CHEMICAL ENGINEERING TRANSACTIONS

VOL. 56, 2017

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Jiří Jaromír Klemeš, Peng Yen Liew, Wai Shin Ho, Jeng Shiun Lim

ISBN 978-88-95608-47-1; **ISSN** 2283-9216

DOI: 10.3303/CET1756234

Interval Type-2 Fuzzy GMC for Nonlinear Stochastic Process of Methane Production in the Anaerobic Digester System

Mohd Fauzi Zanil*[,a], Mohd Azlan Hussain[b]

[a]Chemical & Petroleum Engineering Department, Faculty of Engineering, Technology & Built Environment, UCSI University, 56000 Kuala Lumpur, Malaysia
[b]Chemical Engineering Department, Faculty of Engineering, University of Malaya, 50603, Kuala Lumpur, Malaysia
mohdfauzi@ucsiuniversity.edu.my

The paper focused on the implementation of hybrid Interval Type-2 (IT2) Fuzzy with Generic Model Control (GMC) for the nonlinear stochastic waste treatment process in the anaerobic digester. Development of the deterministic methane process model has been extended to a set of stochastic nonlinear differential equations. The stochastic effect is introduced by adding white noise with unit covariance to give an interesting profile like physical plant dynamic. The IT2 Fuzzy based on Takagi-Sugeno-Mendel and GMC by Lee and Sullivan have been developed to control the holdup pH inside reactor. The pH value is being manipulated by the flowrate of Sodium hydroxide at optimal methane gas production condition. The process variables that need to be controlled and included into the controller are pH, error and change of error while the consequence fuzzy set output is from the GMC backpropagation law equations. As a result from several studies; servo and regulatory, the controller show significant improvement on the set point tracking and disturbance rejection over typical Fuzzy, Fuzzy-GMC and conventional Proportional-Integral-Derivative (PID) controllers. It shows the controller is suitable for stochastic process and nonlinear control system application.

1. Introduction

Several nonlinear control techniques have been proposed lately for an anaerobic digester control system: High loading rate compensator (Charles et al., 2011); Multivariable model based control system (Méndez-Acosta et al., 2010); Dynamic profile mapping by model predictive controller (Padhiyar and Bhartiya, 2009). A fuzzy logic controller is widely proposed due to the ability for nonlinear process and able to operate at many operating conditions like controllability at multiple linear regions (Zanil et al. 2015) has showed the effectiveness of the fuzzy system to handle the process nonlinearity. However, the framework is not sensitive to the uncertainty factor in the process dynamics (Saadat et al., 2013). As a result, the control performance of the conventional fuzzy will vary and may aggravate proportionally with degree of certainty in the process. Hence, the fuzzy calculation framework can be integrated with a mathematical model to improve the control performance (Zanil et al. 2014).

Type-2 fuzzy is able to solve nonlinear processes in abide enough information are utilised but it is mostly used for uncertain process which the membership function in a fuzzy set are difficult to obtain (Lin et al., 2015). Simple approach to this difficulty are to define an uncertain boundary for the control system (Biglarbegian and Mendel, 2015), or to decompose each of fuzzy variable into type-1 fuzzy sub-system (Su and Chen, 2015), or integrate general algorithm inside the general fuzzy framework to guarantee the controller stability (Li et al., 2012).

It has been presented in Tung et al. (2013), type-2 fuzzy are much more effective to solve a process with high degree of uncertainties and nonlinearities. Nevertheless, the trade-off is the inference calculation are more complex (Tang et al., 2011) than type-1 fuzzy systems. Therefore, a special type of type-2 fuzzy called interval type-2 fuzzy is used in Mendel and John (2002). Several control applications have been successfully demonstrated: level control (Zhao et al., 2012); bioreactor control (Van Lith et al., 2002); pH control (Carbureanu, 2014). Like conventional fuzzy, interval type-2 shared a common drawback in which the construction of fuzzy set is complex and depended on the input-output matching (Shamiri et al., 2015). Thus, a mechanism like observer can be integrated to support this limitation. Most of the above studies concluded that further exploration of interval Type-2 Fuzzy is needed. This work, hybrid IT2Fuzzy-GMC controller is designed and implemented in anaerobic digester process to control the alkalinity of the reactor. Without involving model reduction or approximations, a simulation of detailed dynamic mathematical model for the stochastic process has been carried out using MATLAB/Simulink (MATLAB, 2012).

