THE FLOW CHARACTERISTICS OF
COMMERCIAL POWDERED
CATALYSTS. STUDY II

by

GAYLE HOWARD NICHOLS, JR.

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APPROVED:

Redacted for Privacy

Head of Department of Chemical Engineering

In Charge of Major

Redacted for Privacy

Chairman of School Graduate Committee

Redacted for Privacy

Dean of Graduate School

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THE FLOW CHARACTERISTICS OF COMMERCIAL POWDERED CATALYSTS. STUDY II

OBJECTIVE

The fundamental aim of the work described here was to refine the equipment described by D. F. Rynning (1) and to add to the information presented by him. The specific problem investigated was the study of the pressure drop due to fluid friction in a flow system containing a powdered solid of the "fluid catalyst" type and the correlation of this pressure drop with the other variables generally associated with frictional pressure drop; namely, the velocity and density of the material flowing, the size of the conduit through which the pressure drop is measured, and the nature of the material.

A further consideration was the applicability of the flow equation suggested by J. S. Walton and D. F. Rynning (2) following the publication of Rynning's original work and based on that work.

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(1) Delroy Finlay Rynning, THE FLOW CHARACTERISTICS OF COMMERCIAL POWDERED CATALYSTS, M.S. Thesis, Oregon State College, Corvallis, Oregon, 1947.

(2) Jesse Seburn Walton and Delroy Finlay Rynning, FLOWING CHARACTERISTICS OF COMMERCIAL POWDERED CATALYSTS, Presented to American Chemical Society, Regional Meeting, Pullman, Washington, May 1947.

Lastly, it was desired that these investigations should provide more data and fundamental information on the behavior of fluidized solids for future investigators, the data of Rynning (3) being all that is currently available.

(3) D. F. Rynning, loc. cit.

INTRODUCTION

"Fluid catalyst" is a term that has come into general use with reference to an aereated powder of a catalytic material which is circulated through process equipment in the manner of a true fluid. It differs from a gaseous suspension in that the density of the material flowing is much nearer that of the packed solid than that of the gas which is being used to move it.

Fluid catalyst technique has become of major importance in petroleum refining and is expected to find more widespread use in other chemical industries both for catalysis and as a method of treating finely ground solids. Thus it may be seen that it is desirable that information on the behavior of fluidized solids be available as a basis for design calculations. The work which has been done in the petroleum industries has been entirely commercial and the results are not generally available.

APPARATUS

Essentially, the same equipment was used in this work as that described by Rynning (4) with a variation of flow tube diameter and with the addition of a return system to make the apparatus semi-continuous.

Basically the equipment consisted of a standpipe which served to provide a pressure head for the powdered catalyst, a glass flow tube through which the catalyst flow could be measured while the attendant pressure drop was measured, and a line to provide for the return of the catalyst by compressed air to the standpipe. The apparatus is shown schematically in Figure 1.

The standpipe was a five foot section of standard three-inch pipe mounted vertically, with a conical sheet metal hopper at the top. The hopper tapered from two feet in diameter and was two feet deep. The lower end of the standpipe was reduced by standard fittings to a one-inch pipe from which a connection was made to the flow tube by rubber tubing. A 1/4-inch compressed air line was provided at the bottom of the standpipe just above the fittings.

Flow tubes were made of glass tubing with pressure

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(4) Ibid., p. 3.

taps near each end. These pressure taps were of smaller diameter glass tubing which maintained the inside contour of the flow tube as far as possible. The powder was prevented from entering the manometer by glass wool filter plugs in the side outlets. Flow tubes having the following characteristics were used.

Tube Number	Inside Diameter	Distance Between Taps	Overall Length	Volume
1	1.024	41 in	53 in	718 cc
2	1.024	32 1/4 in	53 in	718 cc
3	1.024	26 1/4 in	53 in	718 cc
4	0.997	41 in	53 in	690 cc

The lengths and volumes tabulated here take into consideration the short length of connecting hose extending beyond the ends of the tubes.

The flow tubes having the pressure taps closest together were made so that the intervals between the taps were at the lower end of the tubes in order to provide short calming sections between the regulating clamp and the section across which the pressure drop was to be measured.

This apparatus was mounted vertically in the laboratory with the hopper extending above the second floor level and the standpipe suspended from that floor. The flow tube was mounted independently by suitable clamps and allowed to discharge into a collecting drum. Use of a rubber connecting tube allowed regulation of the catalyst flow by means of a small clamp.

The use of a vertical flow tube made it necessary to correct the manometer reading for the difference in static head of catalyst between the pressure taps.

The return line from the collecting drum was a standard one-inch pipe which discharged into a small cyclone set above the hopper. Bends necessary in the return line were of approximately three-foot radius to prevent the powder from packing.

