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# Control Strategy of Glass-Lined Batch Polymerization Reactor for PVC Resin Industrial Process

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**Abstract**

A well accepted control strategy, enhanced cascade control scheme of glass-lined batch reactor has been developed for PVC resin industrial process. With (i) Split range controller of cascade control scheme act as a local controller for manipulating the jacket temperature of reactor by pumping +10 ℃, cooling water or if necessarily chilled media, diethylene glycol maintained at -38℃. (ii) A Soft computing technique as adaptive neurofuzzy inference system (ANFIS) has been implemented for manipulating the uncertainty in the jacket temperature. The efficiency and robustness of the proposed method have been demonstrated through simulations and real time data. Closed loop response of PVC resin model compared with experimental and other literature models, shows good agreement. Only slight variations can found in Masoud Soroush & Costas Kravaris (1992) and Kiparissides et al. (1997) works due to variation in the operating temperature value. Performance analysis of the control strategy for PVC resin referred process has been discussed. Good tracking of the set point, disturbance rejection and robustness at different operating points in the cascade controller has been shown. The performance of all the controllers for set point changes have been evaluated, using IAE and ISE criteria.

**Keywords**: Glass-lined batch reactor, PVC resin, enhanced cascade control scheme, split range controller, ANFIS.

## INTRODUCTION

For the industrial process to be carried out in an efficient and properly controlled manner, a thorough knowledge regarding the selection of the reactor, knowledge about the feed stock materials, the physical and chemical properties of feed stock, material balance, kinetics and kinematics of the mass energy balance, selection of catalyst and suitable stipulated ambient conditions are required.

In industrial processes, chemical reactors do the production of quality end products on small scale and large scale. Most of the industrial chemical reactors are complex in nature, nonlinear, with uncertain dynamics, unsafe operating conditions and lack of complete state and process parameters and its measurements.

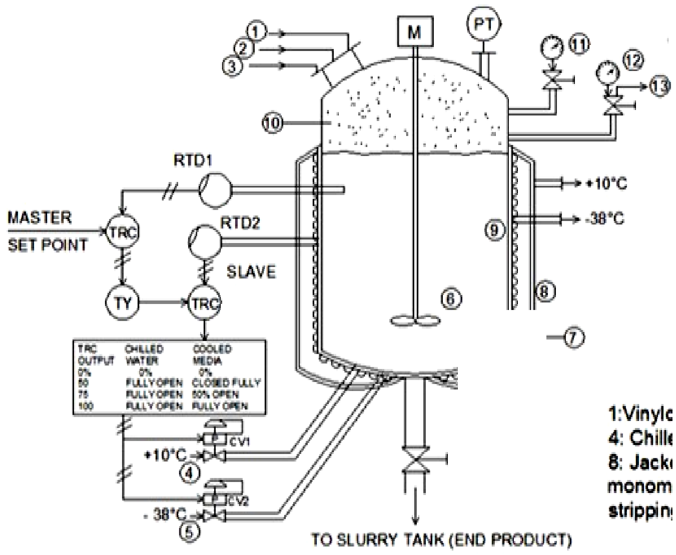
This paper is mainly focused on the implementation of selected control strategy for glass-lined batch reactor for the important industrial Poly Vinylchloride (PVC) resin product and their processes. Poly Vinylchloride (PVC) resin, as an important plastic material used for a wide range of applications due to its unique properties. In the Poly vinylchloride (PVC) production process, vinyl chloride monomer is employed as the main feed stock material. Vinyl chloride monomer is converted into polyvinyl chloride through the polymerization batch process seen in a glass-lined reactor. Glass - lined batch reactor is complex in nature, especially the polymerization process and is a challenging area for research. Most of the polymerization is a time based process, whereas PVC production process takes an extended hours to appear as a final product with temperature to be maintained at 48.5ºC ± 0.25ºC, pressure reaching 12 kg/cm$^2$.

The models of critical batch reactor are obtained by solving mass and energy based model equations which describe the behavior of the reactor. These process models help in selecting appropriate control strategies for improvement of operational efficiency and production rate. The appropriate control strategy depends on the processing method, type of reaction, reactor type, catalyst selection, process operating temperature, application of the product to the need of the universe. This work has been strongly suggested for the cascade control scheme for PVC resin process in batch reactor.

## PROCESS DESCRIPTION OF PVC RESIN - AN EXPERIMENTAL STUDY

A critical glass-lined reactor has been considered in this batch suspension polymerization process, because the temperature and pressure variation are involved continuously in the polymerization process. A catalyst is used for accelerating the polymerization reaction. A peroxide type catalyst is mostly used which is highly corrosive in nature, considering safety is an important prerequisite in the reactor without affecting the metal surface of the reactor. When reacting with the metal surface of the reactor, not only the life of the reactor comes down, but the quality of the final end product also gets detoriated due to oxidation.

Hence the use of a glass-lined batch reactor has been suggested in this study. It has an excellent anti-corrosion property. The term 'lined' refers to the glass coating on the agitator and inner surface of the reactor which provides corrosion resistance.Glass-lined batch reactor used in this polymerization process is a SS316 500L jacketed vessel. A annular space is provided with outer cylinder and the jacket is provided with limbed coil embedded or welded over the outer surface of the inner vessel. The jacket is provided with two cooling systems + 10ºC, chilled water system and –38ºC coolant media system (media is diethylene glycol). The amount of heat liberated is very high in batch polymerization. This excess heat energy can be quenched from the reaction as +10℃ and –38 ℃(in low quantity) which depends on the rate of conversion. The cooling function is controlled by a split range control vave as a local controller. During the initial phase of the reaction chilled water is circulated to the jacket of the reactor while at high reaction phase, chilled media is circulated to the limbed coil provided in the outer surface of the inner vessel inside the jacket. The available measurements of the process are reactor and jacket temperature, RTD type temperature transducers have been used in this study for obtaining the precised temperature values and the deviation should not be more than ± 0.25 ℃. The pressure gauge is mounted for close monitoring of the critical process. This is shown in the schem atic diagram. Vaccum gauges are also shown in this work.

