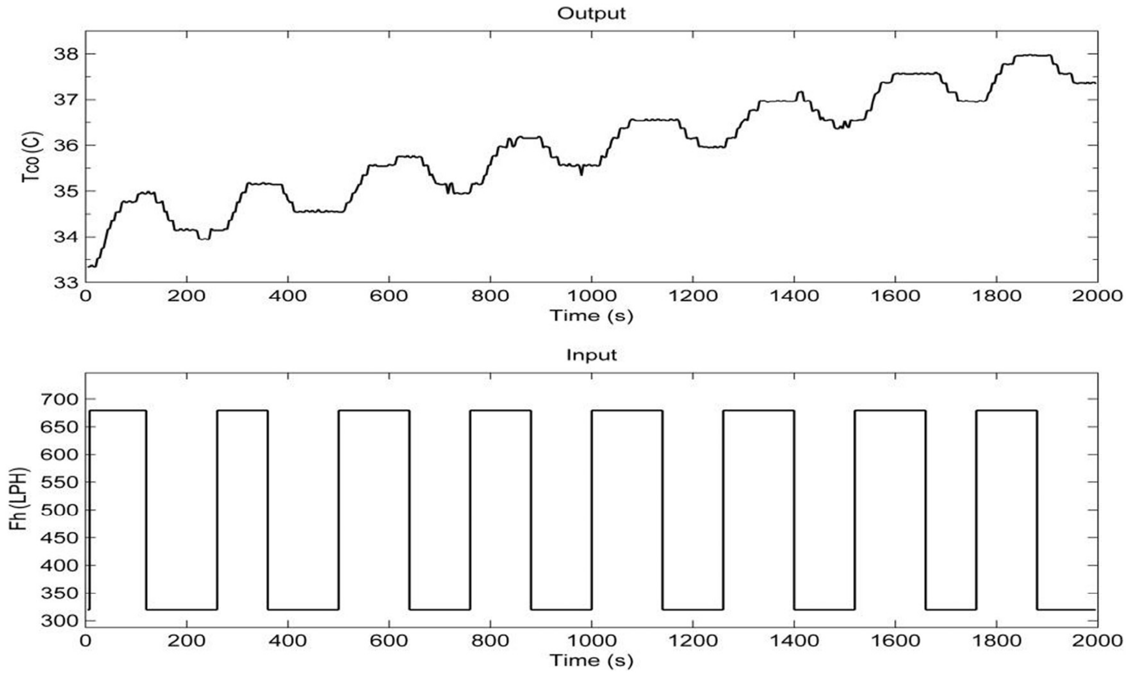

Fig. 2. Input–output data from PRBS experiment.

current to pressure (I/P) converters are installed to convert current signal from the host computer to pressure signal for the pneumatic control valve operation. Outlet temperature of the cold fluid (T_{co}) is the controlled variable of the system. The manipulated variable is the hot fluid flow rate (F_h). A ADAM utility 4000–5000 (Ver. 4.00.05) is used to interface the heat exchanger with the host system. The MATLAB Version 2009 (Mathworks) is used to for data acquisition and to implement control actions on the heat exchanger.

2.1. PRBS experiment

For obtaining empirical model of the system, input/output data is necessary. Experiments are performed on the heat exchanger system for the identification of model. A PRBS signal is given to the input i.e. hot fluid flow rate, and the response of the system to the change is saved. The change in the flow rate of hot fluid is the input signal while the change in outlet temperature of cold fluid is the output. The experiment is carried out for 2000s with a sampling time of 4s. As the experiment is conducted for such a long time period, the outlet temperature of cold fluid gradually increases from 33°C at the beginning to 38°C toward the end as shown in Fig. 2. The cold fluid inlet temperature is maintained constant at 27°C. The flow rate of the cold fluid is maintained constant at 320LPH. The details of the experiment is given in Table 1.The input–output data as acquired from the PRBS experiment is presented in Fig. 2.

3. System identification

System identification is the process of developing a mathematical relationship between the inputs and the outputs of a system or process based on input–output data [11]. Rational polynomial transfer functions are widely used for parametric description of input–output systems where $G(q^{-1})$ represents the plant and $H(q^{-1})$ the noise. They are defined as:

$$G(q^{-1}) = \frac{B(q^{-1})}{A(q^{-1})F(q^{-1})} \quad \text{and} \quad H(q^{-1}) = \frac{C(q^{-1})}{A(q^{-1})D(q^{-1})} \tag{1}$$

where

$A(q^{-1}): 1 + a_1 q^{-1} + \cdots + a_{n_a} q^{-n_a}$ characterizes the common dynamics present in the plant and noise subsystems.

