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Control Analysis Using Tuning Methods for a Designed, Developed and Modeled Cross Flow Water Tube Heat Exchanger

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***Abstract*—**Cross flow water tube heat exchanger can be designed and made operational using methods of model building and simulation of the system. This paper projects the design and development of a model of cross flow water tube heat-exchanger system, simulation and validation of control analysis of different tuning methods. Feedback and override control system is developed using inputs acquired with the help of sensory system. A mathematical model is formulated for analysis of system behaviour. The temperature is regulated at the desired set point automatically.

***Keywords*—**Heat Exchanger, Feedback, Override, Temperature, PID.

I. Introduction

A heat exchanger system is said to be complete with respect to design, operation and automation considering model building and its simulation. The project inculcates an indigenous design of a cross flow water tube heat-exchanger. The process fluid entering the heat exchanger travels around the hot water.

The heat-exchanger is supported by the feedback and override control system. The temperature inputs are obtained by temperature sensors, controlled by controllers and PLC [5] using set point. VFD regulates the pump's speed to control the flow of hot water. The flow is measured with the help of a Rota-meter.

The override control [8] is implemented for automatic and safe starting of the plant. The main application of this technique is to control, modify and regulate the temperature of water for any intermediate output flow at a desired temperature fulfilling the requirement of the process.

II. Design Development of System and Mathematical Modeling

A simple water tube cross flow heat exchanger is fabricated as shown in Fig. 1.

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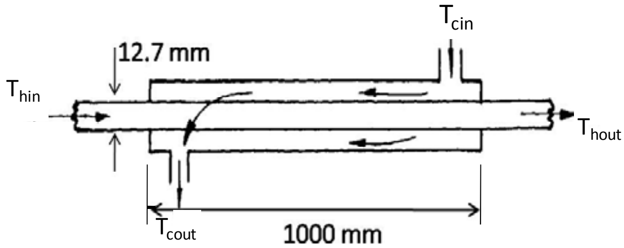

Fig. 1 Water Tube Cross Flow Heat Exchanger [3]

The internal tube is designed to increase heat transfer surface area. Two fluid heat transfer analysis is carried out using energy balance equations, LMTD to estimate the dimensions of heat exchanger.

$$(mC_p\Delta t)_{hot} = (mC_p\Delta t)_{cold} \quad (1)$$

$$Q = C_H(t_{h.in} - t_{h.out}) = C_C(t_{c.out} - t_{c.in})$$

$$q_{max} = C_{min}(t_{h.in} - t_{c.in})$$

The Log mean temperature difference (LMTD) method [2], [4] is employed considering counter current flow of the fluid streams.

$$q = UA\Delta t_{lm} \quad (2)$$

$$LMTD = \Delta t_{lm} \frac{\Delta t_1 - \Delta t_2}{\ln\left({\Delta t_1}/{\Delta t_2}\right)} \quad (3)$$

From (1) we get

$$(m_h C_{ph} \vartriangle t_h) = (m_c C_{pc} \vartriangle t_c)$$

Assuming, $m_h = m_c$

$$C_{ph} = C_{pc} = 4.18\frac{kJ}{KgK}$$

$$\therefore \vartriangle t_h = \vartriangle t_c$$

where $\vartriangle t_h = (t_{hin} - t_{hout})$ and $\vartriangle t_{c=}(t_{cout} - t_{cin})$

$$\text{Let } t_{hin} = 80°C \;\; and \;\; t_{cin} = 30°C$$

$$\therefore t_{hout} = 70°C \;\; and \;\; t_{cout} = 40°C$$

Now $Q = mC_p \vartriangle t$

m =33 LPH (Liters per hour)=91.6*10^{-3} Kg/s

$$\therefore Q = 91.6 * 10^{-3}\text{Kg/s} * 4.181\ \frac{kJ}{KgK} * 10 = 0.3832\ {}^{KJ}/_{S}$$

