AN ON-LINE OPERATING CONTROL SYSTEM FOR A CLASS OF COMBINED BATCH/SEMI-CONTINUOUS PROCESSES

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An operating control system for a class of combined batch/semi-continuous processes based on on-line scheduling is proposed. The class of controlled plants is characterized by a series of units with limited intermediate storage and statistical variabilities in processing time. The proposed system consists of a dynamical plant simulator and an automatic scheduler. The simulator predicts the future state of the plant using the past plant record, the present internal state of the plant and the temporal operating conditions. To make operation of the plant efficient and smooth, the scheduler revises the operating conditions on the basis of the predicted state. A series of simulation experiments has shown that the system is effective in plant operation with uncertainties.

Introduction

The increasing variety of variants in products and/or raw materials has enhanced the reconsideration of batch units because of their inherent flexibility. On the other hand, continuous units have advantages over batch units in systematic design procedure and stability of operation. Therefore, the introduction of combined batch/continuous processes into the process industry is becoming of great interest. However, there are very few studies on the operation of these combined processes.3,4

In actual operation of the plant, uncertainties usually occur which affect the performance of the whole plant. Operation of the plant which ignores these uncertainties may cause unexpected results, as
shown by Smith et al.\textsuperscript{5}) The problem of the design of a batch process with uncertainties has been studied by several workers. For example, Takamatsu et al. derived the relationship between the size of variations and the necessary volume of the storage tank.\textsuperscript{6}) We cannot, however, predict all of the future dynamical behavior of the plant in advance of operation. Thus scheduling based on off-line optimization may not work well for plant operation with uncertainties. To decrease the effects of uncertainties on the whole plant, the use of feedback information seems to be effective in plant operation.

In the present work, we propose an on-line operating control system which is vastly different from the conventional off-line system. It detects the variations in plant operation, predicts the future behavior of the plant and revises the operating conditions. We apply it to some combined processes to examine its effectiveness.

1. Problem Description

We consider the plant shown in Fig. 1, which consists of a series of $L$ sets of batch units in parallel, \{Bl\}_m, \ldots, \{Bl_n\}, followed by a set of semi-continuous units in parallel, \{SC\}_n. Each batch unit may have a preceding or following buffer and cannot be used as a storage tank. To supply \(SC\) with intermediate products continuously, every \(SC\) has a reservoir \(RE\). In addition, every \(RE\) is preceded by a storage tank \(ST\). It is assumed that raw materials and intermediate products are transported instantaneously from one unit to another except from \(RE\) to \(SC\). (For convenience, \(B1\), \(B2\), etc. will denote the set of \(Bl\), \(B2\), etc., respectively.) The plant is characterized by a series of units with limited intermediate storage and its behavior is affected by statistical variabilities in processing times. Such uncertainties are caused by the variations in amount and quality of raw material, those of intermediate product, unit and utility characteristics and other factors.

Before discussing the problem, we define some terminology. The amount of raw material or intermediate product processed in a batch unit at a given time will be termed a batch. Only one batch can be stored in every buffer and also in \(ST\). Semi-continuous units deal uninterruptedly with several batches which are of the same product type. This set of batches will be termed a lot. That is, different lots can be different product types. So, the plant is regarded as a multiproduct production plant. Serial numbers assigned to batches in order of batch processing in \(B1\) will be called batch numbers.

The following is planned in advance of operation:

- the number of batches contained in each lot and the product type of the lot;
- the lot sequence processed in \(SC\).

This discipline is called \textit{production planning}. The problem to be discussed here is how to operate the plant efficiently and smoothly according to production plans. The solution of the problem involves the selection of the following:

- the starting time of lot processing in \(SC\);
- the batch sequence processed in \(B1\);
- the starting time of batch processing in \(B1\).

This decision is called \textit{production scheduling}. Production plans are never altered during operation but production schedules may be revised.

The constraints associated with plant operation are as follows:

\textbf{Constraint 1.} The waiting time of batch in \(ST\), \(t\), should fall into the following range:

\[
0 \leq t \leq t^* \tag{1}
\]

Inequality \(t<0\) implies that a certain \(RE\) becomes empty and that uninterrupted lot processing cannot be continued. When this occurs, we say that \textit{the lot is cut off}. On the other hand, excessive residence of a batch in \(ST\) causes undesirable changes in physical properties of the batch. In such a situation, not only are the product requirements unsatisfied, but also the operation itself may stop. For example, the viscosity rise caused by a temperature drop may block up \(SC\). \(t^*\) is a maximum value of allowable \(t\).

