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Design of PI controllers for Ideal Quaternary Reactive Distillation using Optimization

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Abstract

The temperature inferential control of an ideal hypothetical two feed two product ideal reactive distillation column is reported. The design of the column is an optimal one and the control structure consists of two temperature measurements with fixed reflux ratio policy. The transfer functions of second order relating the input and output variables of the temperature control loops are derived using the unit step responses under open loop. The tuning parameters for proportional-integral (PI) action are estimated using two optimization algorithms namely genetic algorithm (GA) and grey wolf (GW) algorithm. Minimization of integral time averaged error (ITAE) is the objective function for the optimization. Also, relay feedback method is used to estimate the ultimate gains and periods of the loops and the tuning parameters for PI action are calculated using Tyreus-Luyben (TL) settings. The closed loop dynamics of the column using the three sets of tuning parameters (GA, GW and TL) for throughput changes and feed impurity disturbances are compared. The tuning parameters estimated using GW are found to yield superior disturbance rejection characteristics for the RD column.

Keywords: Ideal Reactive Distillation Column, Proportional Integral (PI) Controller, Genetic Algorithm, Grey Wolf Optimization.

Subject classification: Ideal Quaternary Reactive Distillation, Proportional Integral

1. Introduction

The control of reactive distillation is very interesting due to the non-linearity emanating from the combination of reaction and separation [1]. The presence of multiple steady state behaviour of the RD columns poses challenges in the design of robust control structures of superior disturbance rejection characteristics. Nevertheless, the understanding of the non-linearity greatly helps in the design and analysis of the performances of the control structures. To explore the aspects RD control, three ideal reactive distillation systems namely quaternary (A+B ↔ C+D), ternary (A+B ↔ C), ternary with inert (A+B+Inert ↔ C+Inert) were proposed [2,3]. The decentralized control of these three RD systems were addressed in detail. In the case of quaternary ideal RD column, the impact of multiplicity and the interaction of reaction and separation on the control were reported. For an optimized design of this system, a best two point temperature inferential control structure was also identified based on the interaction of reaction and separation [4]. For any control structure, the type of controllers used in the control loops and the setting of tuning parameters of the controllers (design of controllers) are very significant for the performance. In this contribution, the temperature controllers of PI action are designed using genetic algorithm (GA) and grey wolf (GW) optimization and the closed loop disturbance rejection characteristics are compared for throughput changes (±20%) and feed impurity disturbances.

2. Quaternary RD Column

The quaternary ideal RD system involves four hypothetical components namely A, B, C and D in which first two are reactants and the other two are products. The RD system is termed as ideal because the relative volatilities of the components are constant with respect to temperature ($\alpha_C:\alpha_A:\alpha_B:\alpha_D$ =8:4:2:1). Moreover, the values of the exothermic heat of reaction and latent heat of vaporization are also made temperature independent. The physical and chemical parameters of the system can be found elsewhere.

The optimal design of the RD system for 95% conversion of the reaction consists of 7 reactive trays and 5 trays each in the enriching and stripping sections [5]. A schematic of the RD column is shown in Figure 1(a). The feed reactants, B and A enter the column at the top and bottom reactive trays respectively as pure saturated liquids (F_B and F_A). The distillate and bottoms consist of 95 mol% of C and D respectively. Each reactive tray consists of 1000 mol of catalyst holdup.

3. Control Structure

A schematic of the two point temperature inferential control structure is shown in Figure 1(b). This was the best two temperature inferential control structure for the quaternary ideal distillation column [4]. The liquid levels in the reboiler and condenser drum are controlled by bottoms and distillate respectively. The liquid levels are controlled using proportional action only with a gain of 2. The reflux ratio is held constant with perfect control action of ratio controller between the flow rates of distillate and reflux. Two tray temperatures, one in stripping section and another in reactive section, are controlled by feed F_A and reboiler duty, respectively. The flow rate set-point of feed F_B is throughput manipulator. The tray temperatures are selected based on open loop steady state sensitivity analysis. The trays are numbered from bottom to top with reboiler as tray zero. The temperatures of Tray 4 and Tray 10 are controlled by Vapor boilup/reboiler duty and F_A respectively. A span of 50 K was used in the temperature controllers and two first order lags of 1 min each are used in the temperature measurements. All flow valves are half open at the design steady state. The pressure of the column is assumed to be perfectly controlled by the condenser duty.

