Tuning Optimization of Hybrid controller for temperature control of heat exchanger by Gradient Descent method

Pardeep Mittal,Neha Raghu, Kamaldeep Sharma

Faculty of Electrical & Electronics Engineering
Lovely Professional University Jalandhar (Pb.) India.

Abstract— In this research paper, a Hybrid (PI+FF) controller optimized technique is developed to control the outlet temperature of a shell and tube heat exchanger. The aim of the proposed controller is to optimize the temperature control of a heat exchanger around a temperature set point. The controller regulates the temperature around a setpoint in response to external temperature disturbance. The optimization of hybrid controller provides a optimum solution with number of solution. The proposed technique overcomes the drawbacks of conventional feedback controller and feed-forward controller. The developed tuning optimization of Hybrid PI controller for heat exchanger process has demonstrated 81% improvement in the overshoot and 76% improvement in settling time from the classical controller. Also control accuracy is 100% as steady state error becomes zero.

Index Terms—Feedback (PI) and Feed-forward Controller, Shell and tube heat exchanger, tuning optimization

—————————— ◆ ——————————

I. INTRODUCTION

In practice, all chemical processes involve the production or absorption of energy in the form of heat. Heat exchanger is commonly used in industrial chemical processes to transfer heat from a hot liquid through a solid wall to a cooler fluid [1]. A heat exchanger[2] is a device that is used to transfer thermal energy (enthalpy) between two or more fluids, between a solid surface and a fluid, or between solid particulates and a fluid, at different temperatures and in thermal contact [3]. There are different types of heat exchanger used in the industry but most of the industry use shell and tube type heat exchanger system. It consists of parallel tubes enclosed in a shell. There is a variety of application of heat exchanger system. Some of the applications[4] include HVAC (heating, ventilation, and air conditioning), electronic cooling, refrigeration and air conditioning, manufacturing, and power generation. In each of these cases, the purpose of the heat exchanger 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 [5]. The concept of tuning optimization lies with the fact that human intelligence to set the value of K for PI is not up to such extent that gives the better response with sudden changes in process like disturbances. The Hybrid controller provides both feedback and feed forward controlling action. As we know that there are certain limitations of feedback and feed forward so the

combination of these two control actions overcomes that limitations of each other. With an effective technique that is gradient descent technique for controlling the tuning parameters automatically and optimally can replace a skilled human operator. Gradient descent technique is capable of handling approximate information in a systematic way and therefore it is suited for controlling non linear systems and is used for modeling complex systems where an inexact model exists or systems where ambiguity or vagueness is common.

This research paper considers a shell and tube heat exchanger and builds a SISO model of the system with the help of experimental data available. This system also takes in to account different disturbance elements and transportation delay. First of all, a classical controller is implemented in a feedback control loop so as to obtain the control objectives.. Auto-tuning of PI controllers is also implemented and simulated in this paper. To achieve the desired control objective and implement human intelligence in controller architecture a Hybrid PI controller is designed and implemented. All the system level simulation and controller design in this paper are carried out in Simulink. A comparative study of all the control performance is evaluated in this paper.

II. CASE STUDY

A typical interacting chemical process for heating consists of a chemical reactor and a shell and tube heat exchanger system. The process fluid which is the output of the chemical reactor is stored in the storage tank. The process fluid considered in this case is $Al_2(SO_4)_3 + H_2SO_4 + Alum$. The storage tank supplies the fluid to the shell and tube heat exchanger system. The heat exchanger heats up the fluid to a desired set point using super

heated steam at 180°C supplied from the boiler. The storage tank supplies the process fluid to the heat exchanger system using a pump and a non returning valve. The super heated steam comes from the boiler and flows through the tubes, whereas, the process fluid flows through the shells of the shell and tube heat exchanger system. After the steam heats up the process fluid, the condensed steam at 100° C goes out of the heat exchanger system. There is also a path for non-condensed steam to go out of the shell and tube heat exchanger in order to avoid blocking of the heat exchanger.

