A question much debated is whether the length of time a system has boiled will have an effect on the number of active nucleation sites. Experiments were run at heat fluxes of 8,600, 12,000, and 24,500 B.t.u./(hr.)(sq. ft.) and counts of active sites made at times of 15, 60, 90, and 120 min. after start of boiling. No significant change in the number of sites was found to occur as a function of time. The number of sites observed did, however, increase with heat flux. The average concentration of sites ranged from 340/sq. ft. at 8600 B.t.u./(hr.)(sq. ft.) to 820/sq. ft. at 24,500 B.t.u./(hr.)(sq. ft.).

Another variable frequently studied is the effect of surface roughness on boiling. It is generally found that boiling coefficients are higher for rough surfaces than for smooth ones. In these studies a 3-in. by 3-in. area on the stainless steel boiling surface was prepared by wrapping emery paper on a hand sander and rubbing 10 strokes in one direction and then 10 strokes at 90° until the surface was considered reproducible. Three grades of emery paper were used, ranging from fine to coarse. In contrast to what was expected, the surface polished with the finest paper showed approximately twice as many active sites as the surface polished by the coarse paper, and the medium-polished surface had the fewest sites of all three. All runs were made at a heat flux of 8600 B.t.u./(hr.)(sq. ft.).

The final study made was one in which the length of time of active boiling from specific sites was studied. As was anticipated, a small number of sites remained active almost indefinitely, while others produced bursts of bubbles and then became dormant. One aspect that seemed particularly interesting was that the concentration of permanently active sites seemed about the same for all three degrees of surface roughness described above. However, the fine surface appeared to have a much larger number of short-term sites than the coarser surfaces.

CONCLUSIONS

One important conclusion from the studies described above was that the concept of temperature of the boiling surface is rather illusory. Motion picture photographs of the liquid-crystal color changes showed the boiling plate to be swept by convection waves and spotted with numerous temperature patterns resulting from nucleation. It would seem difficult to say how a meaningful average surface temperature might be determined. The main results of the study indicate that a variety of long-standing problems in nucleate boiling can be investigated using the thin plate technique described above.

ACKNOWLEDGMENT

Initial work on the project involved use of infra-red photography in attempts to determine temperature patterns on the underside of the thin boiling surface. When these methods met with little success, Professor R. B. Roemer of the Department of Mechanical Engineering at UCSB suggested the use of liquid crystals for temperature indication. His valuable suggestion is gratefully acknowledged. Valuable assistance was also provided by J. Leaman and W. Swalling of the Learning Resources department of the University of California, Santa Barbara.

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Two-Variable Distillation Control: Decouple or Not Decouple

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Luyben (*1*) presented an exhaustive study of a noninteracting two-variable distillation control system. The aim of this communication is to draw attention to possible advantages of another control structure serving the same purpose.

The designer of a two-variable control system usually has the option between a noninteracting and interacting design. The former is the more celebrated in the technical literature. A number of methods have been developed, based either on the transfer-function approach (*2*) or state-space approach (*3*), which result in a control system noninteracting with respect to only set point changes. This property has some undeniable advantages for multivariable servosystems where set points are variable, but seems to be irrelevant for process regulators where the objective is to maintain the controlled variables equal to the set points in spite of disturbances. Hence for process regulators—and to this class belongs more often than not a distillation control system—the interacting design seems to be an alternative worth considering, because, besides being less expensive, it may give better disturbance attenuation than the noninteracting design. This was first suggested by Mesarovic (*4*) and discussed in detail by Finkelstein (*5*). Besides, the decoupler as proposed by Luyben may turn out to be physically unrealizable whereas the interacting design always exists. The noninteracting design on the other hand has the advantage of simplified controller tuning. What concerns the necessary design effort there does not seem to be a substantial difference between both systems.

