centrifugal-filtering equipment needs to be compared with that of small-scale operations.

CONCLUSIONS

Three types of equipment, a permeability cell, a vacuum filter, and a centrifuge. were successfully used to measure the specific resistance of a bed of spherical particles. The specific resistances agreed among themselves within 20% at the same pressure drop and within 3% at the same cake porosity.

These results constitute the first known experimental data to be reported on the resistances offered by beds of incompressible spheres in all three methods of operation. It is only the third known study of its kind to be done on any sort of porous bed.

The Kozeny-Carman equation predicts specific resistances which are 25% lower than those measured in this work. The matter calls for further investigation.

ACKNOWLEDGMENT

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NOTATION

A = area, sq. ft. or sq. cm.
A_{avg} = arithmetic mean area, sq. ft. or sq. cm.
A_{lm} = logarithmic mean area, sq. ft. or sq. cm.
A_o = area of the filter cloth, sq. ft. or sq. cm.
c = concentration of solids in the slurry expressed as volume of cake forming solids per unit volume of filtrate, dimensionless
D = diameter of particle, ft. or cm.
g = local acceleration of gravity, ft./(sec.)(sec.)
g_c = dimensional constant
h = height of centrifugal basket in centrifugal filtration equation, ft. or cm.
k = Kozeny-Carman constant
K_s = permeability in Storrow equation, $K_s = (\rho_L g)/\alpha_v$
L = length of porous bed in direction of flow, ft. or cm.
M = mass of filtrate, lb. or g.
N = rotational speed, rev./sec.
ΔP = pressure driving force or pressure drop, lb./sq. in. or lb./sq. ft.
q = volumetric flow rate, cu. ft./sec. or cc./sec.
Q = steady state volumetric flow rate in the Storrow equation, cu. ft./sec. or cc./sec.
r_c = radius to inside or exposed surface of centrifuge cake, ft.
r_L = radius to liquid level, ft.
r_o = radius to outside surface of centrifuge cake, ft.
R_m = initial or medium resistance, 1/(ft.)
S_o = solids surface area per unit volume of bed, sq. cm./cc.
V = volume of filtrate, cu. ft. or cc.
w = concentration of solids in slurry expressed as mass of solids per unit volume of filtrate, lb./cu. ft. or g./cc.
W = mass of solids in bed or cake, lb. or g.
x = mass fraction of cake solids deposited per unit mass of filtrate

Greek Letters

α = average specific resistance on a mass basis, ft./lb.
α_v = average specific resistance on a volume basis, ft./cu. ft., $\alpha_v = (1-\epsilon)(\rho_s)$
ϵ = cake porosity or fraction voids, dimensionless
θ = time, sec.
ρ_L = density of liquid, lb./cu. ft. or g./cc.
ρ_s = true density of solid particles, lb./cu. ft or g./cc.
μ = fluid viscosity, lb./(ft.)(sec.)

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Pressure Drop and Liquid Holdup in Concurrent Gas Absorption

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This work presents initial information useful to concurrent gas-absorption design. Data are reported on the variation of pressure drop and liquid holdup obtained with various flow rates, packings, and liquids.

The advantages of concurrent operation for gas absorption were discussed earlier (*1*). Where applicable, this mode of operation may use uncommonly high flow rates, for which correlation and design information are unavailable. To supply such information on pressure drop and liquid holdup, the following work was performed.

PRESSURE DROP

With concurrent gas absorption the main determinant of operating condi-

Additional tables of data and literature references for contiguous countercurrent flow data, coded to type of packing, are filed with the American Documentary Institute, Photoduplication Service, Library of Congress, Washington 25, D. C., as document 6138. They may be obtained for $1.25 for photoprints or 35-mm. microfilm.