A chemical reactor called "stirring tank" is depicted below. The top inlet delivers liquid to be mixed in the tank. The tank liquid must be maintained at a constant temperature by varying the amount of steam supplied to the heat exchanger (bottom pipe) via its control valve. Variations in the temperature of the inlet flow are the main source of disturbances in this process.

A chemical reactor called "stirring tank" is depicted below. The top inlet delivers liquid to be mixed in the tank. The tank liquid must be maintained at a constant temperature by varying the amount of steam supplied to the heat exchanger (bottom pipe) via its control valve. Variations in the temperature of the inlet flow are the main source of disturbances in this process. Different assumptions have been considered. The first assumption is that the inflow and the outflow rate of fluid are same, so that the fluid level is maintained constant in the heat exchanger. The second assumption is the heat storage capacity of the insulating wall is negligible. In this feedback process control loop, the controller is reverse acting, the valve used is of air to open (fail-close) type. A thermocouple is used as the sensing element which is implemented in the feedback path of the control architecture. The temperature of the outgoing fluid is measured by the thermocouple and the output of the thermocouple (voltage) is sent to the transmitter
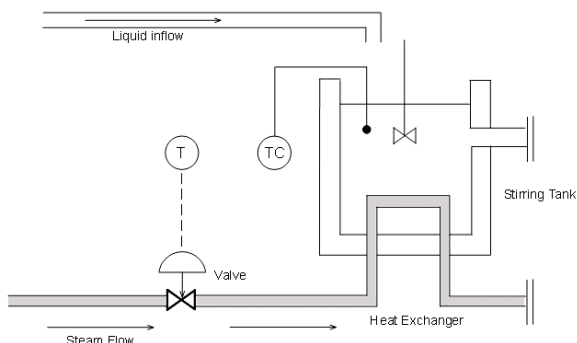

Fig.1: Heat Exchange Schematic Diagram

unit, which eventually converts the temperature output to a standardized signal in the range of 4-20 mA. This output of the transmitter unit is given to the controller unit. In this heat exchanger system a PI controller has been taken as the controlling unit. The PI controller

implements the control algorithm, compares the output with the set point and then gives necessary command to the final control element via the actuator unit. The actuator unit is a current to pressure converter and the final control unit is an air to open (fail close) valve. The actuator unit takes the controller output in the range of 4-20 mA and converts it in to a standardized pressure unit, i.e in the range of 3-15 psig. The valve actuates according to the controller decisions.

There can be two types of disturbances in this process, one is the flow variation of input fluid and the second is the temperature variation of input fluid. But in practice the flow variation of input fluid is a more prominent disturbance than the temperature variation in input fluid. So, in feed forward control loop the input fluid flow is measured and the disturbance in the flow is controlled using a feed forward controller. The output of the feedback and the feed forward controller is added and the resultant output is given to the control valve. With the addition of feed forward controller the control performance is optimized.

III. PROBLEM STATEMENT

In this section we have developed a block diagram of these control loops and modeled the heat exchanger system, actuator, valve, sensor using the experimental data available. The transfer function model of the individual systems are generated which in turn combined to acquire the transfer function of the whole system.

A. Experimental Data

Exchanger response to the steam flow gain- 40° C/(kg/sec)
Time constants-28 sec
Exchanger response to variation of process fluid flow gain -1° C/(kg/sec)
Exchanger response to variation of process Temperature gain -3° C

Control valve capacity-1.6 kg/sec of steam
Time constant of control valve-3 sec
The range of thermocouple-50° C to 150° C
Time constant of thermocouple-10 sec

From the above experimental data the transfer function model of the system is derived.