Please cite this article as: Zanil M.F., Hussain M.A., 2017, Interval type-2 fuzzy gmc for nonlinear stochastic process of methane production in the anaerobic digester system, Chemical Engineering Transactions, 56, 1399-1404 DOI:10.3303/CET1756234

2. Methane Production

The methane production in anaerobic treatment uses a microbiological process for degradation of organic matter. The degradation processes consist of simultaneous reactions for Hydrolysis, Acidogenesis, Acetogenesis, and Methanogenesis process (Vanwonterghem et al., 2015) and the process parameters (Yaldiz et al., 2011). The first stage of anaerobic digestion is a hydrolysis process whereby long-chain organic polymer compounds such as carbohydrates, proteins and fats are hydrolysed to the soluble monomers such as fatty acids or glycerol, amino acids or peptides and monosaccharides or disaccharides are formed from fats, proteins and carbohydrates by hydrolysis bacteria (Bacillus Pumilus). Bio-Organic waste water contains large number of carbon and hydrogen atoms, hydrolysis process is vital in decomposing long-chain hydrocarbons into simple, soluble monomers. After that, Acidogenesis process takes place in which the soluble monomers are converted into volatile fatty acids (VFA), carbon dioxide, water, alcohols and lactic acids. Next, Acetogenesis process which is the oxidization of organic acids to acetic acid, hydrogen, and carbon dioxide. Finally, the Methanogenesis process will take place where the acetate acid is utilised to produce remaining biogas like methane gas and carbon dioxide.

Material balance in liquid phase for microbial biomass X_i (A,AP,AB,M), insoluble substrate, C_{is}, soluble substrate, C_s, acetate, C_{ac}, propionate, C_{pr}, butyrate, C_{bu}, ammonium, C_{NH_4}, and carbon dioxide, C_c are formulated in Eqs(1) to (8):

$$\frac{dX_i}{dt} = \frac{1}{V}\left(X_{i,f} - X_i\right) + r(\sigma_i)\mu_i X_i + f(\vartheta_i) \tag{1}$$

$$\frac{dC_{is}}{dt} = \frac{1}{V}\left(C_{is,f} - C_{is}\right) - kC_{is} \tag{2}$$

$$\frac{dC_s}{dt} = \frac{1}{V}\left(C_{s,f} - C_s\right) + \frac{162y_e}{162+17n}\, kC_{is} - 12.858\,\mu_A \tag{3}$$

$$\frac{dC_{ac}}{dt} = \frac{1}{V}\left(C_{ac,f} - C_{ac}\right) + 3.45\mu_A X_A + 8.006\mu_{AP}X_{AP} + 15.366\mu_{AB}X_{AB} - 24.135\mu_M X_M \tag{4}$$

$$\frac{dC_{pr}}{dt} = \frac{1}{V}\left(C_{pr,f} - C_{pr}\right) + 2.93\mu_A X_A - 10.566\mu_{AP}X_{AP} \tag{5}$$

$$\frac{dC_{bu}}{dt} = \frac{1}{V}\left(C_{bu,f} - C_{bu}\right) + 3.079\mu_A X_A - 3.079\mu_{BP}X_{AB} \tag{6}$$

$$\frac{dC_{NH_4}}{dt} = \frac{1}{V}\left(C_{NH_4,f} - C_{NH_4}\right) + \frac{C_{NH_4}}{V}\left(\frac{17\left(n-m(1-y_e)\right)}{162+17n}\right) k_i S_{is} - 0.15(\mu_A X_A + \mu_{AP}X_{AP} + \mu_{AB}X_{AB} + \mu_M X_M) \tag{7}$$

$$\frac{dC_c}{dt} = \frac{1}{V}\left(C_{c,f} - C_c\right) + 2.413\mu_A X_A + 1.01\mu_{AP}X_{AP} - 3.303\mu_{AB}X_{AB} + 16.726\mu_M X_M - \frac{N_c}{V} \tag{8}$$

