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An Optimal Analysis of Controller Strategies for Different Heat Exchangers – A Review

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Abstract: Heat exchanger is the that process tend to be instable due non-linearity, inertia and time variability, hence perfect controllers has to be designed. In this paper different types of heat exchangers their mathematical modeling, its response for various Non model based controllers and Model based controllers are reviewed and the conclusions are made. Apart from that a new method has been proposed which not only improves the performance but makes the system to work more smoothly and effectively in terms of occurrence of undesirable disturbances in the system and maintains the system in its steady state.

Key words: Heat exchangers · Mathematical Modeling · Non-model based controller · Model based controllers

INTRODUCTION

Heat exchangers are most complicated and important process that is used as one of the thermal component. They are mostly nonlinear in nature due to its complicated dependence of fluid properties. They mainly depend on the heat transfer area, temperature difference in the fluid flow rate and their fluid flow pattern [1, 2].

They are many types of heat exchanger that are widely used for variety of thermal application in chemical process, food, petroleum and petrochemical industries and also used in various steam generation which are used for production of power, electricity and also used for nuclear reaction system, aircraft and space vehicles [3]. The different types of heat exchangers includes.

- Plate type heat exchanger
- Spiral type heat exchanger
- Shell and tube type heat exchanger
- Double pipe heat exchanger
- Cross flow type heat exchanger etc...

This study is concerned with the plate type, spiral type and shell and tube type heat exchanger [4].

Modeling of Heat Exchangers: The modeling of the system here was made mainly to study the how the variables change with time. The process modeling is mainly done to do the simulation studies in order to understand the process behavior which helps in better controlling and optimization studies The dynamic analysis for the heat exchanger gives information about how the process respond to various disturbances [5].

Modeling is a step by step procedure that formulates the unsteady state behavior of the process into mathematical equations which helps in understanding the behavior of manipulated input and disturbances of the system [6]. they are mainly used to analyze, design and define control strategies to the industrial processes. Dynamic modeling is needed to design the control strategies since the steady state modeling is effective only for the studying the start-up process of the system. Transfer functions describe the relationships between the controlled variables and the manipulated and load variables were developed and the system response to various temperature disturbances was simulated using a custom-developed MATLAB program [7].

Plate Type Heat Exchanger: The plate type heat exchanger was first invented by Albretch Dracke in 1878,

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but they are successfully implemented by Dr.Richard Seligman the founder of Aluminum Plant and Vessel Company in 1923 [8]. During 1930 the Alfa Laval Company at Sweden launched the commercial Plate type heat exchanger [9].

The plate type heat exchanger continuously transfer heat from one medium to another without adding energy to the process [10] and they are most efficient type of heat exchanger available today, [11] depending on the plate arranged and on the flow they are configured as series, parallel and multi pass by their opening and closing of the plate corner [8]. This heat exchanger has its application in various fields such as diary, food processing, pharmaceuticals, chemical, petroleum, offshore oil and gas, paper and pulp production etc. [10] since they have increased advantage in flexibility, higher heat transfer, easy maintenance lower rate of fouling and better controllability [12].

The plate type heat exchanger has been well implemented in from 1930s which has been proved effective in single phase heat transfer from liquid- to-liquid in chemical and food processing industries [13]. Here plate acts as a medium to transfer the heat as well as prevents the heat from mixing with the other liquid and thus the heat transfer takes place to the colder fluid in counter current flow arrangement [14].

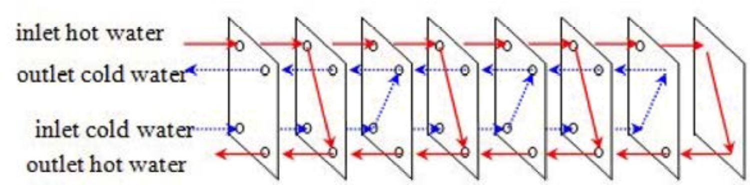


Fig. 1: Schematic representation of flow in plate type heat exchanger

Using the experimental studies of Plate type Heat Exchanger the temperature profile of the heat exchanger was studied for the modeling purpose [15].

