Profile Position Control of Distillation Columns with Sharp Temperature Profiles

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The control of distillation columns with very flat temperature profiles has been extensively studied. The small change in temperature per plate requires a temperature sensor with high sensitivity (narrow temperature span) and therefore involves a signal that is strongly affected by pressure changes. Various schemes have been proposed for overcoming these problems: differential vapor pressure cells, pressure compensated temperature control, differential temperature control, and double differential temperature control. See (*1*) for a recent summary.

On the other hand, distillation columns with very sharp temperature profiles (that is, with a very large temperature change over a few trays) have received little attention in the literature. These columns are fairly common in chemical plants and occur in systems where the separation is an easy one and high purity products are produced.

Control problems are frequently encountered with these columns, usually in the form of a cycling feedback control loop trying to maintain a control tray temperature. This problem was analyzed in a recent paper (*2*) using describing function techniques.

The basic problem in trying to control a temperature on a tray is the very high process gain. This necessitates a very small feedback controller gain to maintain closed loop stability. The system is then quite susceptible to upsets from load disturbances. In addition, the system saturates easily; that is, the temperature drops to the lower limit as the profile drops below the control tray, or it rises to the upper limit as the profile moves up past the control tray.

A previous paper (*2*) explored this problem and proposed an adaptive, nonlinear feedback controller as one method for improving control.

In the current paper, an alternative control system is proposed that appears to offer a simpler, more practical solution to this problem.

BASIC STRATEGY

As discussed in a previous paper (*2*), one commonly used brute-force technique for overcoming this problem is to overdesign the column (add more plates) and run on manual control. The temperature profile then moves up or down the column as disturbances enter the column or if there is any imbalance in the overall heat and material balances. Small, frequent changes must be made by the operator to keep the profile from going out one end of the column or the other.

The basic strategy of the proposed "profile position control" is to simply devise a control system that will do automatically what the operator does manually.

A number of temperature sensors are located up and down the column, above and below the desired location of the profile. From these temperatures, the location of the profile can be determined (hardware implementation is discussed later), and this "profile position" signal fed into a conventional feedback controller as the process variable.

The fundamental effect of controlling profile position instead of a temperature of a control tray is to greatly reduce the process gain. This permits higher controller gains and better load response. The saturation problem is also greatly reduced. The process signal (profile position Z) continues to increase as the profile moves up the column or to decrease as the profile moves down the column until the last temperature sensor has been passed.

SYSTEM

In order to evaluate profile position control, the system used in the previous work was studied. See (*2*) for detailed values of parameters and steady state conditions. Briefly, the column had 20 trays and separated a high boiling organic (312°F. boiling point) from water. Tray 5 was selected as the control tray. Heat input to the reboiler was the manipulative variable. Desired overhead and bottoms product compositions were $X_D = 0.999$ and $X_B = 0.001$. See Figures 1 and 2.

SIMULATION RESULTS

Figures 3 and 4 compare conventional temperature control with profile position control. Disturbances in feed

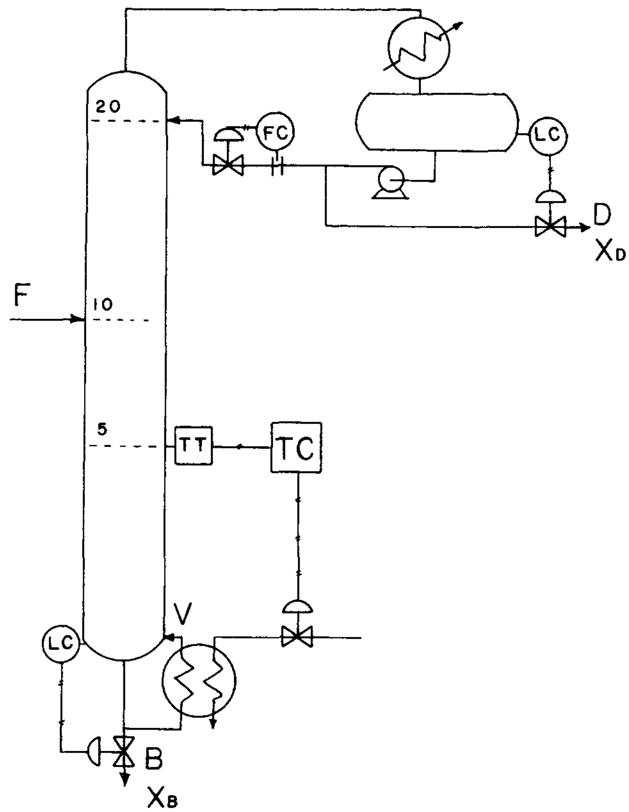

Fig. 1. Conventional temperature control system.

