

Fuzzy Control of a Laboratory Binary Distillation Column

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Abstract—This paper deals with control of a laboratory binary distillation column used for separation of methanol from water. The focus of this paper is the tutorial demonstration of the model-free fuzzy control design for the laboratory device. The performance and the control synthesis of the fuzzy control approach are moreover compared with classical PID controller.

I. INTRODUCTION

In this paper, we present the fuzzy control application of a well-equipped binary distillation plant. Distillation is one of the most common and best understood separation methods, widely used in the process industries, e.g. in partial fractionation of crude oil, separation of noble gases, and production of distilled alcoholic beverages, etc. Hence design and operation of the distillation columns has been studied in many textbooks e.g. [1]–[3]. The separation of the liquid mixture is based on the evaporation and condensation, where the individual substances are separated based on their relative boiling points.

The control of the temperature is therefore the necessity for the efficient and safe operation of the distillation process, and become a standard in process industries, see e.g. [4]–[7]. However as particular distillation units vary in many parameters [8], there is no standard control structure that fits all the units and scenarios. Thus, an individual approach must be chosen for control of a particular column with given specifications. There are many distinct approaches in the controller design for distillation columns. A survey has been published in [9] where the focus is on the construction of the SISO loops governed by PID controllers. Design of the stabilizing controllers for unstable distillation columns was given in [10]. Robust $\mathcal{H}_\infty$ control of the distillation process was described in [11]. Control of the distillation processes based on Model Predictive Control (MPC) was introduced in [12] and since then become a flagship of process control. However to design of the well performing MPC is dependent on the sufficiently accurate model of the system, which is usually time consuming and not straightforward task. In practice, if there is for any reason a substantial obstacle in developing the accurate system model, a model free fuzzy logic can act as a remedy for the fast design of the well performing controller.

Fuzzy control provides a formal methodology for implementing a knowledge of human about a system. Since it gives a convenient method for constructing nonlinear controllers via the use of heuristic information, it is a practical alternative for a variety of control applications [13]. The heuristic information

can be obtained from an operator who acts as a “human-in-the-loop” controller for a process [14]. The operator formulates a set of rules how to control the process, which are applied in a fuzzy controller imitating the human’s decision-making process. Or the information may be provided by an engineer who performed mathematical modeling of the process. In both cases, fuzzy control offers a user-friendly tool for designing a high-performance controller. Simply said, there is a language difference between fuzzy and conventional control: ordinary differential equations are the language of conventional control, and linguistic rules are the language of fuzzy control [14].

Improving temperature control has been an important problem in the recent years. To make it cost effective and less time consuming, fuzzy logic seems to be a convenient option [15]–[18]. In recent years, multiple fuzzy control setups were independently investigated and verified for different distillation columns mainly on simulation scenarios, see e.g. [19]–[23]. Despite the increased academic interest in fuzzy process control, the papers about the actual applications of the fuzzy controllers in the experimental setups are rare. Direct fuzzy control of the batch distillation columns was studied in [24], [25], while in [26] the supervisory fuzzy system for adjusting the parameters of the classical PI controllers is proposed for a binary distillation column.

In this paper we design a fuzzy PD controller and fuzzy PI controller of binary distillation plant. Purely human experience was used in order to guide the fuzzy control design, without using any system model. The experience was obtained from previous attempts for control of the laboratory distillation process as described in [27]–[29]. Our fuzzy PI controller performs better than PD when the goal is to achieve the best temperature control regardless the control actions. On the other hand, the fuzzy PD controller performs better than PI when the smoothness of the control actions are of high importance. The main added value of this paper lies in the experimental verification of the model free fuzzy control approach based exclusively on the human engineer experience on the laboratory process.

The paper is organized as follows. Section II presents a detailed description of the distillation column. Section III is devoted to fuzzy controller synthesis. Experimental results are presented in Section IV. Conclusions are drawn in Section V.

II. PLANT DESCRIPTION

The key function of a binary distillation column is to separate a liquid solution of two substances based on their different volatilities (boiling points). The laboratory distillation column UOP3CC is a self-contained continuous distillation process consisting of two interconnected units [30]. First, the floor standing process unit, which is responsible for the separation process. Second, the bench-mounted control console with information gathering and processing function. The process unit of the laboratory column considered in this paper is shown in Fig. 1, with its corresponding process and instrumentation diagram in Fig. 2.



