Multi-loop Control System Design for Biodiesel Process using Waste Cooking Oil

Dipesh S Patle[1], Ahmad Z[2,3] and G. P. Rangaiah[,4]
[1]School of Chemical Engineering, Engineering Campus, Nibong Tebal, Penang, 14300, Malaysia.
[2]School of Chemical Engineering, Engineering Campus, Nibong Tebal, Penang, 14300, Malaysia.
[4]Department of Chemical & Biomolecular Engineering, National University of Singapore, 117585, Singapore.

E-mail: chzahmad@usm.my

Abstract. Biodiesel is one of the promising liquid fuels for future due to its advantages such as renewability and eco-friendliness. This manuscript describes the development of a multi-loop control system design for a comprehensive biodiesel process using waste cooking oil. Method for controlled variable-manipulated variable (CV-MV) pairings are vital for the stable, effective and economical operation of the process. Liquid recycles, product quality requirements and effective inventory control pose tough challenges to the safe operation of the biodiesel process. A simple and easy to apply effective RGA method [Xiong Q, Cai W J and He M J 2005 A practical loop pairing criterion for multivariable processes *Journal of Process Control* vol. 15 pp 741-747.] is applied to determine CV-MV pairings i.e. control configuration design for the bioprocess. This method uses steady state gain as well as bandwidth information of the process open loop transfer function to determine input-output pairings.

1. Introduction

Typically, biodiesel is made by chemically reacting lipids such as vegetable oil with an alcohol to produce fatty acid esters i.e. biodiesel. It can also be produced by pyrolysis, micro-emulsification and transesterification. Among these alternatives, alkali-catalyzed transesterification is commonly used in the industry [1, 2]. Therefore, in this study, a two-step, acid esterification and alkali transesterification, process is considered. Typically, alkali catalyzed transesterification requires the pure oil as it forms soap in the presence of free fatty acids (FFA). Four biodiesel production processes (alkali-catalyzed process using pure vegetable oil, alkali catalyzed process using WCO, acid-catalyzed process using WCO, and acid-catalyzed process using hexane extraction) were proposed by Zhang et al. [3]. As this study deals with biodiesel production from waste cooking oil (WCO), acid esterification of WCO is carried out to convert FFAs into biodiesel.

[3] To whom any correspondence should be addressed.

The complete process with several reactors and distillation columns requires proper input-output (i.e., manipulated variable-controlled variable) pairings for designing an effective control system. In general, the control structure is centralized or decentralized. The latter is more attractive for complex processes with many unit operations; other advantages include its ease in design and implementation, simple tuning and robust behaviour in dealing with faults and uncertainties [4]. Some control loops can be selected based on process knowledge and heuristics. However, for other multivariable processes, as in case of biodiesel process, systematic and reliable methods are needed to determine input-output pairings and to complement the pairings suggested by heuristics. Relative gain array (RGA) is very widely used to determine input-output pairings due to its simplicity. Several other methods have been proposed to determine these pairings, such as dynamic RGA, Effective RGA (ERGA), block relative array, relative disturbance gain array and non-linear RGA [4]. Steady state RGA based loop pairing criterion yields an incorrect interaction assessment in certain cases [5]. Therefore, ERGA is employed in this work to decide the control configuration. The next section describes the process for biodiesel production from WCO.

2. Biodiesel production from WCO

The biodiesel process (Figure 1) is taken from our previous work [6], where two alternative processes were optimized using an Excel based multi-objective optimization program. The plant capacity is assumed to be 120 kt per annum, based on potential WCO in Malaysia. Steady-state and dynamic simulations are carried out using Aspen Plus V8.0 and Aspen Plus Dynamics V8.0 respectively. The property model used for these simulations is Dortmund modified UNIFAC [6-8]. To obtain more reliable results, detailed components of palm oil and more realistic kinetics that includes mono- and di-glycerides formation are considered. Esterification and trans-esterification are represented by 10 and 96 reactions, whose details can be seen in [6].

3. Effective relative gain array

This method is the extension of the popular RGA into a new method that reflects dynamic interactions of the process under finite bandwidth control. Its main advantages are: it reflects dynamic interaction within the loop without needing the specification of the type of controller and with minimal computation, gives a less conservative controller when the detuning factor design method is employed, and is easy to understand [4]. The loop pairing decision is affected by: steady state gain and response speed. The response speed is proportional to the bandwidth in frequency domain [5]. Therefore, the bandwidth is considered to reflect interactions from finite bandwidth control as well as pairing loops to result in a quick response [5]. ERGA method is summarized as follows (for further details, refer to [5]).