Afraa H. Al-Tae and Safa A. Al-Naimi [16] has studied about the dynamic behavior of Plate type Heat exchanger using Single pass counter current Plate type Heat exchanger, they have studied the dynamic behavior of the Heat exchanger using various advanced controllers and have determined the effective control that can be implemented to get a effective control initially the transfer of the system has been modeled as follows.

The steady state balance around cold plate given as

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

The steady state energy balance around hot plate given as

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

As the cold flow rate of cold stream considered constant, the overall heat transfer expression is given as

$$U = \propto m_h^w$$

Substituting equation (3) into equation (2) and (1) we get

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

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

where,

$$Z = \left[\frac{\propto A}{2}\right] \tag{6}$$

The unsteady state balance around cold plate given as

$$m_c^o C_p T_{ci}^o - m_c^o C_p T_{co}^o + Z m_h^{ow} T_{hi}^o + Z m_h^{ow} T_{ho}^o - Z m_h^{ow} T_{ci}^o - Z m_h^{ow} T_{co}^o = M_c C_p \frac{dT_{co}^o}{dt} \tag{7}$$

The unsteady state balance around hot plate given as

$$m_c^o C_p T_{hi}^o - m_c^o C_p T_{ho}^o - Z m_h^{ow} T_{hi}^o - Z m_h^{ow} T_{ho}^o + Z m_h^{ow} T_{ci}^o + Z m_h^{ow} T_{co}^o = M_c C_p \frac{dT_{ho}^o}{dt} \tag{8}$$

After linearizing non – linear terms and introducing of deviation variables and Laplace Transform in equation (7) and (8) we obtain the Transfer function as follows.

$$G_{(s)} = \frac{T_{co(s)}}{m_{h(s)}} = \frac{H(T_\alpha s + 1)}{T_p^2 s^2 + 2\psi T_p s + 1} \tag{9}$$

where,
$G_{(S)}$ = Transfer function
$T_{co(s)}$ = Outlet cold water temperature
$m_{h(s)}$ = Hot water flow rate
H = Constant
T_α = lead time constant
T_p = Lag time constant
ψ = Damping Coefficient

Similar expression are obtained for the theoretical model based on lumped parameter system where the basic equation that are obtained using the energy balance and by analysis of the system they are considered as the first order lead and second order overdamped lag system of plate type heat exchanger [17]. The transfer function relating to outlet temperature of the cold stream ($T_{co(s)}$) and the mass flow rate of the hot stream (m_h) where represented by an overdamped second order lag coupled with first order lead with dead time [18].

$$G_{(s)} = \frac{T_{co(s)}}{m_{h(s)}} = \frac{H(T_\alpha s + 1)e^{-t_d s}}{T_p^2 s^2 + 2\psi T_p s + 1}$$

Shell and Tube Type Heat Exchanger: The Shell and Tube heat exchanger is mainly used for high pressure application. It consists tubes and a shell where the hot and the cold fluid flow. In this the inter baffle spacing plays vital role in heat transfer and pressure drop in shell and tube heat exchanger [19] and the fouling in this heat exchanger depends on velocity and temperature, these studies are made to analyze the effectiveness [20] and performance of the heat exchanger [21] Dynamic modeling is essential for better understanding of the process which are done using the process physical parameters [22].
The mathematical modeling of the system was done by applying the physical and chemical laws.