\textbf{Constraint 2.} For the preparation of raw materials, the batch numbers assigned to the first several batches which have not yet been put into processing should never be altered.

\textbf{Constraint 3.} In every \(SC\) it takes at least \(\delta\) time units to start processing of the next lot after the completion of processing of the preceding lot.

The batch processing rate in \(SC\), \(v_n\), varies with the value of some attribute \(u\) of the batch such as temperature, pressure or concentration. That is,

\[
v_n = v_n(u) \tag{2}
\]

with

\[
u_a \leq u \leq u^* \tag{3}
\]

where \(u_a\) and \(u^*\) define the allowable range of \(u\). The function type of \(v_n(u)\) depends on the product type. The value of \(u\) can be manipulated when the batch is processed in \(B1\). Equation (2) shows that if we predict unfavorable variations in \(v_n\), we can to some extent avoid the propagation of their influence on the whole plant by manipulating the value of \(u\). We call this control policy \textit{u-control}. It is, for simplicity, assumed that we have a manipulated variable \(u\) only in \(B1\).

However, the discussions in the next sections hold for cases where we have \(u\) in batch units other than \(B1\).
Our aim is smooth, efficient plant operation. To evaluate this quantitatively, we introduce two indices.

For the efficiency of the operation, we consider the total amount of products produced during a time interval \([t_0, t_1]\),

\[
J = \int_{t_0}^{t_1} \sum_{n=1}^{N} v_n \, dt \tag{4}
\]

If the plant is operated smoothly, the dispersion of the waiting times of batches in ST around their desired value \(\theta\) should be small. Thus, as the second criterion, we introduce the standard deviation of \(\tau\),

\[
H = \sqrt{\frac{\sum_{i=1}^{Nb} (\tau_i - \theta)^2}{Nb}} \tag{5}
\]

where \(\tau_i\) is the waiting time of the \(i\)-th batch (batch \(i\)) in ST and \(Nb\) is the number of batches processed in the plant. In the design problem, a compromise between the maximization of \(J\) and the minimization of \(H\) should be found. Smoothness of operation, however, must be the first requirement for actual plants. Hence, our problem can be stated as follows: Design an operating control system to produce the production scheduling that makes \(J\) as large as possible within an allowable range of \(H\).

2. Off-Line Operating Control System

2.1 Production scheduling

The effects of uncertainties on plant operation can be studied analytically by an optimization theory or a queuing theory, as long as they are simple. No general techniques, however, exist which can be adapted to all such studies. More often a simulation technique is required for solutions. In this section, we will study the problem using a computer simulation technique. Before simulation experiments, production schedules are determined so as to make \(J\) large. For this purpose the sum of processing rates in SC, \(\sum_{n=1}^{N} v_n\), should become as large as possible under the constraint

\[
\sum_{n=1}^{N} v_n \leq V_p = \min \left( \sum_{m=1}^{M_1} (BL_m), \ldots, \sum_{m=1}^{M_L} (BL_m) \right) \tag{6}
\]

where \((\cdot)\) represents the maximum processing rate of the corresponding unit. This implies that the plant is operated so that its bottlenecks may work most efficiently. The details of the rules are as follows:

1) Timing of lot processing in SC Using production plans the starting time of lot processing is scheduled. This is done so that every lot processing in each SC\(_n\) may start \(\delta\) time units after completion of the preceding lot processing. Here, if the value of \(\sum_{n=1}^{N} v_n\) exceeds \(V_p\) for some period, we put off the starting time of lot processing which causes this excess by that period. This procedure is repeated till the starting time of every lot processing is scheduled.

2) Batch sequence processed in B1 To prevent lots from being cut off, every batch processing in SC\(_n\) should start at the moment when the preceding batch discharge from RE\(_n\) is completed, except for the leading batch in each lot. Thus the starting times of batch processing in SC are scheduled in turn. This scheduled time is called the expected starting time, denoted by \(f_{sc}\). The sequence of batch processing in B1 is determined in order of increasing \(f_{sc}\). This is based on the assumption that every batch will be processed in SC in the order in which it has been processed in B1.