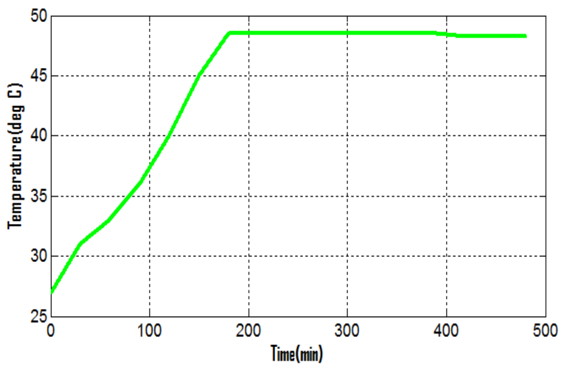



1. vinylchloride monomer, 2. Pure water, 3. Catalyst and initiator, 4. Chilled water, 5. Cooled media, 6. Agitator, 7. Limbed coil, 8. Jacket, 9. Glass lined surface, 10. Unreacted vinyl chloride monomer, 11. Pressure gauge, 12. Vacuum gauge, 13. Vacuum stripping

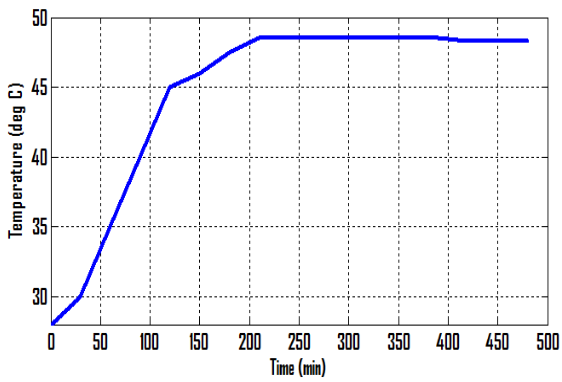
**Figure 1.** Schematic diagram of glass-lined batch reactor for PVC resin polymerization process

Experimental studies have been carried out, with typical ingredients: monomer, 236.75 kg; pure water, 250 kg; catalyst, 47.52 kg. The polymerization temperature was set to 48.5 ℃. When the reactor was empty, jacket was filled with water, temperature was maintained at ambient temperature value 28℃. The reactor was filled with pure water, vinyl chloride monomer and the catalyst and get ceiled, now the ambient temperature was raised to 26℃. Now polymerization reaction get initiated, jacket temperature raised by injecting hot water around 52.5℃, partial reaction has been taking place. The pressure shoot up to 10-11 Kg/cm$^{2,}$ since the reaction is exothermic and has become vigorous, rapid conversion with uncontrolled heat energy get liberated with drastic variations in temperature and pressure. Process requested control over either pressure or temperature, by adopting cascade control scheme, temperature rather than pressure was precisely controlled, reaction rate was very fast till the conversion reached 70%, split range controller, excess heat energy get quenched out from the reaction as +10℃ and -38℃. Adequate care should be taken for achievement of the required performance through the selection of proper controller, temperature sensors and the final control element.

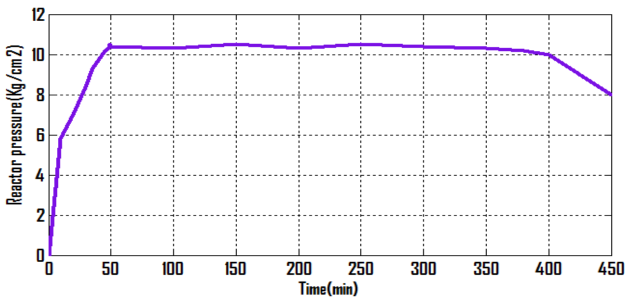
Valued real time data collected from the scaled up industry. The main purpose of this work is to report the valued datas collected from the scaled up industry and to develop models for the process for evaluating the performance of this batch process. Scaled up Industrial graphs are shown in Figure 2 which shows increase of the reaction rate with reactor temperature attaining a steady value of 48.5℃ at 60% conversion rate. The jacket temperature follows the reactor temperature, pressure increases to 11.1 kg/cm$^2$ and drops continuously. Chilled water flow rate decreases and chilled media flow rate increases at the completion of the reaction.



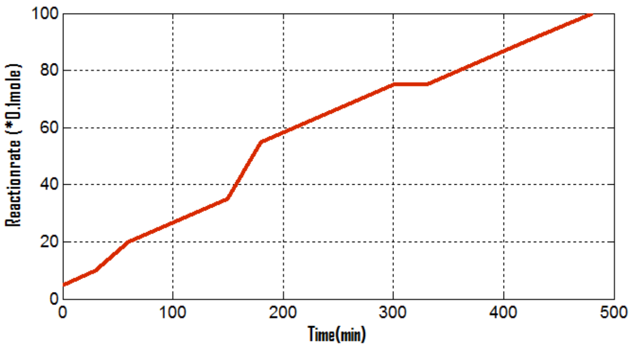

a) Reactor temperature vs time



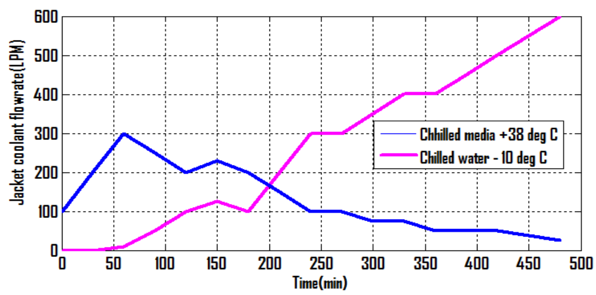

b) Jacket temperature vs time




c) Reactor pressure vs time




d) Reaction rate vs time




(e) Jacket coolant flowrate vs time

**Figure 2.** Experimental response of reactor and jacket temperature, reactor pressure, reaction rate and jacket coolant flow rate of PVC resin process in a glass-lined batch reactor.