$B(q^{-1}): b_{n_k} q^{-n_k} + b_{n_{k+1}} q^{-n_k-1} + \cdots + b_{n_k+n_b+1} q^{-(n_b-1-n_k)}$ represents how input reacts with the system while $F(.)$ accounts for the dynamics of the plant that are unique to it.

$C(q^{-1}): 1 + c_1 q^{-1} + \cdots + c_{n_c} q^{-n_c}$ representing the noise model accounts for the moving average characteristics of the random process $v[k]$ while $D(q^{-1})$ characterizes the auto regressive behavior.

The equation error family structure arises when $F(q^{-1}) = D(q^{-1}) = 1$, and it captures all the dynamics of the system well. The ARMAX model is an extension of

Table 1
Operating conditions of shell and tube heat exchanger.

Sl. No	Parameters	Range/value
1	Cold fluid inlet temperature	27°C
2	Cold fluid outlet temperature	33–38°C
3	Hot fluid inlet temperature	54–56°C
4	Hot fluid outlet temperature	42–47°C
5	Cold fluid flow rate	340LPH
6	Hot fluid flow rate	320–690LPH

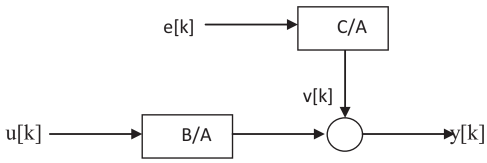

Fig. 3. Circuit diagram of ARMAX structure.

auto-regressive exogenous (ARX) model which incorporates a moving average term and is shown in Fig. 3. The structure is given as:

$$y(k) = \frac{B(q^{-1})}{A(q^{-1})} u(k) + \frac{C(q^{-1})}{A(q^{-1})} e(k) \tag{2}$$

The model is characterized by the orders (n_a,n_b,n_c) and an input delay of n_k samples.

3.1. Identification procedure

The dataset obtained from the experiment is subjected to impulse response for estimation of time delay. The 'cra' function of the Matlab gives the impulse response. For the system the time delay is estimated as 4s as the index at 0 crosses the confidence interval as shown in Fig. 4.

The dataset as shown in Fig. 2 is divided into two parts; training data and test data.

The first 1200 samples have been chosen for training dataset which is used to identify ARMAX model. The remaining data are training dataset which are used for the model validation. The residual analysis is carried out to validate the identified model. It is evident from Fig. 5 that the identified model has a residual autocorrelation function within the confidence interval which indicates that the residuals are uncorrelated and similarly the model has residuals uncorrelated with past inputs. This means that residuals are white so there is no further estimation possible. Fig. 6 shows the result of the comparison, where the fit is computed as the root of the mean square value of the difference between outputs of the actual response and the response obtained from the identified model. It is found that the model fit appears to be quite acceptable. The discrete time ARMAX model obtained is

$$A(z) = 1 - 0.2492\ z\hat{}-1 - 0.7469\ z\hat{}-2 \tag{3a}$$

$$B(z) = 0.0001701\ z\hat{}-4 + 0.0001295\ z\hat{}-5 \tag{3b}$$

$$C(z) = 1 + 0.6089\ z\hat{}-1 - 0.1473\ z\hat{}-2. \tag{3c}$$

The model obtained in 'z' domain is converted to 's' domain for the ease of designing controllers for the system. The final transfer function model thus obtained after pole zero cancellation is

$$G(s) = \frac{4.061 \times 10^{-3}}{s} \times e^{-4s}. \tag{4}$$

The residual analysis and one-step ahead prediction plot is presented in Figs 4 and 5 respectively.