Transfer function of Process:

$$\frac{40e^{-sT_D}}{30s+1}$$

Gain of valve – 0.133
Transfer function of valve :

$$\frac{0.133}{3s+1}$$

Gain of I/P converter- 0.75

Transfer function of disturbance variables (flow and temperature disturbances respectively):

$$\frac{1}{30s+1}, \frac{3}{30s+1}$$

Transfer function of thermocouple-

$$\frac{0.16}{10s + 1}$$

B. PI Controller

The characteristic equation $(1+G(s)* H(s) =0)$ in this case is obtained as below.

$900s^3+420s^2+43s+0.798K_c+1=0$ (1)

Applying Routh stability criterion in eq. (1) gives K_c as 23.8

Auxiliary equation **$420s^2+0.798K_c+1=0$**   **(2)**

From eq. (2) $\omega=0.218$ and $T=28.79$

PI controller in continuous time is:

$$u(t) = b + K_P e(t) + \frac{1}{\tau}\int_0^t e(t)dt \qquad (3)$$

The PI controller is traditionally suitable for second and lower order systems. It can also be used for higher order plants with dominant second order behavior. The Ziegler-Nichols (Z-N) methods rely on open-loop step response or closed-loop frequency response tests. A PI controller is tuned according to a table based on the process response test. According to Zeigler-Nichols frequency response tuning criteria

$K_p = 0.6K_c$ and $\tau_i = 0.5T$

For the PI controller in the heat exchanger, the values of tuning parameters set initially are $K_p=14.28$, $\tau_i=14.395$
.

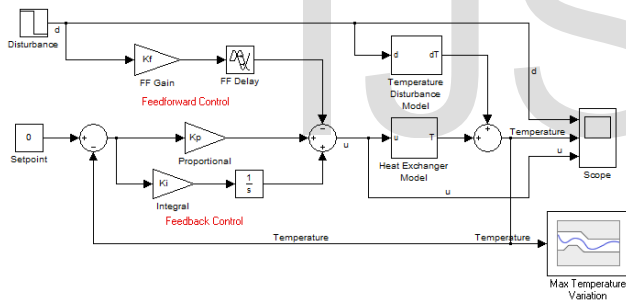### C. Feedback and Feed-forward Controller

Fig.2 Simulink model of Feedback and FF controller

In this configuration, the feed-forward controller F uses measurements of the inflow temperature to adjust the steam valve opening (voltage V). Feed-forward control thus anticipates and preempts the effect of inflow temperature changes. From fig. overall transfer from temperature disturbance d to tank temperature T is

$$T = (G_P F + G_d)d$$

Perfect disturbance rejection requires

$$G_P F + G_d = 0, F = -\frac{G_D}{G_P} = \frac{-21.3s + 1}{25s + 1}e^{-20.3s}$$

In reality, modeling inaccuracies prevent exact disturbance rejection, but feedforward control will help minimize temperature fluctuations due to inflow disturbances. To get a better sense of how the feedforward scheme would perform, increase the ideal feedforward delay by 5 seconds and simulate the response to a step change in inflow temperature. In this

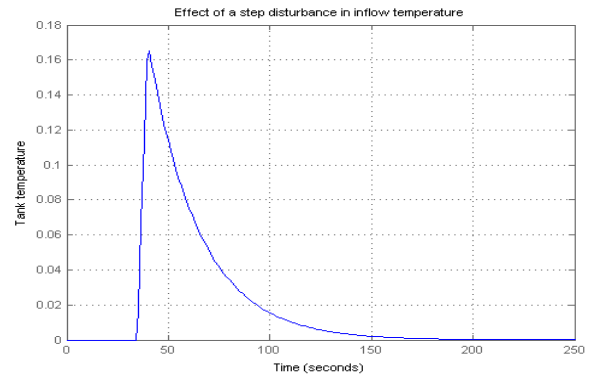configuration, the proportional-integral (PI) controller

