EXPERIMENTAL APPLICATION OF COMBINED FUZZY AND PREDICTIVE CONTROL TO A BINARY DISTILLATION COLUMN

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Introduction

Advanced control techniques utilizing process model are popular in chemical process control. However, when a large disturbance or significant process variation is introduced, discrepancy between model and real process occurs and leads to large error in the prediction of future controlled variable. This is often encountered in the operation of real processes and the model-based control is no longer applicable. Then, manual operation is necessary until the process is stabilized. For example, crude feed is frequently changed in refineries, and when it is switched from one to the other the operating condition of an atmospheric pressure distillation tower has to be adjusted according to the composition of the crude. It is because the compositions are widely different depending upon pumping location. If the feed composition is significantly altered while a model-based control is implemented, its process model may produce large error and the model-based control is ineffective. In this case, a process operator handles the situation manually.

Fuzzy control utilizes fuzzy control rules constructed from operator's experience instead of process model. As a result, in the process having large disturbance it manages the process like a human operator with ample experience[7]. However, the fuzzy control does not handle interaction in multi-input/multi-output (MIMO) system[5), 6)] and does not utilize output prediction. Instead, it refers to present error and change of error that limits its performance.

A combined fuzzy and predictive control can improve performance by mutually making up each other's weak points shown when they are employed separately. In this study the combined control technique is applied to a binary distillation column and its performance is compared with simple predictive control through simulation and experiment.

1. Control Algorithm

The process has two controlled variables, top tray temperature and reboiler temperature, and two manipulated variables, reflex flow rate and steam flow rate. For simplicity, the top tray temperature and the reboiler temperature are hereafter called as top and bottom temperatures, respectively. Among various process disturbances, feed flow rate is considered as a significant disturbance[8)], since it is easy to measure and to be adjusted for experimental purpose.

1.1 Fuzzy control

In order to apply fuzzy control to distillation column control, its MIMO system is decomposed into two SISO systems[5)] : top temperature control with reflux flow rate and bottom temperature control with steam flow rate. Fuzzy membership functions for the two SISO control systems were obtained from the operator's experience in the pilot-size distillation column of this study. Triangle-like membership functions and linguistic control rules were implemented.

There are two fuzzy control inputs, error and change of error of top or bottom temperature, and one fuzzy control output, reflux or steam flow rate. A fuzzy inference procedure, the correlation-minimum inference procedure[4)], activates in parallel the antecedents of all fuzzy control rules and finds minimum fit value of two antecedents, input fuzzy sets, in each rule. The combined output fit value is obtained by summing the minimum fit values of individual fuzzy rules for each output fuzzy set.

The value of fuzzy control output is found from the fuzzy centroid defuzzification scheme. When the process is controlled by fuzzy scheme, this value is implemented as manipulated process value. Two separate fuzzy computations are conducted for reflux and steam flow rates.

1.2 Model predictive control

The dynamic matrix control (DMC)[1)] is widely used as an MPC, but the minimum deviation control (MDC) is implemented in this study since the performance of MDC is better than that of DMC in the control of the distillation column of this study[3)]. It minimizes the sum of absolute output errors in future sampling moments.

In the prediction of future output, a dynamic matrix is employed as in the DMC and the optimization of the control objective is conducted with the linear programming[2)]. The detail of the MDC is available from the reference[3)].

1.3 Combined control

Since the fuzzy control and the MPC are quite different in their structures, combining those two and making

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single computation procedure are not plausible. Therefore, a switching scheme is implemented in this study. Namely, when error or change of error between a controlled variable and the set point of the variable is larger than a certain value the fuzzy control is used in control computation, and otherwise the MPC is employed.

This scheme is mimicked from real process operation where a model-based advanced control technique is applied and, in case that large disturbance or large set-point change is introduced, control is transferred to manual operation. It requires operator's attention and hampers fully computerized process control. The combined control eliminates the manual operation involving a variety of economic and safety problems.

Tuning of the switching criteria between the fuzzy control and the MPC was conducted by trial implementation for the best performance. In simulation study, 0.4 °C for the error and 0.3 °C for the change of error per step in either top or bottom temperature gave the best outcome. In experiment, the values were 1.5 °C for the error and 0.7°C for the change of error per step and these values were used in the rest of study.

1.4 Stability analysis

The analysis of the combined control is complicated because two basic control schemes are of quite different nature. In addition, fuzzy control is less robust than MPC especially in multi-variable system, though robustness of MPC is proved in various chemical processes, However, the MPC has dominant role in the application of the combined control since it is implemented most of time. Fuzzy control is employed only at the initial stage when a large error occurs. Accordingly, the stability of the MPC only is examined.

