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Temperature control of vacuum dividing wall column – case study on oleochemical fatty acid fractionation

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Abstract. Analysis of oleochemical compositions in distillation column often have large process delays. Inferential control is commonly used by means of stage temperature as the measured variable which provide more responsive in composition control. This work aims to evaluate the performance of temperature control in vacuum dividing wall column (VDWC) for fatty acid oleochemical fractionation. Product purity at 99% used as inferred parameter to determine the temperature. Sensitivity analysis was used to determine the relationship between stage and temperature difference for changes in the manipulated variables. The most sensitive tray was selected and implemented to a Distillate- Side Stream- Boilup (DSV) control configuration in Aspen Dynamics following the work by Othman (2019b). Controller adopted with PI and PID settings using Ziegler-Nichols (ZN) and Internal Model Control (IMC) tuning calculation method. Both methods were compared based on the settling time and overshoot. The best setting was then fine-tuned before tested to set point tracking without any disturbances. From the sensitive analysis, temperature at stage 6, 29 and 34 were selected used as controlled variable which inferred distillate, middle and bottom product purity at 99% respectively. PID controller setting based on ZN method provide the best setup with fastest settling time and smallest overshoot and provide good performance for set point tracking.

1. Introduction

Oleochemical industry particularly in Malaysia mostly uses typical distillation column (DC) for its product fractionation. In process design perspective dividing wall column (DWC) shows very promising alternative to DC which able to reduce around 20% of capital and operating cost [1]. However, one of the potential hurdles for commercial implementation of DWC is the challenges in design, simulate, operation and control [2-3] as well as complexity in operating and controllability due to the introduction of a wall within the column internal [4]. Various research has been conducted for DWC control. One of the most common controlled variable in distillation column is composition. However, composition is difficult to measure. For such variable, inferential control is often implemented which uses easily measure process variables i.e. temperature, pressure and flow to infer more difficult process variables such as compositions and molecular weight. Parrish and Brosilow [5] stated that for higher order and long-dead-time processes, inferential control systems will generally outperform conventional feedback control systems. Because of that, inferential control has excellent performances such as disturbance resisting and set point tracking. However, the application is restricted when strong load disturbance exists or stable control accuracy and response speed are highly required in the system. Besides, it can be much less expensive in terms of capital and operating cost as well as can provide measurement that are not available any other way. According to Ansari and Tadé [6] inferential models which are based on fast and continuously available temperature, pressure and flow measurements reduce the negative impact of the sample intervals and time delays with minimum compromise on accuracy. The resulting continuous and fast response keeps the product qualities on specifications and minimizes the quality giveaway. In order to establish composition inferential control, one needs to know the particular correlation between process variables and product composition. According to Marlin [7], a good inferential control is when inferred variable is closely related to true variable so that controlling inferred controlled variable will maintain true controlled variable close to desired value. The use of tray temperature to infer composition is widely used in distillation column [8]. This paper adopted the criteria in selecting the tray that give largest change in temperature upon changes made at manipulated variable as proposed by Luyben [8].

DWC is according to Nguyen is the integration of two or more different separation units into one single device with one or more vertical partitions in the central section. Dividing wall splits a single column into two parts, which are a pre-fractionator section, and a main column. It uses only one reboiler and one condenser. Various studies have been conducted for inferential control in DWC. For example Wang et al. [9] have investigated temperature inferential control of DWC for separating ethanol, n-propanol, and n-butanol ternary mixture. Yuan et al. [10] has studied inferential temperature control for the process medium of benzene–toluene–o-xylene in DWDC system. Ignat and Woinaroschy [11], has analyzed the controllability of inferential temperature of 4 point control structure for a case study of separation of a ternary nonideal methanol – ethanol – 1-propanol mixture in a DWC. Most of inferential control studies of DWC focuses on petrochemical processes. Study on vacuum dividing wall column (VDWC) inferential control particularly for oleochemical industries however received less attention. Moreover, oleochemical products were analyzed using analytic apparatus i.e. High Performance Liquid Chromatograph HPLC which had large process delay. This practically hindered composition as the controlled variable. The composition of product with greater amount of light key will resulting higher vapor pressure thus lessen heat duty required and give lower temperature at particular stage to keep similar product purity. Hence, temperature tray could be adopted to infer product composition. Therefore, this work aims to evaluate the performance of stage temperature control in vacuum dividing wall column (VDWC) for oleochemical application. Oleochemical fatty acid was used as the case study.