Now from (3)

$$LMTD = \frac{\theta_1 - \theta_2}{\ln\left(\frac{\theta_1}{\theta_2}\right)}$$

where

$$\theta_1 = 80° - 30° = 50°\text{C}$$

$$\theta_2 = 70° - 40° = 30°\text{C}$$

$$\therefore LMTD = \frac{20}{\ln\left(\frac{50}{30}\right)} = 39.15$$

From (2)

$$Q = U * A * LMTD$$

where

$$U = 250\ {}^{W}/_{m^2K}\ \ and\ \ A = \pi * d * L$$

$$hence, 0.3832 * 10^3 = 250 * A * 39.15$$

$$\therefore A = 0.03915\ m^2$$

Now, considering L= 1 meter

$$0.03915 = 3.14 * d * 1$$

$$\therefore d = 0.0125\ m$$

To carry out the validation of this theoretical model based on the derived dimensions of heat exchanger an actual heat exchanger was fabricated according to the dimensions. After the setup on running practically in open loop configuration the derived results at 800 rpm of hot water pump and giving a step input of 50^0 C are as under depicted in Table I.

TABLE I
READINGS OF PRACTICAL PERFORMANCE IN OPEN LOOP: (800 RPM) &50^0C

Time (s)	Temperature ˚C
0.5	25
7.71	25.14
21.7	29.03
38.8	31.89
70.27	35.77
114.69	39.53
181.83	42.75
257.65	44.19
297.73	44.8
409.62	45.37
486.44	45.62
573.28	45.76
596.66	45.85
596.66	45.92

Based on these readings the process curve plot showing the response of the heat exchanger system in open loop is given in Fig. 2:

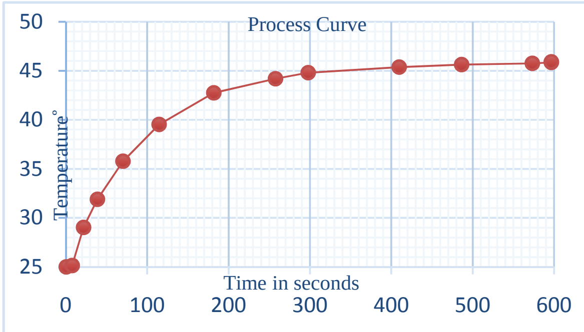

Fig. 2 Practical Response of Heat Exchanger System in Open Loop

Now considering temperature system as a first order system with time delay having transfer function [1]

$$G_p = \frac{\frac{N}{M}e^{-\tau_d s}}{(\tau s+1)} \quad (4)$$

N = Final value of Output; M=final value of the step input; $\tau_d = plant\ input\ delay$; $\tau =$ 63.2% of final value of the response

In Fig. 2; M= 50 (Step input); N=46 (Response final value); Delay time = 0.5s

$$\tau = 63.2\ \%\ of\ the final\ value\ \text{ i.e.} = 29$$

From (4)

$$\therefore \text{G}_\text{p} = \frac{\frac{46}{50}\ \text{e}^{-0.5\text{s}}}{29\text{s} + 1}$$

$$\therefore G_p = \frac{0.92e^{-0.5s}}{29s+1} \quad (5)$$

Now the same model in MATLAB for the step input results obtained were same, as shown in Fig. 3. The response model depicted in Fig. 2 is validated with (5).

