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Control Analysis for Processes with Internal Recycle

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In the presented paper, dynamic state analysis and control aspects of recycle processes are discussed. Investigation of influence of process recycle loop parameters is carried out, applying simulation experiments on linear transfer function models. A new strategy of compensation of the recycle effects is outlined as a combination of direct compensator part and adaptive gain scheduling technique. A hybrid separation process, based on heterogeneous-azeotropic extractive distillation, consisting of a 4 column distillation plant, is considered as case study.

1. Introduction

There has been lot of works devoted to the problem of investigating and handling chemical processes with recycle (e.g. Luyben, 1993a, 1993b; Morud and Skogestad, 1996). In most cases, recycle leads to positive feedback effects. For example, increasing the concentration of a chemical species in a process stream will normally increase the amount of this species in the recycle stream, and, thus, lead to a reinforcement of the original increase. It refers to a self-reinforcing mechanism associated with the recycle. This positive feedback will usually increase the plant time constant, and also increase the process sensitivity to slow disturbances. The aim of this paper is to give a comprehensive picture on dynamic behaviour of processes with internal recycle. A comparison of process dynamic behaviour and investigation of influence of process recycle loop parameters is carried out, applying simulation experiments on linear transfer function models. A compensator is introduced to eliminate recycle loop time constants only (Mészáros et al., 2004). To tune the overall process gain, a new strategy of compensation of the recycle effects is outlined as a combination of direct compensator part and adaptive gain scheduling technique in terms of model reference adaptive system, (Aström and Wittenmark, 1989).

A hybrid separation process, based on extractive heterogeneous-azeotropic distillation, consisting of a 4 column distillation plant, is considered as case study (Szanyi et al., 2004). Its most effective control possibilities are discussed and selected control simulation results are demonstrated.

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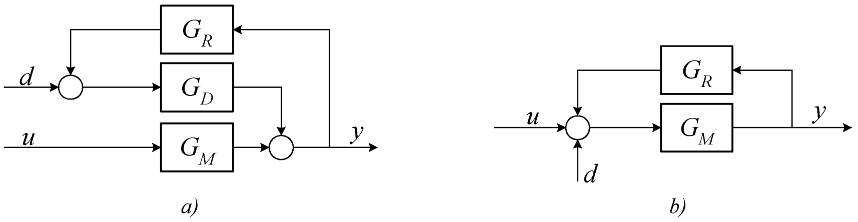


a) *b)*

Fig. 1 a) Open-loop process with recycle, b) Simple open-loop process with recycle

2. Open-loop system with internal recycle

Let us consider a simple linear system consisting of two forward paths and a recycle unit as depicted in Fig. 1a. G_M, G_D and G_R stand for plant forward unit, disturbance and recycle unit, respectively, u, d and y are the input, load disturbance and output, respectively. Assuming $G_M = G_D$, we get the simplified structure of the recycle process, shown in Fig. 1b.

Let the first object of our study be the recycle system in Fig. 1b, assuming $d = 0$. This can be described by the open loop transfer function (s being the derivation operation)

$$G_S(s) = \frac{y(s)}{u(s)} = \frac{G_M}{1 - G_M G_R} \tag{1}$$

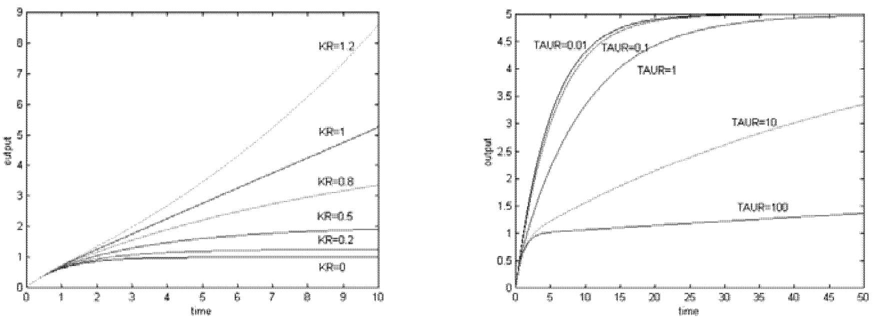
In dynamic analysis of the recycle system (1), we will focus on investigation of influence of the recycle path (G_R) parameters onto the overall plant behaviour. G_M and G_R will be considered as units of first order dynamics, because lot of real plants dynamics can be identified, in a close neighbourhood of the operation regime, as a first order lag with steady-state gain and dead time (if necessary).
Then, the forward path is described by a simple linear transfer function consisting of a steady-state gain, K_M, and a first order lag with time constant, τ_M. The unit in the recycle path also has a simple gain and lag transfer function (with K_R and τ_R), as follows