Fig. 1. The process unit of the laboratory distillation column.

Process unit consists of two sections, each with four plate trays with 50 mm diameters. The peristaltic pump continuously feeds the preheated mixture into the central section of the column. The reboiler with the capacity of 20 l and 2.5 kW immersion type heating element boils the mixture of water and methanol. The waste product is being withdrawn from the reboiler through the bottom-flow valve. The methanol enriched vapour flows from the reboiler through the column and condenses in the coil-in-shell condenser to the liquid phase, which flows to the distillate accumulator. The condensate is brought to the reflux solenoid three-way on-on valve. Hence it can only be returned to the column as reflux or removed as a product. The reflux ratio is limited to $R \in [0, 100]$, where $R = 0$ stands for fully closed reflux valve with 100% return of the distillate into the column, and $R = 100$ for fully open reflux valve with 0% distillate returned to the column. Temperatures in the column are monitored by 15 thermocouples. The insulation minimises the energy loss and decreases the effect of the external temperature fluctuations on the process dynamics.

The multiconductor cable connects the process unit with the control console. Here, the thermocouples signals are converted

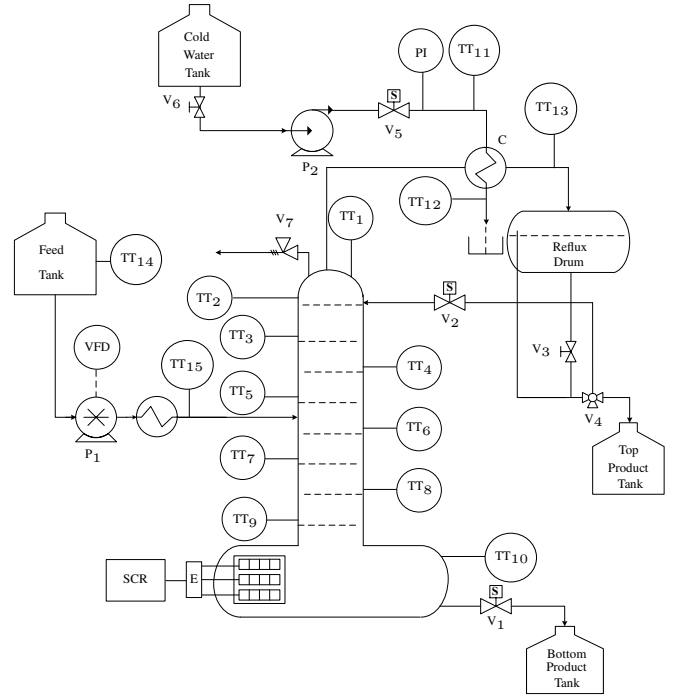


Fig. 2. Process and instrumentation diagram of the process unit.

to the unified signal with range 0–5 V, representing temperature span 0–150 °C. The feed pump speed is controlled by the variable frequency drive (VFD). The heating power of 0–2.5 kW in the reboiler is controlled via UOP3CC console with input signal 0–5 V. The solid-state relay controls pre-heating of the feed mixture via pulse width modulated (PWM) signal. The computer is connected to two I/O PC cards (MF 624), controlled directly from Matlab/Simulink environment, which is capable of either real-time sensing and generating analogue and digital signals.

The compact electrical instrumentation scheme is given in Fig. 3.

III. FUZZY CONTROL

We follow the standard notation with respect to fuzzy sets, see e.g. [31]. A fuzzy set A in a universe X is given by a mapping (membership function) $\mu_A : X \rightarrow [0, 1]$. The general scheme of a fuzzy logic system is shown in Fig. 4. The design of fuzzy controller consists of two phases.

I Preliminary phase

- I.1 Construction of Data base: determination of the input and output variables (linguistic variables), their linguistic values and the corresponding fuzzy sets (membership functions).
- I.2 Construction of Rule base: formulation of rules.
- I.3 Determination of inference method (Decision-making unit), fuzzification and defuzzification method.

II Computational (iterative) phase

- II.1 Normalization of the inputs.