4. Controller design

The controller settings are designed based on the identified model (Eq. 4) by relay auto tuning method and IMC method. The obtained PID settings are implemented on the real time

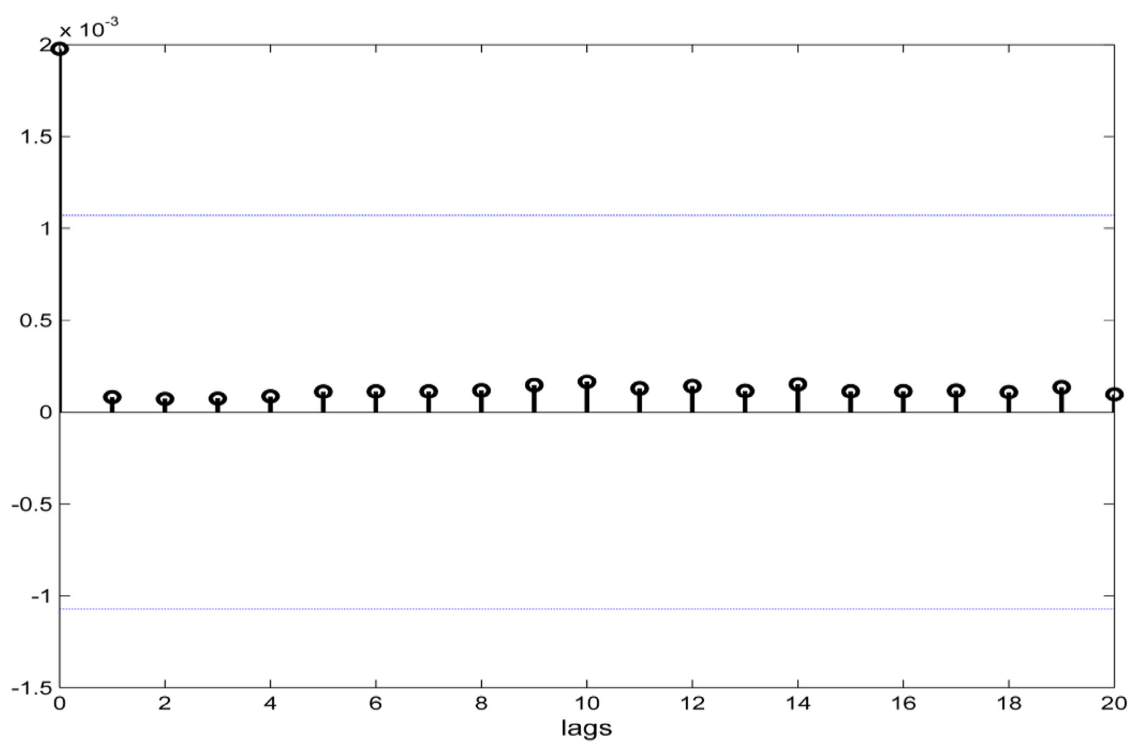

Fig. 4. Estimated impulse response from the input–output data.