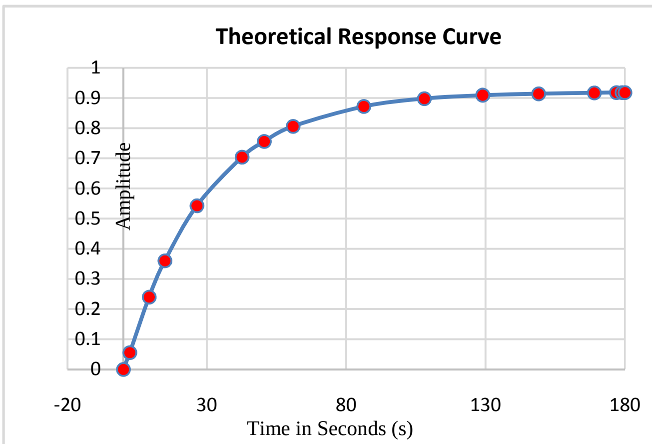

Fig. 3 Theoretical Response Curve obtained from MATLAB

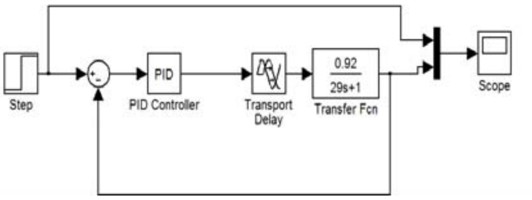

Fig. 4 Control Loop with Transfer Function

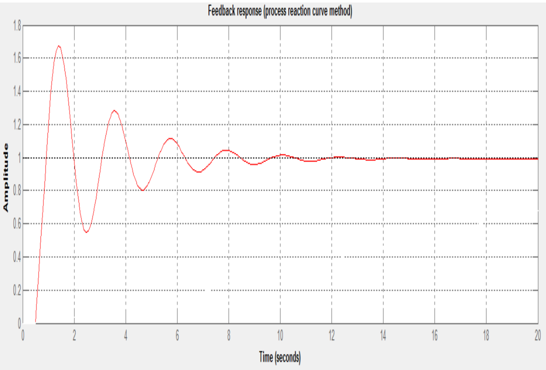

Fig. 5 Process Curve Method response

III. Determination of Control Tuning Parameters and Response

A. Process Reaction Curve Method [1]

Often referred as open loop transient response method, where the process control loop is ‘opened’ so that no control action occurs and a transient (disturbance) is introduced by step change in the signal to the control value.

Transfer function between control value, process and measuring element is approximated to be first order system with dead time.

$$G_v(S)G_p(S)H_m(S) = \frac{Ke^{-t_d S}}{1+\ \tau S}$$

where K=system gain; $t_d = deadtime\ \ in\ seconds$; $\tau = timeconstant\ or\ process\ \ reaction\ time.$

A tangent is drawn at inflection point of curve, which is defined as the point on the curve where slopes start decreasing.

From the (sigmoidal curve) Fig. 2 we get

$$Slope = \frac{B}{\tau} = \frac{46}{29} = 1.586$$

$$\text{Delay time } t_d = 0.5$$
$$\tau = 0.63 * \ 46 = 29$$

The controller parameter settings for PID mode are obtained as follows where K_p = proportional gain; T_i = integral time; T_d= derivative time.

$$k_p = \frac{1.2A}{St_d}$$

$$k_p = \frac{1.2 * 50}{1.586 * 0.5} = 75.66$$

$$T_i = 2t_d$$

$$T_i = 2 * 0.5 = 1s$$

$$T_d = 0.5t_d$$

$$T_d = 0.5 * 0.5 = 0.25s$$

Response obtained in Fig. 5 is with the help of K_p, T_i, T_d as $K_p = 75.66$; Ti =1; Td =0.25; Rise time = 0.335s; Settling time =11.4 s; Overshoot=67.4%; Peak = 1.6; Gain margin = 2.43 dB @ 3.18 rad/s; Phase margin = 22.2 degree @ 2.4 rad/s.