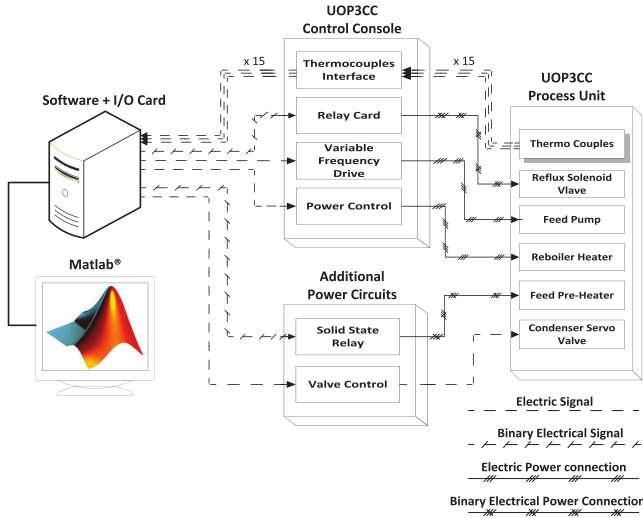


Fig. 3. Implementation scheme of the electrical wiring and instrumentation for laboratory distillation column UOP3C.

II.2 Fuzzification of the normalized inputs.

II.3 Inference - computation of the fuzzy output from the given fuzzy inputs in Decision-making unit.

II.4 Defuzzification of the fuzzy output.

II.5 Denormalization of the defuzzified output.

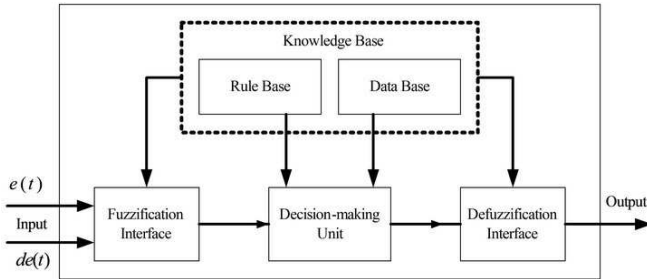


Fig. 4. Fuzzy logic system.

The fuzzy controller applied in this paper was designed in the following way:

I.1 Since the crisp inputs of designed system are error $e(t)$ (the difference between setpoint and actual value), error variation $de(t)$ and the crisp output is reflux variation du , the input linguistic variables are Error E , Error variation dE and output linguistic variable is Reflux variation dU . All the three linguistic variables have the same seven linguistic values LN (Large Negative), MN (Medium Negative), SN (Small Negative), ZE (Zero), SP (Small Positive), MP (Medium Positive), LP (Large Positive) with corresponding fuzzy sets shown in Fig 5.

I.2 All the rules are of the type:

$$\text{If } \langle E \text{ is } \dots \rangle \text{ and } \langle dE \text{ is } \dots \rangle, \text{ then } \langle dU \text{ is } \dots \rangle, \quad (1)$$

for instance:

$$\text{If } \langle E \text{ is } MP \rangle \text{ and } \langle dE \text{ is } SN \rangle, \text{ then } \langle dU \text{ is } SP \rangle. \quad (2)$$

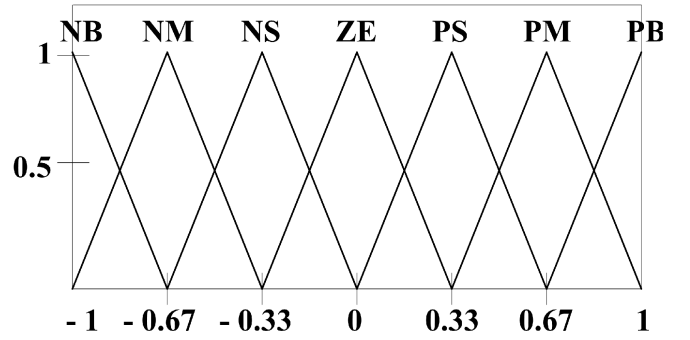


Fig. 5. Membership functions of linguistic values for linguistic variables E , dE and dU .

For two input variables with 7 different values, there are $7^2 = 49$ rules. The list of rules is given in Tab. I. The rules reflect our knowledge of the distillation plant, however, they were formulated without knowledge of mathematical system model.