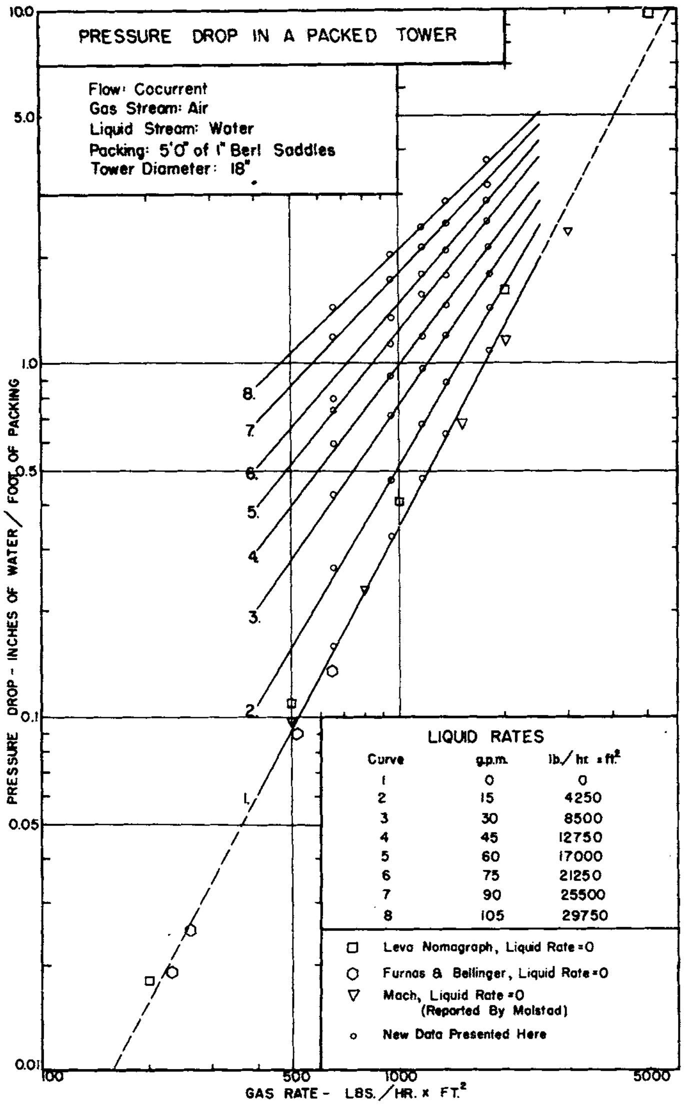

Fig. 1. Pressure drop in packed tower, concurrent flow.

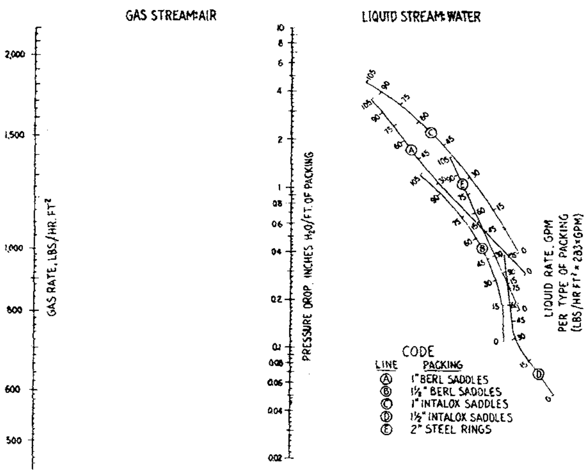

Fig. 2. Alignment chart, pressure drop in packed tower, concurrent flow.

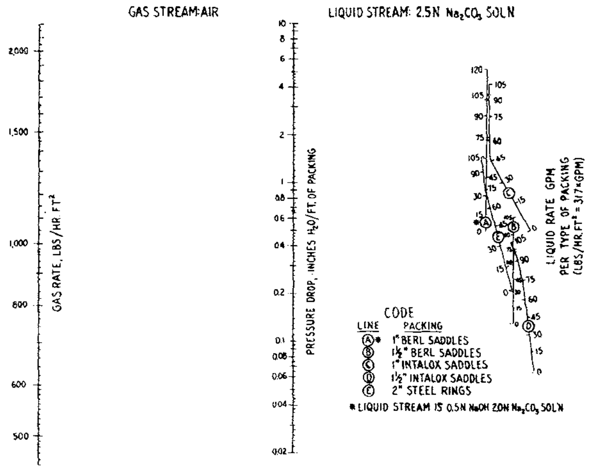

Fig. 3. Alignment chart, pressure drop in packed tower, concurrent flow.

tions may be the power expended in tower pressure drop. Therefore, data on this drop are required to determine the most economical design. In these aspects the literature is limited to the more common countercurrent operation of absorption towers and includes data at rates only up to the loading or flooding points. Extrapolation of these data to high flow rates would be highly subject to error.