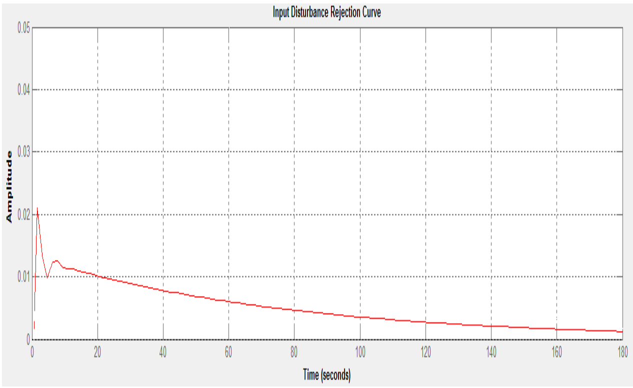

Fig. 6 Input rejection curve

B. Quarter Amplitude Criteria (Cohen–Coon Correction)

Coon corrections for controller parameters obtained from process reaction curve

$$K_p = \frac{\tau}{Kt_d}\left[1.33 + \frac{R}{4}\right]$$

where $R = logratio(unitless) = \frac{t_d}{\tau}$

$$K_p = \frac{29}{0.92 * 0.5}[1.33 + 0.0043] = 84.11$$

$$T_i = \left[\frac{32 + 6R}{13 + 8R}\right] * t_d$$

$$T_i = \frac{32.103}{13.137} * 0.5 = 1.22s$$

$$T_d = t_d\left[\frac{4}{11 + 2R}\right]$$

$$T_d = 0.5 * \left[\frac{4}{11.034}\right] = 0.18s$$

Response obtained in Fig. 7 is with the help of K_p, T_i, T_d as K_p=84.11; T_i=1.22 s; T_d=0.1818 s; Risetime =0.301 s; Settling time = 17.3s; Overshoot = 79.71%; Peak =1.8; Gain margin= 1.49 dB @ 3.17 rad/s; Phase margin = 14.3 degree @ 2.4 rad/s.

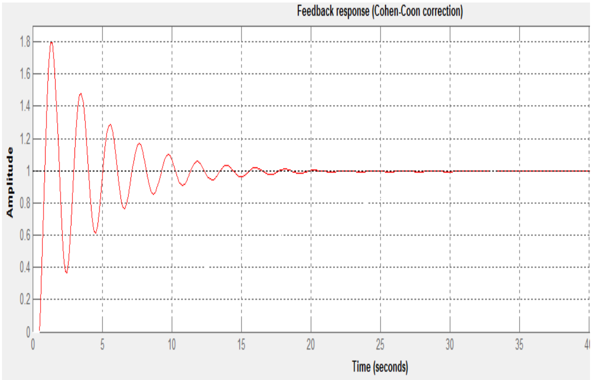

Fig. 7 Cohen-Coon Correction Method

C. Zeigler-Nichols Tuning Method

For critical gain n period, the settings for K_p, T_i, T_d are assigned as follows:

$$K_p = 0.6 * K_c$$

$$K_p = 0.6 * 130 = 78$$

where K_c = controller gain where sustained oscillation occurs.