The equation represented below are based on the energy balance law, (i.e.) the energy supplied to the process are equal to the energy removed

$$T_{co}(t) = \frac{w_c}{\rho_c V_c (T_{ci}(t) - T_{co}(t))} + \frac{U_c A_c}{\rho_c V_c C_{pc} (T_{ho}(t) - T_{co}(t))} \quad (11)$$

$$T_{ho}(t) = \frac{w_h}{\rho_h V_h (T_{hi}(t) - T_{ho}(t))} + \frac{U_h A_h}{\rho_h V_h C_{ph} (T_{co}(t) - T_{ho}(t))} \quad (12)$$

where:

T_{ci} = *Inlet cold fluid tempurature in °C*
T_{co} = *Outlet cold fluid tempurature in °C*
T_{hi} = *Inlet hot fluid tempurature in °C*
T_{ho} = *Outlet hot fluid tempurature in °C*
$w_c = \text{mass flow rate of cold fluid} (\frac{kg}{\sec})$
$w_h = \text{mass flow rate of hot fluid} (\frac{kg}{sec})$
$C_{pc} = \text{heat capacity of cold fluid} (\frac{J}{kg.°C})$
$C_{ph} = \text{heat capacity of hot fluid} (\frac{J}{kg.°C})$
$\rho_c = \text{density of cold fluid} (\frac{kg}{km^3})$
$\rho_h = \text{density of hot fluid} (\frac{kg}{km^3})$
V_c = Volume of cold fluid (cm^3)
V_h = Volume of hot fluid (cm^3)
A_c = *heat transfer surface area of cold fluid* (cm^2)
A_h = *heat transfer surface area of hot fluid* (cm^2)

$U_c = \text{heat transfer coefficient of cold fluid} (\frac{W}{cm^2 °C})$

$U_h = \text{heat transfer coefficient of hot fluid} (\frac{W}{cm^2 °C})$

Non –parametric system identification of shell and tube heat exchanger [22].

In this modeling the system model is estimated by its step response. The technique is based on two point fraction response of the system at 20% and at 60%

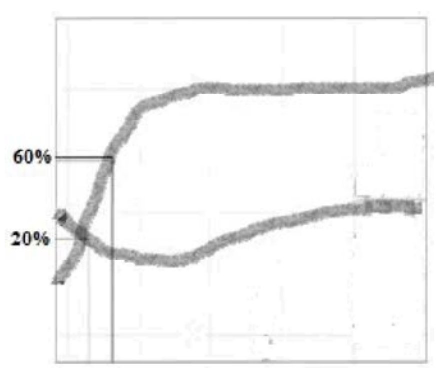


Fig. 2: The heat exchanger step response from experimental data [22].

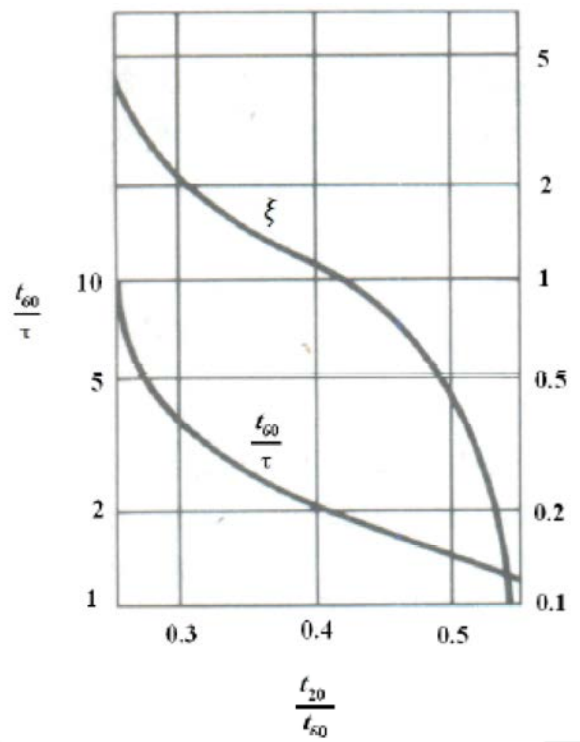


Fig. 3: Smith Chart

The system mathematically represented as

$$G(s) = \frac{Ke^{-t_0}}{(\tau_1 + 1)(\tau_2 + 1)} \tag{13}$$

where:

$\tau_1 = \tau\xi + \sqrt{\xi^2 - 1}$

$\tau_2 = \tau\xi - \sqrt{\xi^2 - 1}$

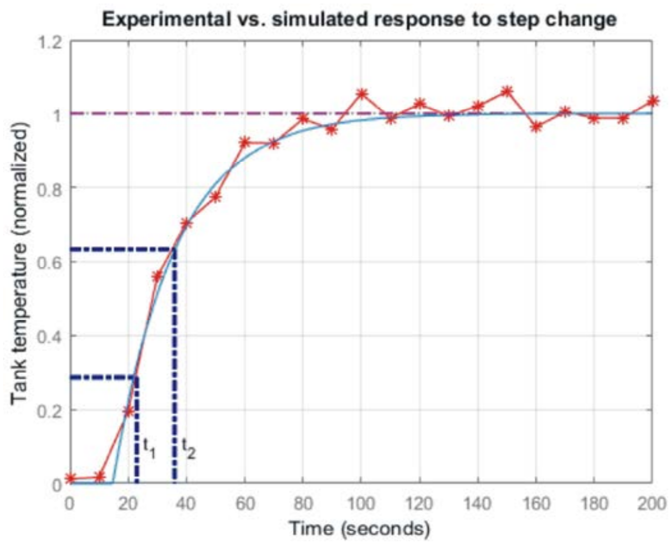
K = gain

t_0 = *time*

Here the damping value ξ is equal to $\frac{t_{20}}{t_{60}}$ and the value of time delay is determined from the graph of $\frac{t_{60}}{\tau}$ versus $\frac{t_{20}}{t_{60}}$.

Spiral Type Heat Exchanger: The spiral type heat exchanger has a helical tube configuration which is commonly a pair of flat surface that are coiled to form two channels. The main advantage of this type of heat exchanger is they efficiently use the space. Since they are compact in size they have smaller footprint and thus lowering the capital cost.

The transfer function of the heat exchanger can be obtained from the experimental reading by obtaining the step response of the system. This is a technique that is based on the rise time of the system at 20% and 60%. From which the values τ_1 & τ_2 are obtained.



Fi. 4: Response of experimented and simulated data

The value of τ is calculated by substituting in the following equation

$$\tau = \frac{3}{2} \times (\tau_2 - \tau_1) \tag{14}$$

The value of ξ is calculated using the following formula

$$\xi = \tau_2 - \tau \tag{15}$$

The transfer function is represented as follows

$$G(s) = \frac{Ke^{-\xi}}{\tau s + 1} \tag{16}$$

Controllers for Heat Exchangers: Now a days it has been increasing demand that the net result is always depends on the quality specification because of the Stronger competition, tougher environmental and safety regulations and hence the operation of the new modern plants tends to be more difficult because of its complex behavior. In general the controller works by receiving the continuous signal from the output that may be(pressure, temperature or level) measurement ; here the temperature measurement is taken which is compared with the set point that in turn produce the actuating signal, the error signal produced by the controller is used to regulate the control valve

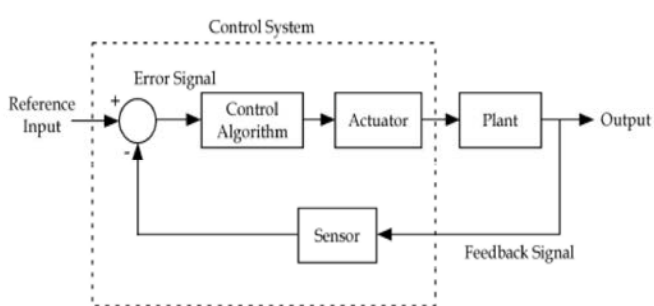


Fig. 5: Block diagram of feedback control loop

The aim of the studying the dynamics of the process control is to maintain the process in desired operating condition and operate them safely and proficiently.

Generally the control design of the process fall under two approaches

- Non Model- based Approach
- Model – based Approach [23]

Non Model- Based Approach: These are the control strategies of the control system where the hardware (i.e.) the controller is designed based on the knowledge of the process in which the controller tends to adjust itself depending on the process disturbances and the process is controlled accordingly.