2. Methodology

2.1. Steady state and dynamic modelling

The process under study involves fractionation of oleochemical fatty acids which constitute of three carbon chains namely C10, C12 and C14 with boiling point of 270 ºC, 299 ºC and 326 ºC respectively. To avoid product degradation, the column temperature was operated below 270 ºC at pressure between 0.01 to 0.1 bar. The product purity for each streams were set to 99 mole%. Due to the polarity of the fatty acid as well as low operating pressure, non-random two-liquid NRTL thermodynamic model and its variances can be used. In this work NRTL was chosen. For process flowsheeting, four RADFRAC model blocks were used for both steady state and dynamic modelling using Aspen Plus and Aspen Dynamics, respectively. RadFrac is a rigorous model use to simulate all types of multistage vapour-liquid fractionation operations which includes ordinary distillation, absorption and stripping. In Aspen Plus, Radfrac model consisted of 4 column sections which are 1 stripper, 2 parallel absorbers and 1 rectifier to resemble actual 1 dividing wall column. Steady state model used for sensitivity analysis to study the relationship between tray temperature and product composition as well as to determine the tray number to be inferred for controlling the product composition. Dynamic model used for controllability analysis of the inferential control configuration. The control configuration used in the dynamic model was based on Othman [12]. Othman [12] conducted a controllability analysis of VDWC for oleochemical fatty acid fractionation using relative gain array (RGA) and singular value analysis (SVA). From his findings, it was found that Distillate-Side Stream- Boilup (DSV) control configuration was the best 3x3 control pairing due to the low interaction between control loops. Therefore, DSV control configuration was adopted for this work. Figure 1 shows the DSV control configuration.

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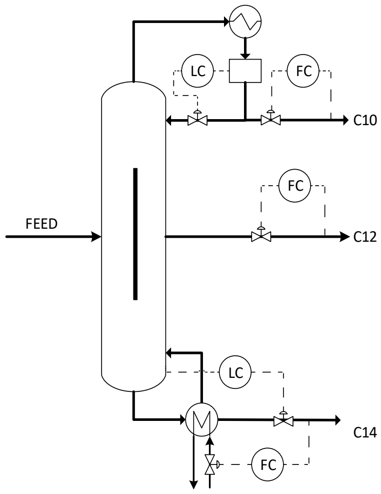

Figure 1. DSV control configuration [12]

2.2. Steady state sensitivity analysis

In this work, sensitivity analysis was applied to establish a column temperature profile for different operating points which was then compared with base case data. Table 1 shows the base case condition. In this work, several operating points were considered by changing the manipulated variables. The changes for distillate rate, side stream rate and reboiler duty at stipulated percentage of deviation are calculated from the base case value in the table. Three conditions were considered (1) ±10% change in distillate flowrate, D (2) ±10% change in middle flowrate, S and (3) ±60 change in reboiler duty, V. The percentage of change for respective manipulated variables are decided based on expected feed composition change from upstream unit resulting the offsetting differences in distillate and middle flow which can be up to 10 % and reboiler duty up to 60 %. The temperature of the most sensitive trays will be the inferred parameters for product composition at 99 % as per Table 1. From the column profile, temperature deviation from the base case (ΔT) were plotted. From this plot, one can determine the most sensitive tray. The identified tray for each product were then implemented in Aspen Dynamics and evaluated for its controllability performance

Table 1. Base case steady state condition.

Parameters	
Flowrate, kg/h	
- Feed	6240
- Distillate	316.11
- Side stream	4405.92
- Bottom	1517.96
Product composition, mol%	
- C10 at distillate	99
- C12 at side stream	99.8
- C13 at bottom	99
Reflux ratio	60.65
Reboiler duty, kW	2275.5