1) Obtain open loop transfer functions (TF)
2) Determine bandwidth from the obtained TF
3) Calculate effective gain matrix $E=G(0)\times\Omega$

where

$$E = \begin{bmatrix} e_{11} & e_{12} & \cdot\cdot & e_{1n} \\ e_{21} & e_{22} & \cdot\cdot & e_{2n} \\ \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot \\ e_{n1} & e_{n2} & \cdot\cdot & e_{nn} \end{bmatrix},\ G(0) = \begin{bmatrix} g_{11}(0) & g_{12}(0) & \cdot\cdot & g_{1n}(0) \\ g_{21}(0) & g_{22}(0) & \cdot\cdot & g_{2n}(0) \\ \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot \\ g_{n1}(0) & g_{n2}(0) & \cdot\cdot & g_{nn}(0) \end{bmatrix} \text{ and } \Omega = \begin{bmatrix} \omega_{B,11} & \omega_{B,12} & \cdot\cdot & \omega_{B,1n} \\ \omega_{B,21} & \omega_{B,21} & \cdot\cdot & \omega_{B,21} \\ \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot \\ \omega_{B,n1} & \omega_{B,n1} & \cdot\cdot & \omega_{B,nn} \end{bmatrix}$$

Thus the bandwidth matrix (Ω) is calculated based on the individual elements of G(s).

4) Find ERGA (ϕ) ($\phi = ExE^{-T}$) where

$$\phi = \begin{bmatrix} \phi_{11} & \phi_{12} & \cdot\cdot & \phi_{1n} \\ \phi_{21} & \phi_{22} & \cdot\cdot & \phi_{2n} \\ \cdot\cdot & \cdot\cdot & \cdot\cdot & \cdot\cdot \\ \phi_{n1} & \phi_{n2} & \cdot\cdot & \phi_{nn} \end{bmatrix}$$

Finally, the pairing is selected according to the following rules;

(a) ERGA elements closest to 1 should be chosen.
(b) The positive value of Niederlinski index (NI) $\left(=\frac{det(G(0))}{\prod_{i=1}^{m} g_{ii}(0)}\right)$ is required.
(c) Selected pair (i.e. corresponding ERGA) element should be positive.
(d) The input-output pair having a large ERGA element should not be preferred.

4. Application of ERGA to biodiesel process

ERGA is employed to select the input-output pairing in CSTRs and distillation columns in the biodiesel process; see Table 1 for these and other MV-CV pairing. These loops are selected based on the guidelines given in the previous section. Other control loops are selected based on heuristics and process knowledge, as mentioned in Table 1. The resulted control structure is shown in Figure 1. In agreement to the results of ERGA analysis, in all distillation columns, the level in reflux drum and in reboiler are controlled using distillate flow and bottoms flow respectively; this is in accordance with heuristics that suggest the level should be controlled so that the disturbances are directed away from the primary process path [3]. Using reflux rates to control the level in reflux drums is not appropriate as the columns are operating at smaller reflux ratios. This is also in agreement with Richardson's rule that states that an inventory variable should be controlled with the manipulated variable that exercises the largest effect on it within that unit [3]. Similarly, the liquid level in reactors and phase separators are controlled using liquid outlets.

To demonstrate the effectiveness of these pairings, the performance of the control loops for ±10% variation in WCO is investigated. Controllers have been tuned using autotuner in Aspen Plus Dynamics. Figure 2 suggests that the control system with the CV-MV pairings in Table 1 works satisfactorily. Note that a complete PWC structure has not been developed in this study as the main focus is on the selection of input-output pairings only. A complete PWC for the process and its performance can be found in our recent work [8].

5. Conclusions

A simple, effective and easy to apply ERGA is applied to determine CV-MV pairings in the biodiesel production process from WCO. Using steady state gain and bandwidth information of the process open loop transfer functions, control loop pairings are identified that reflects the dynamic loop interactions under finite bandwidth control. The developed process model with the derived control structure can be used for further studies, such as evaluation of PWC structure and operator training simulator development.