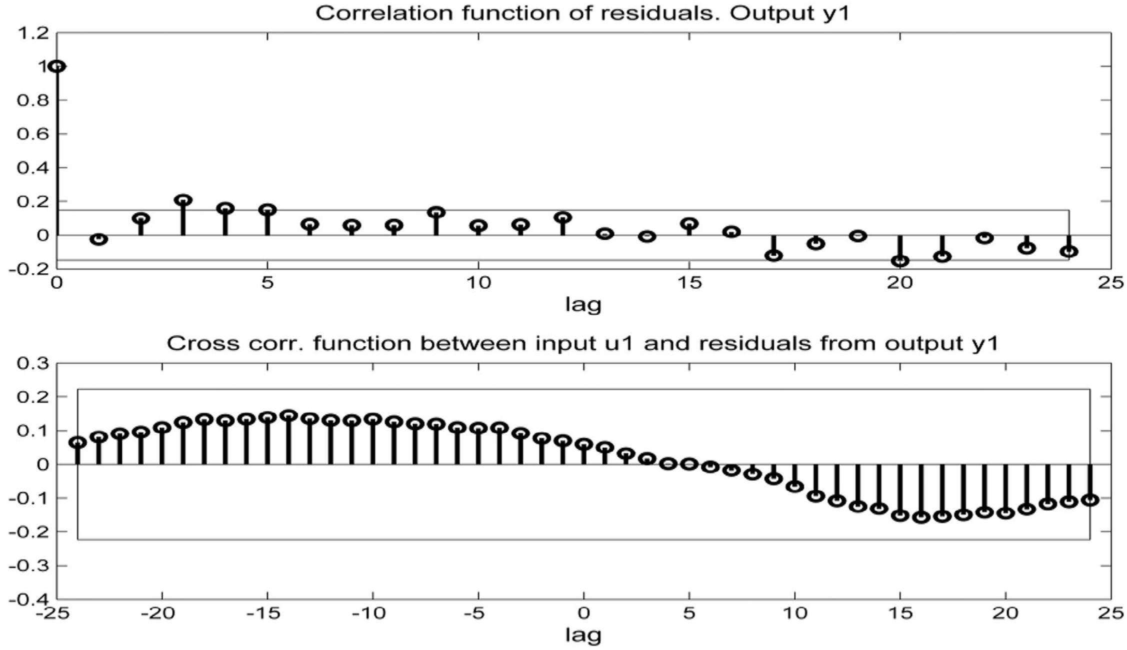

Fig. 5. Residual analysis of ARMAX model.

heat exchanger system for controlling the cold fluid outlet temperature.

4.1. Relay auto tuning

The relay auto-tuning technique is very effective in determining the ultimate gain and ultimate frequency of the system. Instead of bringing the system to the verge of instability, the critical point is obtained by use of a stable limit cycle. The continuous cycling of the controlled variable is generated from a relay feedback experiment and the important process information, ultimate gain (K_u) and ultimate frequency (ω_u) are extracted directly from the experiment [12]. Relay tuning is based on the theory that, when the output lags behind the input by π radians, the closed-loop system may oscillate with a period P_u [7]. The relay feedback test for the given system is implemented in the Matlab-SIMULINK to obtain the model parameters K_u and ω_u. The values of '*h*', '*a*' and P_u are obtained from the graphs generated in the SMULINK shown in Fig. 6. Where '*h'* is the magnitude of the relay and 'a' is the amplitude of the limit cycle.

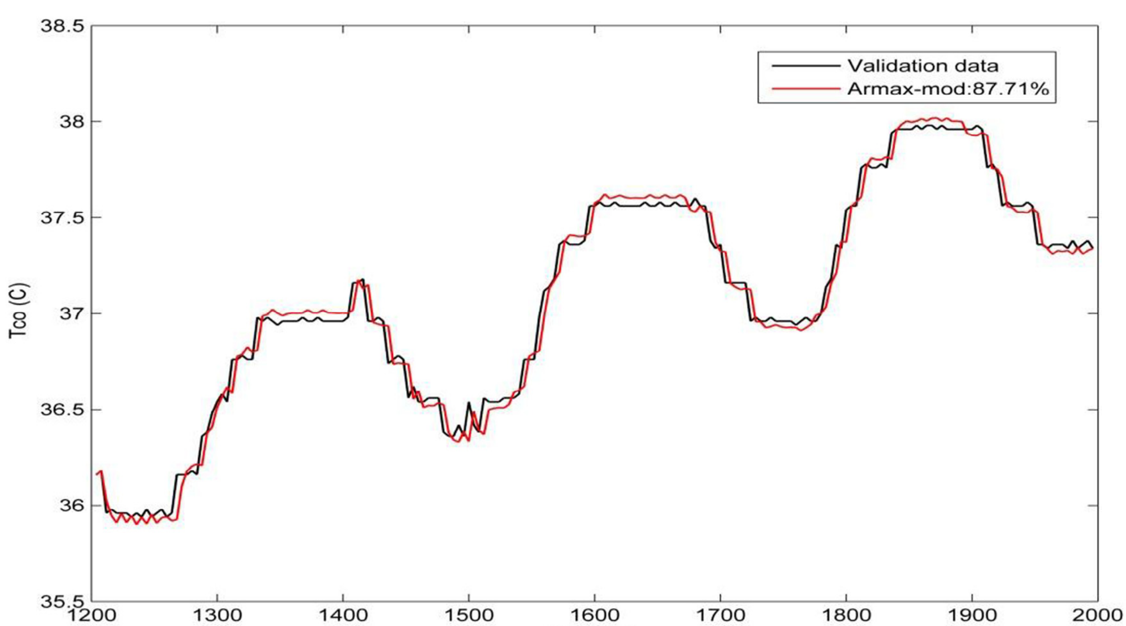

Fig. 6. Comparison of true response with the predicted one.