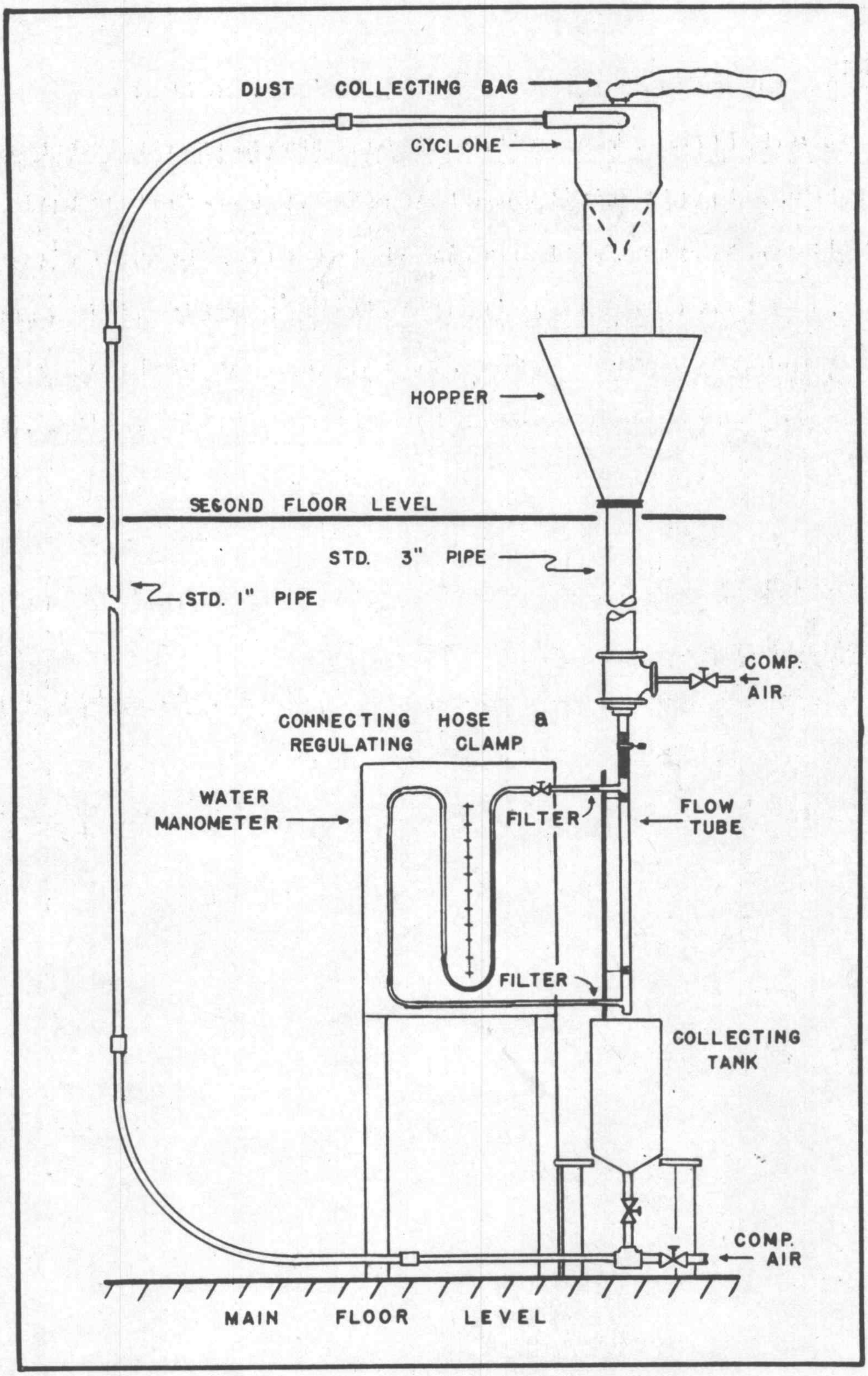

DIAGRAM OF APPARATUS
FIGURE 1

MATERIALS

Three fluid catalysts were used in this project. The first, sold under the name of Filtrol, is a refined form of a naturally occurring substance. The second, manufactured as Catalyst 3A, is a synthetic substance used in petroleum refining; and the third, a synthetic catalyst produced as Aerocat, is also used in petroleum refining. All are hydrated aluminum silicates which have been finely ground. All three will pass about 90 percent through 100 mesh; Filtrol and Catalyst 3A are about 25 percent smaller than 20 microns and Aerocat is about 50 percent smaller than 20 microns. A more complete investigation of the range of particle sizes in these three powdered catalysts is currently being made in these laboratories.

Since some discussion of the effect of physical characteristics will be undertaken later, it is advisable to describe some of the more obvious differences between the three catalysts at this time. Filtrol and Catalyst 3A tend to agglomerate to some extent when not in an areated state while Aerocat does not appear to agglomerate to the same degree. This observation is borne out by microscopic examination. However, the moisture content of the powders may be expected to affect their tendency to agglomerate.

The particles of Filtrol and 3A appear under the microscope as irregularly shaped, somewhat translucent particles. Aerocat, offered by its producers as a catalyst made up of spheroidal particles, appears as a smooth opaque powder.

TECHNIQUE

Flow measurements were made with the hopper initially full of catalyst. For any one run, the change in head was negligible, and while the catalyst head was not the same for all runs, no error was incurred because the pressure difference was measured only across the flow tube.

At the beginning of a run, the clamp on the connecting hose was opened and a small amount of air was admitted to start the powder flowing. The flow rate was adjusted with the clamp and the density of the material flowing was varied by the amount of air allowed to flow. The degree of regulation provided in this manner did not permit fixing the flow condition to a desired point, but did provide for obtaining a range of flow variation over which data could be taken.

When a flow condition was established, the manometer reading was taken and the catalyst flowing for a measured time interval was collected and weighed. Immediately afterward the flow tube was closed off on both ends as nearly simultaneously as possible and the quantity of material trapped was collected and weighed. This information then provided the data for one run. When the collecting drum became full, the catalyst was returned to the hopper. The use of three catalysts and two different tube diameters allowed for the observation of the effect of these factors on the flow.

NOMENCLATURE

u	velocity
ΔP	pressure difference
f	Fanning friction factor
V	volume
R	density
L	length
D	diameter
g	acceleration due to gravity
m	viscosity
G	mass velocity

RESULTS

In order to correlate the data taken, it was necessary that it be converted to the variables under consideration. The apparent density of the material flowing was readily available and from it the flow rate, linear velocity, and mass velocity were calculated. Values for the pressure drop due to friction were computed by correcting the manometer reading for the static head exerted by the flowing catalyst between the points across which the pressure drop was measured. Theoretically, this correction would be large enough to change the direction of the indicated pressure difference, but in many cases this condition did not obtain and the discrepancy was originally attributed to a change of equilibrium conditions within the system during the run. It was found, however, that the provision of a calming section between the regulating clamp and the upper manometer tap overcame this difficulty to a considerable extent and under stable conditions the corrections were reasonable. A typical conversion is shown by sample calculation in the Appendix.

The foregoing pressure correction was established by the application of the Bernoulli theorem to the flow system. However, applying this theorem required the use of some assumptions. The flowing catalyst could not be assumed to be a perfect gas since the solid particles constituted such a large percentage of the material; nor could the material be assumed incompressible. However, since the heat capacity of the solid does not differ widely from that of air, the enthalpy (E + pv) of the system may be considered constant, and the use of Bernoulli's theorem will involve little error.

Correlation was then made in the manner suggested by Walton and Rynning (5). The friction factor was calculated by the Fanning equation and plotted against the mass velocity. The Fanning equation for steady isothermal flow of fluids in circular conduits (6) is $\Delta P = \frac{2fLu^2}{gD}$, the units being consistent. For true fluids, the friction factor has been determined to be a function of the dimensionless group DG/m which is designated as the Reynolds number. The terms in the numerator of this expression were readily available, but

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(5) J. S. Walton and D. F. Rynning, loc. cit.

(6) Complete discussions of fluid flow calculations may be found in J. H. Perry, CHEMICAL ENGINEER'S HANDBOOK, 2nd edition, New York, McGraw-Hill Book Co., 1941, pp. 788-833, or in any general chemical engineering text.

the viscosity was not known. However, the calculations may be reversed and an "apparent viscosity" computed from this data. It was pointed out by Walton and Rynning that there were indications that the "apparent viscosity" did not vary appreciably with the density of the material flowing and experiments currently being conducted in these laboratories indicate that the "apparent viscosity" of these areated catalyst powders does not vary to a great extent with density. It is to be expected, however, that better correlations of flow characteristics will become evident when viscosity values are available. The results of the friction factor-mass velocity correlation are shown in Figures 2 through 4 and Figure 5 shows a comparison of the three catalysts. The dotted line in the latter figure indicates the curve presented by Walton and Rynning for Filtrol. The curve set forth here for Catalyst 3A is substantially the same as that presented by them.