2.3. Tuning and closed loop response

The selected inferential variable from the previous step were added to developed DSV based control configuration by replacing the controlled variables from composition to the designated tray temperature. PID controller was adopted in this work. No measurement delay was included. Ziegler-Nichols (ZN) tuning method is a heuristic method of tuning PID controller which is widely used for tuning. Meanwhile, Internal Model Control (IMC) tuning method is also adopted because of its ability to compensate disturbances and model uncertainty. However, ZN setting result in very good disturbance response for integrating processes, but are otherwise known to result in rather aggressive setting and also give poor performance [13]. On the other hand, IMC setting it result in poor disturbance response for integrating processes but are robust and generally give very good responses for set point changes [14]. The latest current tuning method which is based on IMC known for giving non oscillatory response to setpoint change and load disturbance however it does not address specific application in fatty acid fractionation application compared to ZN which still predominat method in use today. Therefore, in this work both ZN and IMC setting was compared before further fine-tuned. The controller setting was subjected to set point change for distillate, side and bottom product composition. The controller performance was tabled in term of their settling time and overshoot. Tuning with fastest settling time and small overshoot were selected before further fine-tuned.

3. Results and discussions

Sensitivity analysis for distillate, middle and bottom sections are performed individually. For distillate section, Figure 2a gives the temperature deviation for ±10% change in distillate flow. The temperature deviation for increase flow rate was negative, while positive for decrease flow rate. The plot also shows several sensitive trays. Changes in flowrate at particular product stream will register disturbance at temperature column profile. For example greater flow of product resulting heat withdrawal at the column thus create drop in column temperature. However, each stage responds differently depending on the tray location. For flowrate increment tray number 2 to 7 and 28 to 34 were the most sensitive whereas for flowrate decrement tray 2 to 8 and 21 to 31 were the most sensitive. In this work tray 6 were selected as the preferred temperature tray to be inferred to distillate product stream. Note that, For the tray number other than this region, it would be a very poor inferential variable, because the sensor error and low magnitude noise would invalidate any correlation drawn from simulation. Besides, a small temperature deviation indicate that valve saturation can easily occur and operability region could be limited.

Figure 2b gives the temperature deviation for 10% change in the middle stream. The temperature deviation also shows the same pattern as in (a) but with fewer peaks. For flowrate increment tray number 21 to 31 were the most sensitive while tray number 28 to 38 were the most sensitive whereas for decrease in middle flowrate. Tray 29 were selected as the preferred temperature tray to be inferred to middle product stream. Figure 2c gives the temperature deviation for 10% change in the reboiler duty. The temperature deviation was apparent for 60% decrease in reboiler duty with different peak at the stripping section and rectifying section while not so much change for reboiler duty increment. For reboiler duty increment tray number 4 to 8 and 29 and 37 were the most sensitive Tray 34 were selected as the preferred temperature tray to be inferred to middle product stream due its location near the reboiler which quickly affected by changes in reboiler duty. Figure 3a shows updated inferential control loop of DSV based control configuration of the VDWC. The first control loop is using temperature tray no. 6 as controlled variable and distillate flow as manipulated variable. Second loop is measure temperature tray at no. 29 as controlled variable and manipulating middle stream flow as manipulated variable. The third loop is measuring temperature tray at no. 34 while giving the output at steam supply line for reboiler duty regulation. Reflux ratio and column bottom level is held a constant The loop was implemented in Aspen Dynamics as shown in Figure 3b. For PID controller setting, ZN method was compared to IMC. Its performance towards set point tracking were evaluated.