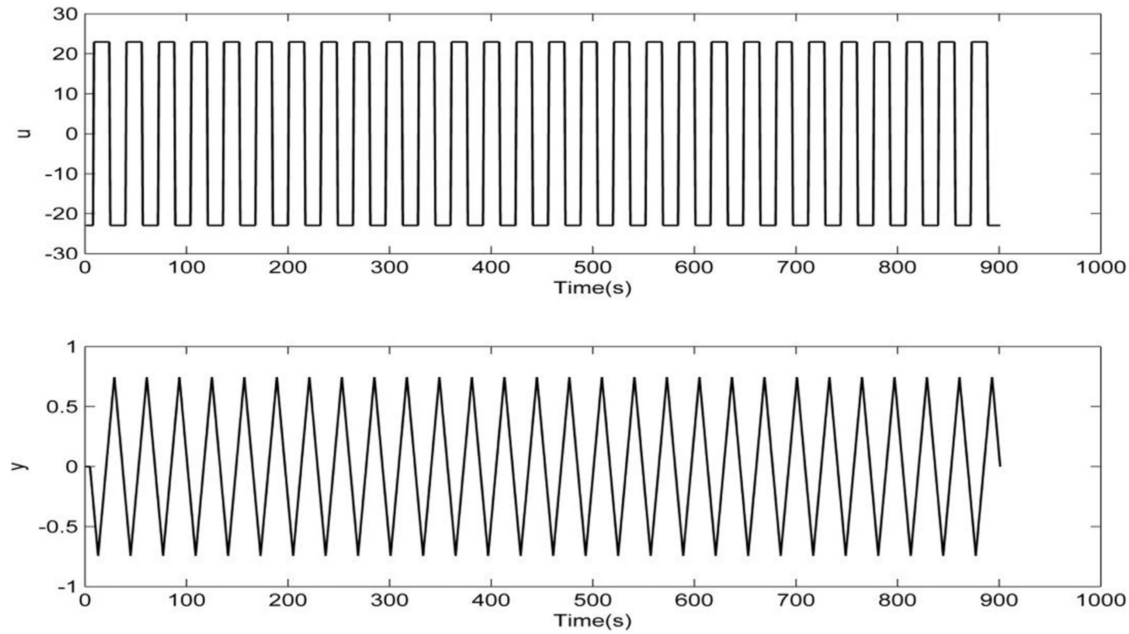

Fig. 7. Result of relay experiment in SIMULINK.

The ultimate frequency ω_u from this relay feedback experiment is given by [12] as:

$$\omega_u = \frac{2\pi}{P_u} \tag{5}$$

where P_u is the ultimate period of the system.

The ultimate gain of the system is given by [12] as:

$$K_u = \frac{4h}{\pi a}. \tag{6}$$

The values of K_u and P_u are obtained from Fig. 7 as 39.05 and 32 respectively. The parameters of the controller obtained by usage of Z-N tuning rules are given in Table 2.

4.2. IMC-based PID tuning

The effectiveness of IMC principle has attracted process industry to design PID controller using IMC structure. It is used for a variety of transfer function models, and tuning rules were proposed by Chien and Fruehauf [13]. Significant development on this tuning methodology has occurred since then. The IMC structure can be given as [10]:

$$y = \frac{G_p Q_c}{1+Q_c(G_p - G)} r + \left[\frac{1-GQ_c}{1+Q_c(G_p-G)}\right] G_p d. \tag{7}$$

Table 2
Estimated PID settings for the heat exchanger system.

Tuning method	K_c	τ_I	τ_D
Relay auto tuning	23.4276	16	4
IMC-based tuning	42.56	18	1.78

Where G_p is the process transfer function, Q_c is the IMC controller. G is the process model.

Here it is assumed that $G_p = G$ and time delay in Gp is approximated by the first order Padé approximation.

The integrating process is given as:

$$G_p = \frac{k}{s} e^{-\theta s}. \tag{8}$$

Following the controller design step as discussed in Ref. [10], the tuning rules for the PID controller is as given:

$$G_c = K_c\left(1 + \frac{1}{T_i s} + T_d s\right) \tag{9}$$

$$\text{where } K_c = \frac{2\lambda + \theta}{k(\lambda + 0.5\theta)^2} \tag{10}$$

$$T_i = 2\lambda + \theta \tag{11}$$

$$T_d = \frac{\lambda\theta + 0.25\theta^2}{2\lambda + \theta}. \tag{12}$$

The parameters of the PID controller obtained are given in Table 2.