The data as shown in Figures 2, 3, and 4 are not as consistent as may be desired, but about 70% of the points fall into a relatively narrow band with the balance at some variance. However, these widely divergent data may be accounted for possibly by the proximity of the transition range in which the flow characteristics change from streamline flow to turbulent flow, and some divergence may also be attributed to elutriation of the catalyst due to repeated handling, but before this latter assumption can be made with any degree of certainty, more specific investigations must be made into the effect of particle size on the flow characteristics of powdered solids.

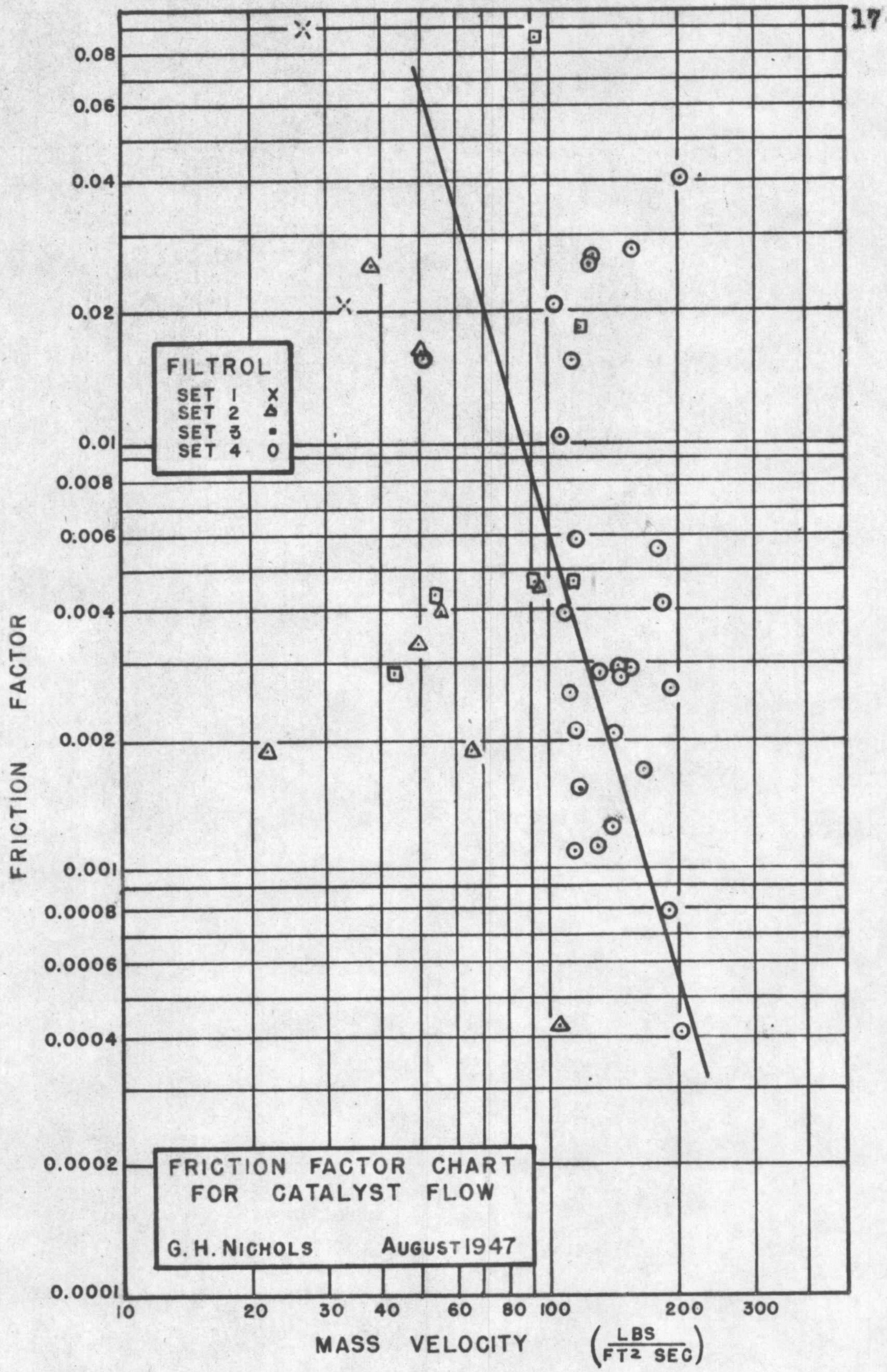
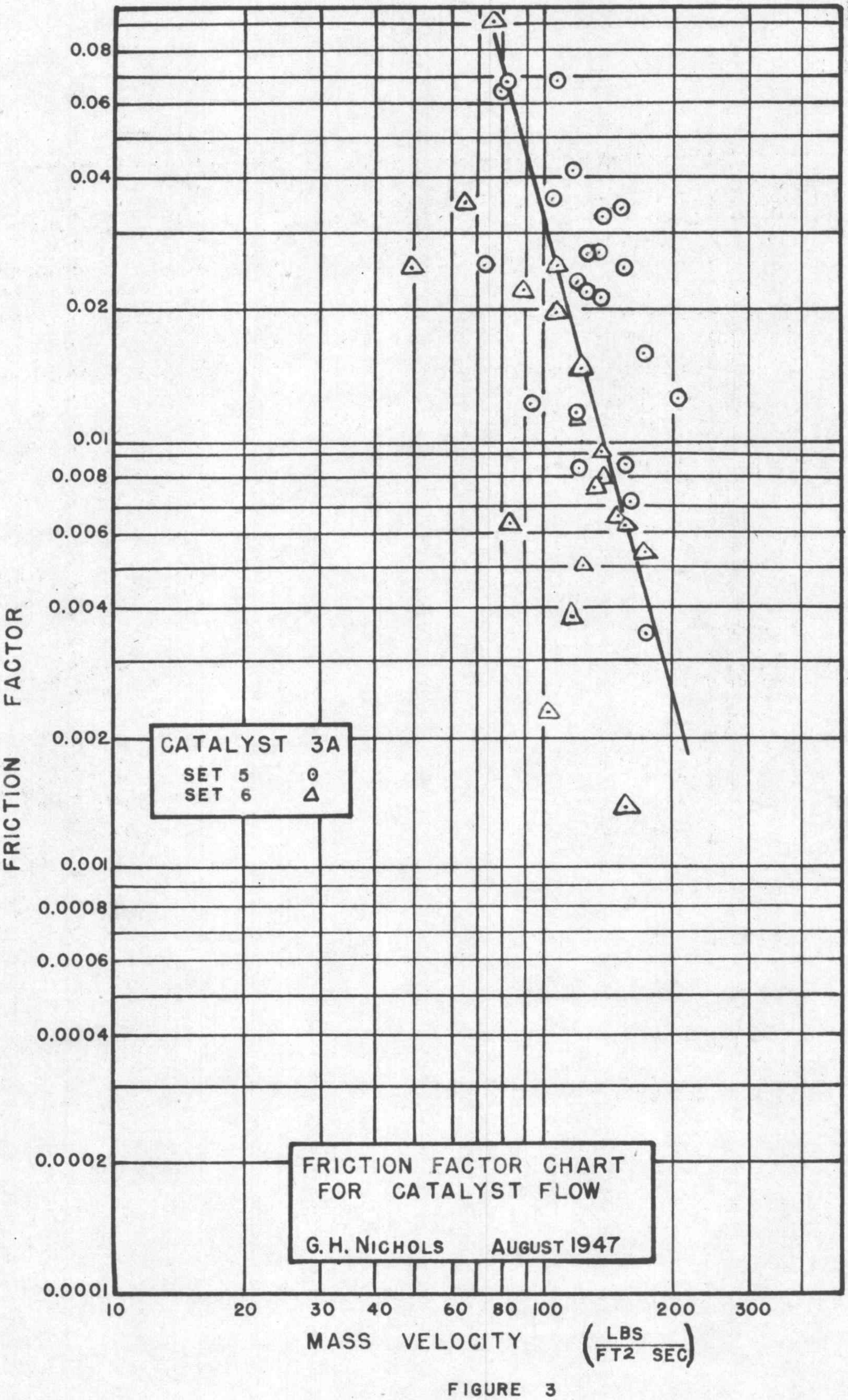