TABLE I
THE RULE BASE OF DESIGNED FUZZY CONTROLLER.

dE	E	LN	MN	SN	ZE	SP	MP	LP
LN		LN	LN	LN	LP	LP	LP	LP
MN		LN	LN	LN	MP	LP	LP	LP
SN		LN	LN	LN	SP	MP	LP	LP
ZE		LN	LN	LN	ZE	SP	MP	LP
SP		LN	LN	LN	SN	ZE	SP	MP
MP		LN	LN	LN	MN	SN	ZE	SP
LP		LN	LN	LN	LN	MN	SN	ZE

I.3 The singleton fuzzification was used, i.e. the fuzzy set A with membership function μ_A was assigned to each crisp input value a (real number):

$$\mu_A(x) = \begin{cases} 1, & \text{if } x = a, \\ 0, & \text{otherwise.} \end{cases} \quad (3)$$

The center of gravity [32] was chosen as the defuzzification method. If a fuzzy set B in a universe Y is the fuzzy output, then the crisp output is

$$\frac{\int_Y y \cdot \mu_B(y) dy}{\int_Y \mu_B(y) dy}. \quad (4)$$

Finally, Mamdani's model [33] was used in the inference process, the minimum was used as 'And method' and 'Implication method', and maximum was used as 'Or method'.

II.1 Before computation in each iteration (steps II.2-II.4) the crisp inputs $e(t)$ and $de(t)$ are normalized, i.e. their natural scale is changed to interval $[-1, 1]$:

$$e_n(t) = \min(1, \max(-1, k_1 e(t))) \quad (5)$$

and

$$de_n(t) = \min(1, \max(-1, k_2 de(t))). \quad (6)$$

The constants k_1 and k_2 were used in controller tuning.

II.2 – II.4 The basic computational steps, that is fuzzification, inference and defuzzification, were performed by MATLAB's Fuzzy Logic Toolbox as described below.

II.5 After computation in each iteration (steps II.2-II.4), the crisp output $du_n(t)$, which is in the scale $[-1, 1]$ as a result of steps II.2-II.4, is denormalized to desired scale:

$$du(t) = dumax \cdot du_n(t). \quad (7)$$

The constant $dumax$ was used in controller tuning too.

Above described controller is a fuzzy PD controller (its inputs are Error and Error variance). In order to construct a fuzzy PI controller (whose inputs should be Error and Integral of error), it is necessary to consider input Integral of error, denoted by $\delta e(t)$, instead of input Error variance $de(t)$, where

$$\delta e(t_0) = \int_0^{t_0} e(t) dt \quad (8)$$

for all $t_0 \geq 0$. All the other specifications of fuzzy PI controller designed in our study remained the same as those of fuzzy PD controller described in this section

Both fuzzy controllers, PD as well as PI, were performed in MATLAB's Fuzzy Logic Toolbox and MATLAB Simulink. The schemes of the controllers are shown in Fig. 6.

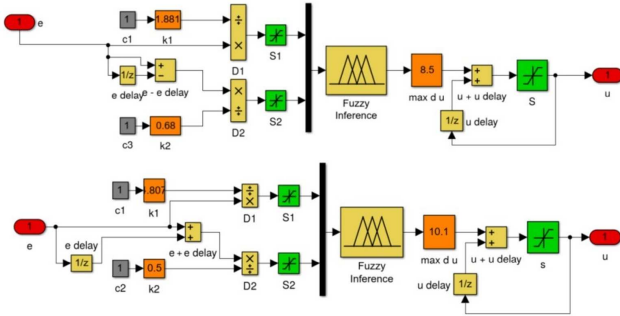


Fig. 6. The schemes of the designed controllers in MATLAB Simulink. Top figure: fuzzy PD controller. Bottom figure: fuzzy PI controller.

The two fuzzy PD controllers were tuned. The fuzzy PD 1 was tuned with respect to provide steady control actions. The fuzzy PD 2 was tuned in favor of the temperature reference tracking regardless the control actions aggressiveness. Similarly the fuzzy PI controller was tuned in favor of the best temperature control regardless the control actions. The values of constants k_1 , k_2 and $dumax$ for optimal control are shown in Tab. II.

TABLE II
THE OPTIMAL VALUES OF CONSTANTS OF DESIGNED FUZZY CONTROLLERS.

controller	k_1	k_2	$dumax$
fuzzy PD 1	35	1	20
fuzzy PD 2	12	12	40
fuzzy PI	12	12	40

PID Control

For comparison with fuzzy controllers the classical PID controller was devised based on the identified model of the process as given in [28]. Subsequently, to improve the performance the controller was tuned based on real experiments. The ideal form of the designed PID is given as,

$$u_k = K_p(e_k + \frac{\Delta t}{T_i} \sum_{i=1}^k e_i + \frac{T_d}{\Delta t}(e_k - e_{k-1})), \quad (9)$$

where $K_p = 4.94$, $T_i = 3.13e + 03$, and $T_d = 0.05$.