For the analysis of the predictive control of this study, the objective function is modified in a generalized form and set to zero. In addition, constraints are deactivated.

$$Q(A\Delta u - y_f) + R\Delta u = 0 \tag{1}$$

where **Q** and **R** are weight matrices in the objective function and $\mathbf{y}_f$ is static error term.

$$y_f = y_s - (y_0 + A'\Delta u + d) \tag{2}$$

where subscript s denotes set point. Then,

$$\Delta u = \left[(QA+R)^T(QA+R)\right]^{-1}(QA+R)^T Q y_f = \psi \tag{3}$$

The implemented input is the first element of Δu and it is calculated from

$$\Delta u(k) = \psi_1 y_f \tag{4}$$

where ψ_l is the first row of matrix ψ.
When Δu's in both sides of Eq. (4) is combined, Eq. (5) is obtained.

$$[\mathbf{1}, \boldsymbol{\Phi}_1]\Delta u(k-m) = \psi_l[y_s - (y_0 + d)] \tag{5}$$

where $\boldsymbol{\Phi}_l$ is the first row of the product of Ψ and **A'**. From Eq. (5), a characteristic equation showing the stability of control scheme is given. Namely,

$$1 + \varphi_1 z^{-1} + \varphi_2 z^{-2} + \cdots + \varphi_m z^{-m} = 0 \tag{6}$$

where φ_l's are the elements of ϕ_l. For the stability, all the roots of Eq. (6) have to be inside unit circle. With numeric values of φ_l's of this study, however, the condition can not be satisfied. Therefore, an implementation filter which scales down the input variation is applied and the filter coefficient is a tuning parameter. The marginal values of the coefficient for stability are 0.24 and 0.11 for top and bottom loops, respectively. Lower than the marginal value ensures stability, but further tuning is necessary for the best performance. This tuning was conducted by simulation and trial operation of the distillation column. The best performance was obtained at 0.03 for both loops and it was used throughout this study.

2. Results and Discussion

2.1 Simulation

A transfer function type process model is formulated and its parameters are from the step test of the distillation column in experiment. The model is used in the simulation of the column control.

In **Fig. 1**, the variations of top and bottom temperatures are shown where dashed line is set point, solid line is the outcome of the combined control and single dashed broken line is the result of the MDC. Two top figures (a) show the temperature variations for the top set-point change. When the set point is raised, the combined control gives faster response than the MDC. It indicates that the fuzzy control in the combined control acts promptly when large error is encountered, even though slightly larger overshoot is observed. For reduced set point the response of the combined control is slower than that of the MDC, but its deviation is less. During the set-point changes, bottom temperature is barely disturbed in both controls to show a good decoupling performance. In two bottom figures (b), the response for varying the set point of bottom temperature is demonstrated.

In order to compare regulatory performance feed flow rate is lowered by 25 % and later returned to the original flow rate. Both the combined control and the MDC give similar deviations in top and bottom temperatures, while higher deviation in bottom temperature than in top temperature is obtained.

The sums of absolute error at every sampling step are computed to be given in Table 1 along with the number of simulation steps. Though slightly higher IAE's are yielded in two cases; the combined control gives 10 % improvement over MDC in total IAE comparison.

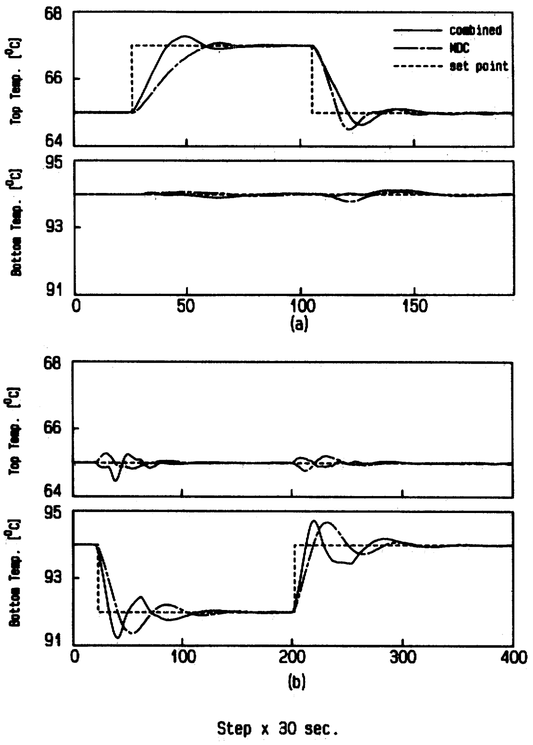

Fig. 1 Comparison of combined fuzzy and predictive control and minimum deviation control: (a) top set-point change, (b) bottom set-point change

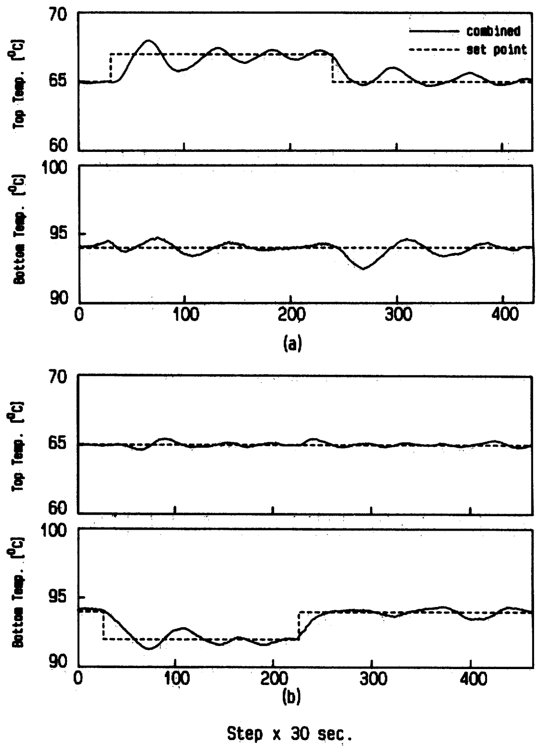

Fig. 2 Experimental results of combined fuzzy and predictive control: (a) top set-point change, (b) bottom set-point change