$$T_i = \frac{T_c}{2} = 1.5$$

where T_c= Oscillation period

$$T_d = \frac{T_c}{8} = 0.375$$

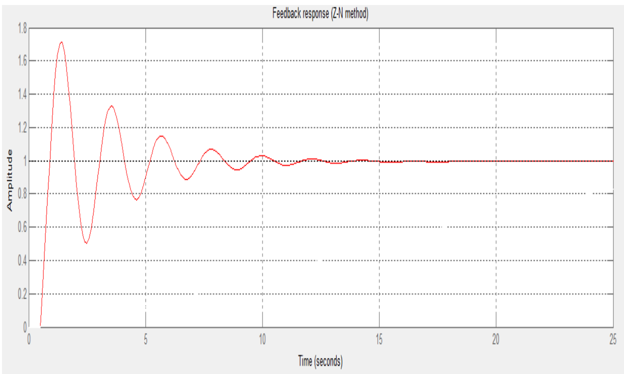

Fig. 8 Ziegler Nicholas Method

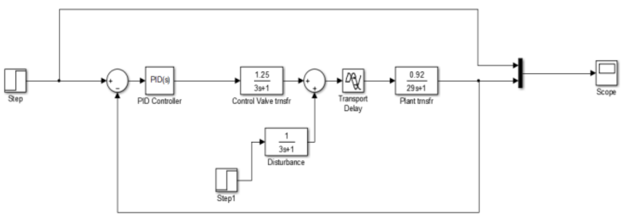

Fig. 9 Control Loop with Transfer Function of Control valve and Disturbance

Response obtained in Fig. 8 is with the help of K_p, T_i, T_d as Kp=78; T_i=1.5; T_d = 0.375; Rise time =0.324 s; Settling time= 11.3 s; Overshoot =71%; Peak = 1.7; Gain margin = 2.18 dB @3.18 rad/s; Phase margin = 20.1 degree @ 2.47 rad/s.

D. Considering Control Valve Transfer Function and Disturbances

The control valve has a maximum travel of 15mm, linear characteristics and a time constant of 3 sec. The nominal pressure range of the valve is 3 to 15 psig.

$$Control\ valve\ gain[6] = \frac{Range\ of\ Stem}{Pressure\ range} = \frac{15mm}{(15-3)psi} = 1.25\ psi/mA$$

The total transfer-function of Actuator

$$G_v(s) = \frac{1.25}{3s+1} \quad (6)$$

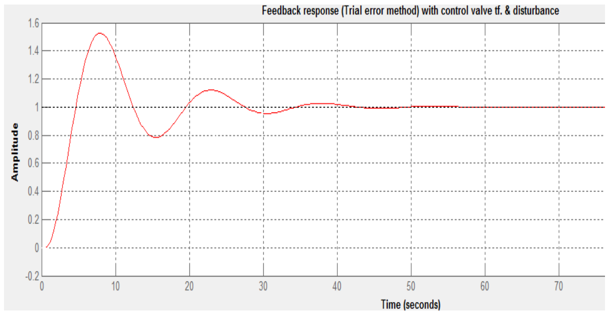

Fig. 10 Feedback Response (Trial Error method) with control valve disturbance

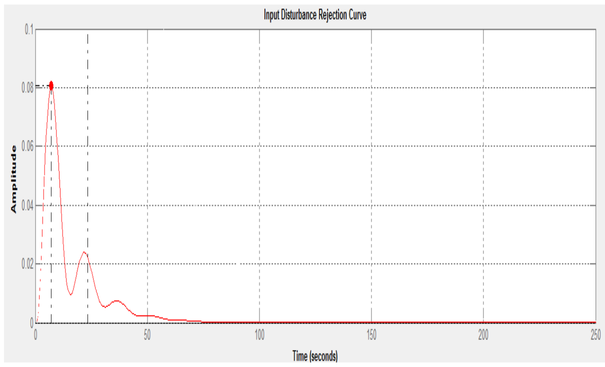

Fig. 11 Input Disturbance Rejection curve

Response obtained in Fig. 10 is with the help of K_p, T_i, T_d as Kp=15; Ti=1; Td = 0.5; Rise time= 2.77 s; Settling time = 39.9 s; Overshoot =52%; Peak = 1.53; Gain margin = 10.1 dB @ 0.769 rad/s; Phase margin =25.3 degree @ 0.391 rad/s.

E. Considering Control Valve and Sensor Transfer Function with Filter Coefficient

Sensor Transfer Function

In the system, 3-wire PT-100 RTD with a range of 0 to 100°C is used as it can withstand high temperature while maintaining stability. The sensor has time-constant of 1 to 2s.

$$Sensorgain[7] = \frac{(20-4)mA}{(100-0)°C} = 0.16\frac{mA}{°C}$$

The Transfer function of the sensor H(s) is

$$H(S) = \frac{0.16}{s+1} \qquad (7)$$

$$K_p = 36.7627, T_i = 1.2979, T_d = 65.8949$$
N=1.129

where N = filter coefficient

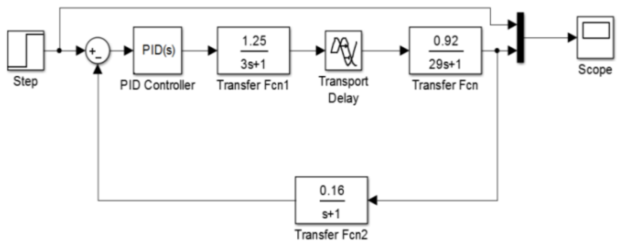

Fig. 12 Feedback loop with control valve transfer function and sensor transfer function