IV. EXPERIMENTAL RESULTS

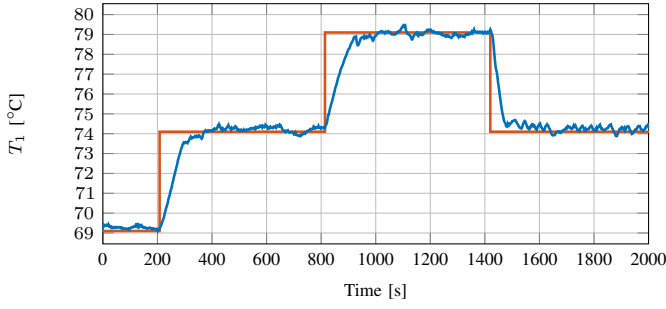
This section presents experimentally collected data under the proposed control strategies. We remind that the objective of the designed controllers is to operate the reflux valve such that the temperature at the head of the column follows a prescribed reference. To demonstrate the controller's performance, we performed a series of step changes of the reference signal. Three consecutive steps with an increase of the reference temperature by 5°C were performed, followed by a step with the decrease of reference temperature by 5°C .

Experimental results were obtained in the distillation column operated at atmospheric pressure. Measurements and control evaluation was realized based on a steady state value of the measured outputs. The steady state was maintained by setting the waste valve fully open, with the reboiler power set to constant 0.73 kW and the flow rate of the feed was 1 mL s^{-1} . The temperature of the feed was maintained at the same value as was the temperature of the mixture on the fifth tray. The sampling time was equal to 1 s.

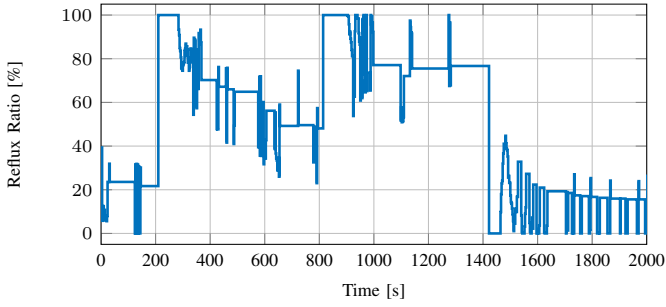
The experimental results of the classical PID, two fuzzy PD and fuzzy PI controllers over the plant are depicted in Fig. 7, 8, 9, and 10 respectively. Specifically, Figs. 7(a), 8(a), 9(a), and 10(a) show the temperature profiles at the top of the column (T_1) with time varying reference y_{ref} , while Figs. 7(b), 8(b), 9(b), and 10(b) illustrate the corresponding control actions of the reflux ratio.

The overall comparison of the performance of individual controllers via various criteria is shown in Tab. III. We choose two reference tracking performance criteria, where ISE denotes the integral square error per sampling instant and IAE stands for integral absolute error per sampling instant. For evaluation of product quantity, we use the integral of the control action divided by a number of sampling instants, resulting in average control action per sampling instant (ACA), which directly accounts for the amount of the distillate being taken out as a product. In our control setup, the higher control actions will provide higher product quantity.

From the performances of the evaluated controllers it is clear that there is a trade-off between product quality and quantity, as well as reference tracking quality and control action steadiness. The first trade-off is caused by the nature of the distillation process itself, while the second trade-off is the property of the controller and its disturbance rejection capabilities. By comparing the setups with different parameters