To explain the differences in disturbance filtering, the interacting and noninteracting two-variable control systems shown in Figure 1 and Figure 2 will be considered. The disturbance transfer functions are for the interacting control systems (dropping $j\omega$ for convenience sake):

$$\frac{y_1}{z} = \frac{G_1}{1 + P_{11}(1 - C\,Q_2)R_1}\left(1 - \frac{G_2}{G_1}\frac{P_{12}}{P_{22}}Q_2\right) \tag{1}$$

and

$$\frac{y_2}{z} = \frac{G_2}{1 + P_{22}(1 - C\,Q_1)R_2}\left(1 - \frac{G_1}{G_2}\frac{P_{21}}{P_{11}}Q_1\right) \tag{2}$$

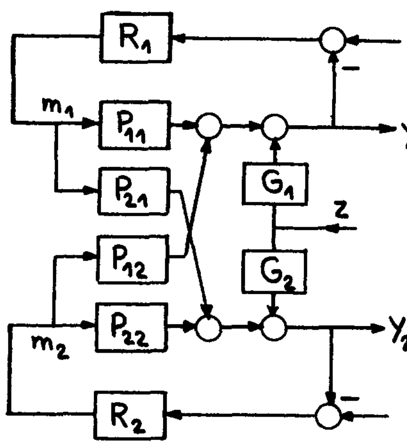

Fig. 1. Two-variable interacting control system.

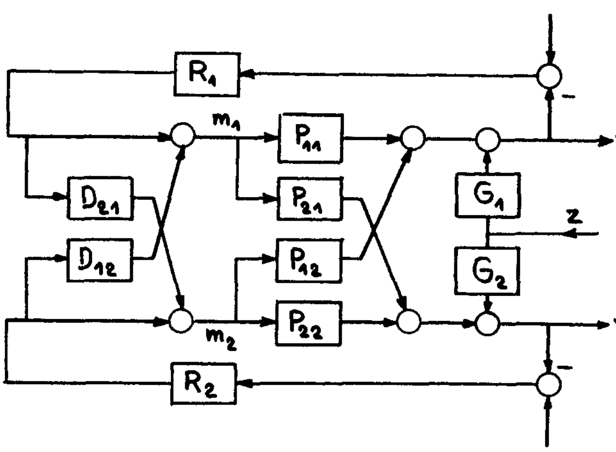

Fig. 2. Two-variable noninteracting control system.

where

$$Q_i = \frac{R_i\,P_{ii}}{1 + R_i\,P_{ii}} \qquad i = 1, 2 \tag{3}$$

$$C = \frac{P_{12}\,P_{21}}{P_{11}\,P_{22}} \tag{4}$$

For the noninteracting system decoupled by putting $D_{12} = -P_{12}/P_{11}$ and $D_{21} = -P_{21}/P_{22}$

$$\frac{y_1}{z} = \frac{G_1}{1 + P_{11}(1 - C)R_1} \tag{5}$$

and

$$\frac{y_2}{z} = \frac{G_2}{1 + P_{22}(1 - C)R_2} \tag{6}$$

In order to determine the effectiveness of the system in disturbance filtering, the deviation ratio (*6*) defined for a given sinusoidal disturbance as

$$\text{deviation ratio} = \frac{\text{deviation with control}}{\text{deviation without control}} = \left|\frac{y_{1,2}\text{ with control}}{y_{1,2}\text{ without control}}\right| \tag{7}$$

is introduced. The deviation ratio for the interacting design is

$$|q_1| = A_1\,B_1 \tag{8}$$

where

$$A_1 = \left|\frac{1}{1 + P_{11}(1 - C\,Q_2)R_1}\right| \tag{9}$$

and

$$B_1 = \left|1 - \frac{G_2}{G_1}\frac{P_{12}}{P_{22}}Q_2\right| \tag{10}$$

and

$$|q_2| = A_2\,B_2 \tag{11}$$

where

$$A_2 = \left|\frac{1}{1 + P_{22}(1 - C\,Q_1)R_1}\right| \tag{12}$$

and

$$B_2 = \left|1 - \frac{G_1}{G_2}\frac{P_{21}}{P_{11}}Q_1\right| \tag{13}$$

For the noninteracting design, the deviation ratios are

$$|q_{1.n}| = \left|\frac{1}{1 + P_{11}(1 - C)R_1}\right| \tag{14}$$

and

$$|q_{2.n}| = \left|\frac{1}{1 + P_{22}(1 - C)R_2}\right| \tag{15}$$

The improved disturbance attenuation in interacting control systems is chiefly due to the factors B_1 and B_2. If

