NONLINEAR EXPONENTIAL FILTER TESTED BY SIMULATION

In order to evaluate the worth of the new filter, it was tested vs. the exponential filter. In all cases, digital sampling was at twice the frequency of the noise. This frequency optimizes exponential filter performance (Goff, 1966*a*, *b*). Figure 1 shows the response of the two filters to a step change with noise superimposed. The filters shown use the tuning constants which give best results for a wide range of signals and noise. The ratio of the step signal magnitude to the peak-to-peak sinusoidal noise signal (signal-to-noise ratio) is 2 for this figure. Note that the nonlinear exponential filter ($R = 3.5$) reaches 100% of the signal value in just two sample intervals with no overshoot and thereafter reduces noise level by approximately 80%. This compares to the standard exponential filter which requires ten sample intervals to reach 90% of the final value with the same noise suppression as the nonlinear exponential filter.

Figure 2 shows the response of the same two filters to a sinusoidal signal of amplitude of 1, with sinusoidal noise superimposed. Note that the nonlinear exponential filtered signal follows the actual signal closely. However, the exponential filter substantially alters the magnitude of the signal and also introduces significant phase lag. These two examples are typical.

Since the nonlinear exponential filter is tuned for noise of a particular noise level, it works best for signals whose noise level is steady. It is not recommended for filtering signals with spikes of noise.

USE IN A CONTROL LOOP

The nonlinear exponential filter is, as explained above, equivalent to an exponential filter with a variable filter constant. This means that it acts like a variable time constant lag in the control loop. However, this is not as much of a problem as would first appear. In fact, it is the main strength of the filter. That is, it allows a feedback controller to be tuned without concern for filter lag. The resulting response for large disturbances will then be optimum, since for large disturbances there is no filter lag. Naturally, if the loop is tuned assuming no filter lag, it will be less well tuned for disturbances which are smaller than the noise level. However, the presence of the noise makes tight control of these low level disturbances difficult, no matter what type of filter is used.

COMMERCIAL EXPERIENCE

This filter has been applied in a field location within the Exxon circuit. Figure 3 shows the results of the nonlinear exponential filter applied to a typical flow signal. The tuning parameter (R) selected is 4. The filtered signal has been given a small bias to provide separation between pens. Note that the filtered signal closely follows the actual signal trend while significantly smoothing the signal. This filtered signal was the wild flow in a feedforward control application. The nonlinear nature of the filter did not turn out to be a problem in this application. This application confirms the simulation results presented here.

CONCLUSION

The nonlinear exponential filter seems to be an attractive alternative method for smoothing signals which have a steady noise level.

ACKNOWLEDGMENT

I would like to thank Dr. R. E. Zumwalt of ER&E for his help and encouragement during the development of this filter. Also, I would like to thank Mr. M. J. Veraa who applied the filter at Exxon's Baton Rouge Chemical Plant.

NOTATION

P = exponential filter tuning constant
R = filter tuning constant
X_n = measured value at time n
Y_n = filtered value at time n
Y_{n-1} = filtered value at time $n - 1$
ΔX_n = the difference between the present measurement and the last filtered value
σ = standard deviation of the process noise (after sampling)

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Olefin Hydration Catalyst Evaluation in a Backmix Reactor

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A catalytic life study for an olefin hydration catalyst which normally requires 2 mos of testing in a tubular reactor can be accomplished in the short time span of only 4 days in a backmix reactor. The drastic reduction in time is made possible by capitalizing on the fact that the life of a supported, phosphoric acid catalyst is intimately associated with the retention of the acid on the support (Millidge, 1969). By suitably adjusting the impeller speed in a backmix reactor, the mass velocity can be controlled so as to permit an increased rate of phosphoric acid loss from the catalyst, thereby enabling the test to be completed in a substantially shorter time. Increasing the impeller speed could theoretically cause further reductions

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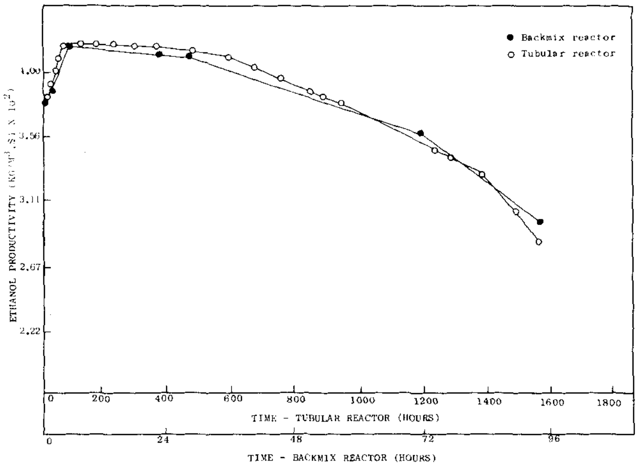
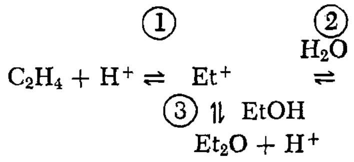


Figure 1. Ethylene hydration catalyst: activity tests in the backmix and tubular reactors.

in testing time, but this would then make it difficult to correlate backmix reactor results with tubular reactor operation by the application of a kinetic model. Since impeller speed can be related to mass velocity, it is possible to extend applicability of this technique to any backmixed system studying a catalyst subject to similar aging. Not only does this technique reduce the time of testing, enhancing the prospects of carrying tests to completion, but it is especially desirable for laboratory testing of small catalyst quantities (10^{-4} m³).