3) Timing of batch processing in B1 Let \(x\) be the average time spent by the batches from the starting time of batch processing in B1 to the arrival time at ST. \(x\) is dependent on the product type and the amount of batch. Neglecting statistical variabilities, the expected starting time of batch processing in B1, \(f_{B1}\), is given by

\[
f_{B1} = f_{sc} - (x + \theta) \tag{7}
\]

If no uncertainties exist, the above is a set of heuristic rules for maximum value of \(J\) under the constraint of Eq. (6). In the above discussion, it is, for simplicity, assumed that the sequence of process tasks for each batch has been fixed. However, the basic idea of the rules is also applicable when some process tasks are skipped according to the kind of batch.

2.2 Simulation experiment

The behavior of batch processes can be represented by describing how batches flow through the processes.
The GASP IV is a powerful modeling tool for simulating combined processes\(^1\)\(^2\) but it is not transparent. So we developed a simple simulation language based on the BSF\(^3\) to model discrete event systems easily and transparently. The plant model was constructed by it.

We applied the above production scheduling to a melting plant consisting of one converter (B1), one vacuum degassing unit (B2) and three continuous casting machines (SC). The actual processing does not start on schedule because of various variabilities. In the experiments, every batch processing in B1 started at

\[
T_{B1} = \max(t_{B1}, t_a)
\]

where \(t_a\) is a time when at least one B1 becomes available. The processing rate in each unit and the amount of charge (batch) were given statistical variabilities by random numbers with distributions obtained from actual plant operation data.

Figures 2 and 3 show some experimental results. Each line graph in Fig. 2 corresponds to the flow of a batch through the plant with elapsing time. The events indicated in Fig. 2 describe the activities related to batches as they pass through the plant. Some lines go against the lapse of time. They mean that some batches are not in time for batch processing in SC, resulting in the cut-off of lots. Figure 3 shows that the waiting times of batches in ST are widely distributed. These results suggest that the uncertainties strongly affect the operation of the whole plant and that the production scheduling considered here cannot attain smooth plant operation.

3. On-Line Operating Control System

3.1 System configuration

The above production scheduling could not deal with uncertainties occurring in the plant because it was essentially an off-line (open-loop) operating system. In this section we propose an on-line (closed-loop) operating control system, consisting of a dynamical plant simulator and an automatic scheduler. Its configuration is shown in Fig. 4. Every time a batch is put into B1, the simulator predicts the state of the plant in future using information about the past plant record, the present internal state of the plant and the production schedules. The scheduler revises the production schedules on the basis of the predicted state of the plant. The feature of the system is the fact that it deals with scheduling problems on the same level as control ones.

3.2 Production scheduling

Production scheduling in this system is repeated during plant operation. This is always done, not for all batches but for a few. The information about these batches is stored in the schedule file as the production schedules, which are logically arranged in the file in order of batch number. The first production schedule is determinate and the remaining ones are temporal.
While the determinate production schedule is never revised, the temporal ones may be revised with the progress of the operation. The plant is operated according to the determinate production schedule which is removed from the head of the schedule file.

1) Initial production scheduling Prior to plant operation, production scheduling is carried out for a few batches which are to be processed at the beginning of the operation. The manner is the same as that described for the off-line control system. Operation starts after this initial production scheduling.

2) On-line production scheduling On-line production scheduling is carried out every time a batch is put into B1. The plant simulator predicts the future flows of the batches which have already been in the plant and a few scheduled batches. This is done under the initial conditions obtained from the present plant state by ignoring all the statistical variabilities. After this, the simulator informs the automatic scheduler of the prediction results. The scheduler revises the temporal production schedules as follows:

3) Revision of expected starting time of processing Using the predicted completion time of batch processing in SC which has already started, the scheduler returns the completion of the discharge of batch i from RE to SC. It then inserts this information into the schedule file as the revised production schedules.