## Modeling the glass-lined batch reactor for PVC resin process

Glass-lined batch reactor control is complex in nature, especially the polymerization process, and is a challenging area for research. Most of the polymerization is a time based process, where-as PVC production process takes extended hours to appear as a final product with temperature to be maintained at 48.5°C± 0.25°C,pressure reaching 12 kg /cm$^2$.

In this research, the models of critical batch reactor are obtained by solving mass and energy based model equations which describe the behavior of the reactor. The following models are referenced from Kiparissides et al. (1997), Masoud Soroushan & Costas Kravaris (1992) works.

## Mass balance model

Reactor polymerization rate and monomer conversion rate model. The factors influencing monomer conversion are initiator and monomer concentration, reaction temperature and the rates of the reaction and polymerization are given by the following equations.

$$R_p = \frac{dX}{dt} = K_p \left( \frac{2fK_d}{Kt} \right)^{1/2} I^{1/2} X \qquad (3.1)$$

$$K_p = K_0 e^{-Ea/RT} \qquad (3.2)$$

Equation (3.1) shows the polymerization rate of monomer (conversion rate) as a nonlinear function of batch reactor temperature Contillo (2002). The polymerization rate decreases with increase in temperature. The relation between reaction rate constant $K_p$ and reactor temperature seen in equation (3.2) was stated by Arrhenius. The values of $E_a$ and R are referenced from related works. Where $R_p$ is polymerization rate of the reaction or the overall rate of the reaction, $K_p$, $K_d$, $K_t$ are rate constants, $K_o$is pre-exponential factor, $E_a$ is activation energy, R is the gas constant, T is reactor temperature, f is initiator decomposition factor, I is initiator concentration, X is monomer concentration.

## Energy balance model

Monomer (VCM) to polymer (PVC) resin conversion depends mainly on the reactor temperature. It is the main variable affecting PVC resin end product quality and production. Reactor temperature has to be controlled to a 48.5 ± 0.25°C by implementing a cascade control strategy for PVC resin process.

Reactor temperature model: Polymerization process in a batch reactor, energy is absorbed or released as a result of the following:

i) Heating of the reactor through the heating jacket.
ii) Heating of the incoming monomer.
iii) Heat produced in the exothermic equation.
iv) Heat loss to the surroundings.

Reaction heat capacity is calculated from the total heat capacity in the reactor that is mass of the raw materials in the reactor. By taking in to account all the contributing factors, the reactor temperature model is given as follows:

$$\frac{dT}{dt} = \frac{Q_{rea} + \overset{o}{m}_m C_{pm}(T_{amb} - T) - UA(T - T_j) - UA_{loss}(T - T_{amb})}{m_m C_{pm} + m_p C_{pp} + m_w C_{pw}} \qquad (3.3)$$

Jacket temperature model: The temperature in the jacket is kept constant during the heating phase, jacket dynamics is very important in the batch process control and efficiently controlled by manipulating the jacket coolant inlet temperature, using two cooling systems which have been taken in the cascade control strategy implementation. The jacket temperature model is given as follows:

$$\frac{dT_j}{dt} = \frac{\dot{m}_j C_{pj}(T_{jin} - T_j) + UA(T - T_j)}{m_j C_{pj}} \quad (3.4)$$

Where $T_{jin}$ is Jacket inlet temperature, $T_j$ is Jacket temperature, T is Reactor temperature, U is Overall thermal conductivity, A is Reactor area, m is mass of content in reactor, $C_p$ is heat capacity of content in the reactor, $m_j$ is mass of coolant in jacket, $C_{pj}$ is heat capacity of content in the jacket, $\dot{m}$ is mass flow rate of the monomer, $\dot{m}_j$ is mass flow rate coolant in the jacket.

Reactor pressure model : In a batch reaction, the pressure shoots up to 10-11 kg/cm$^{2.}$ As the reaction is exothermic and has become vigorous, rapid conversion with uncontrolled heat energy gets liberated with drastic variation in temperature and pressure. The Process requires control, either pressure or temperature can be controlled, by adopting the cascade control scheme, while there is precise control on temperature rather than on pressure. The pressure model alone is formulated here as follows:

$$P \exp^{\frac{P}{RT}[B_m + (1-\gamma_m)^2 \delta_{mw})]} = \exp^{\ln[f_m^0(1-\varphi_2)+\varphi_2+\chi\varphi_2^2]-\ln\gamma_m} \quad (3.5)$$

Where P is reactor pressure, R is ideal gas constant, $\gamma$ is overlap factor, $B_m$, is second viral coefficient, $\delta_{mw}$ is monomer solubility, $\varphi_2$ is polymer volume fraction, $\chi$ is interaction parameter.

**Heat released by the reaction**

A change in enthalpy of a system when a reaction occurs at constant is the heat of the reaction. The system may have to give off or absorb heat (q) in order to maintain a constant temperature in the system.