Next, Eq(9) to (11) show the material balance that took place for each species in gas phase; carbon dioxide, P_c, methane, P_m:

$$\frac{dP_c}{dt} = \frac{RT}{V_g}\left(\frac{N_c}{44} + \frac{P_c}{P}F_t\right) \tag{9}$$

$$\frac{dP_m}{dt} = \frac{RT}{V_g}\left(\frac{N_m^{\alpha}}{16} + \frac{P_m}{P}F_t\right) \tag{10}$$

$$F_t = \frac{P}{P-P_w}\left(\frac{N_m}{16} + \frac{N_c}{44}\right) \tag{11}$$

where, F_t is total flowrate in gas, P_m, P_w, R, T and V_g represent the partial pressure of methane and water, gas constant, temperature and gas volume.

The pH of the reactor can be obtained by the Eqs(12) and (13), which the ionic disassociation rate at 35 °C are tabulated as in Table 1 (Lange and Dean, 1979):

$$pH = -\log[C_{H^+}] \tag{12}$$

$$C_{H^+} + C_{NH_4^+} = C_{OH^{-1}} + C_{HCO_3^-} + 2C_{co_3^{2-}} + C_{ac^-} + C_{pr^-} + C_{bu^-} - +C_{Anion^-} - C_{Cation^+} \tag{13}$$

Table 1: Chemical equilibrium and ionic disassociation of methane production

Chemical Equilibrium	Disassociation rate, k_n and Value	
$CO_2 + H_2O \leftrightarrow HCO_3^- + H^+$	$k_{a1} = [C_{HCO_3^-}][C_{H^+}]/[C_c]$	$k_{a1} = 4.909 \times 10^{-7}$
$HCO_3^- \leftrightarrow CO_3^{2-} + H^+$	$k_{a2} = [C_{co_3^{2-}}][C_{H^+}]/[C_{HCO_3^-}]$	$k_{a2} = 5.623 \times 10^{-11}$
$HAc \leftrightarrow Ac^- + H^+$	$k_{a3} = [C_{ac^-}][C_{H^+}]/[C_{ac}]$	$k_{a3} = 1.730 \times 10^{-5}$
$HPr \leftrightarrow \mathrm{Pr}^- + H^+$	$k_{a4} = [C_{pr^-}][C_{H^+}]/[C_{pr}]$	$k_{a4} = 1.445 \times 10^{-5}$
$HBu \leftrightarrow \mathrm{Bu}^- + H^+$	$k_{a5} = [C_{bu^-}][C_{H^+}]/[C_{bu}]$	$k_{a5} = 1.445 \times 10^{-5}$
$NH_4^+ \leftrightarrow NH_3^- + H^+$	$k_{a6} = [C_{am}][C_{H^+}]/[C_{NH_4^+}]$	$k_{a6} = 1.567 \times 10^{-9}$
$H_2O \leftrightarrow OH^- + H^+$	$k_w = [C_{OH^-}][C_{H^+}]$	$k_w = 2.065 \times 10^{-14}$

3. Control system and IT2Fuzzy-GMC controller design

The objective of control system is to control a pH inside the digester. A combination of interval type-2 fuzzy system (IT2Fuzzy) and generic model control (GMC) is proposed as a controller in this work (Figure 1). The IT2Fuzzy consist of five interface; Fuzzification, Fuzzy Rules, Fuzzy Inference, Type reducer and Defuzzification. While, GMC is designed to compute good manipulated variable to achieve desire trajectory for the set-point. The formulation of GMC has been integrated inside the output membership function. As the outcome, an appropriate control output which are based on plant characteristic (from GMC) and expert knowledge (from IT2fuzzy).