4) Decision of u-control Using the u-control described earlier the scheduler adjusts the completion time of batch discharge from RE. We consider two batches, batch i and batch j (i < j), which should be processed consecutively in SC. If batch j is predicted not to be in time for tcj, completion of the discharge of batch i from RE should be put off till the arrival of batch j at ST. The expected arrival time of batch j at ST is given by (tcj - 0). Its value may, however, differ from that of the predicted arrival time of batch j at ST, tcj, because of uncertainties. For the waiting time of batch j in ST to be close to 0, the scheduler determines the value of u for batch i, u1, by the following equation:

\[ u_1 = \begin{cases} u^* & \text{for } w > u^* \\ u & \text{for } u_0 \leq w \leq u^* \\ u^* & \text{for } w < u^* \end{cases} \tag{9} \]

with \( w = u_0 + \gamma(t_{c,j} - (tcj - 0)) \),

where \( u_0 \) is the nominal value of \( u \) and \( \gamma \) is a constant. Equation (9) shows that u-control is a saturated proportional control.

5) Supplement of production schedule The scheduler chooses a batch which is to be processed in SC earliest among the batches not yet scheduled and determines its expected starting times of processing in B1 and SC. It then inserts this supplemented schedule into the hindermost location in the schedule file.

3.3 Plant operation

Before the simulation experiments, the gain \( \gamma \) in Eq. (9) was determined by a well-known method in control theory. Neglecting uncertainties, the batches spend \((a + \theta)\) time units from the starting moment of batch processing in B1 to that in SC. If the deviation of \( u \) from \( u_0 \), \( du \), hardly changes on the way from B1 to SC, the transfer characteristic from \( du \) in B1 to that at an entrance of SC may be regarded as a dead time element with unit gain, \( e^{-a_0 + \theta} \). For the value of \( du \) of batch \( i \), \( \Delta u_i \), the deviation of time spent on batch discharge from RE, \( \Delta \eta_i \), is given by

\[ \Delta \eta_i = A \Delta u_i, \quad A = \frac{\partial}{\partial u_i} \left\{ \frac{W}{\{u(u_0)\}} \right\} \tag{10} \]

where \( W \) is the nominal amount of batch \( i \). To guarantee uninterrupted lot processing, the deviation of the expected arrival time of batch \( j \) at ST, \( \Delta(t_{c,j} - \theta) \), should be equal to \( \Delta \eta_j \). Thus the u-control system is modeled as shown in Fig. 5. This system is stable if only if \( \gamma A \leq 1 \). According to the ultimate sensitivity method, the value of \( \gamma \) is determined by

\[ \gamma^* = 0.5/A \tag{11} \]

By replacing \( a \) by the time spent by batches from BJ to ST, a similar operating control system is applicable when we have \( u \) in BJ.

3.4 Simulation experiment

We applied the on-line operating control system depicted in Fig. 4 to the previously described melting plant. In the simulation experiments, the plant model takes account of the statistical variabilities obtained from actual plant operation data but the simulator ignores them and uses the averages.

An example of the flows of batches through the plant is shown in Fig. 6. Lines going against the lapse of time such as were observed in Fig. 2 were not detected. This shows that the proposed on-line system worked successfully. The frequency of dispersion of the waiting times of batches in ST is shown in Fig. 7. It is usually rather smaller than that for the off-line system. The plant model is about half that for the off-line system. There is little difference between the value of \( H \) for the on-line system and that for the off-line system. However, the value of \( H \) for the on-line system is usually rather smaller than that for the off-line system. Thus the on-line system effectively controls a plant with uncertainties. In general, the more remarkable the difference in processing capacities among the units, the more effective is the on-line system.

We also determined the value of \( \gamma \) experimentally
so that it minimized the value of $H$. It was finally confirmed that the value of $H$ for $\gamma^*$ did not differ essentially from that for the optimal value of $\gamma$. This shows that the use of the ultimate sensitivity method is suitable for the design of the $u$-control system.

Conclusions

We proposed an operating control system for a class of multiproduct production plants. The feature of the proposed system is that it includes a plant simulator to predict the state of the plant in future. The system revises the starting times of processing and other operating conditions on the basis of the predicted state.

We applied the system to several combined batch/semi-continuous processes characterized by uncertain variations in processing rate and amount of batch. A series of simulation experiments showed that conventional off-line scheduling interrupted the continuous operation in semi-continuous units because of statistical variabilities. On the other hand, the proposed on-line system made the operation of the plant smooth and efficient. The greater the difference in processing capacities among the units, the greater was the effectiveness of the system.