Acknowledgments

"RU grant (1001/PJKIMIA/814155) and IPS graduate fund" for the financial support. Thanks to Prashant Wankhede of Reliance India Limited, Chandrakant Bende of Mylan Pharmaceutical limited and Chetan Sayankar, Consultant of Inventive Engineering & Technology Pvt. Ltd. & SRS Biodiesel and Engineering Pvt. Ltd. for giving us important insights into the biodiesel process.

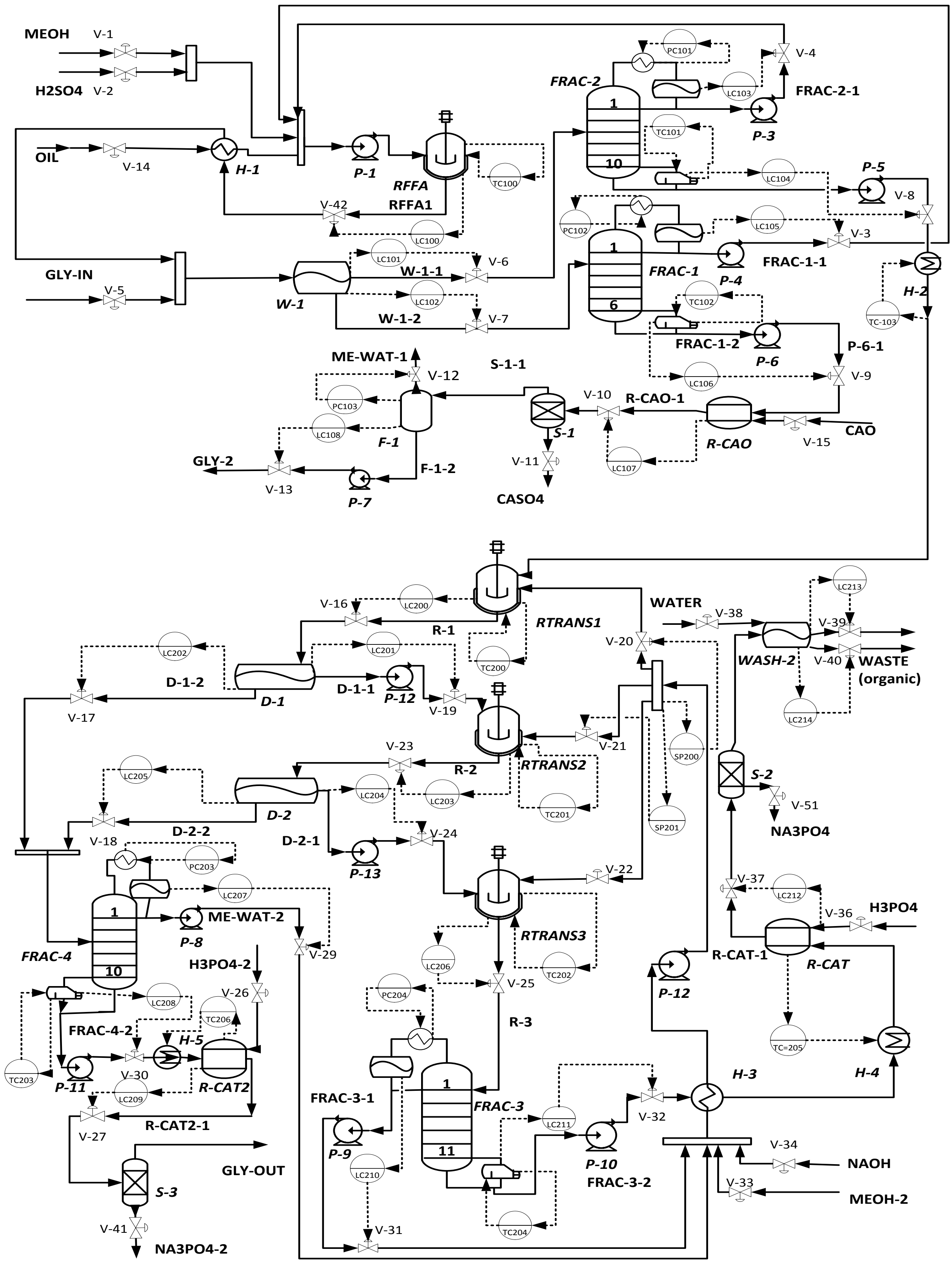

Figure 1. Control scheme designed for the biodiesel plant using waste cooking oil.