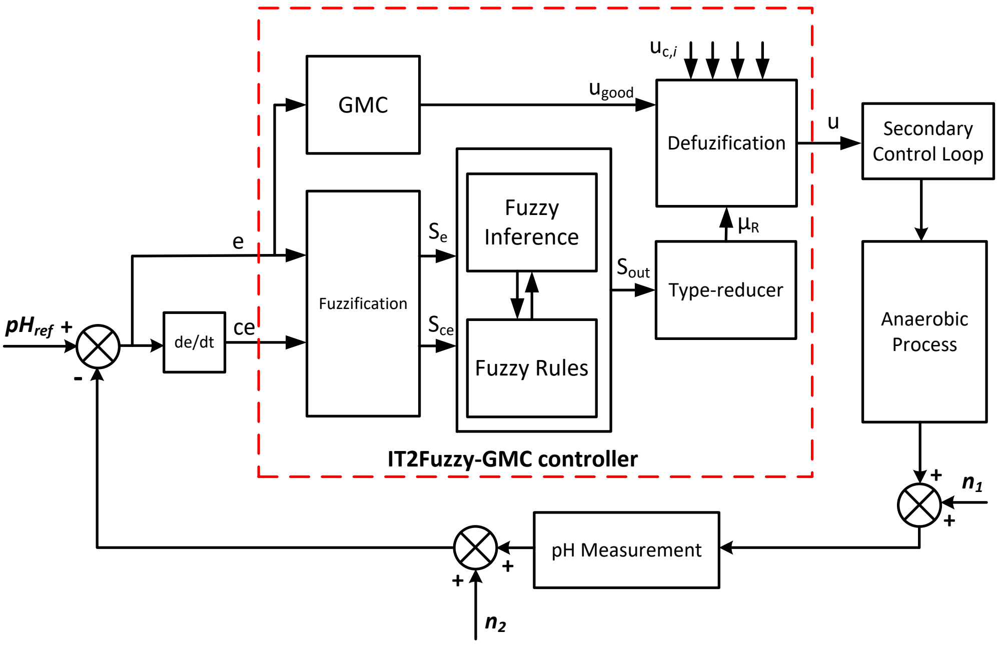

Figure 1: Control system with IT2Fuzzy-GMC controller architecture

The feedback control with cascade system is used in this work and the process is exposed to a stochastic white Gaussian noise, n_1 and unmeasured random distributed noise, n_2 at the anaerobic digester process and pH measurement. In this work, the controller architecture with multiple input and single output (MISO) has been selected, there are 2 inputs from error,e and change of error, ce., while, the output of controller is flowrate, u of caustic soda which to regulate the alkalinity of the process. Inside secondary loop, a PI controller is used to manipulate the control valve of caustic soda stream where the control valve is varied to track the reference flow rate.

Interval type-2 fuzzy system is similar to the conventional fuzzy system where as the difference is that the type-reducer is added before the defuzzification block. The outputs are then processed by the type-reducer which combines all the output sets and then centroid defuzzification is performed to produce minimum and maximum crisp outputs (Mendel and John, 2002). This work, two inputs and single output has been considered which input 1, $x_e \in X_e$; input 2, $x_{ce} \in X_{ce}$ and output $u \in U$. The fuzzy rules represent the input space of $X_e \times X_{ce}$ and output space of U. The combination of three membership functions are used for each fuzzy input and it resulted to 3^2 number of fuzzy rules (refer Table 2), where the *l*^th rule has the form as Eq(14);

$$R^l: IF\ x_e\ is\ \tilde{F}_e^l\ AND\ x_{ce}\ is\ \tilde{F}_{ce}^l\ THEN\ u\ is\ \tilde{U}^l\ \ ; l = 1, 2, 3 \ldots 9 \qquad (14)$$

Table 2: Fuzzy Rule of control loop system

IF e → / AND ce ↓	Positive, $x_{e,1}$	Zero, $x_{e,2}$	Negative, $x_{e,3}$
Positive, $x_{ce,1}$	Mid Open, u_2	Mid Close, u_4	Close, u_5
Zero, $x_{ce,2}$	Mid Open, u_2	Good,$u_3 \equiv u_x$	Mid Close, u_4
Negative, $x_{ce,3}$	Open, u_1	Mid Open, u_2	Mid Close, u_4