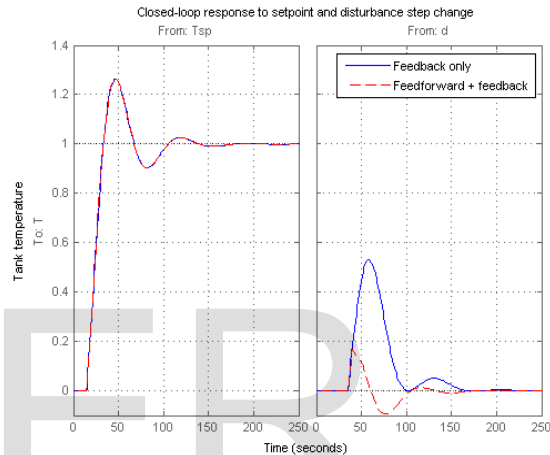Fig.3: Step disturbance in inflow temperature

Fig.4: Response of Feedback(FB) and FF+FB.

D. Gradient Descent Method

Gradient descent is descent is one of those algorithm that can offer a new perspective for solving problems. At theoretical level, gradient descent is an algorithm that minimizes functions. Given a function defined by a set of parameters, gradient descent starts with an initial set of parameters values and iteratively moves towards a set of parameters values that minimizes the function. This iterative minimization is achieved using calculus, taking steps in the negative direction of function gradient.

Given a differentiable scalar field f(x) and an initial guess x_1, gradient descent iteratively moves the guess toward lower values of f by taking steps in the direction of the negative gradient $-\nabla f(x)$. Locally, the negated gradient is the steepest descent direction, i.e., the direction that x would need to move in order to decrease f the fastest. The algorithm typically converges to a local minimum, but may rarely reach a saddle point, or not move at all if x_1 lies at a local maximum. The first order Taylor approximation of f(x) about $f(x_1)$ is:

$$f(x) = f(x_1) + \nabla f(x_1) \cdot (x − x_1) + O(\|x − x_1\|^2). \qquad (1)$$

Consider moving from x_1 a small amount h in a unit direction u. We want to find the u that minimizes $f(x_1 + hu)$. Using the Taylor expansion, we see that

$$f(x_1 + hu) - f(x_1) = h\nabla f(x_1) \cdot u + h^2 O(1). \quad (2)$$

If we make the h^2 term insignificant by shrinking h, we see that in order to decrease $f(x_1 + hu) - f(x_1)$ the fastest we must minimize $\nabla f(x_1) \cdot u$. The unit vector that minimizes $\nabla f(x_1) \cdot u$ is $u = -\nabla f(x_1)/\|\nabla f(x_1)\|$ as desired.

Algorithm: The algorithm is initialized with a guess x_1, a maximum iteration count N_{max}, a gradient norm tolerance g that is used to determine whether the algorithm has arrived at a critical point, and a step tolerance x to determine whether significant progress is being made. It proceeds as follows.

1. For $t = 1, 2, \ldots, N_{max}$

2. $x_{t+1} \leftarrow x_t - \alpha_t \nabla f(x_t)$

3. If $\|\nabla f(x_{t+1})\| < g$ then return "Converged on critical point"

4. If $\|x_t - x_{t+1}\| < x$ then return "Converged on an x value"

5. If $f(x_{t+1}) > f(x_t)$ then return "Diverging"

6. Return "Maximum number of iterations reached"

The variable α_t is known as the step size, and should be chosen to maintain a balance between convergence speed and avoiding divergence. Note that α_t may depend on the step t.

val(1,1) =
    Name: 'Kf'
    Value: 1.0453
  Minimum: 0
  Maximum: Inf
    Free: 1
    Scale: 0
    Info: [1x1 struct]
val(2,1) =

    Name: 'Ki'
    Value: 0.0161
  Minimum: 0
  Maximum: Inf
    Free: 1
    Scale: 0
    Info: [1x1 struct]
val(3,1) =
    Name: 'Kp'
    Value: 1.1854

