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

Dipesh S Patle¹, Ahmad Z²,³ and G. P. Rangaiah⁴

¹School of Chemical Engineering, Engineering Campus, Nibong Tebal, Penang, 14300, Malaysia.
²School of Chemical Engineering, Engineering Campus, Nibong Tebal, Penang, 14300, Malaysia.
³Department 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.

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

\[
E = \begin{bmatrix}
    e_{11} & e_{12} & \cdots & e_{1n} \\
    e_{21} & e_{22} & \cdots & e_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    e_{n1} & e_{n2} & \cdots & e_{nn}
\end{bmatrix}, \quad G(0) = \begin{bmatrix}
    g_{11}(0) & g_{12}(0) & \cdots & g_{1n}(0) \\
    g_{21}(0) & g_{22}(0) & \cdots & g_{2n}(0) \\
    \vdots & \vdots & \ddots & \vdots \\
    g_{n1}(0) & g_{n2}(0) & \cdots & g_{nn}(0)
\end{bmatrix}
\]

and

\[
\Omega = \begin{bmatrix}
    \omega_{B,11} & \omega_{B,12} & \cdots & \omega_{B,1n} \\
    \omega_{B,21} & \omega_{B,22} & \cdots & \omega_{B,2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    \omega_{B,n1} & \omega_{B,n2} & \cdots & \omega_{B,nn}
\end{bmatrix}
\]

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

4) Find ERGA (\( \phi = ExE^{-1} \)) where

\[
\phi = \begin{bmatrix}
    \phi_{11} & \phi_{12} & \cdots & \phi_{1n} \\
    \phi_{21} & \phi_{22} & \cdots & \phi_{2n} \\
    \vdots & \vdots & \ddots & \vdots \\
    \phi_{n1} & \phi_{n2} & \cdots & \phi_{nn}
\end{bmatrix}
\]
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) \(\frac{\text{det}(G(0))}{\prod_{i=1}^{m} \theta_i(0)}\) 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.

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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                                     |
| PC103       | Condenser pressure in FRAC-1 | Condenser duty in Frac-1 | 2; 10                                     |
| TC100       | Temperature in RFFA         | Vapor flowrate [V-12]    | 2; 10                                     |
| TC101       | Bottom stage temperature in Frac-2 | Utility flow | 6.56; 13.2                                |
| TC102       | Bottom stage temperature in Frac-1 | Reboiler duty in Frac-2 | 21.71; 13.56                              |
| TC103       | Temperature of heater ‘H-2’ outlet | Heat duty in ‘H-2’ | 33.3; 11.3                                |
| 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                                          |
| Reference | Description |
|-----------|-------------|
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