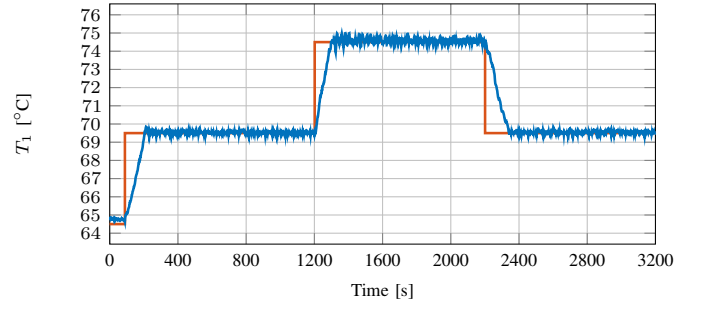


(a) Temperature profile

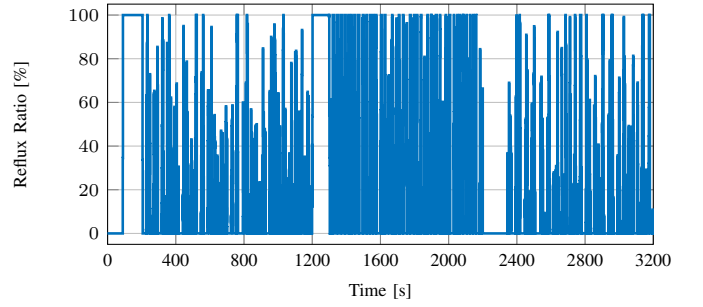


(b) Control action profile

Fig. 7. Control performance of the PID controller. Top figure: controlled process variable, i.e. T_1 (blue) w.r.t. the desired reference (red). Bottom figure: profile of the control actions.

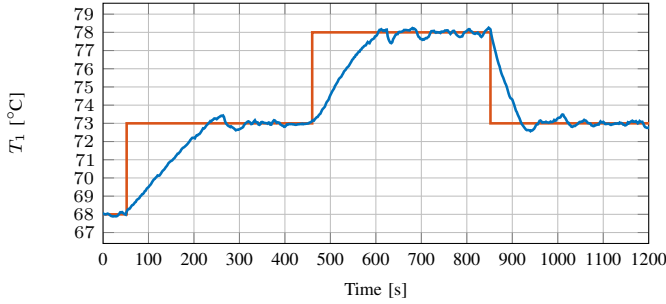


(a) Temperature profile

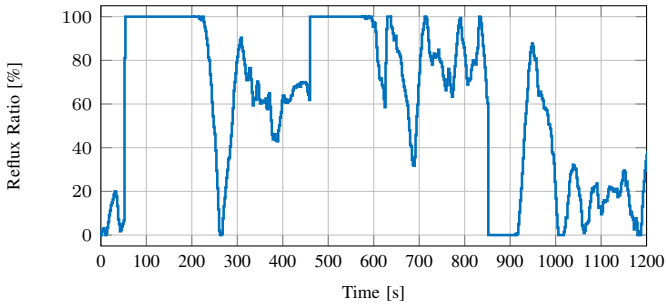


(b) Control action profile

Fig. 9. Control performance of the fuzzy PD controller with parameters setup 2 shown in Tab. II. Top figure: controlled process variable, i.e. T_1 (blue) w.r.t. the desired reference (red). Bottom figure: profile of the control actions.

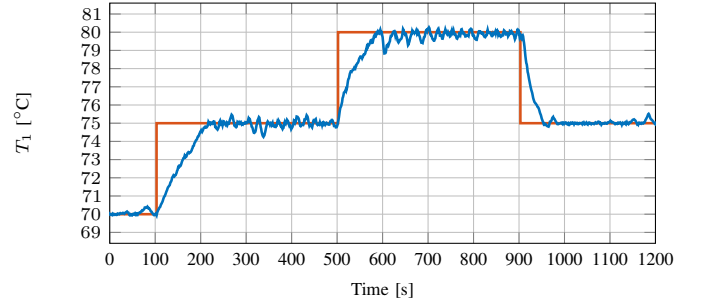


(a) Temperature profile

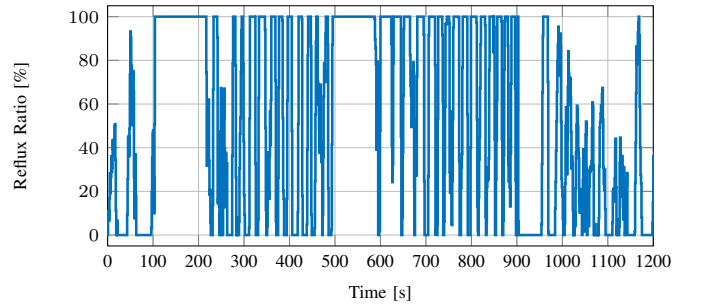


(b) Control action profile

Fig. 8. Control performance of the fuzzy PD controller with parameters setup 1 shown in Tab. II. Top figure: controlled process variable, i.e. T_1 (blue) w.r.t. the desired reference (red). Bottom figure: profile of the control actions.