Model Based Approach: Here in this approach the controller is designed keeping in mind the general control laws of the process, initially basic model of the controller is designed then they are directly incorporated with the control law finally inferred using the computer simulation to check the control strategies and using the pre values the controller setting is made. In many heat exchangers are difficult to control because of the non linearity [24, 25] in the process which is due to the complications that occur in the process.

Proportional Controller: The proportional controller is mainly used to reduce the effect of the rise time [25] but they don't eliminate the steady-state error or the offset. The main disadvantage this controller is that they change the output only if there is change in signal, hence the controller can never fully return the output variable to its set point [26]

The proportional control is mathematical represented as [p-88]

$$C(t) = K_c E(t) + C_s \tag{17}$$

where

$C(t) = Controller\ output.$

$K_c = Proportional\ gain\ of\ the\ controller$

$C_s = initial\ value\ of\ the\ controller$

$E(t) = error\ (difference\ between\ measured\ signal\ and\ set\ point)$

The transfer function of the Proportional controller is represented as

$$G_s(s) = K_c \tag{18}$$

Proportional-Integral Controller: In many process the commonly used controller is Proportional plus Integral control [27]. They are much used because they control the process by feedback controller calculating the sum of error and the integral of that value [28]. Here the measured value is returned to the set point without excessive oscillation. When the integral time is smaller the error tends to be reduced faster, but the system becomes under damped, if τ_i is reduced and the system becomes unstable. The PI controller when compared with that of the proportional control is slower and the response period id 50% longer than that of Proportional control.
The Proportional-Integral control is mathematical represented as [29]

$$C(t) = K_c E(t) + \frac{K_c}{\tau_I}\int_0^t E(t)\,dt + C_s \tag{19}$$

where:

$\tau_I = integral\ time\ constant$

The transfer function of Proportional-Integral controller is represented as

$$G_c(s) = K_c + \frac{1}{\tau_I s} \quad (20)$$

Proportional – Integral – Derivative Controller: PID Controller is also one of the earliest technologies and the most common controller that are used to control the process more effectively and are easily implemented and this controller has a remarkable advantage that they can be handled efficiently even with little knowledge [30]. In many literatures the PI control has been used to control heat exchangers [31-44].

The main purpose of using the PID controller is that they tend to respond faster as Proportional Control without any offset error and also they overcome the disadvantage of PI controller by responding faster [p-20].

The Proportional-Integral-Derivative control is mathematical represented as [45]

$$C(t) = K_c E(t) + \frac{K_c}{\tau_I}\int_0^t E(t)\,dt + K_c \tau_D \frac{dE}{dt} + C_s \quad (21)$$

where:

$\tau_D = Derivative\ time\ constant$

The transfer function of Proportional-Integral controller is represented as

$$G_c(s) = K_c + \frac{1}{\tau_I s} + \tau_D s \quad (22)$$

The tuning of the controllers is done mainly by two methods. They are Cohen-Coon method and Ziegler-Nichols method. The Cohen-Coon method is known as process reaction curve derived from the open loop system, while the Ziegler-Nichols method is based on the frequency response analysis that mainly depends on the closed loop system [46].

In industries the process are highly non linear in nature hence the application of conventional or non model based controller does not yield effective results since the processes are Multi input and Multi output in nature hence modern and intelligent controller capable of handling MIMO systems and non linearity is considered [47].

The intelligent controller technique that are widely used are Fuzzy Logic, Artificial Neural Networks etc, [48] they also included model based controllers such as Internal model control, Model Predictive Control and Hybrid Controllers.

Fuzzy Logic Control: Fuzzy logics depend on the concepts of fuzzy set which was first introduced by Zadeh in 1965. Fuzzy set theory are considered as generalization of the classical set theory which states that the element of the universe belong to or does not belongs to the set taking this into account along with the requirement and constrains of the problem the fuzzy with the help of membership functions estimates the desired output needed for the process [49, 50]

The fuzzy Logic control system consist of fuzzification interface, data base, interference mechanism, rule base and defuzzfication interface [51-55].this data and the rule base are often known as knowledge base [51, 52].

