Recuperative Rinsing—A Mathematical Approach

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Rinsing operations, which generate most of the plating waste, are at the core of the problem of creating a clean plating industry. While much effort in the field is directed towards the development of different recovery techniques, the most straightforward approach of recuperation, i.e. return of rinsewater to the source bath, has not been investigated thoroughly enough. In this paper results of a computer assisted 3-stage countercurrent recuperative rinse mathematical model investigation are described.

Earlier work on the problem done by Kushner,[1] lacked generality and precision for two main reasons: plating times and rinsewater flows were not taken properly into account, and evaporation from rinses was not considered.

THE MODEL

The investigated model (Fig. 1) includes a process tank, 1 and a series of rinse tanks, 2, 3, 4. Evaporation rates from the tanks are denoted E(1) through E(4), respectively. The drag-out per unit surface area of work, D, is assumed to be equal in each tank. Fresh water enters the rinse tank 4 and proceeds through tanks 3 and 2 to the plating tank 1. The respective flow rates are denoted G(4) through G(1). The solution volumes in each tank are kept constant. Part of the spent rinsewater may be directed to the sewer from any of the rinse tanks with the respective flow rates W(2), W(3) and W(4).

Under stationary conditions (constant evaporation and flow rates, as well as work flow) in such a system, certain constant average concentrations of rinsed solution will be established in each rinse tank with time,[1] which will be denoted as C(2), C(3) and C(4). The plating bath concentration C(1) is assumed to be constant, and for the sake of generality, equal to unity. All the tanks are considered of the ideal mixed type.

For the stationary conditions, the model may be described by the following set of algebraic equations:

$$G(1) = E(1) \quad (1)$$

$$G(i) = G(i\text{-}1) + W(i) + E(i) \quad (2)$$

$$G(i\text{-}1) \times D + C(i+1) + G(i) = C(i) \times [W(i) + G(i\text{-}1) + D] \quad (3)$$

where $i = 2,3,4 \qquad C(5) = 0$

INITIAL DATA

In practice the drag-out value D changes in the range of 0.02 to 0.8 L/m^2.[2] It was desirable to express the evaporation and flow rates in the same specific units (L/m^2 of work surface area). To this end the following formula was used:

$$E = E_s(T) + \tau / F_s \quad (4)$$

where E is the specific evaporation rate, L/m_2 of work surface area.

$E_s(T)$ is the evaporation rate at solution temperature T, dm^3/m^2 of solution surface area per hour.

τ is plating time, hr.

F_s is the surface tank load rate, m^2 of work surface area/m^2 of solution surface area.

While the solution temperature T rises between 20 and 80°C, the evaporation rate $E_s(T)$ changes from 0.2 to 9.3 L/m^2 per hr.[2] The data show that in air stirred tanks the figures are 2.5 to 3 times larger. For rack plating processes plating times might be assumed to lie in the range of 0.05 to 1.0 hr and surface tank load rates will vary from 0.5 to 2. Using equation 4, the practical specific evaporation rate range is then 0.2 to 20 L/m^2. For cold rinse tanks the specific evaporation rate was assumed to be equal to 0.1 L/m^2 as the surface area is usually smaller than that of the plating tank.

The rinsing criterion K° values, which are of practical importance, lie in the range of 500 to 25000.[3] With this model K° = 1/C.[4]

MODEL INVESTIGATION RESULTS

Equations 1 to 3 were solved for three different cases:

1. Maximum achievable rinsing criterion values were computed for the case where no effluent is directed to sewer and with natural tank evaporation rates. These results are presented in Table I. The unknown quantities were C(2), C(3), C(4).

2. For given rinsing criteria, chosen from the practical range, forced evaporation rate values $E(1)_f$-$E(3)_f$ were determined, which provide the achievement of the preset rinsing quality. (The unknown quantities were C(2), C(3)

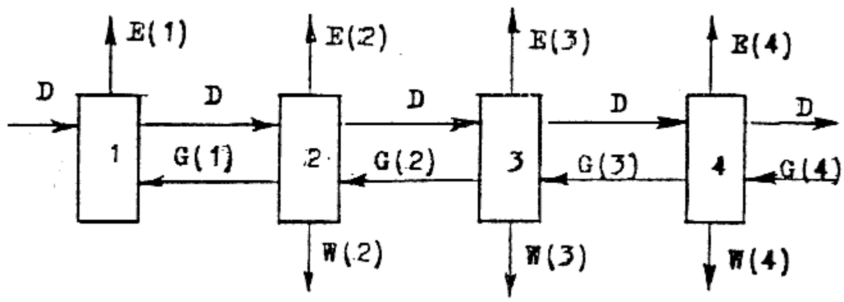

Fig. 1. Three-stage countercurrent recuperative rinse schematic. 1 — plating tank; 2,3,4 — rinsing tanks, E(1)-E(4) — evaporation flows, D — drag-out flow, G(1) — G(4) — rinsewater flows W(2)-W(4) — spent water to waste flows.