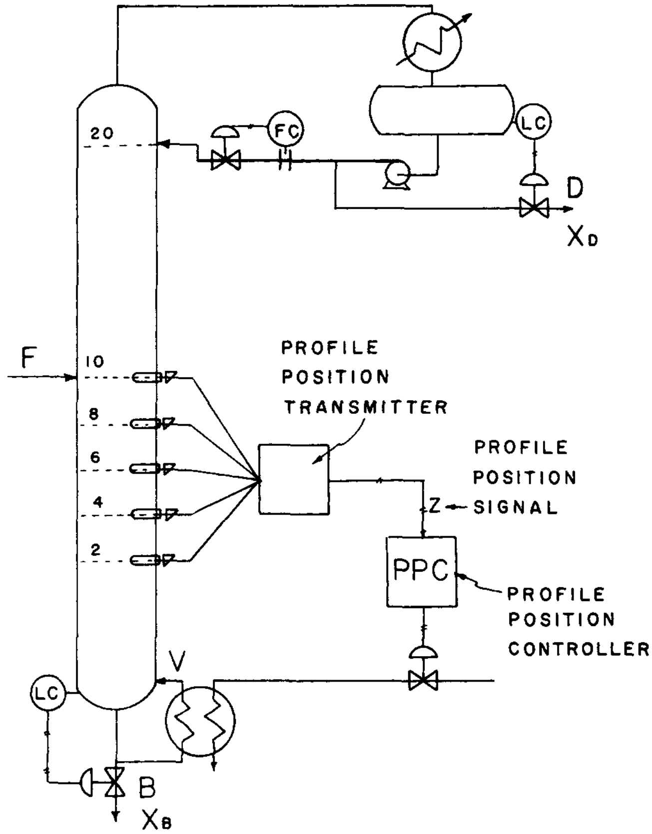

Fig. 2. Profile position control system.

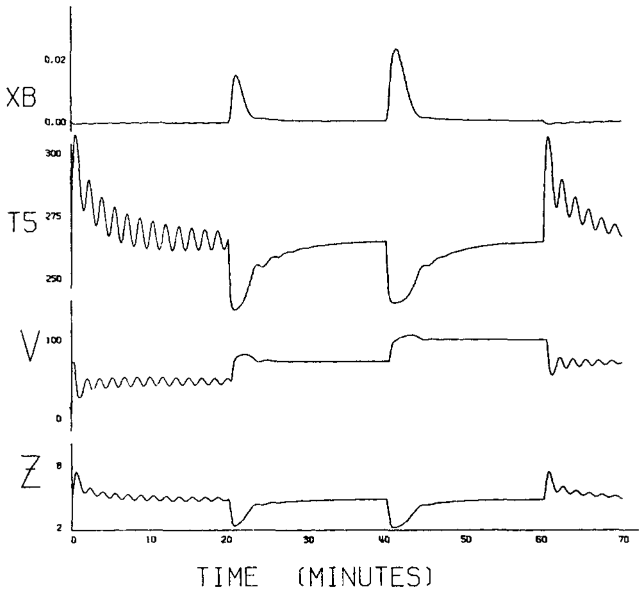

Fig. 3. Response to feed rate disturbances with conventional temperature control.

rate from the steady state value of 100 mole/min. were made by changing the feed at zero time to 50 mole/min., at 20 min. to 100 mole/min., at 40 min. to 150 mole/min., and at 60 min. to 100 mole/min. Conventional proportional-integral controllers were used with the following settings:

	Temperature control	Profile position control
Gain	1	15
Reset time (minutes)	5	5

These settings were determined by empirical tuning methods. Notice the order of magnitude increase in gain with profile position control as opposed to temperature control, despite the fact that the temperature control loop was tuned more tightly. This was deliberately done to make the response of the temperature control system to load disturbances as good as possible.

Notice that the loops become more underdamped as feed rate is decreased. This is due to the nonlinearity of the system (the process gain increases with decreasing feed rate).

When feed rate is increased, the response of temperature control system is quite sluggish, resulting in a large jump in bottoms composition X_B which lasts for an extended period. The profile has dropped out the bottom of the column.

The response of the profile position control system is much less sensitive to the direction of the feed rate change and gives more rapid recovery from disturbances. Profile position controllers have been designed for two new industrial columns that are currently in the design or construction phases.

HARDWARE IMPLEMENTATION

The key problem in implementing the proposed control system is devising a means of detecting the profile position.

If a digital computer is controlling the process, the position of the profile can be calculated in a straightforward manner by having the computer scan a number of thermocouples installed up and down the column to find out in between which trays a temperature in the middle of break lies. A simple "DO" loop calculation with a test and a linear extrapolation can be used to calculate a profile position signal Z.

If analog hardware is to be used, resistance bulbs or thermocouples hooked up in series or in parallel will give an average temperature signal that is essentially equivalent to profile position. Alternatively, the signals (pneumatic or electronic) from several temperature transmitters could be averaged in adding relays.

Wilson, in a recent paper (3), described another alternative in applying a similar detection strategy to a continuous casting machine in steelmaking.