Table 1 Integral of absolute errors

case		simulation				experiment			
		MDC		combined		MDC[3]		Combined	
		step	IAE	step	IAE	step	IAE	step	IAE
set-point	change								
top	y_1	195	53.2	195	46.3	455	207.1	430	186.3
	y_2	195	7.2	195	6.8	455	136.7	430	138.3
bottom	y_1	400	15.9	400	17.2	478	100.9	464	55.9
	y_2	400	90.1	400	80.6	478	197.5	464	159.1
feed flow change									
	y_1	195	10.6	195	5.3	285	61.5*	286	48.9
	y_2	195	23.5	195	23.8	285	97.8*	286	140.4

* Feed flow rate change in MDC is 17 % instead of 25 % in the combined control

2.2 Experimental application

A six-inch distillation column with 10 bubble-cap trays was used in the experimental application of the combined control and its detailed description is found in Kim and Sohn[3].

In **Fig. 2**, the variations of top and bottom temperatures are illustrated for the set-point change of top and bottom temperatures. The imposed set-point changes are the same sequence as applied in simulation study. The number of sampling steps is larger than twice of that the simulation. It is largely responsible to the slow and unstable response caused by unmodeled disturbance in real process. Also, temperature deviation is much higher compared with simulation result for both set-point changes. However, the outcome indicates that the proposed control scheme performs a relatively good set-point tracking.

When top set point is raised as dashed-line in Fig. 2(a), the top temperature slowly follows the set point. An overshoot is observed followed by several diminishing oscillations before it finally settles. Reducing the set point gives fluctuation again and a similar settling process to the previous change is obtained. While the set point of top temperature varies, bottom temperature deviates from the unchanged set point owing to the coupling effect between top and bottom control loops as seen in simulation study. A fast settling of the bottom temperature demonstrates the effectiveness of the proposed control scheme. In Fig. 2(b), the set point of bottom temperature is altered and the variations of top and bottom temperatures are shown.

Feed flow rate to the distillation column is intentionally varied as shown in the bottom figure of **Fig. 3**. Both top and bottom temperatures are showing deviation after a change is introduced. The deviation of bottom temperature is much larger than that of the top temperature

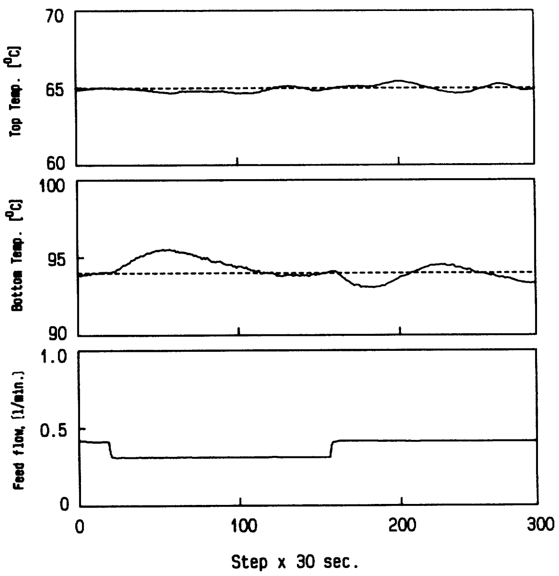

Fig. 3 Experimental result of combined fuzzy and predictive control for feed flow rate change

as the same difference is observed in the simulation study.

The sums of absolute error between measured temperature and set point in the control experiment are included in Table 1 and the results[3] using the MDC are also listed in the table for comparison. The combined control shows superior performance to the MDC in general. The sum of bottom temperature deviation of the MDC in feed flow change is the result of smaller feed change then the change in the combined control. In over-all IAE comparison, 9 % improvement of the combined control over the MDC is obtained.

Conclusion

A combined fuzzy and predictive control is proposed and its performance is investigated through simulation and experiment. The control performance of the combined control is compared with that of the MPC and its applicability to a real process is examined by experimenting the scheme in a pilot-size distillation column.

The combined control improves the control performance for set-point tracking and disturbance regulation and numerical comparison with IAE indicates that the combined control enhances the performance by 9 % over the MPC, In addition, the practical applicability of the proposed control scheme is experimentally proved.

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Nomenclature

A	=	dynamic matrix
d	=	disturbance vector
m	=	number of model steps
Q	=	output error weight matrix
R	=	input suppression weight matrix
u	=	manipulated variable vector
y	=	controlled variable vector
y_0	=	measured output vector at the moment of N step prior to step k

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