Table I. Rinsing Criteria K°, Achieved with Unenhanced Evaporation and Zero Effluent Flow Rate

D	E(1)=20		E(1)=5		E(1)=1.0		E(1)=0.2	
0.8	16,514	0.04	247	0.16	6.55	0.678	1.39	1.12
	1	1.59×10^{-3}	1	0.025	0.848	0.382	0.281	1.08
0.2	10^6	0.01	17,240	0.04	198.5	0.20	6.5	0.846
	1	10^{-4}	1	0.0016	1	0.035	0.846	0.462
0.02	10^9	10^{-3}	17×10^6	4×10^{-3}	17×10^4	0.02	3,160	0.10
	1	10^{-6}	1	1.6×10^{-5}	1	3.6×10^{-4}	1	6.6×10^{-3}

Key: K° C(2) / R C(3)

Notes: E(1) and D in L/m² of work
W(i)=0
E(i)=0.1, for i=2,3,4

Table II. Forced Evaporation Total Recuperation Rinsing

K° / C(4)	E(1)n	D	$E(i)_f$	G(4)	C(2)	C(3)
25000 / 4×10^{-5}	20	0.8	$E(1)_f=3.02$	23.32	0.0347	1.2×10^{-3}
			$E(2)_f=4.74$	25.04	0.04	1.3×10^{-3}
			$E(3)_f=10.8$	31.1	0.04	1.6×10^{-3}
	5	0.2	$E(1)_f=0.68$	5.98	0.352	1.2×10^{-3}
			$E(2)_f=1.07$	6.37	0.04	1.3×10^{-3}
			$E(3)_f=2.44$	7.74	0.04	1.6×10^{-3}
	0.2	0.2	$E(1)_f=5.68$	5.98	0.352	1.2×10^{-3}
			$E(2)_f=31.2$	31.6	1.0	6.36×10^{-3}
			$E(3)_f=3340$	3340	1.0	0.667
5000 / 2×10^{-4}	5	0.8	$E(1)_f=8.3$	13.6	0.06	3.58×10^{-3}
			$E(2)_f=17.$	22.3	0.16	5.77×10^{-3}
			$E(3)_f=94.2$	99.5	0.16	0.025
	2	0.2	$E(1)_f=1.25$	3.55	0.061	3.65×10^{-3}
			$E(2)_f=2.22$	4.52	0.1	4.62×10^{-3}
			$E(3)_f=7.10$	9.40	0.1	9.5×10^{-3}
500 / 0.002	0.2	0.8	$E(1)_f=5.76$	6.26	0.133	1.74×10^{-2}
			$E(2)_f=35.0$	35.4	3.96	0.09
			$E(3)_f=505.$	505.4	3.96	1.26

Notes: E(i), D and G(4) in L/m² of work
$E(i)_n$ are natural (unenhanced) tank evaporation rates
$W(i)\times0$ for i=2,3,4
$E(i)=E(i)_n + E(i)_f$ for i=1,2,3
$E(2)_n \div E(4)_n=0.1$

and $E(i)_f$). These results are shown in Table II.

3. Where forced evaporation was impossible or impractical, the necessary effluent flow rates from separate rinse tanks were determined, which provide the achievement of the preset rinsing criteria. The unknown quantities were C(2), C(3) and W(i). In this case, part of the drag-out chemicals are lost with the effluent. The recuperation factor R (fraction of drag-out chemicals returned to the plating tank) was calculated by equation 5.

$$R=G(1)\times C(2)/D \qquad (5)$$

The results for case 3 are presented in the Table III.