Response obtained in Fig. 13 is with the help of K_p, T_i, T_d as K_p= 36.7627; T_i =1.2979; T_d =65.8949; N=1.129; Rise time =5.47 s; Settling time= 19 s; Overshoot = 7.53%; Peak =1.08; Gain margin =14dB @ 0.719 rad/s; Phase margin = 60 degree @ 0.207 rad/s.

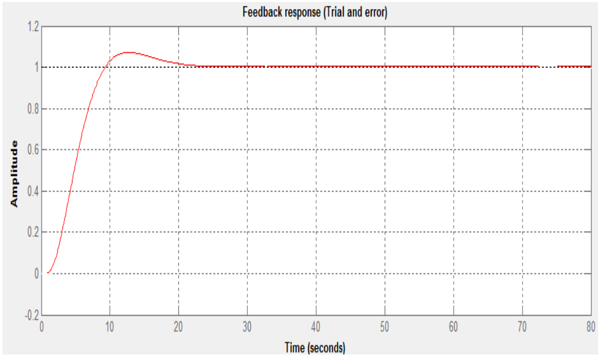

Fig. 13 Feedback Response with filter co-efficient

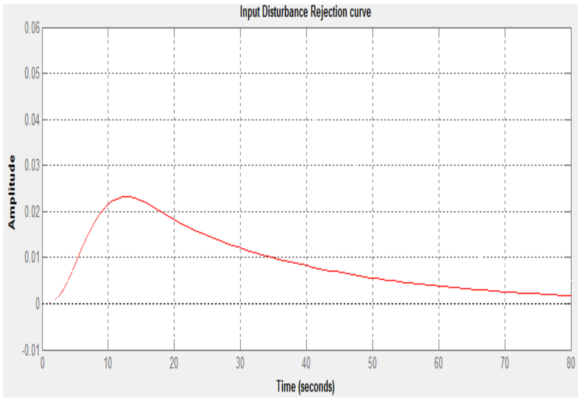

Fig. 14 Input Disturbance Rejection curve

IV. Results and Conclusion

TABLE II
DEPICTING HEAT-EXCHANGERS CALCULATED PARAMETERS

$Q(^{KJ}/_{S})$, Heat transfer rate	M, mass flow rate (LPH)	U, Heat transfer co-efficient	LMTD	Inlet Temp.	Outlet temp. (^{0}C)	A, Area (m^2)	L (m)	D, diameter (m)
0.3832	33	250	39.15	T_{hin}=80 T_{cin} =30	T_{hout}=70 T_{cout} =40	0.03915	1	0.0125

TABLE III
RESULTS OF THE ANALYSIS CARRIED USING THREE METHODS

Sr no	Method Employed	PID Parameters	Rise time(s)	Settling time (s)	Over-shoot (%)	Peak	Gain margin dB	Phase margin (^{0})
1	Process Reaction method	K_p=75.66 T_i=1 T_d=0.25	0.335	11.4	67.41	1.67	2.43	22.2
2	Cohen-Coon correction	K_p=84.11 T_i=1.22 T_d=0.1818	0.3013	17.33	79.71	1.8	1.49	14.3
3	Ziegler Nicholas method	K_p=78 T_i=1.5 T_d=0.375	0.324	11.35	71	1.71	2.18	20.1

TABLE IV
OBTAINED EQUATION OF TRANSFER FUNCTION

Components	**Transfer functions obtained**
Plant	$G_p = \frac{0.92e^{-0.5s}}{29s+1}$
Actuator	$G_v(s) = \frac{1.25}{3s+1}$
Sensor	$H(S) = \frac{0.16}{s+1}$