Exothermic reaction, system losses heat

$\Delta H =$ negative

Endothermic reaction, system gains heat

$\Delta H =$ positive

When reactants and products are in their standard states, the enthalpy change or heat of the reaction,

$\Delta H = \Delta H_{pr} - \Delta H_{re}$

Where, $\Delta H_{pr}$ is the sum of enthalpy of all the products and $\Delta H_{re}$ is the sum of enthalpy of all the reactants.

A change in enthalpy or heat of the reaction means heat released or absorbed during the reaction is given by the following equation.

$$Q_{rea} = -\Delta H R_p \quad (3.6)$$

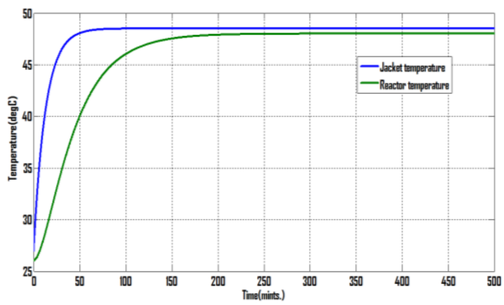
Where, $Q_{rea}$ is heat released from the exothermic reaction, $\Delta H$ is heat of the reaction, $R_p$ is polymerization rate of the reaction or overall rate of the reaction.

Equations (3.1)-(3.6) are solved in MATLAB. The process parameter values of the batch reactor for PVC resin process are listed in Table 1 and the derived parameters of the batch reactor are referenced from Kiparissides et al. (1997). The meanings of other variables and parameters are given in the Nomenclature.

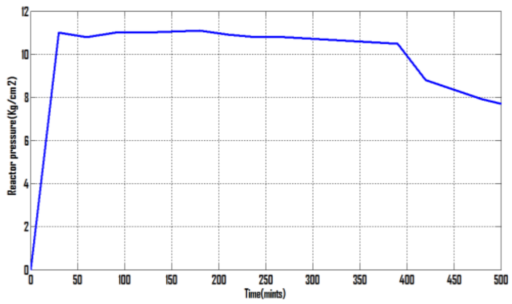
**Table 1.** The parameter values used in the batch reactor model

| **Process parameter** | **Value** |
|---|---|
| Heat of the reaction | -1540KJ/kg |
| Rate constant | $0.705\times10^{3}$l/mol s |
| Propagation constant | $1.80\times10^{-10}$ l/mol s |
| Termination constant | $2.55\times10^{7}$ l/mol s |
| Pre-exponential factor | $3.92\times10^{14}$/ s |
| Activation energy | 45.7KJ/mol |
| Initiator decomposition factor | $0.5\leq f \leq 0.8$ |
| Initiator concentration | 47.52 kg |
| Monomer concentration | 236.75 kg |
| Jacket inlet temperature | + 10°C to -38°C |
| Overall thermal conductivity | 40.842 kJ/ (min m K) |
| Reactor area | 0.282 m$^2$ |
| Mass of content in reactor | 534 kg |
| Heat capacity in reactor | 8 kJ / (kg K) |
| Mass of coolant in jacket | 250 kg |
| Heat capacity in jacket | 4.18 kJ / (kg K) |
| Mass flow rate of the monomer | 16 kg/min |
| Mass flow rate of coolant in the jacket | 4 kg/min |

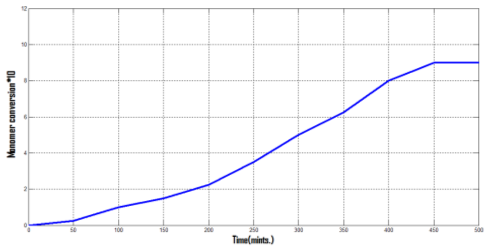
Equations (3.1) – (3.6) are solved in MATLAB and the model (transient) responses of the reactor temperature, jacket temperature, reactor pressure, monomer conversion rate and polymerization rate for step changes in inputs of PVC resin process in a glass-lined reactor are plotted (Figure 3).



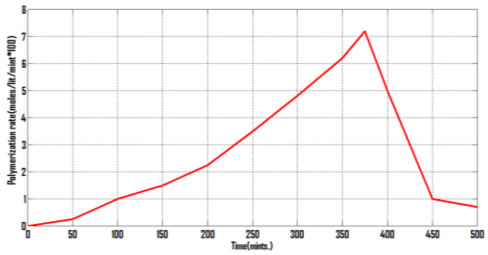

a) Jacket temperature and




b) Reactor pressure




c) Monomer conversion rate




d) Polymerization rate

**Figure 3.** Model responses of jacket and reactor temperature, reactor pressure, monomer conversion rate and polymerization rate for PVC resin process in a glass lined batch reactor

In the case of model responses of PVC resin polymerization process, (a) Jacket temperature varies from ambient temperature to 48.5℃ while reactor temperature varies from ambient temperature to 47.8℃, reactor pressure reaches a pressure value of 10.8 kg/cm$^2$ and shoots down at 380 minutes, (c) and (d) show a sharp increase in monomer conversion rate followed by an increase in the polymerization rate.

### Control strategy of glass-lined batch reactor for PVC resin polymerization process

In the design of closed loop control schemes for PVC resin process, the validated mathematical model and the referred process model, see Simon Stampar et al.(2013) are used for designing a suitable control strategy for the PVC resin process. Jacket coolant temperature and jacket temperature are the two manipulated variables in this process while the reactor temperature is the only output variable to be controlled.