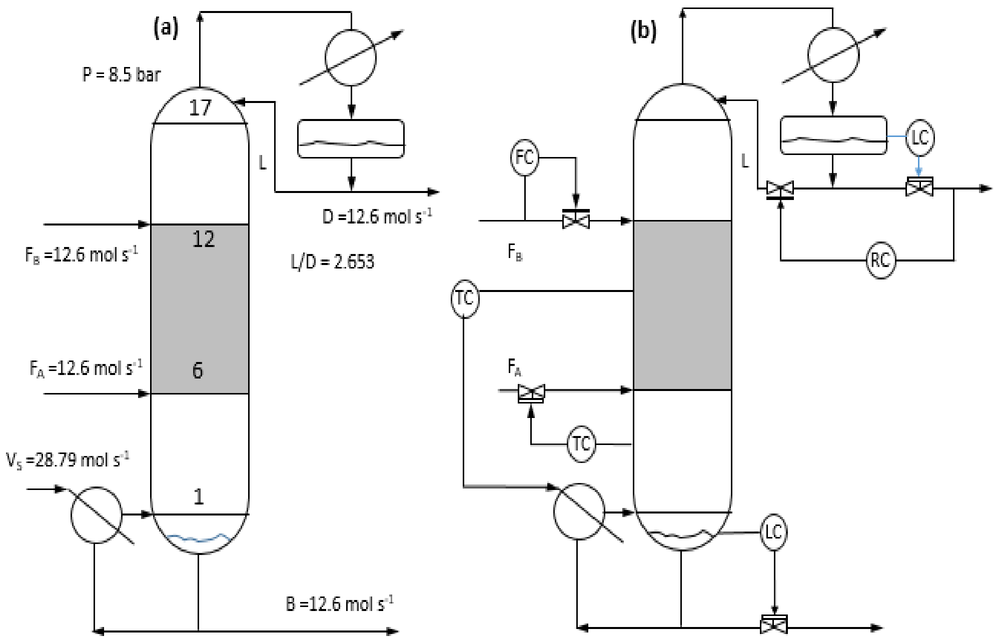

Figure. 1 (a) Example RD Column, (b) Control Structure

4. Design of Proportional Integral controllers

The tuning parameters for the PI action of the temperature controllers are obtained as follows. Firstly, open loop transfer functions between the manipulated (V_S and F_A) and controlled variables (T_{10} and T_4) are estimated using system identification method. For this purpose, a step change of ±1% is given in the flow of the manipulated variable and the responses are averaged. The averaged response in each case is fitted for second order transfer functions and shown below as equations (1) and (2). Individually, for these transfer functions best tuning parameters for PI action are obtained employing genetic algorithm (GA) and grey wolf (GW) algorithms [6]. The objective function is the minimization of integral time averaged error (ITAE). Relay feedback method is used to obtain the ultimate gains and ultimate periods of the control loop pairings and Tyreus-Luyben (TL) settings are used for the PI action in the the third method. Accordingly, the calculated values of K_P and τ_I values for the PT action (K_P: gain, τ_I: reset time) are given in Table 1.

$$\frac{T_{10}(s)}{V_S(s)} = \frac{0.01567}{s^2+0.4817s+0.005514} \quad \text{.......(1)}$$

$$\frac{T_4(s)}{F_A(s)} = \frac{0.03959}{s^2+0.1787s+0.001479} \quad \text{......(2)}$$

Table. 1. Tuning Parameters of The Temperature Control Loops

	$V_S - T_{10}$		$F_A - T_4$	
	K_P	τ_I	K_P	τ_I
GA	2.499	21.540	2.298	19.080
GW	2.954	8.350	1.770	16.330
TL	0.943	11.537	0.621	15.985

5. Results and Discussion

The closed loop dynamics of the column for ±20% in F_B and feed impurity disturbances are shown in Fig 2 (a) and 2(b) respectively for a comparison of the three tuning methods. In the case of throughput changes (Fig 2(a)), the responses are fastly completed. According to the direction of the throughput changes, the flow rates of V_S and F_A have changed and the purities of C and D in the respective streams have reached their final steady state values. The final product purities are with in ± 1mol % of the design steady state value of 95 mol%. The deviations are due to the fact that the column is in kinetically controlled regime of operation. The dynamics of distillate and bottoms are very smooth. For a quantitative comparison, the Integral Absolute Error values of the mole fraction of C and D are shown in Table 2 for the three tuning methods. From the table, it can be seen that the tuning parameters obtained using GW algorithm have yielded to minimal deviations in the product purities. Similarly, the IAE values for the feed impurity disturbances are shown in Table 2. In this case, for the case of 5 mol% of B in F_A, the tuning parameters of GA have yielded to slightly better response.