A centre of set type-reduction method is selected due to the less computational complexity in firing rules. It is used to compute the input-output uncertainty u_l and u_r. It can be calculated iteratively by Karnik and Mendel algorithm and it is expressed as Eq(15):

$$U_{cos}(U^1,\dots,U^9,F^1,\dots,F^9)=[u_l,u_r]=\int_{y^1}\dots\int_{y^9}\int_{f^1}\dots\int_{f^9}\frac{\sum_{i=1}^{9}f^i}{\sum_{i=1}^{9}f^i u^i} \tag{15}$$

where U_{cos} is an interval value of T2Fuzzy which covers the most left and right in the output set. The total firing strength, $\overline{f}^{\,i}$ and $\underline{f}^{\,i}$ can be written as Eqs(16) and (17):

$$\overline{f}^{\,i}(e,ce)=\overline{\mu}_{F_e}(x_e)\cap\overline{\mu}_{F_{ce}}(x_{ce}) \tag{16}$$

$$\underline{f}^{\,i}(e,ce)=\underline{\mu}_{F_e}(x_e)\cap\underline{\mu}_{F_{ce}}(x_{ce}) \tag{17}$$

The fuzzy output; minimum, u_l and maximum, u_r are reordered such that $u_l^1\le u_l^2\le\cdots u_l^N$ and $u_r^1\le u_r^2\le\cdots u_l^N$ which $u_r^{(R)}$ and $u_l^{(L)}$ in the range of $0\le L,R\le N$ as Eqs(18) and (19):

$$u_l^{(L)}(e,ce)=\frac{\sum_{j=1}^{L}\overline{f}^{\,j}(e,ce)\,u_l^j+\sum_{j=L+1}^{N}\underline{f}^{\,j}(e,ce)\,u_l^j}{\sum_{j=1}^{L}\overline{f}^{\,j}(e,ce)+\sum_{j=L+1}^{N}\underline{f}^{\,j}(e,ce)} \tag{18}$$

$$u_r^{(R)}(e,ce)=\frac{\sum_{j=1}^{R}\underline{f}^{\,j}(e,ce)\,u_l^j+\sum_{j=R+1}^{N}\overline{f}^{\,j}(e,ce)\,u_l^j}{\sum_{j=1}^{R}\underline{f}^{\,j}(e,ce)+\sum_{j=R+1}^{N}\overline{f}^{\,j}(e,ce)} \tag{19}$$

The interval set is defuzzified by using average of u_l and u_r, thus the crisp value output is calculated as Eq(20):

$$u(e,ce)=\frac{u_l^{(L)}(e,ce)+u_r^{(R)}(e,ce)}{2} \tag{20}$$

The fuzzy output is divided into five membership functions comprised of control action, $u_x(e,y^*)$ from Eq(21) and several constants, $u_{c,i}$. Details of control action for GMC can be referred to Lee and Sullivan (1988).

$$u_x(e,y^*)=K_1(y^*-y)+K_2\int(y^*-y)dt \tag{21}$$

At one instance, the final control action can be obtained from the distribution of several possible membership output which is based on the GMC output value and degree of association in IT2Fuzzy.

4. Result and Discussion

The control system with proposed controller has been simulated to shows the feasibility of control system performance. In recent year, the interest of stochastic nonlinear control system have been increased tremendously. Coherent to this, any propose controller must implies to have a good control performance for unpredictable environmental changes, either these changes occurs internal or external to it. Figure 2 shows the trajectory of control system for servo case analysis. The tracking performance of proposed controller overtake all tested controllers by 12 % improvement in response time without any overshoot and zero offset.

From Figure 3, when system is exposed to external disturbance, conventional Proportional-Integral-Derivative (PID) controller failed to regulate the set-point at desire value. At this condition, conventional fuzzy logic controller shows less effective in which the rejection time is higher than proposed controller by 12 unit time. The proposed controller is suitable for both cases in these simulation analyses.