### Design of cascade controller scheme for referred PVC resin process model

Cascade control technique can be effectively deployed to control reactor temperature within a very narrow specification limit within $\pm$ 0.25℃. Cascade control is mainly used in this process control to obtain a fast rejection of disturbance in the jacket dynamics, before it propagates to the other parts of the batch reactor. It is one of the most successful methods for enhancing single-loop control performance particularly when the disturbances are associated with the manipulated variable or when the final control element exhibits a nonlinear behaviour. Figure 4 is the block diagram of cascade control scheme for a batch reactor.

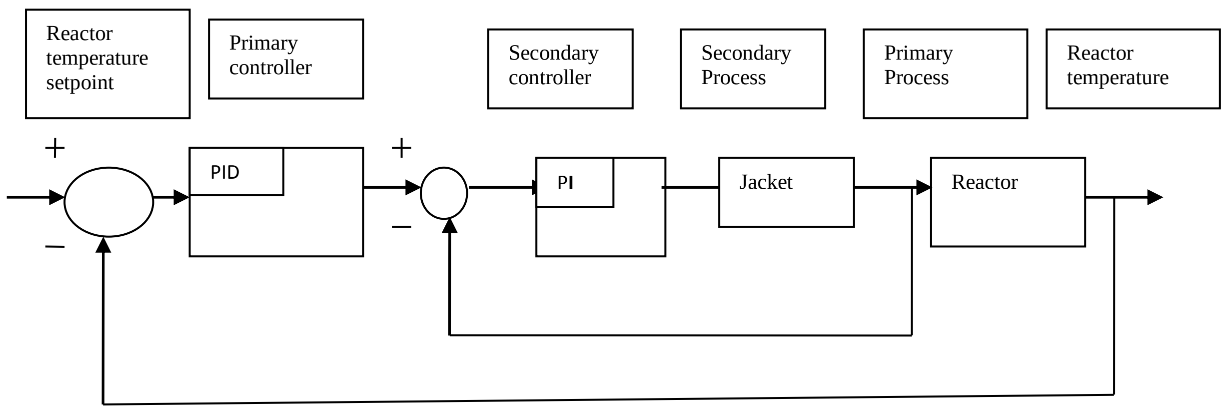



**Figure 4.** Block diagram of closed loop cascade control scheme for PVC resin process

Reactor temperature T and Jacket temperature $T_j$ have been taken as two measurements. Coolant temperature $T_{jin}$ is the only manipulated variable. The complete system is a feedback and cascaded control system, where the controller in the outer loop is the primary controller that regulates the primary controlled variable, reactor temperature T by setting the set-point for the inner loop.

Controller in the inner loop is the secondary controller that regulates the secondary controlled variable, jacket temperature $T_j$ by manipulating the coolant temperature $T_{jin.}$ For a cascade control system to function properly, the inner loop should respond much faster than the outer loop, this improves the fast rejection of disturbances before it propagates to the Primary process. The control objective is to improve the efficiency of PVC resin production process with minimum overshoot, constant reactor temperature of 48.5 ℃ and with fast settling time with in allowable tolerance levels of $\pm$0.25℃.

**Development of enhanced cascade controller Structure for referred PVC resin process model**

Servo and regulatory performances of the enhanced cascade controller have been investigated.

***Split range controller in Cascade control scheme***

Cascade control scheme is enhanced with a split range controller as local controller. Split range controller with multiple valves can be operated for injecting two different types of cooling substance to the jacketed glass lined batch reactor, Bequette (1991). The split range controller consists of a chilled water inlet valve and a coolant media inlet valve. At the initial phase of the reaction, chilled water at +10 ℃ is injected in to the reactor jacket. During the course of the reaction, when the reaction is vigorous, coolant media as diethylene glycol at -38 ℃ is injected to the limbed coils inside the jacket of the reactor. Cascade control with split range controller configuration is effectively deployed to control the reactor temperature within very tight specification limits.

The split range control algorithm can be stated as

$$0 \leq u \leq 50\% : v_{cw} = 100 - 2u, v_{cm} = 0$$

$$50 \leq u \leq 100\% : v_{cw} = 100,\ v_{cm} = 2(u - 50)$$

Where, u is jacket temperature controller output, $v_{cw}$ is chilled water control valve for +10ºC, $v_{cm}$ is coolant media control valve for –38ºC.

The split range control scheme has been simulated in MATLAB and the performance of the split range controller is shown in Figure 4.5 and the Table 4.4 pictures the controller and multiple valve characteristics.

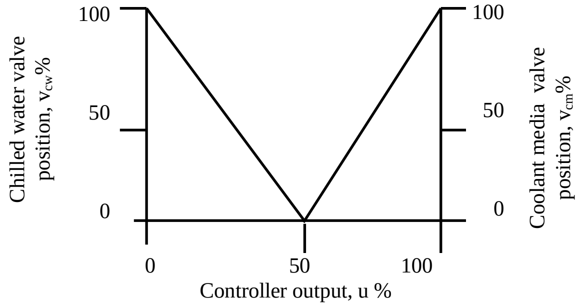



**Figure 5.** Cascade control scheme with split range controller for PVC resin process

**Table 2.** Controller output and multiple valves characteristics

| Controller output % | Chilled water valve position % | Coolant media valve position % |
|---|---|---|
| 0 | 0 | 0 |
| 50 | Fully open | Fully closed |
| 75 | Fully open | 50% open |
| 100 | Fully open | Fully open |

Split range controller brings in a better control of the batch reactor process in manipulating the jacket inlet temperature by actuating the two control valves for +10ºC coolant water circulation and - 38ºC water for chilled media circulation.