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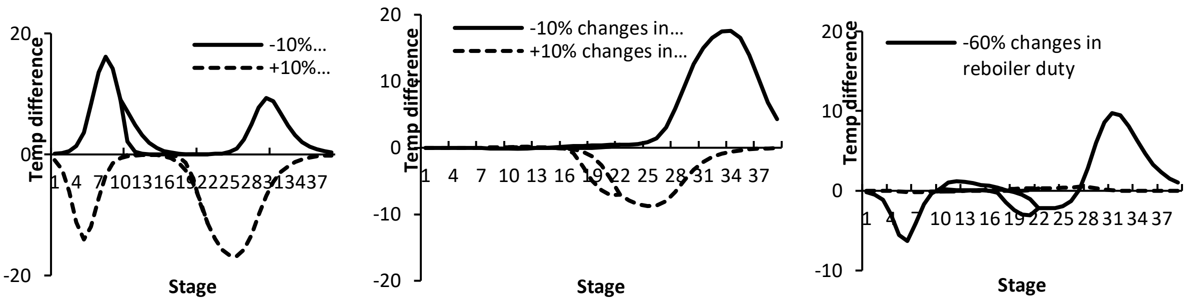
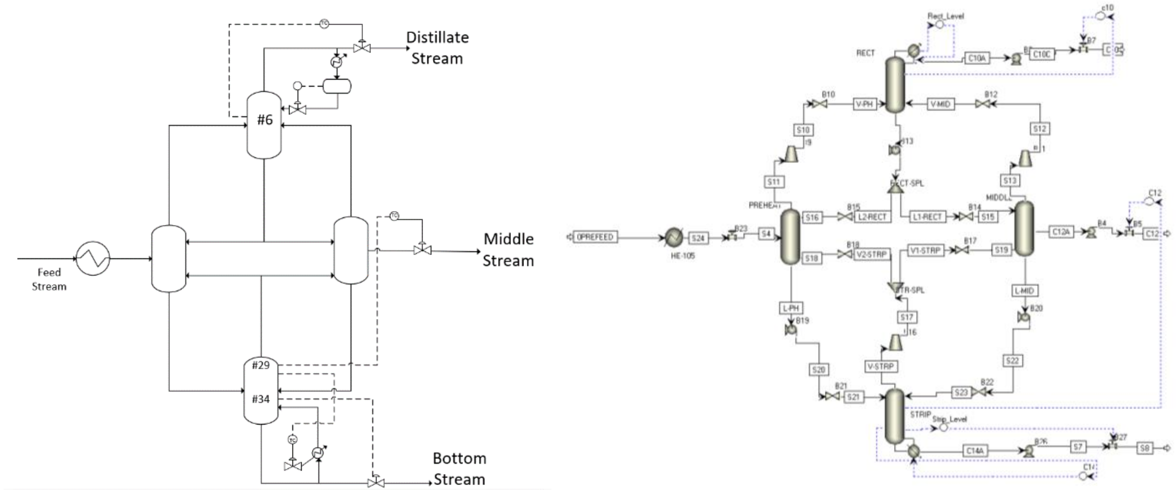


(a) (b) (c)

Figure 2: Stage temperature sensitivity analysis (a) ±10% changes in distillate flow (b) ±10% changes in middle flow (c) ±60% changes in reboiler duty



(a) (b)

Figure 3 (a) Inferential control using identified tray in DSV control configuration (b) the corresponding flowsheet in Aspen Dynamics

Table 2 shows the ZN and IMC tuning value as well as its corresponding controller performance for set point tracking. Prior to that open loop step test were performed at 5 % output change to identify process model values such as process gain, time constant and dead time respectively for each control loop which subsequently give the tuning values depending on tuning calculation used either ZN and IMC. Overall, in terms of settling time and overshoot both approach able to compromise and meet the satisfactory target. PID controller based on ZN tuning however provides better performance in term of settling time and overshoot. The settling time shall be short as possible and in ideal case settling time lesser than 10 multiply by dead time, t_d however any value approaching towards that is consider acceptable since no valid data available to be compare with. Hence, PID-ZN setting adopted and further fine-tuned.

Table 2: Control settings for the proposed inferential control in DSV control configuration with the comparison between Ziegler-Nicols and IMC method as well as comparison between PI and PID

Control Loop		Ziegler Nichols		IMC
		PI	*PID	PID
Distillate Stream, C10	Gain	86.87513	**144.7919**	2.350773
	Integral Time	35.47682	**26.63425**	375.1321
	Derivative Time	0	**4.26148**	5.251207
	Settling Time	6.09 hours	**2.64 hours**	3.42 hours
	Overshoot	0.45 %	**5 %**	0.45 %