(a) Temperature profile



(b) Control action profile

Fig. 10. Control performance of the fuzzy PI controller with parameters shown in Tab. II. Top figure: controlled process variable, i.e. T_1 (blue) w.r.t. the desired reference (red). Bottom figure: profile of the control actions.

we wanted to demonstrate the ability of the fuzzy controllers to be tuned ad hoc with respect to particular control requirements.

TABLE III
THE PERFORMANCE CRITERIA COMPARISON OF THE INVESTIGATED CONTROLLERS.

controller	ISE [$^{\circ}\text{C}^2$]	IAE [$^{\circ}\text{C}$]	ACA [%]
PID	1.1075	0.4754	50.5372
Fuzzy PD 1	1.3986	0.5530	53.7551
Fuzzy PD 2	0.9696	0.3492	22.0903
Fuzzy PI	2.4973	0.8507	60.7477

V. CONCLUSIONS

Fuzzy PD and PI controllers of binary distillation plant were designed in this paper. Important feature of the proposed controllers lies in the fact that they are model-free, i.e. they were designed without knowledge of mathematical model, only based on human operator experience with the system. This approach has the following advantages comparing to classic control:

- it offers a user-friendly (intuitive and easy understandable) tool for fast design of a high-performance controller,
- convenient especially for experienced engineers from practice - there is no need to use mathematical tools and difficult design of the advanced controllers,
- the possibility of a simple and intuitive correction in case of significant change of system qualities,
- the possibility to use the same controller for many various systems with different properties (after fast tuning).

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REFERENCES

- [1] R. H. Perry and D. Green, *Perry's Chemical Engineers' Handbook, Eighth Edition*. McGraw Hill professional, McGraw-Hill, 2008.
- [2] R. H. Nayed Ghasem, *Principles of Chemical Engineering Processes: Material and Energy Balances, Second Edition*. Mortimer House, 37-41 Mortimer Street, London: CRC Press, Taylor and Francis Group, ISBN 9781482222289, 2014.
- [3] H. S. Andrzej Gorak, *Distillation: Operation and Applications*. Elsevier, ISBN: 978-0-12-386876-3, 2014.
- [4] W. Luyben, *Practical Distillation Control*. van Nostrand Reinhold, 1992.
- [5] P. Deshpande, *Distillation Dynamics and Control*. Instrument Society of America, 1985.
- [6] F. Shinsky, *Distillation Control*. McGraw-Hill, 1977.
- [7] M. O. Rademaker, J.E. Rijnsdorp, *Dynamics and Control of Continuous Distillation Units*. Elsevier, 1975.
- [8] B. G. Liptak, *Instrument Engineers Handbook, Fourth Edition, Volume Two, Process Control and Optimization*. CRC Press, ISBN: 978-0-8493-1081-2, 2005.
- [9] S. Skogestad, "Dynamics and control of distillation columns – a tutorial introduction," 1997.
- [10] E. W. Jacobsen and S. Skogestad, "Control of unstable distillation columns," in *American Control Conference, 1991*, pp. 773–778, June 1991.