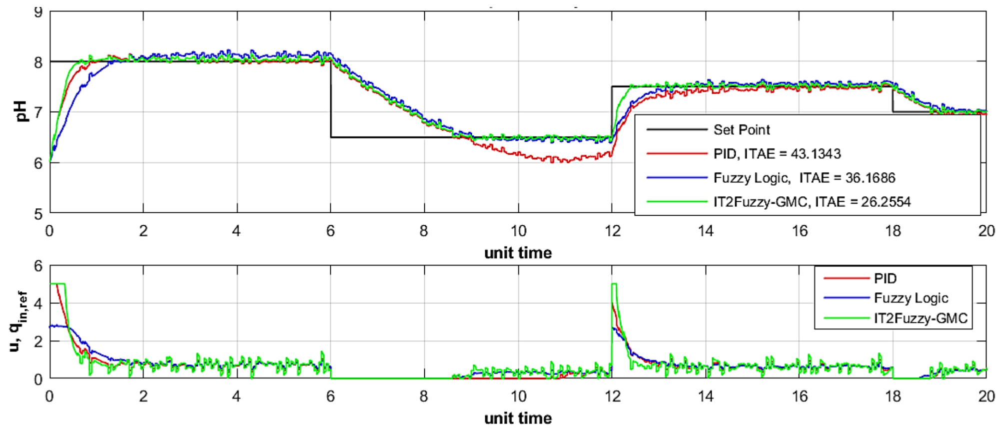

Figure 2: Comparison trajectories of multiple set-point tracking

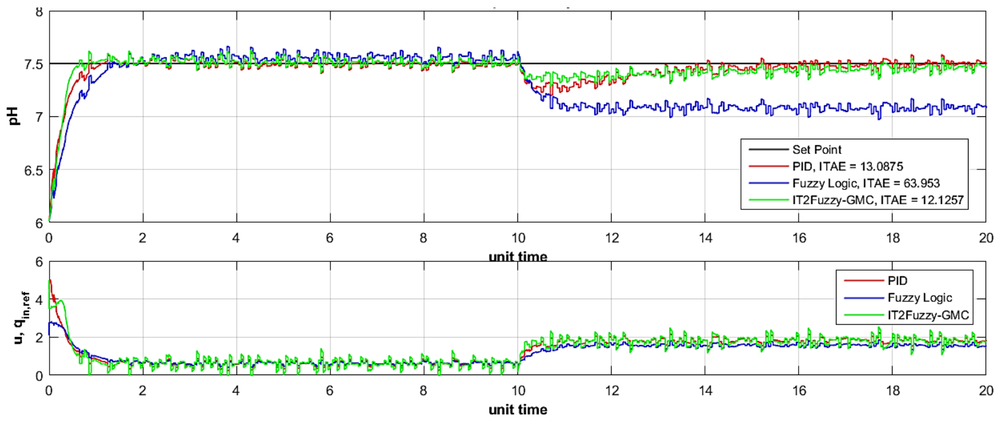

Figure 3: Comparison trajectories of the pH variable with external disturbances

5. Conclusion

In this work, control performance of hybrid IT2Fuzzy and GMC controller has been demonstrated. The proposed controller has showed a significant improvement for process with stochastic dynamic compared to conventional fuzzy and PID controllers. The implementation of proposed controller is recommended for a control system with high degree of uncertainty and nonlinearity process.

Acknowledgement

This work was supported by the UCSI University Pioneer Scientist Incentive Fund (Grant number: PSIF-2016-00017).