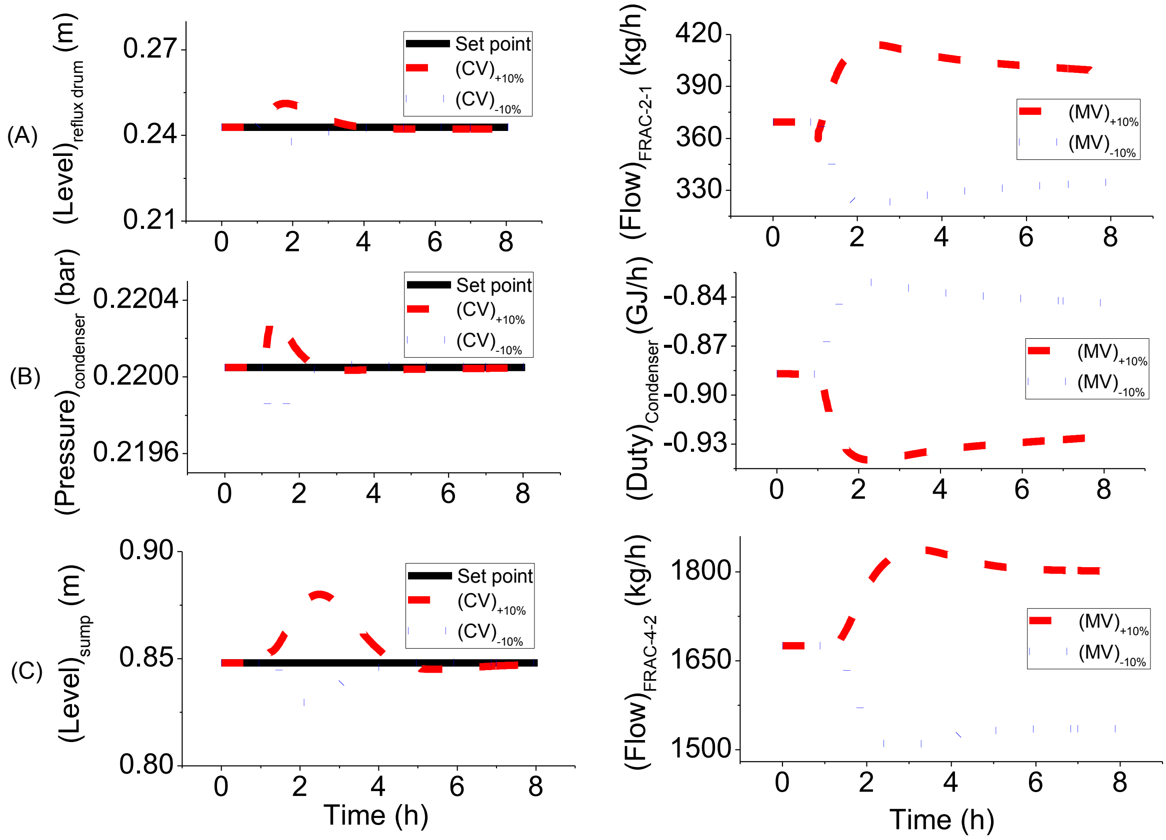

Figure 2. Dynamic behaviour of controllers for ±10% change in WCO: (A) Reflux drum level control in FRAC-2, (B) Pressure control in FRAC-2, (C) Sump level control in FRAC-4. The corresponding manipulated variable is shown in the plots on the right side.

Table 1. Control structure (i.e., MV-CV pairings) and controller parameters for the biodiesel process

Controllers	Controlled variable (CV)	Manipulated variable (MV)	Controller parameters [Kc (%/%), τ_i (min)]
PC101	Condenser pressure in FRAC-2	Condenser duty in Frac-2	2; 10
PC102	Condenser pressure in FRAC-1	Condenser duty in Frac-1	2; 10
PC103	Pressure in F-1	Vapor flowrate [V-12]	2; 10
TC100	Temperature in RFFA	Utility flow	6.56; 13.2
TC101	Bottom stage temperature in Frac-2	Reboiler duty in Frac-2	21.71; 13.56
TC102	Bottom stage temperature in Frac-1	Reboiler duty in Frac-1	33.3; 11.3
TC103	Temperature of heater ‘H-2’ outlet	Heat duty in ‘H-2’	22.9; 12.6
LC100	Level in RFFA	Liquid outlet flow [V-42]	10; 60
LC101	Light phase level in W-1	Light phase outlet flow [V-6]	5
LC102	Heavy phase level in W-1	Heavy phase flow [V-7]	5
LC103	Reflux drum level in FRAC-2	Distillate flow [V-4]	2