FRICTION FACTOR
MASS VELOCITY $\left(\frac{LBS}{FT^2\ SEC}\right)$
0.08
0.06
0.04
0.02
0.01
0.008
0.006
0.004
0.002
0.001
0.0008
0.0006
0.0004
0.0002
0.0001
10
20
30
40
60
80
100
200
300
FILTROL
SET 1 X
SET 2 Δ
SET 3 ▪
SET 4 O
FRICTION FACTOR CHART
FOR CATALYST FLOW
G. H. NICHOLS
AUGUST 1947

FIGURE 2



0.08
0.06
0.04
0.02
0.01
0.008
0.006
0.004
0.002
0.001
0.0008
0.0006
0.0004
0.0002
0.0001
FRICTION FACTOR
CATALYST 3A
SET 5 ⊙
SET 6 △
FRICTION FACTOR CHART
FOR CATALYST FLOW
G. H. NICHOLS AUGUST 1947
10
20
30
40
60
80
100
200
300
MASS VELOCITY (LBS / FT2 SEC)

FIGURE 3

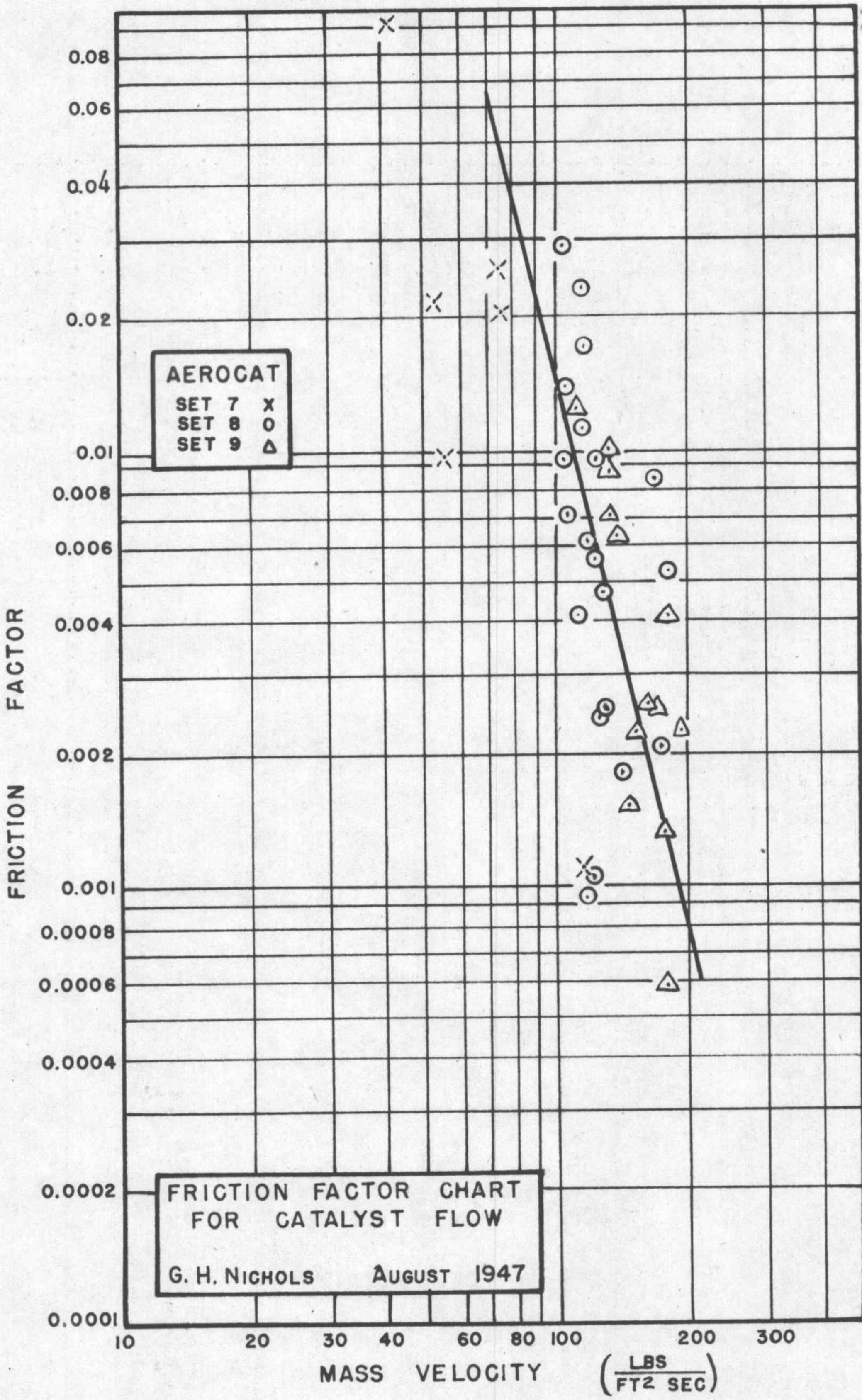

0.08
0.06
0.04
0.02
0.01
0.008
0.006
0.004
0.002
0.001
0.0008
0.0006
0.0004
0.0002
0.0001
FRICTION FACTOR
AEROCAT
SET 7 X
SET 8 O
SET 9 Δ
FRICTION FACTOR CHART
FOR CATALYST FLOW
G. H. NICHOLS AUGUST 1947
10 20 30 40 60 80 100 200 300
MASS VELOCITY (LBS / FT2 SEC)