Minimum: 0
Maximum: Inf
  Free: 1
  Scale: 1
  Info: [1x1 struct]
val(4,1) =
    Name: 'tau'
    Value: 21.7467
Minimum: 1.0000e-03
Maximum: Inf
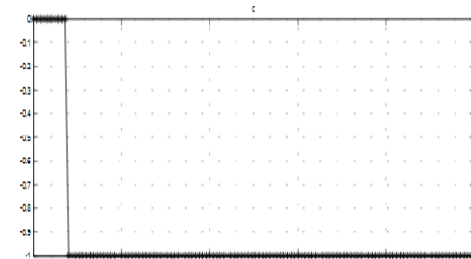 Free: 1
  Scale: 15
  Info: [1x1 struct]
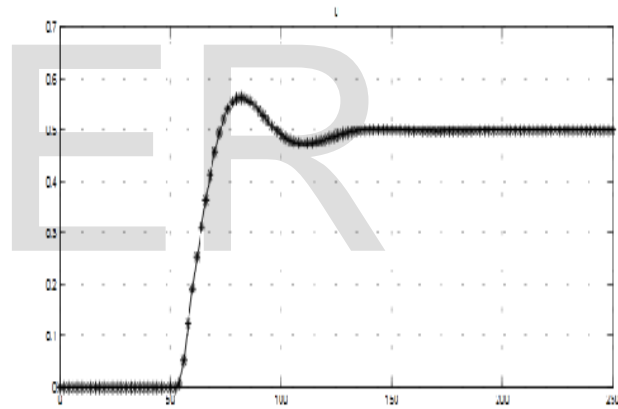

Fig.5: step disturbance in inflow temperature

Fig.6: Response of PI+FF before applying gradient descent method
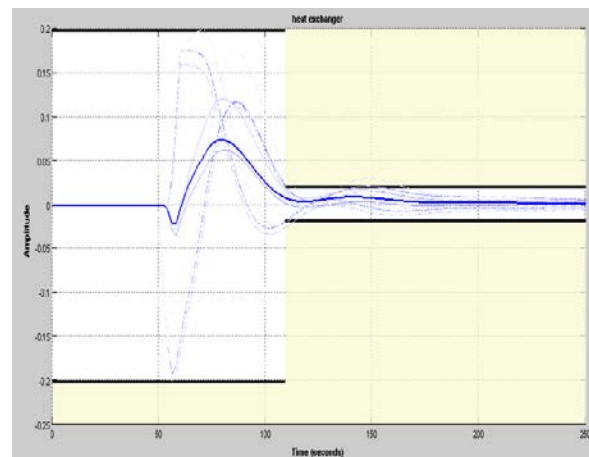

Fig.8: Tuning Optimization after applying gradient descent

Iter	F-count	Max. constraint
0	7	27.383
1	16	11.3971
2	25	2.7096
3	34	2.0088
4	43	0.6431
5	54	0.6175
6	63	0.3839
7	72	0.0139
8	81	0.0016
9	90	1.8258e-04

Table: I

Design Optimization workspace 'heatex_operation updated with optimized values Optimized requirement values written to 'Req Values' in the Design Optimization workspace: Optimization solver output: Local minimum found that satisfies the constraints. As shown in Table 1, Optimization completed because the objective function is non-decreasing in feasible directions, to within the selected value of the function tolerance, and constraints are satisfied to within the selected value of the constraint tolerance.Stopping criteria details: Optimization completed: The first-order optimality measure, 1.133360e-04, is less than options.TolFun = 1.000000e-03, and the maximum constraint violation, 1.825798e-04, is less than options.TolCon = 1.000000e-03. Optimization Metric Options first-order optimality = 1.13e-04 TolFun = 1e-03 (selected) max(constraint violation) = 1.83e-04 TolCon = 1e 03 (selected).