$$\frac{G_2(0)}{G_1(0)}\,P_{12}(0) > 0 \tag{16}$$

and

$$\frac{G_1(0)}{G_2(0)}\,P_{21}(0) > 0 \tag{17}$$

the factors B_1 and B_2 are for the most important low frequency range smaller than 1. Moreover the factors A_1 and A_2 are in the same frequency range usually smaller than $|q_{1.n}|$ and $|q_{2.n}|$, respectively, which further improves the disturbance attenuation of these interacting systems compared with noninteracting ones.

The kind of interaction present in distillation column while controlling distillate and bottom concentration is precisely such that it gives better disturbance attenuation while not decoupled. To demonstrate this fact by a numerical example the model considered by Rosenbrock (7) will be resorted to since Luyben's paper (1) and the reference quoted there (8) does not present explicitly the column's transfer functions used in deriving the noninteracting controller. However the data published by Luyben (8) do fulfill conditions (16) and (17) and this implies a kind of interaction which favors an interacting design. The column transfer function matrix considered by Rosenbrock (7) is

$$\mathbf{P}(s) = \begin{bmatrix} \dfrac{1}{(1+167s)(1+s)(1+0.1s)^4} & \dfrac{0.85}{(1+83s)(1+s)^2} \\ \dfrac{0.85}{(1+167s)(1+0.5s)^4(1+s)} & \dfrac{1}{(1+167s)(1+s)^2} \end{bmatrix}$$

The decoupler D_{12} is for this case physically unrealizable but can be approximated to a high degree of accuracy by physically realizable elements because of the low frequency range involved. In what follows ideal decoupling is assumed. Let us assume that the disturbance z appears at the plant input m_1, that is, $G_1 = P_{11}$ and $G_2 = P_{21}$. An analog computer study revealed that for the interacting system a very satisfactory disturbance attenuation can be achieved with two PI controllers having gains $K_{c.1} = K_{c.2} = 8$ and $T_{R.1} = T_{R.2} = 400$. For these settings the polar plots of $P_{11}(1 - C\,Q_2)$ and $P_{22}(1 - C\,Q_1)$ are compared with the polar plots of $P_{11}(1 - C)$ and $P_{22}(1 - C)$ in Figure 3. These plots represent, according to conditions (1), (2), (5), and (6), the dynamic properties of the plants seen by both controllers in the interacting and noninteracting control system correspondingly. The plots for the noninteracting system are more favorable because of the larger critical gain making the factors A_1 and A_2 in the important low frequency range smaller than $|q_{1.n}|$ and $|q_{2.n}|$, while preserving the same degree of stability.

The deviation ratio frequency characteristics for both systems are shown in Figure 4 and Figure 5. For the noninteracting system the settings $K_{c.1} = K_{c.2} = 3$ and $T_{R.1} = T_{R.2} = 350$ were chosen for the PI controllers. They correspond to the well-known Ziegler-Nichols rules. Figures 4 and 5 demonstrate the superiority of the interacting design as far as disturbance filtering is concerned.