This control scheme minimizes the offsets in reactor temperature and introduces fast control of the process in terms of two controlled variables and two manipulating variables and hence this scheme has been proved to be efficient control scheme. Table 3 indicates controller parameters for split range control scheme.

**Table 3.** Split range control based controller settings in cascade control scheme

| PID parameter | $K_p$ | $T_i$ | $T_d$ |
|---|---|---|---|
| Industrial set up | 88 | 1.5 | 1 |
| Referred Mathematical set up | 3.6 | 0.6135 | 1.98 |

***Adaptive neurofuzzy inference system (ANFIS) in cascade controller scheme***

The uncertainties in the batch reactor process are coolant system failure, environmental conditions, high exothermic reaction, reactor physical dynamics, producing undesired end product value. These uncertainties, need to be addressed by an efficient control scheme.A Soft computing technique Abdul Wahab et al. (2000), Nagaraj (2008) as adaptive neurofuzzy inference system (ANFIS) has been implemented for manipulating the uncertainty in the jacket temperature.

ANFIS is a combination of artificial neural network (ANN) and fuzzy inference system (FIS). The operation of ANFIS is obtained through neural network learning algorithm to estimate the membership function parameters of FIS to map the input-output data values. The parameters are estimated using a hybrid learning algorithm. The parameters associated with this membership function can be changed through the learning rules (Abraham & Ajith 2000). The parameters are computed by a gradient vector, which only gives a measure of how well the ANFIS is mapping the input-output data values for a given parameter set. Once the gradient vector is determined, hybrid learning algorithm can be implemented in order to adjust the parameters (Gorzalczany &Gluszek 2000, Abraham & Ajith 2000).

Design of ANFIS

a) ANFIS structure: ANFIS structure consists of five layers in fuzzy inference system (FIS), this system is based on Sugeno type system as given in Figure 6. Each layer consists of many nodes representing the node function. A bell-shaped membership function is used; the output is modeled as a constant.

$$\mu(x) = \frac{1}{\left(1 + \left|\frac{(x-C)}{A}\right|^{2B}\right)} \qquad (3.7)$$

Where, A, B, C are the parameters of the membership function.

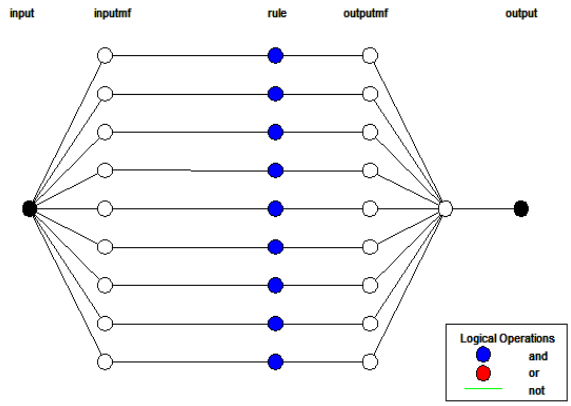



**Figure 6.** ANFIS structure

ANFIS Primary Controller : The fuzzy inference system uses measurements of primary output, reactor temperature and manipulated variable, jacket coolant inlet temperature to estimate the effect of uncertainties (high disturbance) in the jacket temperature on the PVC resin process. In this enhanced cascade control scheme, ANFIS as a primary controller is used to determine the set point of secondary controller. This work designed with nine rules, which is equal to nine membership functions. In Figures 7, 8, the membership functions editor and FIS editor shows the primary error as input variable and jacket coolant inlet temperature as the output variable. The ANFIS learning rules are mentioned as follows:

1. If (input1 is in1mf1) then (output is out1mf1) (1)
2. If (input1 is in1mf2) then (output is out1mf2) (1)
3. If (input1 is in1mf3) then (output is out1mf3) (1)
4. If (input1 is in1mf4) then (output is out1mf4) (1)
5. If (input1 is in1mf5) then (output is out1mf5) (1)
6. If (input1 is in1mf6) then (output is out1mf6) (1)
7. If (input1 is in1mf7) then (output is out1mf7) (1)
8. If (input1 is in1mf8) then (output is out1mf8) (1)
9. If (input1 is in1mf9) then (output is out1mf9) (1)

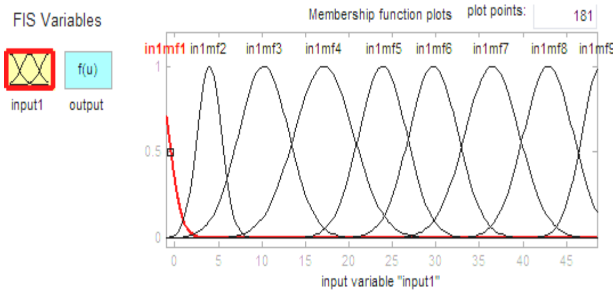



**Figure 7.** Membership function editor

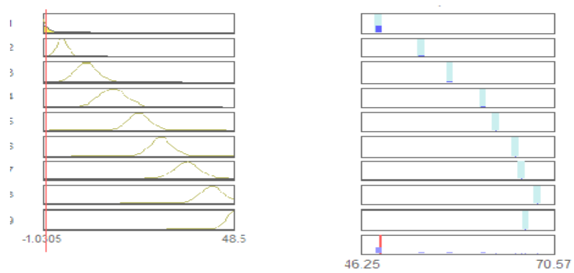



**Figure 8.** Rules viewer of input and output variable

ANFIS training process

i) The process starts by obtaining the training data set (the input-output data). These training data are used to train the Neuro-Fuzzy system, the data sets given to anfis must be in matrix form Ayla Altınten et al. (2003).