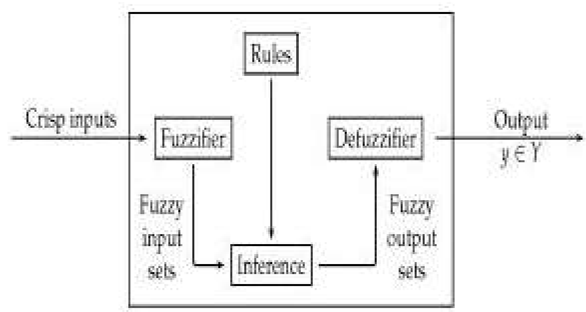


Fig. 6: Fuzzy logic control system

The fuzzfication interface measures the values of the input variables and after performing the mapping they convert the data into suitable linguistic variables [51], these transformation is determined by the membership function defined by the user that may take any forms including triangular, trapezoidal and Gaussian function [56].

The data base defines the linguistic control rules and data manipulation in fuzzy logic control [51].

The rule base and the inference mechanism is the main part in Fuzzy logic controller where the rule base defines the control goals and policy to set the linguistic control rules [51]. In the Fuzzy Logic controller the error (e) and the change in error (de) act as an input linguistic variable depending on it the control action (u) is taken as the output linguistic variable. The membership function of error and change in error has the control action negative (N), zero (Z) and Positive (P).

		E		
		N	Z	P
De	N	N	N	Z
	Z	N	Z	P
	P	Z	P	P

Fig. 7: IF-THEN rule base for fuzzy logic control

The interference mechanism is decision making logic of the Fuzzy Controller they have the capability to simulate the decision-making based on fuzzy concepts [51] by interpreting and applying the knowledge.

The defuzzification interface gives the overall performance of the system under control by determining the control signal; here they convert the controlled linguistic variables from the interference mechanism into suitable output variables to control the process.

Fuzzy Logic is computational logical system which that imparts the human thinking and natural language than classical logical systems [43, 51, 57], they are sets of linguistic variables rather than numerical variables [58].

Fuzzy has a great advantage since the human knowledge about the process is required for designing the controller through which a proper and a correct control of the plant is done. And hence they can be more easily applied to the industrial process [59].

The fuzzy logic is a method of translating the human knowledge into control strategies, thus through its implementation results in good performance of heat exchangers [60]. Hence many research has been conducted in this Fuzzy logic that has been reported in literature [42, 61, 62]

Artificial Neural Network: ANN was first introduced by McCulloch and Pitts in 1943 [63]. The ANN resemble the network of nerve cells in the brain and they are logical structures that have similar functions as that of the biological brain hence most of the functions are similar to that of neuroscience [64]. Since they are composed of large number of highly interconnected neurons [60-67] they form a powerful tool to solve complex problems. By applying algorithms that mimics the real time process the ANN can learn many and solve problem.

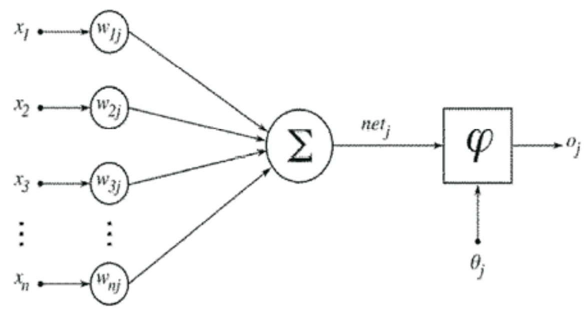


Fig. 8: Basic model of neuron

The threshold function of the sigmoid activation function

$$\varphi(x) = \frac{1}{1 + e^{-cv_h}} \tag{23}$$

where c is the constant that determines the shape of the sigmoid [68]. These sigmoid functions are used for the activation [69]. The ANN is classified as feed forward and recurrent networks. In most of the heat exchanger application the Multi Layer Perceptron (MLP), which is a feed forward neural network. It is used because its ability to perform complex modeling and helps in understanding the relationship between the variable more easily. It is Multi Layered structure from one input and output layers along with at least one processing unit in between them. Where the outputs from the input are fed to the hidden layer, from which the data are fed to the next hidden nodes which transforms the net activation function through a linear function such as the logistic sigmoidal to compute their outputs [67].