- [11] P. Lundstrom, S. Skogestad, and J. Doyle, "Two-degree-of-freedom controller design for an ill-conditioned distillation process using mu-synthesis," *Control Systems Technology, IEEE Transactions on*, vol. 7, pp. 12–21, Jan 1999.
- [12] C. R. Cutler and B. L. Ramaker, "Dynamic matrix control—a computer control algorithm.," *AIChE national meeting, Houston, TX.*, 1979.
- [13] W. Pedrycz, *Fuzzy control and fuzzy systems (2 ed.)*. Research Studies Press Ltd., 1993.
- [14] K. M. Passino, S. Yurkovich, and M. Reinfrank, *Fuzzy control*, vol. 2725. Citeseer, 1998.
- [15] L. A. Zadeh, "Is there a need for fuzzy logic?," *Information Sciences*, vol. 178, no. 13, pp. 2751 – 2779, 2008.
- [16] R. R. Yager and D. P. Filev, *Essentials of Fuzzy Modeling and Control*. New York, NY, USA: Wiley-Interscience, 1994.
- [17] S. Afzal, M. Jamil, A. Waris, S. Butt, and G. Mufti, "Fuzzy logic controller for boiler temperature control using labview and matlab," *International Journal of Control and Automation*, vol. 9, no. 9, pp. 89–104, 2016. cited By 0.
- [18] H. Dong, J. Lu, P. Chen, and P. Sun, "Fuzzy adaptive pi control of steam temperature in a canadian scwr," *Hedongli Gongcheng/Nuclear Power Engineering*, vol. 37, no. 6, pp. 66–70, 2016. cited By 0.
- [19] A. Vasičkaninová, M. Bakošová, and A. Mészáros, "Fuzzy control of a distillation column," in *26th European Symposium on Computer Aided Process Engineering (Z. Kravanja and M. Bogataj, eds.)*, vol. 38 of *Computer Aided Chemical Engineering*, pp. 1299 – 1304, Elsevier, 2016.
- [20] P. Mishra, V. Kumar, and K. Rana, "A fractional order fuzzy {PID} controller for binary distillation column control," *Expert Systems with Applications*, vol. 42, no. 22, pp. 8533 – 8549, 2015.
- [21] M. Miccio and B. Cosenza, "Control of a distillation column by type-2 and type-1 fuzzy logic {PID} controllers," *Journal of Process Control*, vol. 24, no. 5, pp. 475 – 484, 2014.
- [22] F. Barceló-Rico, J. M. Gozávez-Zafrilla, J. L. Díez, and A. Santafé-Moros, "Modelling and control of a continuous distillation tower through fuzzy techniques," *Chemical Engineering Research and Design*, vol. 89, no. 1, pp. 107 – 115, 2011.
- [23] A. Khelassi, C. Bouyahiaoui, A. Maidi, A. Benhalla, and M. Djellal, "Optimal fuzzy control to optimise energy consumption in distillation columns," *IFAC Proceedings Volumes*, vol. 35, no. 1, pp. 307 – 312, 2002. 15th IFAC World Congress.
- [24] A. Fileti, A. Antunes, F. Silva, V. S. Jr, and J. Pereira, "Experimental investigations on fuzzy logic for process control," *Control Engineering Practice*, vol. 15, no. 9, pp. 1149 – 1160, 2007.
- [25] R. Stenz and U. Kuhn, "Automation of a batch distillation column using fuzzy and conventional control," *IEEE Transactions on Control Systems Technology*, vol. 3, pp. 171–176, Jun 1995.
- [26] S. Glankwamdee, K. Tarathammakorn, and T. Chattana-anan, "Fuzzy supervisory control system of a binary distillation column," in *TENCON 99. Proceedings of the IEEE Region 10 Conference*, vol. 2, pp. 1055–1058 vol.2, 1999.
- [27] J. Drgoňa, M. Klaučo, R. Valo, J. Bendžala, and M. Fikar, "Model identification and predictive control of a laboratory binary distillation column," in *Proceedings of the 20th International Conference on Process Control (M. Fikar and M. Kvasnica, eds.)*, (Štrbské Pleso, Slovakia), Slovak University of Technology in Bratislava, Slovak Chemical Library, June 9-12, 2015 2015.
- [28] J. Drgoňa, M. Klaučo, F. Janeček, and M. Kvasnica, "Optimal control of a laboratory binary distillation column via regionless explicit mpc," *Computers & Chemical Engineering*, vol. 96, pp. 139–148, 2017.
- [29] A. Sharma, J. Drgoňa, D. Ingole, J. Holaza, R. Valo, S. Koniar, and M. Kvasnica, "Teaching classical and advanced control of binary distillation column," in *Preprints of the 11th IFAC Symposium on Advances in Control Education*, vol. 11, pp. 348–353, 2016.
- [30] Armfield, *Continuous Distillation Column, Armfield UOP3CC Instruction Manual*, 2010.
- [31] D. DuBois, *Fuzzy Sets and Systems: Theory and Applications*. Orlando, FL, USA: Academic Press, Inc., 1997.
- [32] W. V. Leekwijck and E. E. Kerre, "Defuzzification: criteria and classification," *Fuzzy Sets and Systems*, vol. 108, no. 2, pp. 159 – 178, 1999.
- [33] E. H. Mamdani, "Application of fuzzy algorithms for control of simple dynamic plant," *Electrical Engineers, Proceedings of the Institution of*, vol. 121, pp. 1585–1588, December 1974.