Reference

Biglarbegian M., Mendel J.M., 2015, On the justification to use a novel simplified interval type-2 fuzzy logic system, Journal of Intelligent and Fuzzy Systems 28, 1071-1079.
Carbureanu M., 2014, The Development of a Neuro-Fuzzy Expert System for Wastewater pH Control, Control Engineering and Applied Informatics 16, 30-41.
Charles W., Carnaje N.P., Cord-Ruwisch R., 2011, Methane conversion efficiency as a simple control parameter for an anaerobic digester at high loading rates, Water Science and Technology 64 (2), 534-539.
Lange N.A., Dean J.A. 1979, Lange's Handbook of chemistry, 12th Ed., McGraw-Hill, New York, United States.
Li Y.M., Yang Y., Li L., 2012, Adaptive Backstepping Fuzzy Control Based on Type-2 Fuzzy System, Journal of Applied Mathematics 2012, Paper 658424.
Lin C.T., Pal N.R., Wu S., Liu Y., Ling Y., 2015, An Interval Type-2 Neural Fuzzy System for Online System Identification and Feature Elimination, IEEE Transactions on Neural Networks and Learning Systems 26 (7), 1442-1455.
MATLAB 2012b, The MathWorks Inc., Natick, Massachusetts, United States.
Mendel J.M., John R.I.B., 2002, Type-2 fuzzy sets made simple, IEEE Transactions on Fuzzy System 10, 117-127.

Méndez-Acosta H.O., Palacios-Ruiz B., Alcaraz-González V., González-Álvarez V.,García-Sandoval J.P., 2010, A robust control scheme to improve the stability of anaerobic digestion processes, Journal of Process Control 20 (4), 375-383.

Padhiyar N., Bhartiya S., 2009, Profile control in distributed parameter systems using lexicographic optimization based MPC, Journal of Process Control 19, 100-109.

Saadat A.,Alvanagh A.A., Rezaei H., 2013, pH Control in Biological Process Using MMPC based on Neuro-Fuzzy Model by LOLIMOT Algorithm, 9th Asian Control Conference (Ascc), 23-26 June 2013, Turkey.

Shamiri A., Wong S.W., Zanil M.F., Hussain M.A., Mostoufi N., 2015, Modified two-phase model with hybrid control for gas phase propylene copolymerization in fluidized bed reactors, Chemical Engineering Journal 264, 706-719.

Su S.F., Chen M.C., 2015, Enhanced Fuzzy Systems for Type 2 Fuzzy and their Application in Dynamic System Identification, Proceedings of the 16th World Congress of the International Fuzzy Systems Association and 9th Conference of the European Society for Fuzzy Logic and Technology, Spain,118-122.

Tang M., Chen X., Hu W., Yu W., 2011, A Fuzzy Rule-Based Classification System Using Interval Type-2 Fuzzy Sets, Integrated Uncertainty in Knowledge Modelling and Decision Making 7027, 72-80.

Tung S.W., Quek C., Guan C., 2013, eT2FIS: An Evolving Type-2 Neural Fuzzy Inference System, Information Sciences 220, 124-148.

Van Lith P.F., Betlem B.H.L., Roffel B., 2002, A structured modeling approach for dynamic hybrid fuzzy-first principles models, Journal of Process Control 12 (5), 605-615.

Vanwonterghem I., Jensen P.D., Rabaey K., Tyson G.W., 2015, Temperature and solids retention time control microbial population dynamics and volatile fatty acid production in replicated anaerobic digesters, Scientific Reports, 5, Article No. 8496.

Yaldiz O., Sozer S., Caglayan N., Ertekin C., Kaya D., 2011. Methane Production from Plant Wastes and Chicken Manure at Different Working Conditions of a One-stage Anaerobic Digester, Energy Sources Part a-Recovery Utilization and Environmental Effects 33 (19), 1802-1813.

Zanil M.F., Chow Y.T., Hussain M.A., 2015, Segmentation of Fuzzy Logic Inference to a Conventional PID Controller for Nonlinear pH Neutralization Application, International Journal of New Technologies in Science and Engineering 2 (4), 174-181.

Zanil M.F., Norhuda A.M., Hussain M.A., Omar R., 2014, Hybrid model of pH neutralization for a pilot plant, Journal of Intelligent & Fuzzy Systems 26, 551-561.

Zhao T., Li P., Cao J., 2012, Study of Interval Type-2 Fuzzy Controller for the Twin-tank Water Level System, Chinese Journal of Chemical Engineering 20 (6), 1102-1106.