ANN is termed as a powerful tool because they have the ability to detect the pattern and find the relationship within that data through training not by programming even though the relationships within the datas are unknown [70].

ANNs have their wide application in System Identification, Pattern Recognition and Dynamic control as they are capable of simulating the complex, non linear and uncertain systems with the knowledge of input and output data's collected. Hence many papers regarding the implementation of ANN in various complex types heat exchangers [67, 71-74].

Internal Model Controller: Internal model control has been in research since 1980, the accurate model of the process leads the control system to be more stable and robust. In IMC the controller model has been designed by considering the model of the process, model uncertainty, the type of input and the performance objective [75].

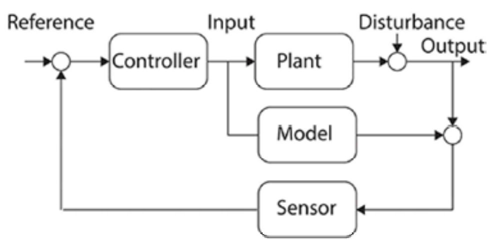


Fig. 9: Block diagram of Internal model Control

The principle of IMC states that the system is controlled when the controller that is designed has some representation of the process.

The process with the delay are generally represented as

$$G = \frac{Ke^{-\tau ds}}{\tau d + 1} \tag{24}$$

In the model of the process with time delay the approximation to the lag is done by the first order Pade approximation.

$$e^{-\tau ds} = \left(\frac{1 - \left(\frac{\tau d}{2}\right)s}{1 + \left(\frac{\tau d}{2}\right)s} \right) \tag{25}$$

The model becomes

$$G_m = K\left(\frac{1 - \left(\frac{\tau d}{2}\right)s}{1 + \left(\frac{\tau d}{2}\right)s} \right) \tag{26}$$

Thus,

$$G_I = \frac{1}{G_{m_m}} \tag{27}$$

The result of applying the above equation will obtain a transfer function that is stable and does not require prediction; On the other hand it will have terms that cannot be implemented because they require pure differentiation

The IMC controller is obtained by multiplying it with the transfer function of the filter f(s) that can be represented as

$$f(s) = \frac{1}{(\lambda s + 1)^n}$$

where ◎◎ is the filter parameter and n is an integer finally the equation of IMC can be obtained as

$$G_I = \frac{f}{G_{m_m}}$$

The transfer function G_c, is obtained with the help of G_I and the filter equation. Finally the, G_c turns out to be equal to a PID controller multiplied by a first-order transfer function thus

$$G_c = K_c\left(1 + \tau_D s + \frac{1}{\tau_I s}\right)\left(\frac{1}{\tau_1 s + 1}\right)$$

where, K_c, τ_D, τ_I, τ_1 are the function of the process in the G_I and G

The experimental data are taken and are modeled accordingly as stated above [76, 77]

Model Predictive Controller: MPC technology known as a next generation technology since it determine similarities and differences between the various approaches for both linear and non linear process[78].Model predictive control (MPC) has been used for process control in process industries such as chemical plants and oil refineries since 1980s. They rely on dynamic models of the process, which are often linear empirical models obtained by system identification. The main advantage of MPC is that it allows the current timeslot to be optimized, by keeping in account future timeslots that are achieved by optimizing a finite time-horizon, implementing the current timeslot.