Otherwise, the tuning parameters obtained using GW have resulted in lesser deviations in the product purities. The presence of the other reactants in a feed stream in the form of impurity has resulted in the increase of the vapor boilup in both impurity disturbances. For this reason, the bottom product purity is close to or above 95 mol% at the final steady state. On the other hand, the purity of C in the distillate has suffered a lot when A is a impurity in F_B. Overall, the tuning parameters calculated using GW algorithm have resulted in favourable disturbance rejection characteristics of the column for the tested disturbances.

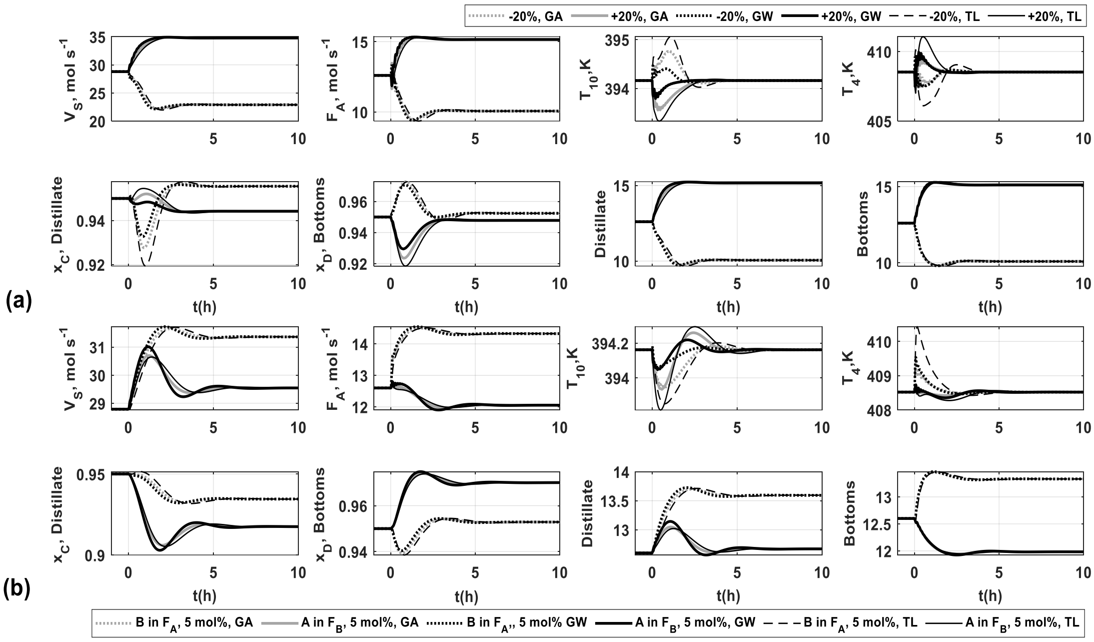

Figure.2. Closed Loop Dynamics of the Column For (A) Through Changes, ±20% In F_B and (B) Feed Impurity Disturbances

Table.2. IAE values

			x_C, D	x_D, B
Throughput Changes	**-20%**	GA	2.1800	1.8283
		GW	1.6070	1.4814
		TL	3.0064	2.0894
	+20%	GA	0.8939	2.0000
		GW	0.4917	1.4080
		TL	1.2544	2.6423
Feed impurity disturbances, 5 mol%	**A in F_B**	GA	2.4265	1.0910
		GW	2.5691	1.1215
		TL	2.7594	1.1811
	B in F_A	GA	1.6909	1.2094
		GW	1.4879	1.0507
		TL	2.1491	1.4103

6. Conclusion

As RD control is challenging, the control of RD using simple decentralized control schemes is always desirable. However, the multiple steady state behaviour of RD poses several challenges. After the identification best control structure based on the understanding of the reaction-separation interaction, the performance of the structure can still be improved with the suitable estimation of the tuning parameters for the controllers. For the example RD column, the two temperature inferential control structure has yielded to stable closed loop operation for the three sets of tuning parameters of PI action. Upon comparison, the designed controller using GW is found to work very efficiently. The article highlights the advantages of the controller design using soft-computing tools for RD columns.

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