FIGURE 4

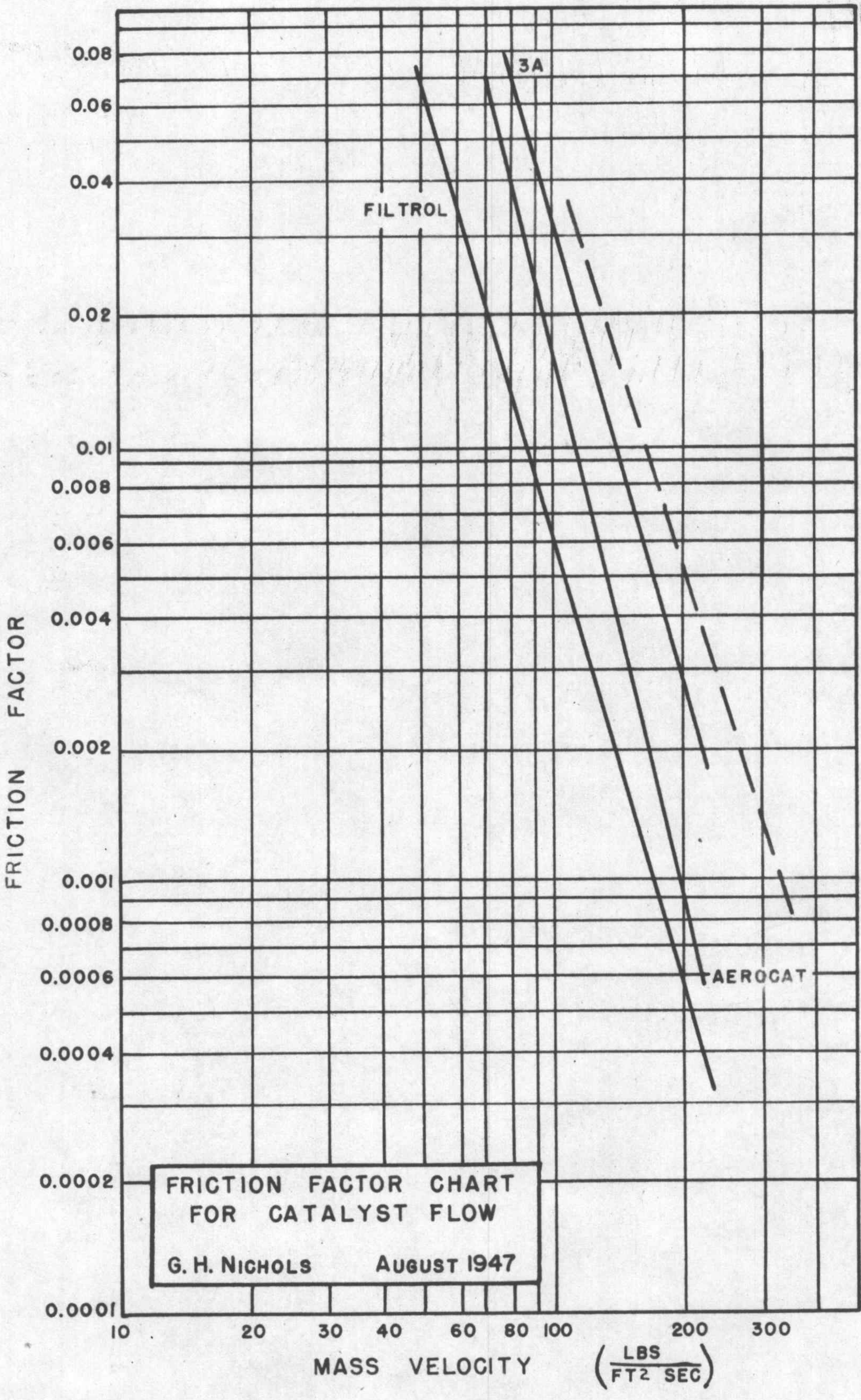

0.08
0.06
0.04
0.02
0.01
0.008
0.006
0.004
0.002
0.001
0.0008
0.0006
0.0004
0.0002
0.0001
FRICTION FACTOR
FILTROL
3A
AEROCAT
FRICTION FACTOR CHART
FOR CATALYST FLOW
G. H. NICHOLS
AUGUST 1947
10
20
30
40
60
80
100
200
300
MASS VELOCITY
LBS
FT2 SEC

FIGURE 5

These possible explanations do not, however, preclude variation due to experimental technique.

The discrepancy between the two Filtrol lines will need some explanation. Walton and Rynning (7) point out that differences in tube diameter appear to have little or no effect on the correlation as made and this appears to be borne out to some extent by the Catalyst 3A data. However, there is the possibility that this effect will vary to some extent with the nature of the substance under investigation. It must be pointed out also that there is not as yet sufficient information to make any definite conclusions along this line because correlations attempting to take into account the variance in diameters of the flow tubes appeared to be unsatisfactory. There is the possibility, however, since the data compiled here for Filtrol are not so profuse as that accumulated by the foregoing investigators, that a greater amount of data would have more nearly tended to coincide with the previous work.

The curves as drawn may be described by the following equations:

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(7) J. S. Walton and D. F. Rynning, loc. cit.

Catalyst	Investigator	Equation
Filtrol	Rynning	$f = (2.5)(10^5)/G^{3.34}$
Filtrol	Author	$f = (5.4)(10^4)/G^{3.48}$
3A	both	$f = (7.4)(10^5)/G^{3.75}$
Aerocat	Author	$f = (4.6)(10^6)/G^{4.25}$

The fact must be recognized that since the data fall into somewhat of a band, the lines chosen to represent them are not unique and the equations as offered are subject to some modification. Assuming that the differences in the characteristics of the curves are valid as presented, it is not unreasonable to connect these differences with the nature of the powdered material being handled. In this respect, it is pertinent to point out that pressure drops of the same magnitude are not to be expected for different materials of the same density flowing through the same tube at identical velocities; and this difference is apparently due to the physical characteristics of the materials. The characteristics pointed out in the description of the catalyst used probably all contribute to this variation.

The moisture content of the material introduced to the system is probably a highly contributing factor to its flow characteristics and it would no doubt be desirable to conduct further studies with materials of a constant degree of dryness.

The effect of the physical characteristics of powdered solids on their flow behavior is basically important and this information must be accumulated for many substances of a widely varying nature before general calculations can be made applicable to all systems of powdered solids in a flow system.

CONCLUSIONS

The foregoing results may be summarized with a few general conclusions;

<u>One</u>. The results of the studies to date on fluidized solids indicate that they may be treated much in the same manner as true fluids and the flow variables involved may be correlated with but slight variation on the classical treatment of these variables. The viscosity factor necessary for the usual treatment of the variables could not be predicted from the data compiled, but it is expected that this term, when made available, will modify the correlation as presented only slightly.