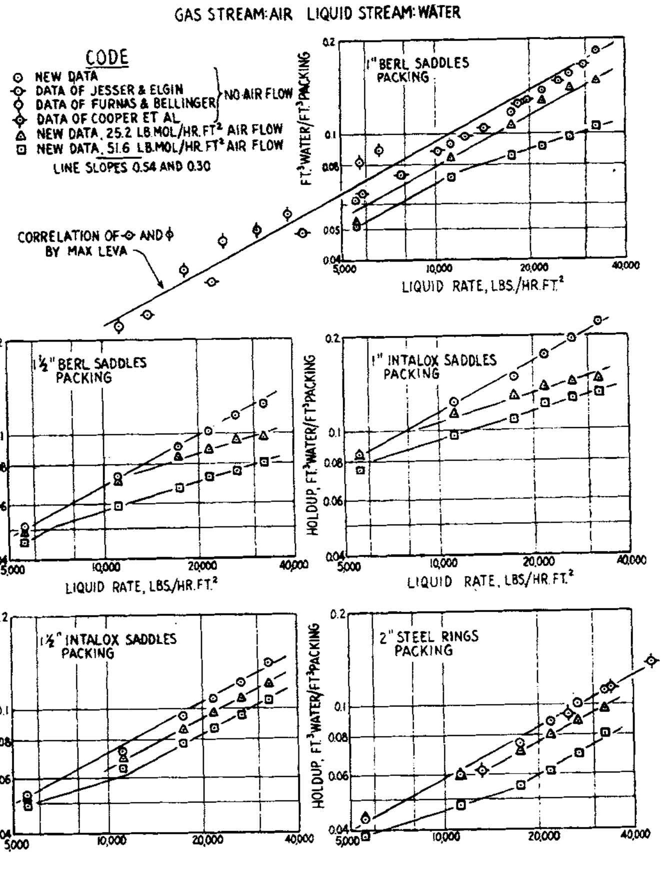

Fig. 4. Liquid holdup in packed tower, concurrent flow.

The same equipment was used as in a previous mass transfer study (*1*).

The variables under test included gas rate at six levels, liquid rate at seven levels, two types of liquid, and five types of packing. The data conformed to a statistical design, so that statistical interpretation might be facilitated. Operating procedure provided sufficient time before readings to ensure stable conditions: packing was settled and wetted, and the transients from resetting rates were dissipated. Checks were made to assure that the approach to any set of rates was immaterial, that is that no combination of a prior decrease or increase in liquid or gas rate would alter the pressure-drop result.

The experimental results are tabulated in Tables 1, and 2. The relationship between variables at any point of interest may be simply obtained by a log-log plot. An example is presented in Figure 1 which graphs one system (water-1-in. Berl saddles) with related correlations noted on the plot. For brevity the graphs for all results are condensed into the alignment charts of Figures 2 and 3, which offer quick but rough reference. In general for the carbonate-solution system the slopes of the correlating lines, hence the exponents to be attached to gas rate, were relatively constant. Conversely, the water systems yielded decreasing slopes with increasing liquid flow rates, hence a gas rate exponent influenced by liquid rate.* This complication and difference between the only two liquid systems tested precludes advancing a general correlation. Otherwise the data appeared amenable to correlation, albeit with interactions between variables.

A comparison with countercurrent flow relations may be adduced. The two flow systems are contiguous and similar at lower flow rates. In each case log plots of pressure drop vs. gas rate would yield similar parallel lines per liquid-rate parameter and hence the same exponent to be attached to gas rate. With countercurrent operation this exponent is sharply increased at the loading point and again at the flooding point. Conversely, with concurrent operation the exponent is not increased by higher flow velocities and may be decreased, as indicated in Figure 1. It would appear that at some higher range of gas velocity the lines of correlation would curve to converge with the extended line for zero liquid rate, as liquid hold-up is progressively depressed under increasing gas pressure.

* The behavior of this system at higher gas rates would be of interest (Figure 1). Beyond the point where the lines of correlation converge would liquid rate be of no effect or would pressure drop be decreased by greater liquid flow, from additional liquid head?

TABLE 1. PRESSURE DROP IN CONCURRENT FLOW IN A PACKED TOWER

Air-water system in 18-in.-diameter tower at tower pressure 745 to 760 mm. Hg., tower temp. 85° to 90°F.