4.3. Procedure for controller testing

For servo test of the controller, the system is brought to a steady state by indirect contacting of the hot and cold fluid. Steady state is reached when cold fluid reaches a temperature of 32°C from initial temperature of 28°C. Then, a step change of 3°C is given to the cold fluid. The controllers take action to reach the set point.

Two types of disturbance are given to the system;

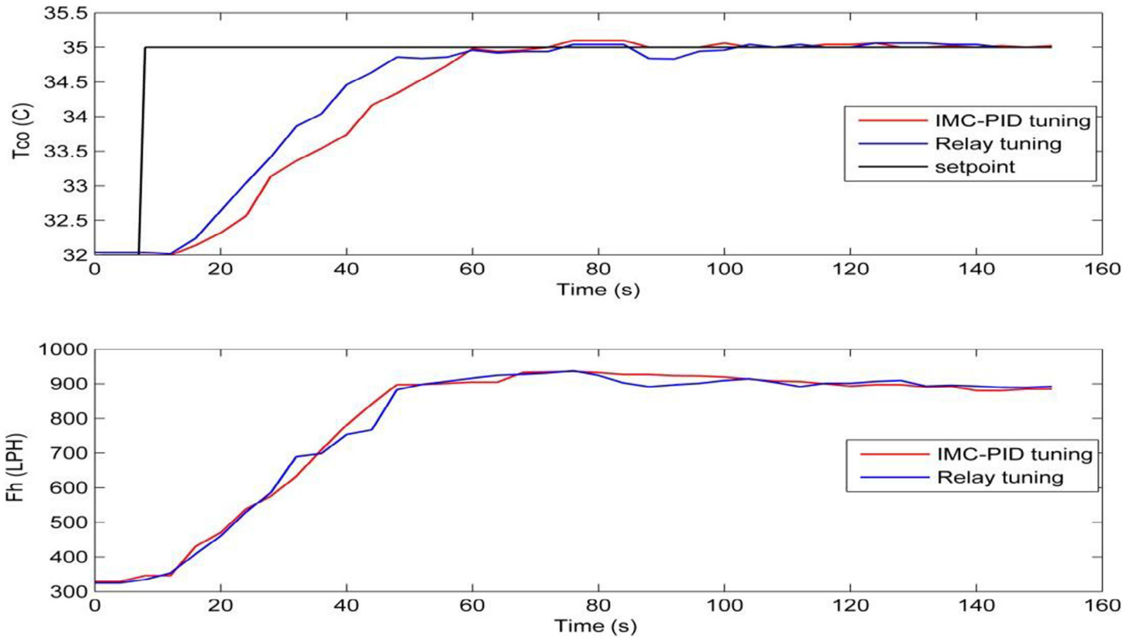

Fig. 8. Experimental closed loop servo performance of heat exchanger system.

- Regulatory response 1 – A change in the cold fluid inlet flow rate by 60LPH.
- Regulatory response 2 – A change in the temperature of hot fluid by 10°C.

The disturbance is given when the set point is reached. The controllers should follow the set point by negating the disturbance.

5. Results

The controllers are implemented in real time to check their performance in set point tracking and disturbance rejection. The results of servo response are presented in Fig. 8. The results for Regulatory response 1 are presented in Fig. 8. The inlet flow rate of the cold water is decreased by 60LPH from initial 320LPH as a disturbance to the system. The controllers act to reject the effect while tracking the given set point. From Fig. 9, it can be observed that the IMC-based PID controller acts faster to reject the given disturbance compared to the relay auto tuned controller. The results of Regulatory response 2 are presented in Fig. 10. The water in the disturbance tank is heated to a temperature of 50°C and passed through the heat exchanger as a disturbance for some time and then withdrawn. The controllers act to negate the effect. From Fig. 10, it can be observed that the