$$G_M = \frac{K_M}{\tau_M s + 1}, \quad G_R = \frac{K_R}{\tau_R s + 1} \tag{2}$$

2.1 Influence of recycle loop gain and time constant

In order to show the effect of recycle parameters, K_R and τ_R, we can express the overall process steady-state gain, K_S, and time constant, τ_S, as follows

$$K_S = \frac{K_M}{1 - K_M K_R}, \quad \tau_S = \sqrt{\frac{\tau_M \tau_R}{1 - K_M K_R}} \tag{3}$$



a) *b)*

Fig. 2 a) Influence of recycle loop gain onto process dynamics, b) Influence of recycle loop time constant onto process dynamics

If we calculate the limits of G_S for boundary values of K_R and τ_R, it becomes obvious that the recycle effect is diminishing for "very small" values of the gain as well as "very large" values of the time constant. Large values of K_R causes instability and "very large" values stop the whole process operation while "very small" values of τ_R reduce the order of process.

In Fig. 2a and Fig. 2b, a comparison of the plant output responses is given for various values of K_R and τ_R, respectively. The other process parameters during the two courses of simulation kept the following values: $K_M = \tau_M = \tau_R = 1$ and $K_M = \tau_M = 1$, $K_R = 0.8$, respectively. It can be concluded that the effect of K_R is more straightforward because it influences both, overall gain and dynamics, while τ_R changes system behaviour in transient stage only.

3. Compensation of recycle effect

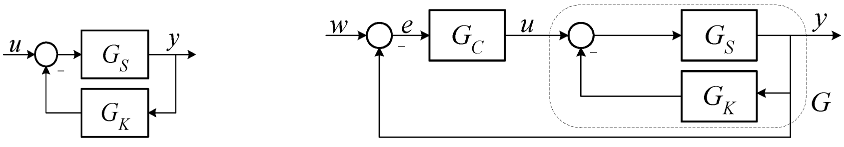
Negative effects of the recycle can be neutralized by adopting a recycle compensator, which acts according to the scheme in Fig. 3a where G_S, defined by (1), stands for the process with internal recycle and G_K for the compensator. Then, the transfer function of the compensated plant is

$$G(s) = \frac{y(s)}{u(s)} = \frac{G_S}{1 + G_S G_K} \tag{4}$$

If the compensator given by (4) is physically realizable and there are no modelling errors, the effect of recycle can be completely eliminated and the controller G_C in Fig. 3b can be designed for the process without recycle.

Let the compensator transfer function take the form of first order lag

$$G_K = \frac{K_K}{\tau_K s + 1} \tag{5}$$



a) b)

Fig. 3 a) Recycle plant with compensator, b) Feedback control of recycle plant with compensator

The modelling mismatch problem in recycle path can lead to 4 different cases, as follow:

a) Ideal case: $G_K \equiv G_R$, this yields $G = G_M$
b) $G_K \neq G_R$: $\tau_R = \tau_K$, $K_R \neq K_K$
c) $G_K \neq G_R$: $K_K = K_R$, $\tau_K \neq \tau_R$
d) $G_K \neq G_R$: $K_K \neq K_R$, $\tau_K \neq \tau_R$

4. Adaptive gain scheduling for plants with recycle

It has been shown (Mészáros et al., 2004) that a compensator alone, although its benefit is undoubted, can hardly cope with the recycle plant control problem. Model mismatch problems between the recycle loop and its compensating model can be overcome extending the control design by an adaptive term. To tune the overall process gain, an MIT rule based open-loop adaptive strategy is adopted and applied in the sense of model reference adaptive system. The adaptive system structure is depicted in Fig. 4, where G_{ref} designates the reference model with output y_{ref} and ε is the reference error

$$\varepsilon(t) = y - y_{ref} \tag{6}$$

Let K_C be the only parameter of controller G_C to be adjusted (single tuning knob), then the adaptive control law will be as follows

$$\frac{dK_C}{dt} = -\gamma' \frac{\partial \varepsilon}{\partial K_C} \varepsilon = -\gamma' \frac{K}{K_0} y_{ref} \varepsilon = -\gamma . y_{ref} \varepsilon \tag{7}$$