<u>Two</u>. It is shown that for small diameter glass flow tubes the tube diameter does not enter into the correlations as a major variable as may be expected from inspection of the classical treatment of the variables involved.

APPENDIX

SAMPLE CALCULATION

Set No. 6. Run No. 210

Data

Manometer reading	26	cm H_2O
Flow rate	264	gr/sec
Weight of catalyst trapped in tube	253	gr
Tube volume	690	cc
Overall length (including connection)	53	in
Distance between taps	41	in

Apparent Specific Gravity

$$\frac{253}{690} = 0.367$$

Corrected ΔP

$$(0.367)(41)(2.54) - 26 = 12.2 \text{ cm } H_2O$$

Velocity

$$\frac{(264)(53)}{(253)(12)} = 4.61 \quad \text{ft/sec}$$

Mass velocity

$$(0.367)(62.3)(4.61) = 105.5 \quad \frac{\text{lb}}{\text{ft}^2\text{sec}}$$

Friction factor

$$\frac{(12.2)(32.2)(0.997)}{(0.367)(2.54)(12)(2)(4.61^2)(41)} = 0.01981$$

EXPERIMENTAL DATA ON THE FLOW OF FLUID CATALYSTS

Run No	Manometer cm of H_2O	Flow Rate $\frac{gr}{sec}$	Quant in Tube gr	Apparent Sp Gr	ΔP due to Flow cm of H_2O	Velocity u $\frac{ft}{sec}$	Mass Velocity G $\frac{lb/ft^2}{sec}$	Friction Factor f
				Set No. 1. Filtrol in Tube No. 1				
1	6.5	32.5		run incomplete				
2	13	53.5	71.3	0.0993	- 2.69			
3	12	87.1	104	1448	3.05	3.69	33.2	0.0205
4	11	76.8	226	315	21.8	1.50	29.5	408
5	13	84.9	72.4	1009	- 2.52			
6	17	102.9	251	349	19.3	1.81	39.3	223
7	38	155.4	136	1891	-18.31			
8	40	86.4	81.3	1132	-28.22			
9	23	124.2	97.4	1358	- 8.9			
10	15	89.5	64.5	0898	- 5.66			
11	9	46.0	45.7	0636	- 2.49			
12	11	76.5	34.2	0476	- 6.05			
13	13	79.7	65.7	0915	- 3.49			
14	49	137.0	185.5	258	-46.32			
15	13	50.1	32.4	0451	- 8.31			
16	11	53.7	37.2	0507	- 5.73			
17	6	42.3	26.2	0365	- 2.20			
18	6	44.1	22.5	0314	- 2.73			
19	28	139.0	115.5	161	-11.28			
20	17	99.6	203	283	12.4	2.17	38.3	1228
21	10	61.6	35.7	0497	- 4.83			
22	11	65.3	50.0	0696	- 3.76			
23	17	81.0	58.5	0815	- 8.53			
24	15	84.2	82.0	1141	- 3.19			
25	13	81.5	82.5	1149	- 1.07			
26	17	154.9	113	1571	- 0.65			
27	23	142.8	100	1391	- 8.51			
28	11	61.3	37	0516	- 5.64			
29	7	48.1	20	0279	- 4.10			
30	10	48.2	47	0655	- 4.19			
31	14	130	51	0710	- 6.62			
32	14	60.5	32	0446	- 9.36			
33	12	57.7	31	0432	- 7.50			
34	24	97.8	100	1391	- 9.51			
35	20	93.8	42	0585	-13.93			
36	17	70.8	158	220	5.9	1.98	27.1	0901

Run No	Manometer cm of H_2O	Flow Rate $\frac{gr}{sec}$	Quant in Tube gr	Apparent Sp Gr	ΔP due to Flow cm of H_2O	Velocity u $\frac{ft}{sec}$	Mass Velocity G $\frac{lb/ft^2}{sec}$	Friction Factor f
37	11	62.6	30	0.0418	- 6.65			
38	19	82.8	57	0783	-10.86			
39	21	103.0	102	1421	- 6.2			
40	14	62.4	50	0696	- 6.76			
41	16	75.6	24	0339	-12.48			
42	17	106.2	112	1561	- 0.78			
43	17	85.1	58	0809	- 8.60			
44	23	93.9	138	1921	- 3.0			
45	23	126.0	98	1365	- 8.81			
46	19	94.6	46	0641	-12.34			
47	10	59.4	26	0362	- 6.24			
48	23	133.5	73	1018	-12.42			
49	21	114.1	85	1182	- 8.70			
50	27	103.9	65	0906	-15.57			
51	15	91.0	68	0948	- 5.15			
52	17	97.1	65	0906	- 7.57			
		Set No. 2.	Filtrol in	Tube No. 4				
53	41	118.9	196	0.284	-11.5			
54	27	138.8	185	268	0.9	3.32	55.5	0.00391
55	30	236	215	313	2.6	4.86	94.8	00448
56	19	125	150	218	3.7	3.69	50.1	01593
57	32	156.8	70	1015	-21.45			
58	31	187.0	136	1975	- 8.55			
59	20	149.1	67	0972	- 9.90			
60	38	158.2	157	228	-14.3			
61	21	152.8	89	1290	- 7.60			
62	24	146.1	106	1538	- 8.0			
63	28	164.3	190	275	0.6	3.83	65.5	001890
64	50	397	301	436	- 4.6			
65	27	328	179	260	0			
66	17	153.5	32	0646	-12.17			
67	11	115.4	54	0784	- 2.85			
68	27	189.0	95	1378	- 2.69			
69	22	152.2	130	1881	- 2.42			
70	40	289	235	341	- 4.5			
71	26	236	158	229	- 2.2			

Run No	Manometer cm of H_2O	Flow Rate $\frac{gr}{sec}$	Quant in Tube gr	Apparent Sp Gr	ΔP due to Flow cm of H_2O	Velocity u $\frac{ft}{sec}$	Mass Velocity G $\frac{lb/ft^2}{sec}$	Friction Factor f
72	30	195	123	0.1780	-11.5			
73	27	236	164	238	- 2.3			
74	37	245	200	290	- 6.9			
75	16	155.4	78	1130	- 4.25			
76	40	252	242	341	- 4.5			
77	37	288	208	301	- 5.7			
78	24	247	151	219	- 1.2			
79	40	204	125	1812	-21.15			
80	30	271	135	1954	- 9.7			
81	20	112.5	89	1291	- 6.56			
82	13	95.3	110	1595	3.6	3.82	38.0	0.0261
83	14	110.5	80	1160	- 1.94			
84	16	123.8	113	1638	1.0	4.84	49.4	00333
85	19	270	136	1971	0.5	8.78	107.8	000419
86	27	218	149	216	- 4.5			
87	20	88	107	1550	- 2.89			
88	17	147	108	1566	- 0.72			
89	20	133.2	123	1781	- 1.49			
90	22	127.5	106	1536	- 6.02			
91	4	54.5	30	0435	0.42	8.05	21.8	001902
92	19	135.8	97	1406	- 4.39			
93	27	167.2	123	1781	- 8.49			
94	44	301	267	387	- 3.8			
95	40	312	239	347	- 3.9			
96	40	382	261	378	- 0.7			
97	42	332	227	329	- 7.8			
98	38	264	193	280	- 8.9			
99	40	409	256	371	- 1.4			
100	42	215	317	459	- 4.3			
101	32	209	150	217	- 9.4			
			Set No. 3. Filtrol in Tube No. 2					
102	36	220	299	0.416	- 1.8			
103	27	186.5	197	274	- 4.5			
104	31	255	232	327	- 4.2			
105	15	145.5	79	1100	- 6.0			