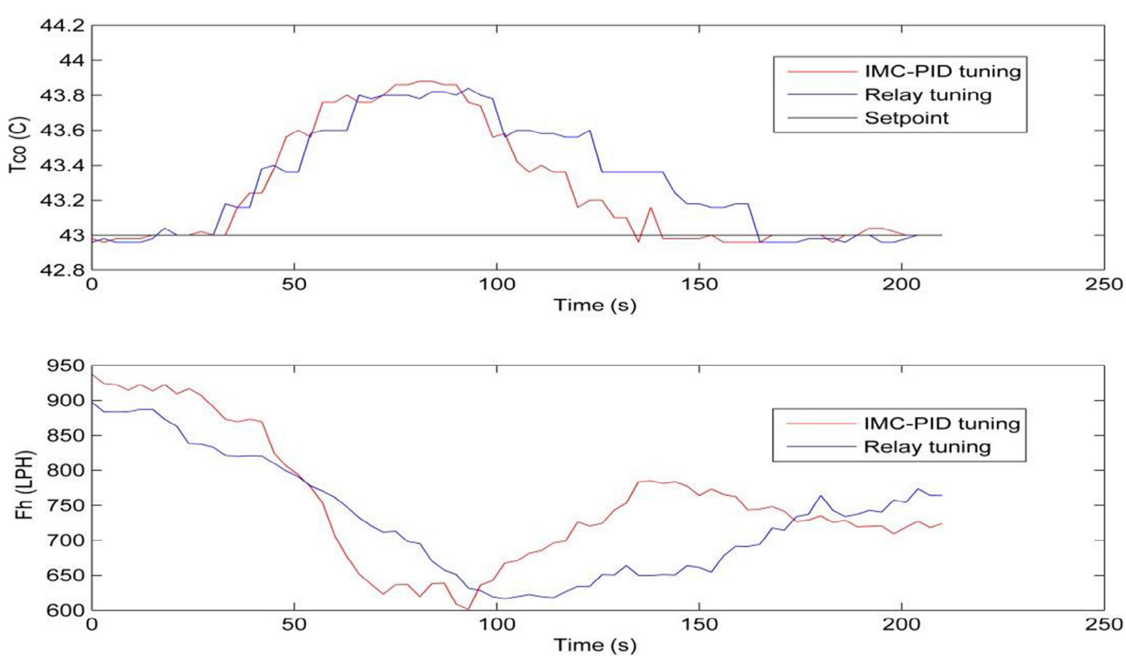

Fig. 9. Experimental closed loop regulatory response 1 of heat exchanger system.

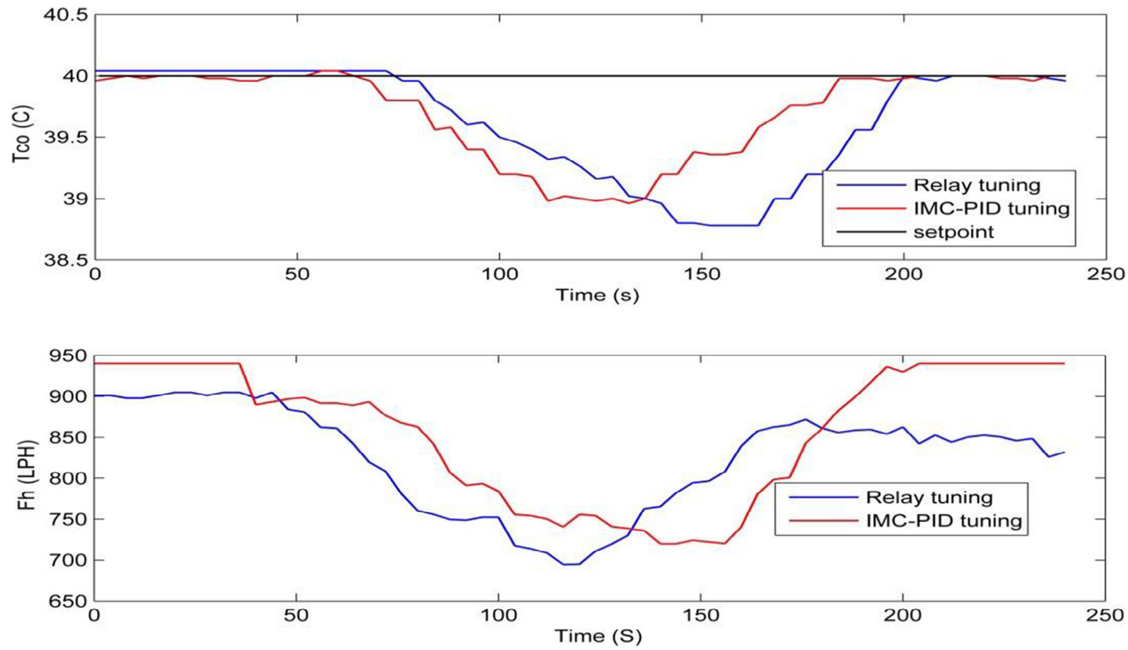

Fig. 10. Experimental closed loop regulatory response 2 of heat exchanger system.