ii) The step involved in the training of an ANFIS is to use the genfis command in MATLAB of the initial Sugeno type FIS to create the membership functions, input parameters, hybrid learning algorithm, number of epochs and error tolerance.

iii) The Sugeno type FIS thus created can be trained by using ANFIS command in MATLAB. Once the training is completed, the final membership functions and average training errors are produced. The Table 4 shows the details of ANFIS primary controller for manipulating the uncertainty in the jacket temperature

ANFIS structure parameters of the Sugeno type FIS:
Number of linear parameters : 9
Number of nonlinear parameters : 18
Total number of parameters : 27
Number of training data pairs : 500
Number of fuzzy rules : 9
Error tolerance : 0.001

**Table 4.** ANFIS primary controller details

| Membership type | Number of epochs | Average training error |
|---|---|---|
| Bell -shaped | 2 | 0.48188 |
| | 5 | 0.48189 |
| | 10 | 0.48191 |
| | 15 | 0.48195 |
| | 20 | 0.48201 |
| | 25 | 0.48209 |
| | 30 | 0.48219 |
| | 35 | 0.4823 |
| | 40 | 0.48243 |

The performance of ANFIS as primary controller is shown in Figure 4.9. The enhanced cascade control scheme with ANFIS as primary controller is more effective in manipulating the uncertainty in jacket temperature and the response shows faster settling time than cascade control scheme without ANFIS and it can be effectively deployed in the place of unmeasured uncertainties in the jacket dynamics.

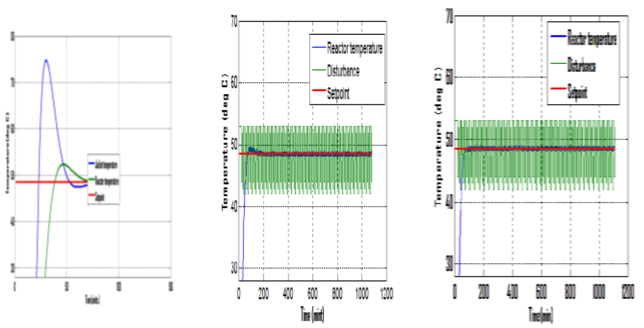
**Simulation analysis**

The closed loop response of various tuning techniques for the primary controller in split range controller of cascade control loop and closed loop response of PVC resin process for uncertainty in jacket temperature using ANFIS are shown in Figure 9.

(a) Split range controller in cascade control scheme

(b) Cascade controller scheme with ANFIS

(c) Cascade controller scheme without ANFIS




Servo operation

Regulatory operation

**Figure 9.** Closed loop cascade controller response of PVC resin process

The performance analysis of the closed loop controller for the referred PVC resin is given in Table 5 for servo operation and regulatory operation. From the Figure 9 for set point tracking, cascade controller with split range controller scheme attains fast settling time value due to two types of cooling arrangement.

For regulatory operation, high disturbances in the jacket temperature, cascade controller with ANFIS attains the settling time quickly in terms of offset error, cascade controller without ANFIS shows minimum offset with slow settling time value.

**Table 6.** Performance analysis of the closed loop controller for PVC resin process

| **S. No** | **Closed loop analysis methods** | **Performance analysis** | | | |
|---|---|---|---|---|---|
| | | **Steadystatevalue** $K_p$°C | **Offset** °C | **Settling time** $t_s$ $*10^4$**min** | **Maximum overshoot** $M_p$°C |
| **Servo operation** | | | | | |
| 1. | Cascade control scheme with Split range controller | 48.598 | 0.098 | 0.6700 | 4.000 |
| **Regulatory operation** | | | | | |
| 2. | Cascade controller with high uncertainty in jacket temperature. | 48.52 | 0.02 | 1.0 | 0.150 |
| 3. | Cascade controller with ANFIS withhigh uncertainty in jacket temperature. | 48.72 | 0.320 | 0.52 | 0.22 |

Among the control strategies designed for PVC resin processes, cascade controller has good tracking of the set point within the specified offset limit of ±0.25°C, and the disturbance rejection for uncertainities in jacket temperature is smoother and the robustness of the controller is appreciable.

Comparison of Experimental, Simulated, Masoud Soroush & Costas Kravaris (1992) and Kiparissides et al. (1997) works. Compared results have been shown in Figure 10.

Servo operation of the controller scheme for the jacket temperature

Servo operation of the controller scheme for the reactor temperature

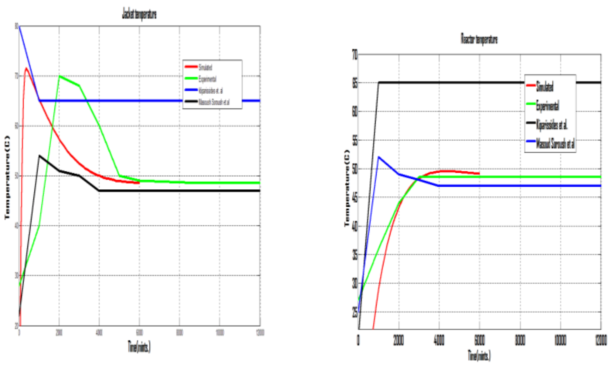


**Figure 10.**Comparison of experimental, Simulated (Masoud Soroush & Costas Kravaris 1992, Kiparissides et al. 1997) models for jacket and reactor temperature response of PVC resin process

The simulated model is compared with the experimental model (valued real time datas collected from scaled up industry for 500 L glass-lined batch reactor) and it has been matched well. Also the simulated model is compared with Kiparissides et al. (1997 ) method (operating point is changed) and Masoud Soroush & Costas Kravaris (1992)works.