Run No	Manometer cm of H_2O	Flow Rate $\frac{gr}{sec}$	Quant in Tube gr	Apparent Sp Gr	ΔP due to Flow cm of H_2O	Velocity u $\frac{ft}{sec}$	Mass Velocity G $\frac{lb/ft^2}{sec}$	Friction Factor f
106	12	105.0	90	0.1251	- 1.75			
107	12	114.2	110	1551	0.56	4.64	44.3	0.00286
108	15	140	140	1950	0.98	4.42	53.7	00434
109	25	222	166	231	- 6.1			
110	31	200	240	334	- 3.6			
111	32	224	272	378	- 1.0			
112	32	310	184	256	-11.0			
113	27	271	175	244	- 7.0			
114	37	316	391	545	7.7	3.58	121.8	01858
115	35	285	299	417	- 0.8			
116	33	236	301	420	1.4	3.47	90.8	00467
117	33	239	255	356	- 3.8			
118	36	331	336	457	2.4	4.35	124.0	00467
119	36	342	308	429	- 0.8			
120	40	296	332	239	-12.7			
121	39	587	293	409	- 5.5			
122	40	412	264	368	- 9.9			
123	30	286	190	265	- 8.3			
124	31	242	437	609	13.9	2.45	92.8	0871
125	32	249	158	221	-13.95			
126	38	365	326	454	- 0.7			
127	37	464	281	392	- 4.9			

Set No. 4. Filtrol in Tube No. 3

128	33	383	337	0.469	- 1.7			
129	32	363	330	459	- 1.4			
130	32	418	341	475	- 0.3			
131	24	512	267	362	0.1	8.47	191.2	0.000795
132	35	399	500	697	11.5	3.53	153.5	0274
133	30	488	362	504	3.6	5.97	187.5	00412
134	37	384	412	575	1.3	4.12	147.5	00274
135	29	338	254	354	- 5.4			
136	27	329	268	374	- 9.8			
137	34	434	394	549	- 8.7			
138	26	266	235	327	- 5.0			
139	30	483	220	307	-10.3			
140	16	277	266	370	7.7	4.61	106.5	0203

Run No	Manometer cm of H_2O	Flow Rate $\frac{gr}{sec}$	Quant in Tube gr	Apparent Sp Gr	ΔP due to Flow cm of H_2O	Velocity u $\frac{ft}{sec}$	Mass Velocity G $\frac{lb/ft^2}{sec}$	Friction Factor f
141	28	131.1	325	0.453	1.1	1.782	50.3	0.01578
142	25	338	286	399	0.6	5.22	130	001128
143	36	221	363	506	- 3.6			
144	25	301	339	472	5.3	3.92	115.2	01514
145	24	371	278	387	0.8	5.90	142.1	001231
146	34	272	306	426	- 6.7			
147	31	411	334	465	- 1.2			
148	35	280	347	483	- 2.8			
149	37	538	341	475	- 5.3			
150	32	346	359	500	1.4	4.26	132.5	00285
151	34	264	365	508	- 0.1			
152	35	277	333	464	- 4.1			
153	30	285	356	496	3.1	3.54	109.2	01034
154	37	348	387	526	-11.2			
155	28	447	317	441	1.4	6.24	171.5	001680
156	36	319	379	553	0.8	3.73	128.8	00212
157	37	287	406	566	0.7	3.12	110.0	00266
158	36	380	403	562	1.4	4.16	146.0	00298
159	37	536	389	542	- 0.9			
160	35	326	463	645	8.0	3.12	125.0	0261
161	32	367	356	496	1.0	4.56	140.9	00201
162	30	600	330	459	0.6	8.04	230	000418
163	36	315	394	548	0.5	3.54	121.0	001514
164	33	470	398	555	4.0	5.21	180.0	00549
165	27	504	320	446	2.7	6.96	193.3	00257
166	34	308	371	517	0.4	3.67	118.0	001178
167	30	288	341	475	1.6	3.74	110.8	00495
168	32	321	369	514	2.2	3.85	123.1	00595
169	33	417	304	423	- 4.8			
170	31	398	353	491	1.7	4.98	152.1	00288
171	26	350	401	559	11.3	3.86	134.2	0270
172	30	362	298	415	- 2.3			
173	34	231	437	609	6.6	2.33	205	0414
174	35	330	378	526	0			
175	36	264	373	520	- 1.4			

Run No	Manometer (cm of H_2O)	Flow Rate (gr/sec)	Quant in Tube (gr)	Apparent Sp Gr	ΔP due to Flow (cm of H_2O)	Velocity u (ft/sec)	Mass Velocity G (lb/ft^2/sec)	Friction Factor f
Set No. 5. Catalyst 3A in Tube No. 3								
176	20	186.5	264	0.368	4.5	3.12	71.5	0.0260
177	20	207	334	465	10.9	2.74	79.2	0646
178	16	307	337	469	15.2	4.03	117.8	0414
179	18	275	318	443	11.5	3.82	105.0	0367
180	18	315	243	339	4.6	5.74	121.0	00850
181	22	210	358	498	11.1	2.60	80.5	0680
182	18	331	326	454	12.2	4.49	127.0	0275
183	23	300	367	436	11.0	3.61	114.9	0341
184	18	322	302	573	10.0	4.72	123.5	0219
185	24	395	319	455	5.6	5.48	152.0	00865
186	24	408	313	615	5.0	5.76	156.8	00715
187	26	386	412	539	12.1	4.14	151.8	0255
188	27	470	327	499	3.3	6.35	179.8	00360
189	25	280	441	371	15.9	2.81	107.5	0699
190	24	525	387	472	11.9	6.01	201	01260
191	22	444	358	488	11.2	5.46	169.1	01559
192	19	311	266	457	5.7	5.17	119.4	01180
193	19	340	339	505	12.4	4.44	130.5	0275
194	18	346	350	488	14.5	4.38	133.1	0318
195	21	316	328	457	9.4	4.26	121.2	0233
196	24	352	363	505	9.6	4.29	134.8	0213
Set No. 6. Catalyst 3A in Tube No. 4								
197	32	396	267	0.387	8.2	6.56	158.1	0.00625
198	39	368	196	284	- 9.5			
199	34	347	276	400	7.6	5.56	138.2	00785
200	34	330	278	403	7.9	5.25	131.9	00911
201	35	186	225	326	- 1.1			
202	34	257	168	244	- 8.6			
203	30	231	171	248	- 4.2			
204	26	192	324	470	22.8	2.62	76.4	0901
205	32	222	273	396	9.2	3.60	88.5	0228
206	16	73.4	170	246	9.6	1.91	29.2	1368
207	36	286	182	264	- 8.5			
208	24	297	226	328	10.1	5.81	118.4	01158