Liquid rate, lb./hr./sq. ft.	Gas rate, lb./hr./sq. ft.	Pressure drop in various packings in. water/ft. of packing height				
		1-in. Berl 5 ft.	1½-in. Berl 4 ft. 7 in.	2-in. rings 4 ft. 3 in.	1-in. Intalox 4 ft.	1½-in. Intalox 4 ft. 5 in.
0	461	—	—	—	0.091	0.030
	661	0.159	0.090	0.119	0.184	0.064
	953	0.323	0.182	0.234	0.364	0.131
	1178	0.471	0.269	0.350	0.546	0.197
	1362	0.629	0.354	0.478	0.728	0.273
	1745	—	0.549	0.747	1.150	0.474
	1810	1.075	—	—	—	—
4250	461	—	—	—	0.145	0.039
	661	0.265	0.126	0.148	0.263	0.080
	953	0.470	0.245	0.288	0.517	0.163
	1178	0.672	0.350	0.434	0.775	0.243
	1362	0.894	0.469	0.564	1.021	0.331
	1745	—	0.738	0.899	1.530	0.530
	1810	1.424	—	—	—	—
8500	461	—	—	—	0.203	0.043
	661	0.426	0.159	0.185	0.356	0.094
	953	0.716	0.303	0.352	0.709	0.185
	1178	0.960	0.424	0.516	1.025	0.275
	1362	1.178	0.561	0.681	1.296	0.372
	1745	—	0.863	1.061	1.867	0.592
	1810	1.766	—	—	—	—
12750	461	—	—	—	0.343	0.047
	661	0.594	0.168	0.228	0.558	0.109
	953	0.921	0.327	0.428	1.023	0.217
	1178	1.189	0.457	0.623	1.375	0.316
	1362	1.450	0.597	0.806	1.695	0.423
	1745	—	0.899	1.238	2.322	0.678
	1770	2.142	—	—	—	—
17000	461	—	—	—	0.517	0.060
	661	0.733	0.233	0.282	0.817	0.125
	953	1.125	0.410	0.502	1.385	0.243
	1178	1.550	0.578	0.743	1.809	0.365
	1362	1.760	0.731	0.969	2.171	0.485
	1745	—	1.069	1.450	2.815	0.762
	1770	2.570	—	—	—	—
21250	461	—	—	—	0.686	0.069
	661	0.782	0.273	0.329	1.083	0.140
	953	1.313	0.496	0.603	1.716	0.275
	1178	1.784	0.688	0.856	2.192	0.406
	1362	2.095	0.870	1.099	2.564	0.534
	1745	—	1.314	1.648	3.236	0.846
	1770	2.895	—	—	—	—
25500	461	—	—	—	0.972	0.079
	661	1.170	0.377	0.411	1.489	0.152
	953	1.705	0.637	0.736	2.202	0.298
	1178	2.134	0.861	1.035	2.708	0.432
	1362	2.470	1.058	1.290	3.101	0.566
	1745	—	1.531	1.932	3.866	0.961
	1770	3.375	—	—	—	—
29750	461	—	—	—	1.272	0.099
	661	1.422	0.484	0.525	1.881	0.193
	953	2.006	0.800	0.878	2.695	0.371
	1178	2.461	1.038	1.205	3.174	0.569
	1362	2.853	1.249	1.518	3.597	0.708
	1745	—	1.758	2.216	4.435	1.120
	1770	3.731	—	—	—	—

Table 2. Pressure Drop in Concurrent Flow in a Packed Tower

Tower pressure 745 to 760 mm. Hg., tower temp. 85° to 90°F., 18-in. diameter tower

Air–2.0N Na_2CO_3, 0.5N NaOH system with 5 ft. of 1-in. Berl Saddles

Liquid rate, lb./hr./sq. ft.	Air rate, lb./hr./sq. ft.	Pressure drop, in. H_2O/ft. pack. ht.
4730	516	0.169
	749	0.323
	984	0.508
	1225	0.738
	1491	1.040
9540	515	0.198
	741	0.375
	950	0.559
	1244	0.892
	1523	1.290
13940	516	0.227
	749	0.440
	986	0.705
	1232	1.025
	1500	1.449
18920	504	0.235
	744	0.496
	1015	0.779
	1223	1.191
	1545	1.801
23740	507	0.303
	744	0.614
	986	0.981
	1225	1.427
	1570	2.188
28000	505	0.339
	742	0.681
	984	1.183
	1230	1.813
	1500	2.481
32800	513	0.435
	741	0.835
	984	1.409
	1229	2.054
	1449	2.699
37400	484	0.513
	742	1.151
	985	1.852
	1221	2.493
	1339	2.936