The simulation performance shows cascade controller with less offset within $\pm 0.25$℃, fast settling time and minimum overshoot. The performance of all the controllers for set point changes has been analyzed, using IAE and ISE criteria. This is represented in Table 7. The satisfactory work of the cascade control scheme for set point changes can be shown as it produces lower IAE and ISE values.

**Table 7.** Performance criteria of controllers for PVC resin process

| Closed loop analysis methods | IAE | ISE |
|---|---|---|
| Cascade controller | 10829.1723 | $3.53e^{+005}$ |
| Continuous cascade controller for mathematically described process | 2819.0246 | 40632.8177 |
| Discrete cascade controller for mathematically described process | 109.9497 | 1173.0989 |

## CONCLUSIONS

Cascade control have been found to be superior, meeting the control objective of maintaining the PVC resin batch reactor temperature within a narrow tolerance level of $\pm$ 0.25℃ from the set point with minimum overshoot and fast settling time.Control strategy are illustrated with the use of the split range control scheme. The split range controller act as a local controller for manipulating the jacket temperature by pumping +10 °Ccooling water or chilled media maintained at -38°C if found necessary, thereby improving monomer to polymer conversion efficiency.

The purpose of the proposed cascade control strategy is to take advantage of uncertainties in the jacket temperature inline to improve the disturbance rejection capability. A Soft computing technique as adaptive neurofuzzy inference system (ANFIS) in cascade control scheme has been developed for a study of the uncertainties in the jacket temperature. The result shows that ANFIS has satisfied the required operating value for all possible cases of the uncertainty and leads to better performance than conventional control system. The inference, therefore, is that cascade control strategies have been found to be more effective and robust in tracking the reactor temperature and the performance of the glass-lined batch reactor for PVC resin process can be improved significantly by the proposed control strategy in terms of performance index. Simulation results indicate the effectiveness and validity of the proposed control strategy. It can meet the requirements of real time control for PVC resin process and further improve the PVC production quality with strict operating temperature value and reduce the production cost with minimum overshoot and it is recommended.

## REFERENCES

[1] Abdul Wahab, AK, Mohd Azlan Hussain, Mohd.Zaki Sulaiman 2000, 'Temperature Control for Chemical Reactor using Adaptive Neural Network Control Strategy', IEEE.

[2] Ajith Abraham & Baikunth Nath 2000, 'Optimal design of neural nets using hybrid algorithms', Proceedings of PRICAI, pp. 510-520.

[3] Ayla Altınten, Sebahat Erdogan, Hale Hapoglu & Mustafa Alpbaz 2003, 'Control of a polymerization reactor by fuzzy control method with genetic algorithm', Computers and Chemical Engineering, vol. 27, pp. 1031-1040.

[4] Bequette, BW 1991, 'Nonlinear control of chemical processes: A review', Industrial and Engineering Chemistry, vol. 30, pp. 1391-1413.

[5] Contillo, G 2002, 'Nonlinear Dynamics and Control in Process Engineering – Recent Advances', Springer-Verlag Italia,

[6] Gorzalczany MB, & Gluszek A 2000, 'Computational intelligence in control - A comparison of several neurofuzzy systems', Proceedings of the 2000 'International Symposium on Industrial Electronics, ISIE 2000, Vol. 1, pp. 31-36.

[7] Ivanchev, S, Goncharenkoa, MV, Kondratiev, Yun, M, Savelieva, AM & Sofiev, A 2007, 'Mathematical modeling and experimental study of high-pressure ethylene polymerization reactors', Chemical Engineering Journal, vol. 134, pp. 175-179.

[8] Jie Zhang 2008, 'Batch-to-batch optimal control of a batch polymerisation process based on stacked neural

network models', Chemical Engineering Science, vol. 63, pp. 1273-1281.

[9] Kaya, N Tan & Atherton, DP 2007, 'Improved cascade control structure for enhanced performance', vol. 17, pp. 3U-16.

[10] Kiparissides, C, Daskalakis, G, Achilias, DS & Sidiropoulou, E 1997, 'Dynamic Simulation of Industrial Poly(vinyl chloride) Batch Suspension Polymerization Reactors', Industrial and Engineering Chemistry Research, vol. 36, pp. 1253-1267.

[11] Masoud Soroush, & Costas Kravaris 1992, 'Nonlinear Control of a Batch Polymerization Reactor: an Experimental Study', American Institute of Chemical Engineers Journal, vol. 55, no. 8, pp. 3577-3593.

[12] Mohammad, Anwar, Hosen, AN, MohdAzlan Hussain, Farouq, S & Mjalli 2011, 'Control of polystyrene batch reactors using neural network based (NNMPC):An experimental investigation', Control Engineering Practice Journal, vol. 19, pp. 454-467.

[13] Nagaraj, B, Subha, S & Rampriya, B 2008, 'Tuning Algorithms For PID Controller Using Soft Computing Techniques', International Journal of Computer Science and Network Security, vol. 8, no. 4, pp. 278-281.

[14] Shah, M, Zondervan, E & de Haan, AB 2010, 'Modeling and Simulation of unsaturated Polyester Process', Journal of Applied Sciences, vol. 10, no. 21, pp. 2551-2557.

[15] Simon Stampar, Sasa Sokolic & Gorazd Karer 2013, 'Nonlinear Control of a Hybrid Batch Reactor', Journal of Mechanical Engineering, vol. 59, no. 2, pp. 112-123.

[16] Yongho Lee & Sun won Park 1998, 'PID controller tuning to obtain desired closed loop responses for cascade control systems', Industrial Engineering Chemical Research, vol. 37, pp. 1859-1865.