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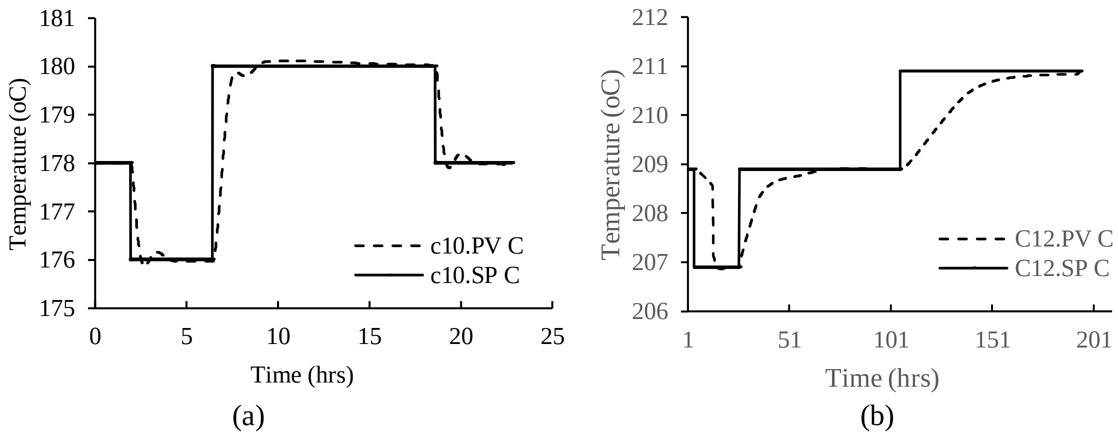
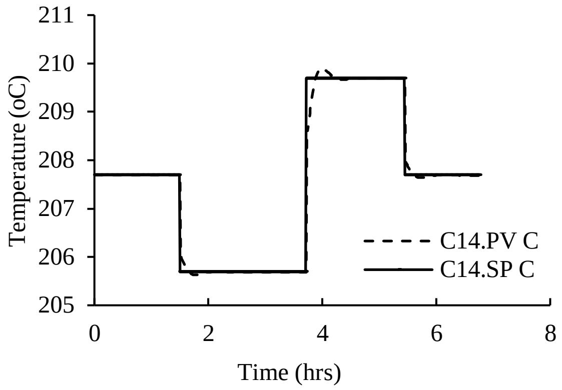
Control Loop		Ziegler Nichols		IMC
		PI	*PID	PID
Middle Stream, C12	Gain	5.742162	**95.7021**	22.86846
	Integral Time	7150.78564	**2000**	2171.743
	Derivative Time	0	**858.9532**	295.5417
	Settling Time	1983 hours	**321.1 hours**	359.1 hours
	Overshoot	0 %	**0%**	0 %
Bottom Stream, C14	Gain	0.921668	**1.536113**	0.393431
	Integral Time	60.83798	**45.67416**	39.798
	Derivative Time	0	**7.307865**	7.038206
	Settling Time	16.83 hours	**11.62 hours**	30.31 hours
	Overshoot	44.2 %	**36.35 %**	70.7 %

Table 3 and figure 4 shows the tuning values and well as the controller performance for set point tracking after fine-tuned. Both distillate and bottom stream shown fast response with minimal overshoot. However, for middle stream when the settling time is longer than other controller loop. This due to the large amount of C12 which is require longer time for heating. The disturbance rejection test at feed change is not consider in this paper due invalid preset tray temperature set point to keep product quality at stipulated specification of 99 mole %. The new feed changes introduce will alter temperature profile of the column thus require new set point to keep the product quality steadily uninterrupted. The estimator shall be incorporate to predict the new set point upon registration of disturbance at feed flow.

Table 3: After tuning of ZN PID controller for distillate, middle and bottom stream

Control Loop		**Before tuning**	**After tuning**
Distillate Stream, C10	Gain	144.7919	6.6
	Integral Time	26.63425	600
	Derivative Time	4.26148	4.2618
	Settling Time	2.64 hours	1.82 hours
	Overshoot (< 5 %)	5 %	4.75%
Middle Stream, C12	Gain	2521.756	2.2
	Integral Time	35.80275	39
	Derivative Time	5.72844	5
	Settling Time	46.7	50.62 hours
	Overshoot (< 5 %)	12.4 %	0 %
Bottom Stream, C14	Gain	1.536113	80
	Integral Time	45.67416	3
	Derivative Time	7.307865	7.03826
	Settling Time	11.62 hours	1.31 hours
	Overshoot (< 5 %)	36.35 %	3.05%





(c)

Figure 4: Set-point tracking for tray temperature change in (a) stage 6 (b) stage 29 (c) stage 34

4. Conclusions

The sensitivity analysis was successfully determining the best tray temperature location for distillate at 6th stage, middle at 29th stage and bottom at 34th stage based on the most temperature deviation from base case. The comparison from two tuning methods; ZN and IMC, with different controller setting of PI and PIC reveal that PID-ZN setting was preferred with good controller response in term of better settling time and minimum overshoot. The fine-tuned has improved the quality of controller response target thus give good set point tracking in the stage temperature.

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