Air-2.5*N* Na_2CO_3 system

Liquid rate, lb./hr./sq. ft.	Gas rate, lb./hr./sq. ft.	Pressure drop in various packings in. water/ft. of packing height: 1½-in. Berl 4 ft. 7 in.	2-in. rings 4 ft. 3 in.	1-in. Intalox 4 in.	1½-in. Intalox 4 ft. 5 in.
4750	461	—	—	0.126	0.039
	661	0.117	0.160	0.256	0.084
	953	0.229	0.311	0.519	0.167
	1178	0.336	0.457	0.767	0.247
	1362	0.444	0.609	1.009	0.333
	1745	—	0.961	1.602	0.534
	1770	0.731	—	—	—
9500	461	—	—	0.165	0.043
	661	0.126	0.191	0.333	0.096
	953	0.258	0.362	0.614	0.187
	1178	0.379	0.535	0.895	0.279
	1362	0.491	0.706	1.176	0.373
	1745	—	1.109	1.861	0.607
	1770	0.827	—	—	—
14250	461	—	—	0.209	0.049
	661	0.150	0.222	0.395	0.103
	953	0.280	0.424	0.738	0.206
	1178	0.415	0.634	1.069	0.303
	1362	0.574	0.829	1.387	0.404
	1745	—	1.288	2.161	0.657
	1770	0.904	—	—	—
19000	461	—	—	0.248	0.056
	661	0.159	0.253	0.476	0.125
	953	0.309	0.500	0.891	0.243
	1178	0.475	0.732	1.274	0.365
	1362	0.632	0.965	1.658	0.485
	1745	—	1.494	2.737	0.772
	1770	1.036	—	—	—
23750	461	—	—	0.292	0.067
	661	0.182	0.309	0.527	0.140
	953	0.347	0.584	1.003	0.275
	1178	0.520	0.852	1.501	0.410
	1362	0.690	1.117	1.977	0.549
	1745	—	1.722	3.128	0.886
	1770	1.132	—	—	—
28500	461	—	—	0.345	0.083
	661	0.200	0.358	0.655	0.163
	953	0.390	0.687	1.259	0.333
	1178	0.579	1.002	1.836	0.494
	1362	0.762	1.298	2.349	0.655
	1745	—	1.973	3.467	1.047
	1770	1.256	—	—	—
33250	461	—	—	0.387	0.099
	661	0.233	0.420	0.703	0.197
	953	0.466	0.778	1.307	0.395
	1178	0.695	1.134	2.053	0.590
	1362	0.942	1.454	2.655	0.779
	1745	—	2.212	3.992	1.223
	1810	1.513	—	—	—

LIQUID HOLDUP

Knowledge of the liquid holdup in an absorption tower can be useful in estimating the required surge capacity of a sump or the added weight that supports must carry or in correlating other properties such as pressure drop and mass transfer rates. Most published information on holdup pertains to countercurrent tower operation at conditions below the flooding point where the holdup is not affected by the gas rate. The following work was done to supply necessary data for the design of concurrent flow absorption towers, particularly at higher liquid and gas flow rates.

The variables tested include liquid rate at six levels, gas rate at three levels, and five types of packing; water was the only liquid used. The data were arranged in a statistical design to facilitate interpretation. Experimental procedure utilized an overflow drain to measure volumetric changes in the recycled liquid system. Each series of runs commenced at the highest liquid rate with the liquid at overflow level. Successive changes in holdup were measured by the liquid collected from overflow as liquid rates were decreased by increments down to zero flow. Appropriate corrections for liquid evaporation losses were calculated from inlet and outlet air humidities, air rates, and time intervals.

The data obtained are graphed in Figure 4. The values agree well with prior data, available only for 1-in. Berl saddles and 2-in. steel rings at zero air flow. The effects of variables and the presence of interactions between variables are apparent from an inspection of Figure 4.

In comparison with countercurrent operation, the relationships appear similar at low flow rates but diverge at higher rates. It might be generalized that with increasing flow velocities countercurrent operation tends toward the behavior of a liquid-filled tower and concurrent operation toward that of a tower empty of liquid. With concurrent flow higher gas rates flatten the holdup to liquid-rate relationship, and the relative increase of holdup lessens at higher liquid rates. Loading and flooding points are not obtained. These differences between the systems are expected and define the conditions where concurrent flow may be advantageous.

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