V. RESULTS AND OBSERVATION

The simulation results clearly shows that the proposed tuning optimization technique gives a much better control of temperature rather than classical PI controller and PI controller in conjunction with feed forward controller. To evaluate the performance of the different controllers we have considered two parameters of the step response of the system. The first parameter is the maximum overshoot and the 2nd parameter is the settling time.

In all the three controllers these two parameters are evaluated and a comparative study of their performance has been shown in the table below.

TABLE I
COMPARISION OF DIFFERERNT PARAMETERS IN CONTROLLERS

S.No	Parameters	Feedback PID	Feedback plus feed forward controller	Optimization using gradient descent technique
1	Overshoot	36.11%	28.4%	6.61%
2	Settling time	118.2 sec	95 sec	24 sec

TABLE II
COMPARISION OF PERFORMANCE INDICES VALUES OF CONTROLLERS

S.No	Parameters	Feedback PID	Feedback plus feed forward controller	Optimization using gradient descent technique
1	IAE	4.71	4.428	7.453
2	ISE	0.3598	0.312	0.903

From the above observations it is clear that in conventional PID controller in feedback loop the heat exchanger produces an overshoot is 36%. To compensate this kind of high overshoot we implemented a feed-forward controller in conjunction with the conventional PID. By implementing this method the system overshoot was reduced to 28%. Though the overshoot has some what decreased we can further reduce the overshoot by implementing fuzzy logic based PID controller. By implementing hybrid fuzzy PID controller in the feedback loop the overshoot reduces to 5.6%. In feedback controller the settling time was 118 sec where as in feed forward plus feedback controller the settling time decreases to 95 sec, and in hybrid fuzzy PID controller the settling time decreases to 30 sec.

Table2. shows the performance indices of different controllers. IAE and ISE of hybrid fuzzy PID controller are high compared to other classical controller which indicates the robust control of the controller.

From these observations it is clear that fuzzy logic controller is a much better option for control rather than conventional feedback and feedback plus feed-forward controller.

VI. CONCLUSION

This paper emphasizes on the temperature control aspect of the shell and tube heat exchanger system. To efficiently control the temperature we have designed three kinds of controllers and evaluated their performance according to two basic parameters. It is observed that intelligent controller like fuzzy PID controller gives a much better response than any other conventional controller.

A lot of further works can be done in this current proposal. A GA based fuzzy PID controller can be developed which can increase the efficiency of the fuzzy PID controller. Instead of the conventional feed forward structure a neural network based multi layer feed forward architecture can be implemented.

REFERENCES

[1] Kaddour Najim, *Process Modeling and Control in Chemical Engineering*, New York: Marcel Dekker, Inc., 1989.

[2]   Guanrong Chen and Trung Tat Pham, *Introduction to fuzzy sets, fuzzy logic and fuzzy logic control systems*, New York, USA: CRC Press, 2000.

[3]   Ramesh K. Shah and Dusan P. Sekulic, *Fundamentals of Heat Exchanger Design*, USA: John Willey and Sons, 2003

[4]   M. Gopal, *Control Systems Principles and Design,* 2nd ed., New Delhi, India: Tata Mcgraw-Hill Publishers, 2007

[5]   Arturo Pacheco-Vega, Claudia Ruiz-Mercado, Kevin Peters, and Luis Enrique Vilchiz, "On-line fuzzy-logic based temperature control of a concentric-tube heat exchanger facility", *Taylor & Francis Group Heat Transfer Engineering*, 30 (14), pp. 1208-1215, 2009

[6]   M. Mizumoto, "Realization of PID control by fuzzy control methods," *Proceedings of IEEE International Conference of fuzzy systems.* pp. 709-715, 1992

[7]   Isin Erenoglu, Ibrahim Eksin, Engin Yesil and Mujde Guzelkaya, "An intelligent hybrid fuzzy PID controller," *Proceedings of 20th European Conference on Modeling and Simulation*, 2006.

IJSER