The mechanism first proposed by Whitmore (1934) for the hydration of ethylene as catalyzed by an acid catalyst is



$$C_2H_4 + H^+ \underset{}{\overset{①}{\rightleftharpoons}} Et^+ \overset{\overset{②}{H_2O}}{\rightleftharpoons} EtOH + H^+ \qquad ③ \upharpoonleft\downharpoonright EtOH \qquad Et_2O + H^+ \tag{1}$$

The expressions developed by Nelson and Foster (1975) for the depletion of ethylene r_1 and formation of ether r_2 are

$$r_1 = k_1 \cdot f(P_{C_2H_4}, P_{H_2O}, P_{EtOH}, T^*) \tag{2}$$

and

$$r_2 = k_2 \cdot f(P_{Et_2O}, P_{H_2O}, P_{EtOH}, T^*) \tag{3}$$

respectively.

For plug flow operation in a tubular reactor, a material balance provides the following equations for ethylene and ether, respectively:

$$-r_1 = F\frac{dx_1}{dV} \tag{4}$$

$$r_2 = F\frac{dx_2}{dV} \tag{5}$$

If we utilize Equations (2) and (3) with (4) and (5) and vary k_1 and k_2, it is possible to determine x_1 and x_2. From the stoichiometry of the reactions it was then possible to determine the mole fraction (hence moles) of ethanol produced. Finally, ethanol production rates were plotted graphically in terms of k_1 for different values of k_2.

For backmixed operation in a gradientless reactor, the material balance equations are

$$r_1 = \frac{F}{V}(x_{1_{in}} - x_{1_{out}}) \tag{6}$$

$$r_2 = F\frac{x_2}{V} \tag{7}$$

and if we utilize (2) and (3) with (6) and (7) and solve for x_1 and x_2, ethanol production rates in the backmix reactor can similarly be expressed as functions of k_1 and k_2. These two correlations of production rate with the reaction rate constants permit the translation of ethanol rates obtained experimentally from the backmix reactor to the tubular reactor and vice versa.

In employing this technique to evaluate the olefin hydration catalyst in a backmix reactor, k_1 and k_2 would be determined by solving Equations (2) and (3) with (6) and (7). (From the knowledge of the ethylene inlet and outlet rates, as well as ethanol, ether, and water outlet rates, and therefore the mole fractions, a calculation of the partial pressures of the different components follows.) Once k_1 and k_2 are calculated for a particular analysis in the backmix reactor run, the graphical correlation derived from the solution of Equations (2) and (3) with (4) and (5) is used to determine the calculated value of the ethanol production rate corresponding to a run in the tubular reactor. Figure 1 displays the degree of reliability which this technique affords for testing the activity of an olefin hydration catalyst. The results of a test which was conducted for 1 600 hr in a tubular reactor can now be obtained by running a backmix reactor for a mere 96 hr.

In order to quantify backmixing and identify its role in decreasing catalyst testing time, it was necessary to determine the mass flow rate in the backmix reactor. Unlike tubular reactor operation, mass velocity and space velocity are independent in a backmix reactor; the former