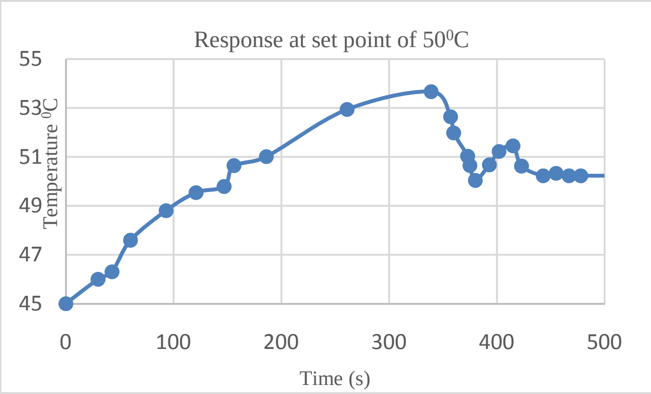

Fig. 15 Practical Step response after tuning of PID

TABLE V
READINGS AT SET POINT =50°C, WITH KP=100, TI=5.5, TD=0.01

Process value (°C)	Controller output (%)	Time (s)
46	58	0
46.306	63.5	30
47.589	65.6	43
48.8	66.001	60
49.54	65.554	93
49.786	64.524	121
50.336	53.037	147
50.64	51	156
51.01	30.67	186
52.94	25.15	261
53.668	16.34	339
52.64	32	357
51.98	43.56	360
51.03	49.67	373
50.65	50.788	375
50.034	59.324	380
50.67	49.53	402
51.22	37	415
51.45	34.54	423
50.62	45.53	443
50.23	50.12	455
50.33	49.865	467
50.33	50.356	502

The results shown in Table II indicates that using LMTD method for the cross flow heat exchanger the flow is laminar considering the mass flow rate of both the fluids to be equal and no heat transfer to the atmosphere, the temperature difference is 10^0C when the flow rate is 33 LPH. The heat transfer co-efficient is 250 the dimensions of the heat exchangers is obtained as 0.0125 m diameter and 1m length.

MATLAB simulation is carried out in three ways for analysis of different approaches for setting controller tuning parameters which are listed in Table III.

1. Considering the feedback loop without control valve and sensor transfer functions the response obtained by Process Curve method, Cohen-Coon method and Ziegler Nicholas method. The graphs are plotted and shown in Figs. 6-8 and it is observed that in Fig. 8 the settling time, overshoot and peak are less compared to those observed in the other two graphs i.e. 11.3 seconds.
2. Considering the feedback loop with control valve and disturbance transfer function the response obtained only using trial and error method and is depicted in the Figs. 10 and 11 where it is observed that due to the introduction of external input disturbance the settling time increases to 39.9s. Here input disturbance rejection curve is also shown where the controller action removes the disturbance after 55 s.
3. Considering feedback loop with control valve and sensor transfer function the response is obtained by only using trial and error method. It is observed from the Figs. 13 and 14, that when filter co-efficient is introduced, it removes the noise disturbance of the sensor which generates a permanent error in the final value of the response.

The transfer equation are obtained for plant (5), actuator (6) and sensor (7) where plant transfer is assumed to be of first order with time delay and obtained with help of the process reaction curve plotted from practical readings of the open loop system which is listed in Table IV.

This plant transfer is generated in MATLAB using the MATLAB code and it is observed that the plant transfer obtained from the practical readings shows the same set of result when a step input is given to the open loop transfer function which validates the plant model.

The results from the practical performance show that the controller output is 50% when the process value reaches the set point which validates the basic theory for the controller action. The table V observations also shows the above results i.e. above the set point value the controller percentage output decreases from 50% and below the set point it increases.

These controller parameters set practically for tuning are observed to be very much nearer to the parameters obtained by Cohen-Coon Correction method in the theoretical analysis.

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