LC104	Column base level in FRAC-2	Bottoms flow [V-8]	2
LC105	Reflux drum level in FRAC-1	Distillate flow [V-3]	2
LC106	Column base level in FRAC-1	Bottoms flow [V-9]	2
LC107	Level in R-CAO	Liquid outlet flow [V-10]	10; 60
LC108	Level in F-1	Liquid outlet flow [V-13]	5; 60
PC203	Condenser pressure in FRAC-4	Condenser duty in Frac-4	2; 10
PC204	Condenser pressure in FRAC-3	Condenser duty in Frac-3	2; 10
TC200	Temperature in RTRANS1	Utility flow	13.87; 19.8
TC201	Temperature in RTRANS2	Utility flow	12.11; 13.2
TC202	Temperature in RTRANS3	Utility flow	15.54; 26.4
TC203	Bottom stage temperature in Frac-4	Reboiler duty in Frac-4	21.22; 9.62
TC204	Bottom stage temperature in	Reboiler duty in Frac-3	23.23; 13.83
TC205	Temperature in R-CAT	Heat duty in ‘H-4’	9.63; 17.23
TC206	Temperature in R-CAT2	Heat duty in ‘H-5’	13.63; 7.92
LC200	Level in RTRANS1	Liquid outlet flow [V-16]	10; 60
LC201	Light phase level in D-1	Light phase outlet flow [V-19]	5; 60
LC202	Heavy phase level in D-1	Heavy phase flow [V-17]	5; 60
LC203	Level in RTRANS2	Liquid outlet flow [V-23]	10; 60
LC204	Light phase level in D-2	Light phase outlet flow [V-24]	5
LC205	Heavy phase level in D-2	Heavy phase flow [V-18]	5
LC206	Level in RTRANS3	Liquid outlet flow [V-25]	10; 60
LC207	Reflux drum level in FRAC-4	Distillate flow [V-29]	2
LC208	Column base level in FRAC-4	Bottoms flow [V-30]	2
LC209	Level in R-CAT2	Liquid outlet flow [V-27]	10; 60
LC210	Reflux drum level in FRAC-3	Distillate flow [V-31]	2
LC211	Column base level in FRAC-3	Bottoms flow [V-32]	2
LC212	Level in R-CAT	Liquid outlet flow [V-37]	10; 60
LC213	Light phase level in WASH-2	Light phase outlet flow [V-39]	5
LC214	Heavy phase level in WASH-2	Heavy phase flow [V-40]	5

References

[1] Biodiesel solutions. Malaysian Palm Oil Board, Washington, DC, http://www.palmoilworld.org/biodiesel.html (accessed March 2014).

[2] Lurgi, acquired by Air Liquide Global E&C Solutions in 2007, Paris, France, http://www.engineering-solutions.airliquide.com/en/welcome.html (accessed March 2014).

[3] Zhang Y, Dubé MA, McLean DD and Kates M 2003 Biodiesel production from waste cooking oil: 1. Process design and technological assessment Bioresource Technol **89(1)** 1–16.

[4] Moaveni B and Kariwala V 2012 Input-Output pairing selection for design of decentralized controller in *Plantwide control - recent developments and applications* Edited by G P Rangaiah and V Kariwala, Wiley.

[5] Xiong Q, Cai W J and He MJ 2005 A practical loop pairing criterion for multivariable processes *J of Process Control* **15** 741-747.

[6] Patle DS, Sharma S, Ahmad Z and Rangaiah GP 2014 Multi-objective optimization of two alkali catalyzed processes for biodiesel from waste cooking oil *Energy Convers and Manage* **85** 361-372.

[7] Aspen Plus: Aspen Plus Biodiesel Model (Examples); Aspen Technology: Cambridge, MA, 2012.

[8] Patle DS, Ahmad Z and Rangaiah GP 2014 Plantwide control of biodiesel production from waste cooking oil using integrated framework of simulation and heuristics *Ind Eng Chem Res:* **53** 14408-14418.