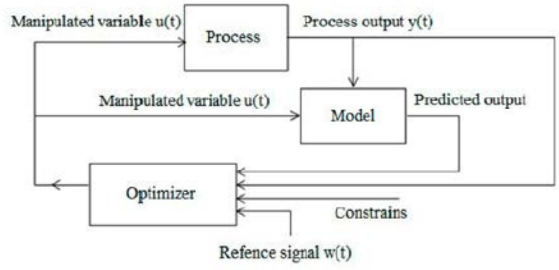


Fig. 10: Block diagram of Predictive Control

The model reference non linear controller with PID control action for heat exchanger system. Has proved to be efficient from other controllers and robust for modeling errors and disturbances [79]. The design process of the predictive controller has the general characteristics of predictive control which helps in calculating the control law for different process parameters. Through the simulations it is suggested it has a improved control performance in terms of energy and comfort compared with the previously installed industry-standard control strategy [80], which helps the nonlinear chemical plant models to show the efficiency, stability and robustness to step set point changes and load disturbance rejection when moving the operating point of the plant around its nonlinear region [81]. Hence it can be inferred that the future challenges to temperature control and cost optimization in building an energy systems can be indentified and controlled using this controller. Since the MPC is a Model based controller they can be effectively implemented using the extended Kalman filter which helps in controlling the non linear plants minimizing energy consumption using current energy sources and minimal retrofitting.

Control of Heat Exchanger: In this paper the above paragraphs discusses the research on heat exchanger by implementing different controllers for obtaining the desired response and analyzing various controlling strategies. In most of the papers the process is controlled by traditional feedback control or a feed forward control is in which, it is observed that each controller respond differently at various conditions. Hence it is necessary to find an optimal solution for effectively controlling the process at various process conditions and also during sudden disturbances. So, instead of controlling the process using a single loop the response of the process will be greatly increased if the process is controlled using a cascade loop control in addition to a feed forward control this approach is called as an integrated approach which performs more effectively and smoothly since each loop handles different parameter that causes trouble in maintaining or controlling the parameter that has to be controlled.

A controllers performance are evaluated using its responses to the process such as overshoot, Rise time, Settling time and the Steady state response.

The following table explains the controller response in a crisp manner in terms of their steady state condition.

Table1: Analysis of performance of Controllers

		Plate Type Heat Exchanger			Shell and Tube Type Heat Exchanger			Spiral Type Heat Exchanger		
Controller	Cascade Control +Feed forward Control	Without dela yand noise	With delay	With noise	Without delay and noise	With delay	With noise	Without delay and noise	With delay	With noise
PI	PI+PI+FF	C	SO	C	C	C	C	C	SO	U
PID	PID+PID+FF	C	U	SO	C	C	SO	C	O	O
IMC	IMC+IMC+FF	C	C	SO	C	C	SO	C	C	O
	IMC+PID+FF	C	O	VSO	C	C	SO	C	SO	U
MPC	MPC+PI+FF	C	C	C	C	VSO	C	C	C	C
Smith Predictor	Smith PI+PI+FF	C	C	C	C	C	C	C	VSO	U
	Smith IMC+PI+FF	C	VSO	C	C	C	C	C	C	U
	Smith IMC+IMC+FF	C	C	C	C	C	C	C	C	VSO
	Smith MPC+PI+ FF	C	C	C	C	C	C	C	C	C
	Smith MPC+IMC+FF	C	C	C	C	C	C	C	C	VSO

Where,

C – Controlled

O – Oscillatory

SO – Slightly Oscillatory

VSO – Very Slightly Oscillatory

U – Unstable

The above table gives the steady state response of the process heat exchanger when they are implemented using advanced controller n terms of their steady state response.

CONCLUSION

From all the above discussion and results it is inferred that the integrated approach has much advantage when compares it with the single loop feedback controller. Artificial Neural Network performs well as a controller and acts a good optimizer for the heat exchanger system. The other controller such as Model Predictive Controller, Internal Model Controller performs well in controlling the nonlinearities of the process but it takes time and also these controllers have high errors, rise time and settling time when compared to that of the Artificial Neural network. Even though the conventional controllers are much in practice nowadays the main disadvantage of this controller is its derivative part that makes the system more sensitive to disturbance hence to overcome this the model based controllers and intelligent controllers are used. If these controllers are implemented in combination as determined by the above proposed method the controlling of the system become highly effective and optimized.

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