Run No	Manometer cm of H_2O	Flow Rate $\frac{gr}{sec}$	Quant in Tube gr	Apparent Sp Gr	ΔP due to Flow cm of H_2O	Velocity u $\frac{ft}{sec}$	Mass Velocity G $\frac{lb/ft^2}{sec}$	Friction Factor f
209	26	164.5	233	0.338	9.2	3.12	65.7	0.0355
210	26	264	253	367	12.2	4.61	105.5	01981
211	31	292	227	329	3.2	5.69	116.5	00385
212	37	313	237	343	- 1.3			
213	30	225	151	219	- 7.2			
214	34	258	235	341	1.5	4.85	102.8	00238
215	36	466	221	320	- 2.7			
216	30	207	218	316	2.8	4.20	82.7	00643
217	32	228	250	363	5.8	4.04	91.4	01248
218	34	310	295	428	10.5	4.65	124.0	01449
219	52	348	210	304	-20.4			
220	37	364	225	326	- 3.1			
221	36	386	196	284	- 6.5			
222	36	386	250	363	1.8	6.81	153.8	001359
223	30	426	255	369	8.4	7.40	170.1	00531
224	31	346	260	377	8.2	5.88	138.1	00800
225	21	124.5	173	251	5.1	3.18	49.6	0255
226	30	260	288	418	13.5	3.99	103.8	0258
227	32	306	241	349	4.3	5.60	121.4	00501
228	38	202	241	349	- 1.7			
229	40	374	310	449	6.7	5.34	148.9	00666

Set No. 7. Aerocat in Tube No. 4

230	40	191.0	203	0.438	5.6	2.79	76.3	0.0209
231	53	112.1	396	573	6.5	1.252	44.8	0918
232	42	140.8	288	418	1.5	2.16	56.1	00978
233	35	182.0	191	277	- 6.2			
234	37	189.2	211	306	- 5.2			
235	55	240	298	432	-10.1			
236	52	200	270	391	-11.4			
237	29	109.2	150	217	- 6.3			
238	37	282	250	363	0.8	4.98	112.7	001140
239	34	186.2	183	265	- 6.4			
240	52	232	237	344	-16.2			
241	52	234	270	391	-11.3			
242	36	195.0	228	331	- 1.6			
243	44	266	288	418	- 0.5			

Run No	Manometer cm of H_2O	Flow Rate $\frac{gr}{sec}$	Quant in Tube gr	Apparent Sp Gr	ΔP due to Flow cm of H_2O	Velocity u $\frac{ft}{sec}$	Mass Velocity G $\frac{lb/ft^2}{sec}$	Friction Factor f
244	36	243	176	0.255	- 9.5			
245	56	135.9	393	570	2.3	1.529	54.3	0.0222
246	38	273	199	289	- 8.0			
247	55	184	397	576	5.0	2.05	73.6	0268
248	38	277	176	255	-11.5			
249	45	243	210	305	-13.3			
250	50	144.2	281	407	- 7.7			
251	39	123.7	226	328	- 4.9			
252	49	253	230	334	-14.3			
		Set No. 8. Aerocat in Tube No. 3						
253	26	445	349	0.486	6.3	5.63	170.4	0.00845
254	32	335	357	497	1.1	4.15	128.0	00264
255	30	396	297	414	- 2.5			
256	30	484	323	450	- 0.1			
257	30	370	322	448	- 0.2			
258	27	369	303	423	1.1	5.38	141.4	001838
259	35	363	374	521	- 0.3			
260	25	326	282	393	1.2	5.11	125.1	00245
261	32	335	367	511	2.0	4.04	128.5	00475
262	34	277	393	548	2.5	3.12	106.2	00957
263	28	372	302	421	0			
264	26	311	369	514	8.2	3.73	119.2	0235
265	29	461	332	463	1.8	6.14	176.8	00211
266	37	317	419	584	1.8	3.35	121.5	00564
267	29	471	359	500	4.3	5.80	180.4	00524
268	38	297	439	612	2.8	3.17	120.9	00945
269	38	400	430	599	1.8	3.18	118.5	00611
270	36	298	437	608	4.5	3.01	113.8	01680
271	30	269	313	436	9.0	3.80	103.0	0293
272	22	309	269	375	3.0	5.08	118.9	00611
273	25	290	287	400	1.6	4.47	111.3	00410
274	28	274	325	453	2.2	3.74	105.2	00715
275	25	296	273	381	0.4	4.80	113.8	000930
276	32	422	346	482	0.1	5.40	162.0	000071
277	30	307	328	457	0.4	4.14	117.5	001048

Run No	Manometer cm of H_2O	Flow Rate $\frac{gr}{sec}$	Quant in Tube gr	Apparent Sp Gr	ΔP due to Flow cm of H_2O	Velocity u $\frac{ft}{sec}$	Mass Velocity G $\frac{lb/ft^2}{sec}$	Friction Factor f
278	32	304	384	0.536	3.7	3.51	117.1	0.01143
279	31	278	329	458	- 0.5			
280	35	279	416	579	3.5	2.97	106.8	01408
Set No. 9. Aerocat in Tube No. 2								
281	40	372	299	0.417	- 5.8			
282	34	358	336	468	4.4	4.71	137.0	0.00708
283	34	391	293	408	- 0.5			
284	33	382	299	417	1.2	5.66	146.5	001519
285	38	390	346	482	1.6	4.99	149.8	00223
286	36	443	320	446	0.6	6.13	170.1	000597
287	34	496	339	472	4.8	6.48	190.5	00404
288	36	512	340	474	2.9	6.66	196.1	00230
289	39	417	360	501	2.1	5.12	159.5	00268
290	40	470	308	428	- 4.8			
291	38	450	344	479	1.3	5.79	172.1	001352
292	40	354	395	551	5.2	3.97	136.0	01004
293	32	351	327	456	5.4	4.75	134.9	00878
294	45	291	431	600	4.2	2.98	111.2	01319
295	40	415	368	513	2.0	4.98	158.9	00264
296	38	365	365	508	3.7	4.42	139.5	00623