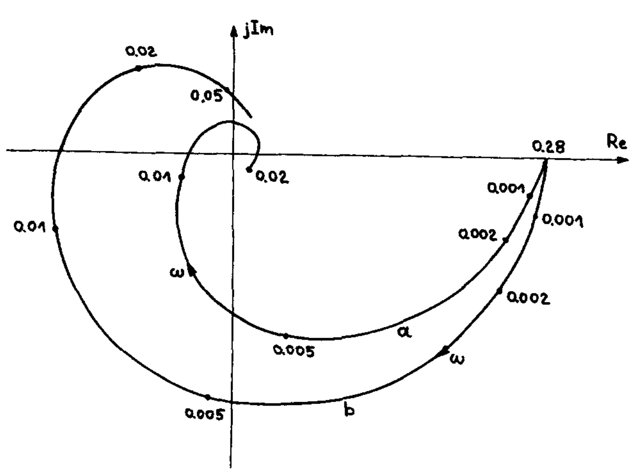

Fig. 3. (a) Polar plot of $P_{11}(1 - C\,Q_2)$ and $P_{22}(1 - C\,Q_1)$ for the interacting system. (b) Polar plot of $P_{11}(1 - C)$ and $P_{22}(1 - C)$ for the noninteracting system.

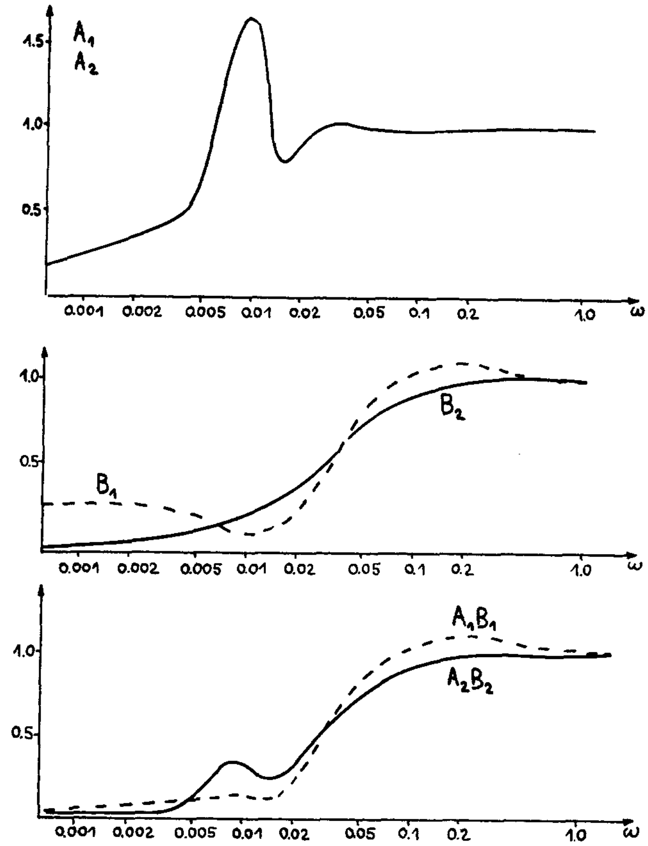

Fig. 4. Deviation ratio frequency characteristics for the interacting system.

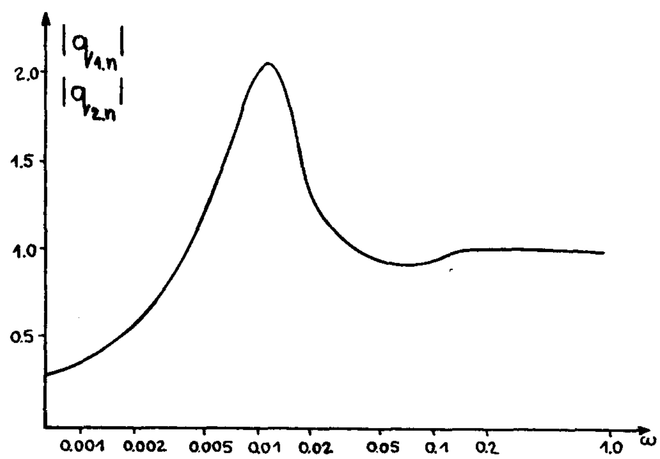

Fig. 5. Deviation ratio frequency characteristic for the noninteracting system.

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