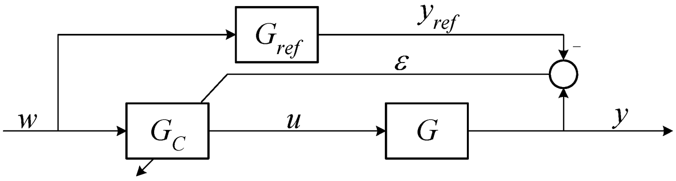


Fig. 4 Block diagram of adaptive gain tuning

5. Case study – hybrid separation process

5.1 Process Description

A hybrid separation process, based on heterogeneous-azeotropic, extractive distillation, consisting of a 4 column distillation plant, is studied according to work of Szanyi et al. (2004). The mixtures studied are the waste streams of printing companies and consist of ethanol (ETOH), ethyl acetate (ETAC), isopropyl acetate (IPAC) and water (H_2O).

The feeding stream of this system is an industrially used mixture, the so-called Andreas-mixture, of the following composition: Water - 49,6 mole%; Ethanol - 28,6 mole%; Ethyl-acetate - 12,6 mole%; Isopropyl-acetate - 9,2 mole%.

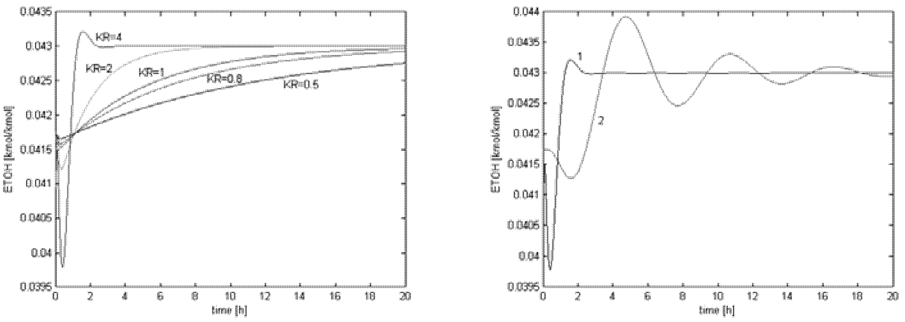
In the first column (C1), a two-phase separation process is going on. The distillate (D1) contains all the four components. In phase-separator (F), the water rich phase and the organic phase are separated. The water rich phase is fed back onto the first plate of the first column. The organic phase enters the second column (C2). The bottom products of the first column are water and ethanol. Their separation takes place in the fourth column (C4). After azeotropic distillation, the distillate is ethanol (95% purity), and the bottom-product is water. The C2 column is a conventional, one-phase column separating isopropyl-acetate, which exits as a component of the B2 stream, from the bottom of C2 column. In the C3 column, ethyl-acetate is separated; it exits as the bottom product. The distillate can entirely recycled back to the mixer (mix) and, subsequently, to the first column. The flow-rate of this recycle stream is appr. 8 kmol/hour.

5.2 Adaptive Control of ETOH

The control aim selected is to maintain the ETOH concentration at the bottom of the first column by manipulation of flow-rate of the extractive agent while distillate of the third column is recycled back to the feed of first column. To design the adaptive gain compensator for this particular case, linear transfer functions were identified using process dynamic responses.

Let us introduce the direct recycle compensator corresponding to the case of model-mismatch b). The plant model is corrupted by an unknown (and, therefore, uncompensated) recycle gain, K_R. Its elimination by applying the adaptive gain scheduling technique in the presence of internal compensator is shown in Fig. 5a, where ETOH concentration profiles are depicted for various values of K_R. The desired gain given by reference model, K_{ref} was chosen such that to maintain the ETOH concentration at 0.043 [kmol/kmol]

The adaptive gain scheduling method can be successful also without using “internal” compensator. However, elimination of the corrupting recycle gain in such a case is less effective and this results in poor control performance. This is demonstrated in Fig. 5b, where a comparison of the two considered cases is provided.



a) *b)*

Fig. 5. a) Adaptive gain scheduling using recycle compensator, b) Adaptive gain scheduling with (curve 1) and without (curve 2) recycle compensator (K_R = 4)

6. Conclusion

In this paper, dynamic state analysis and control aspects of recycle processes have been studied and demonstrated on the case of a hybrid separation with internal recycle, based on extractive heterogeneous-azeotropic distillation. Simulation experiments on ethanol concentration control by manipulating the extractive agent flow-rate have confirmed the qualities of the adaptive recycle gain compensator proposed.

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