The following points should be studied in future:

1. Effects of simulator accuracy on the performance of the proposed system
2. Quantitative evaluation of the system to decrease the statistical variabilities.

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Nomenclature

- $H$ = standard deviation of waiting times of batches in ST defined by Eq. (5) [min]
- $J$ = amount of products produced during the operation defined by Eq. (4) [kg]
- $L$ = number of sets of batch units
- $M_i$ = number of batch units in $B_i$, $i=1, \cdots, L$
- $N$ = number of semi-continuous units
- $N_b$ = number of batches to be processed
- $T_{B_i}$ = actual starting time of batch processing in $B_i$ [-]
- $t_a$ = time when at least one $B_1$ becomes available
- $t_{B1}$ = expected starting time of batch processing in $B_1$ [-]
- $t_{SC}$ = expected starting time of batch processing in $SC$ [-]
- $t_{ST}$ = predicted arrival time of batch at ST
- $u$ = attribute associated with batch
- $u_0$ = nominal value of $u$
- $u^*$ = maximum value of $u$
- $u^*_a$ = minimum value of $u$
- $v_{sc}$ = batch processing rate in $SC_n$ [kg·min$^{-1}$]
- $W$ = nominal amount of batch [kg]
- $\alpha$ = average amount of time spent by batches from starting time of batch processing in $B_1$ to arrival time at ST [min]
- $\gamma$ = gain in Eq. (9) [min]
- $\gamma^*$ = gain obtained from ultimate sensitivity method
- $\delta$ = lead time for lot processing [min]
- $\eta$ = time spent on batch discharge from RE [min]
- $\theta$ = desired value of $\tau$ [min]
- $\tau$ = waiting time of batch in ST [min]
- $\tau^*$ = maximum value of $\tau$ [min]

Literature Cited

A STUDY OF SEPARATION EFFICIENCY OF THE CONTINUOUS THERMAL DIFFUSION COLUMN WITH AN IMPERMEABLE BARRIER BETWEEN PLATES

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Key Words: Thermal Diffusion, Improved Column Design, Separation Efficiency, Optimal Barrier Positions, Back Mixing

Properly installing an impermeable barrier between the plates of a continuous flat-plate thermal diffusion column may substantially increase the separation efficiency by reducing the remixing effect, while still preserving the cascading effect. Theoretical considerations show that when the column is designed with the best barrier position, maximum concentration of top product, minimum concentration of bottom product and maximum degree of separation are obtained simultaneously.

Introduction

Thermal diffusion is an unusual process which can be used to separate mixtures that are hard to separate by means of conventional methods such as distillation or extraction. It was the great achievement of Clusius and Dickel to introduce the thermogravitational thermal diffusion column to make this separation process practical. The first complete presentation of the theory of the C-D column was given by Furry et al.

A more detailed study of the mechanism of separation in the Clusius-Dickel column indicates that the convective currents actually have two conflicting effects: a desirable cascading effect and an undesirable remixing effect. The convective currents have a multistage effect which is necessary in securing high separation, and it is an essential feature of the Clusius-Dickel column. However, since the convective currents bring down the fluid at the top of the column, where it is rich in one component, to the bottom of the column, where it is rich in the other component, and vice versa, there is a remixing of the two components. It appears, therefore, that proper control of the convective strength might effectively suppress this undesirable remixing effect while still preserving the desirable cascading effect, and thereby lead to improved separation. Based on this concept, some improved columns have been reported in the literature, such as inclined columns, inclined moving-wall columns, rotary columns, packed columns, rotary wired columns and permeable barrier columns.

Recently, Tsai and Yeh have developed a simple but effective batch-type thermal diffusion column in which an impermeable barrier is inserted between the plates for properly adjusting the convective strength. It is found that when the barrier is installed at the best position, considerable improvement in the degree of separation and product concentrations is obtained under fixed heat consumption. In general, a thermal diffusion column is designed for continuous operation. Therefore, it is the purpose of this work to extend the separation theory and investigate the separation efficiency of a barrier column under continuous operation.

1. Column Theory

1.1 The open column

Consider a continuous flat-plate thermogravi-