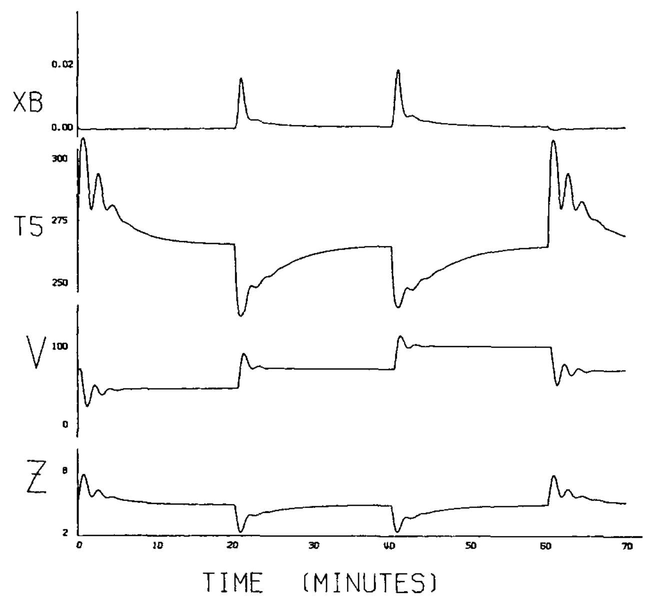

Fig. 4. Response to feed rate disturbances with profile position control.

CONCLUSIONS

Profile position control appears to offer a simple, practical solution to the problem of controlling distillation columns with sharp temperature profiles.

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NOTATION

B = bottoms product flow, mole/min.
D = overhead product flow, mole/min.
F = feed rate, mole/min.
FC = flow control loop
LC = level control loop
$T5$ = temperature on tray 5, °F.
TT = temperature transmitter
TC = temperature controller
X_B = composition bottoms product, mole fraction more volatile component
X_D = composition overhead product, mole fraction more volatile component
V = vapor boilup, mole/min.
Z = profile position, number of plates from base

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On Optimality Criteria for Constrained Optima

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In a recent paper, Law and Fariss (*9*) introduced the generalized matrix inverse to aid in the verification of the well-known Lagrangian first-order necessary and, especially, the second-order sufficient conditions for equality constrained optima. Relying on the inverse construction, they sought, furthermore, to extend both classical results to accommodate redundant constraints and the sufficient conditions to encompass inequality constraints. The purpose of this note is threefold: 1. to indicate that the proposed extension of the necessary conditions is not universally valid; 2. to demonstrate that the claimed extension to inequality constraints cannot be made and to provide a correct statement of that result; 3. to correct some inaccuracies in the use of the generalized inverse constructions.

In the notation of (*9*) which will be used throughout the subsequent discussion the problem under consideration is to identify the optimum values of a function $q(x)$ of the n-vector argument x subject to constraints $f_j(x) = 0$, $j = 1, \ldots, m$.

Necessary Conditions. The necessary conditions suggested by Law and Fariss are that there exist multipliers λ, one for each constraint such that

$$g + J^T\lambda = 0$$

where g is the gradient of q and J is the Jacobian of f, with *no restrictions* on the rank of J. The classical result requires J to have *full row rank* (*3*). As illustrated by the following well-known example (*8*) unqualified relaxation of the rank restriction leads to difficulties.

Example 1:

maximize x_1

subject to $x_2 + (x_1 - 1)^3 \leq 0$ and $x_2 \geq 0$

A graph of the feasible region readily indicates the solution (1, 0). Rewritten in equality form by the introduction of slack variables x_3 and x_4, the problem becomes

maximize x_1

subject to $x_2 + (x_1 - 1)^3 + x_3^2 = 0$

$x_2 - x_4^2 = 0$

Following the authors' relaxed form of the necessary conditions, there must exist at the point $x^0 = (1, 0, 0, 0)$ multipliers λ_1 and λ_2 such that

$$\begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 1 & 1 \\ 0 & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \end{bmatrix} = 0$$

Obviously, no such solution exists. Hence, the contradiction is forced that x^0 is not a local maximum. The example, thus, invalidates the proposed relaxed Lagrangian conditions. However, other examples presented in (*9*) indicate that there do exist situations in which the extension is valid. The problem, then, which the authors have disregarded, is to provide a general criterion for establishing whether a test point at which the constraint gradients are linearly dependent is of a benign type (such as occurs when the constraints have been unwittingly duplicated in problem formulation) in which case the relaxed condition is valid, or if it is of a pathological type (such as example 1) in which case the relaxed condition is invalid. This problem has been actively discussed in the optimization literature (*1* to *8*, *10*, *11*). Numerous abstract regularity conditions—constraint qualifications have been formulated but, especially in the equality constrained case, no computationally satisfactory approach has yet appeared (*11*). An alternative approach which obviates the need for regularity con-