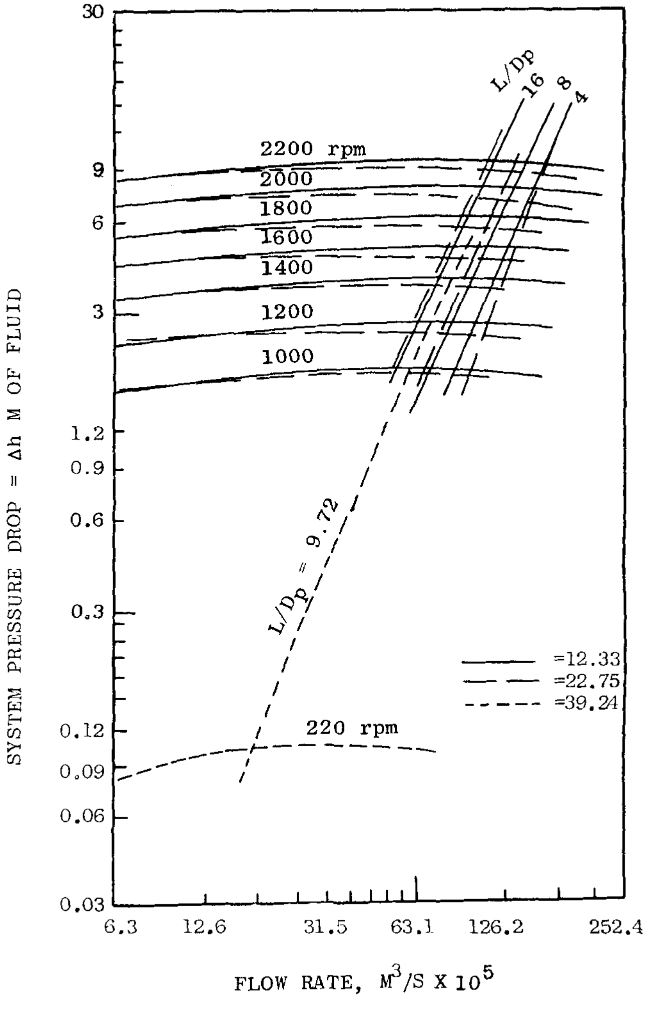


Figure 2. Determination of flow rate in a backmix reactor.

TABLE 1. ETHYLENE HYDRATION: COMPARISON OF BACKMIX AND TUBULAR REACTORS

	Backmix reactor	Tubular reactor
Mole ratio C_2H_4: H_2O	2:1	2:1
Reaction pressure, N/m^2	7 E + 06	7 E + 06
Reaction temperature, °K	543	543
Impeller speed, rev/min	220	—
Catalyst bed c-s, A, m^2	0.0020	0.00027
Catalyst bed depth, L, m	0.0445	2.1336
Space velocity, SV vol/vol/s	0.555	0.5555
Mass velocity, $G = W/A$ kg/m^2 · s	3.63	1.34†
Mass flow rate, W kg/s	0.0074*	0.00036
$NR_e = DpG/\mu$	2 257	833

* From Figure 2, using ρ = 39.237 kg/cm^3.
† For a tubular reactor, $G/SV = M_{av} L/22.4$.

is controlled by impeller speed and the latter by the feed rate. Assuming the flowing gases to be incompressible for small pressure drops in a backmix reactor, Berty et al. (1969) varied gas density, impeller speed, and L/D_p ratios and measured pressure drop as a function of flow rate. It follows, then, that if any two of the following three parameters, are defined, the third can be estimated by the use of Figure 2 (L/D_p ratio, impeller speed, flow rate).

By extrapolating the data of Berty et al. in Figure 2, a determination of flow rate, and finally mass velocity, are tabulated in Table 1. Comparing the operating conditions in the backmix versus tubular reactor, it can be seen that while space velocities are identical in both reactors, mass velocity is approximately three times higher in the backmix reactor. What is more striking is the high mass flow rate inside the backmix reactor, some twenty times that in the tubular reactor. This greater agitation is responsible for the rapid loss of phosphoric acid and the concomitant loss in catalytic activity and explains the shorter duration of a catalytic life test in the backmix reactor, about one sixteenth the time required in a tubular reactor.

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NOTATION

A = cross-sectional area of the catalyst bed, m^2
D_p = equivalent diameter of catalyst particles, m
F = flow rate, kg mole/s
G = mass velocity, kg/m^2·s
k_1 = reaction rate constant for ethylene consumption, N·kg/m·s at 550°K
k_2 = reaction rate constant for diethyl ether formation, N·kg/m·s at 550°K
L = catalyst bed depth, m
M_{av} = average molecular weight of vapor
N_{Re} = Reynolds number = D_pG/μ
P = pressure, total, N/m^2
$P_{C_2H_4}$ = partial pressure of ethylene, N/m^2
P_{H_2O} = partial pressure of water, N/m^2
P_{Et_2O} = partial pressure of ethanol, N/m^2
P_{EtOH} = partial pressure of ethanol, N/m^2
R = universal gas constant = $8{\cdot}3 \times 10^{-3}$ J/kg mole
r_1 = rate of ethylene consumption, kg mole/m^3·s of catalyst bed
r_2 = rate of diethyl ether formation, kg mole/m^3·s of catalyst bed
SV = space velocity = F/V, std m^3/s/m^3 of catalyst bed
T = reaction temperature, °K
T^* = temperature function = $1/R[1/T - 1/550]$, kg mole/J
V = volume of reactor, m^3
x_1 = mole fraction of ethylene
x_2 = mole fraction of diethyl ether
W = mass flow rate, kg/s
ρ = vapor density, kg/m^3
μ = viscosty, N·s/m^2

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An Approximate Solution for the Graetz and Lévêque Problems from the Advancing Front Theory

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The freezing of a lake, the regeneration of coked reformer catalyst, the tarnishing of a metal surface, the impregnation of supports with catalytically active materials, or the oxygenation of venous blood are examples of moving boundary problems. These problems involve the transport of heat or mass to a moving boundary. The

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