Table 3
Closed loop performance of heat exchanger system for servo and regulatory response.

Tuning method	ISE			ITAE		
	Servo	Regulatory-1	Regulatory 2	Servo	Regulatory 1	Regulatory 2
Relay tuning	46.3076	23.42	22.9	1705.6	2506.5	1899.62
IMC-PID tuning	38.612	18.56	18.26	1190.26	1986.36	1514.72

PID controller based on IMC tuning method acts faster to reject the given disturbance and hence the deviation from the set point is least. The time integral errors such as ISE and ITAE indices for the experimental closed loop responses are enlisted in Table 3. Analyzing the values of Table 3, the closed loop response obtained from the IMC based tuning method is better than that of the relay auto tuning method in terms of cross validation. For servo response, The IMC based PID tuning method is improved by almost 20% and 43% in terms of ISE and ITAE value. Almost 26% and 25% of improvement is achieved by the IMC based method for both the regulatory responses (i.e., regulatory 1 and regulatory 2) in terms of ISE and ITAE indices.

6. Conclusions

The ARMAX model of the heat exchanger is obtained from the input/output data of PRBS experiment. Two conventional tuning methods such as relay auto tuning and IMC-based PID tuning methods are used to design controller for the heat exchanger system. The controllers are subjected experimentally to both servo and regulatory changes. The experimental results show that the IMC-based PID controller makes the system reach the desired set point earlier than relay auto tuned PID controller. In both the regulatory responses, it can be observed that the system responds to the disturbance earlier and returns to set point faster in the case of IMC-based PID controller than relay auto tuned PID controller. The performance of the controller designed by the IMC-based PID tuning method produces lowest ISE and ITAE indices for both regulatory and servo responses. Hence, IMC-based PID tuning method gives better performance than that of the relay auto tuned PID controller for all the cases.

References

[1] Y.B. Khare, Y. Singh, PID control of heat exchanger system, Int. J. Comput. Appl. 8 (2010) 22–27.
[2] S. Padhee, Controller design for temperature control of heat exchanger system: simulation studies, WSEAS Trans. Syst. Cont. 9 (2014) 485–491.
[3] V. Bobál, M. Kubalčík, P. Dostál, J. Novák, Adaptive predictive control of laboratory heat exchanger, WSEAS Trans. Syst. 13 (2014) 470–481.
[4] P.R. Raul, H. Srinivasan, S. Kulkarni, M. Shokrian, G. Shrivastava, R.R. Rhinehart, Comparison of model-based and conventional controllers on a pilot-scale heat exchanger, ISA Trans. 52 (2013) 391–405.
[5] M.H.F. Rahiman, M.N. Taib, Y.M. Salleh, Black box modeling of steam distillation essential oil extraction system using ARMAX structure, in: International Conference on Intelligent and Advanced Systems, 2007, pp. 1059–1062.
[6] N. Silva, H. Bispo, R. Brito, J. Manzi, Auto tuning applied to distillation column based on Armax model parameter estimation, in: CONTROLO'2014 Proceedings of the 11th Port. Conference on Automation Control, 2015, pp. 261–272.

[7] K.J. Astrom, T. Hagglund, Automatic tuning of simple regulators with specifications on phase and amplitude margin, Automatica 20 (5) (1984) 651.

[8] D.E. Rivera, M. Morarl, S. Skogestad, Internal model control 4 PID controller design, Ind. Eng. Chem. Process Des. Dev. 25 (1986) 252–265.

[9] M. Morari, E. Zafiriou, Robust Process Control, Prentice Hall, Englewood Cliffs, NJ, 1989.

[10] P.K. Paul, C. Dey, R.K. Mudi, IMC-PID controller for pure integrating process with large dead time, in: International Conference on Control, Instrumentation, Energy & Communication (CIEC), Calcutta, 2014, pp. 76–80.

[11] A.K. Tangirala, Principles of System Identification: Theory and Practice, 1st ed., CRC Press, Boca Raton, 2015.

[12] C.C. Yu, Autotuning of PID Controllers: A Relay Feedback Approach, 2nd ed., Springer Science + Business Media, Germany, 2006.

[13] I.-L. Chien, P.S. Fruehauf, Consider IMC tuning to improve controller performance, Chem. Eng. Prog. 86 (1990).