In cases 2 and 3 the equations 1 to 3 are essentially nonlinear and have to be solved by numerical methods. This was done by a specially designed rinse computer program, which employed the parallel tangents method.[4]

DISCUSSION AND CONCLUSION

As is evident from Table I, for a number of investigated cases (see the lower left hand corner) total recuperation along with high rinsing criteria could be achieved without any additional evaporation or spent water discarding. These are the cases where the plating tank evaporation rate/drag-out rate ratio is roughly over 20 to 25.

As can be seen from Table II, forced evaporation was considered separately for each tank: $E(1)_f$ from the plating tank and $E(2)_f$ and $E(3)_f$ from the first and second stage rinse tanks, respectively. The data show, that for such cases, where E(1)/D is big enough (10 to 20), there is a choice: excess water may be evaporated either from the plating tank itself, or from the first-stage rinse tank with insignificant differences in the amounts of water to be evaporated. With E(1)/D ratio getting smaller, the forced evaporation rate rises, as well as the concentration in the first rinse C(2).

After the ratio gets below unity, total recuperation becomes attainable only with first rinse concentrations being actually higher than the plating bath concentration itself. Such an arrangement is hardly ever practical, which means that for these cases the only remaining choices are either to force evaporate the plating bath itself, or else to reduce the drag-out rate.

When forced evaporation is considered impractical and no total recuperation is needed, for E(1)/D ratios above five quite high recuperation factors can be realized (over 85%) with relatively low rinsewater consumption (Table III). Unfortunately, for smaller E(1)/D ratios, recuperation factors without forced evaporation get too low and water consumption rises, so that at least one more rinsing step should be added to get real water and chemical savings.

The results of this investigation prove that total recuperation can be achieved with three countercurrent rinsing stages. Forced evaporation doesn't necessarily mean buying an evaporation unit. In many cases it would be enough to install an air agitation system or to turn a cold rinse into a hot one. Practical systems, designed on the lines described here, can work under relatively simple level control. They would be easy to install and maintain.

Naturally, full recovery means that methods for maintaining solution quality and control of the build-up of impurities in the baths should be developed. **MF**

References

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Table III. Partial Recuperation Rinsing

K° / $C(4)$	$E(1)$	D	$W(i)$	$G(4)$	$C(2)$	$C(3)$	R
	20	0.8	W(2) = 3.02	23.32	0.035	1.2×10^{-3}	0.869
			W(3) = 4.65	24.95	0.04	1.28×10^{-3}	0.993
			W(4) = 10.38	30.68	0.04	1.57×10^{-3}	0.999
	5	0.2	W(2) = 0.68	5.98	0.035	1.22×10^{-3}	0.88
25000			W(3) = 1.05	6.35	0.04	1.29×10^{-3}	0.993
4×10^{-5}			W(4) = 2.34	7.64	0.04	1.55×10^{-3}	0.999
	0.2	0.2	W(2) = 5.48	5.98	0.035	1.22×10^{-3}	0.035
			W(3) = 22.0	22.5	0.50	4.51×10^{-3}	0.503
			W(4) = 1428	1428.5	0.714	0.286	0.714
	5	0.8	W(2) = 8.3	13.6	0.06	$3.58\cdot10^{-3}$	0.376
5000			W(3) = 15.8	21.1	0.143	$5.45\cdot10^{-3}$	0.892
2×10^{-4}			W(4) = 79.74	85.04	0.157	$2.14\cdot10^{-2}$	0.98
	2	0.2	W(2) = 1.25	3.55	0.0615	$3.65\cdot10^{-3}$	0.615
			W(3) = 2.11	4.41	0.095	$4.51\cdot10^{-3}$	0.952
			W(4) = 6.43	8.73	0.099	$8.83\cdot10^{-3}$	0.998
	0.2	0.8	W(2) = 5.76	6.26	0.133	1.74×10^{-2}	0.033
500			W(3) = 15.36	15.8	0.812	4.14×10^{-2}	0.203
0.002			W(4) = 297.0	297.5	1.02	0.745	0.256

Notes: E(i), W(i), D and C(4) in L/m^2 of work
E(i) = 0.1 for i = 2,3,4

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4. H.H. Rosenbrock and C. Storey, "Computational Techniques for Chemical Engineers," Pergamon Press, 1966.

Biography

Bob Stein is a 1974 chemical engineering graduate of the Moscow Institute of Fine Chemical Technology. Since then he worked in the fields of printed circuits and electroplating. Currently he is responsible for plating operations at a domestic electrical appliances plant in Chernovtsy, USSR.