AN INVESTIGATION OF THE SIMULTANEOUS DRYING AND GRINDING OF ALFALFA

Thesis for the Degree of M. S.

MICHIGAN STATE COLLEGE

Wilbur William Kennett

1950

This is to certify that the

thesis entitled

AN INVESTIGATION OF THE SIMULTANEOUS

DRYING AND GRINDING OF ALFALFA

presented by

Wilbur William Kennett

has been accepted towards fulfillment
of the requirements for

Master's degree in Chemical Engineering

Major professor

Date July 7, 1950

O-169

AN INVESTIGATION OF THE SIMULTANEOUS DRYING AND GRINDING OF ALFALFA

By

WILBUR WILLIAM KENNETT

A THESIS

Submitted to the School of Graduate Studies of Michigan
State College of Agriculture and Applied Science
in partial fulfillment of the requirements
for the degree of

MASTER OF SCIENCE

Department of Chemical Engineering

1950

ACKNOWLEDGEMENT

The author is greatly appreciative of the untiring help and valuable advice of Professor J. W. Donnell. Appreciation is also extended to W. B. Clippinger for his advice and assistance in the mechanical aspects of the problem.

TABLE OF CONTENTS

INTRODUCTION

This paper deals with the mass transfer and mass transfer coefficients while drying and grinding alfalfa simultaneously. This information is greatly needed in the field of alfalfa meal production.

The method now employed to produce alfalfa meal is the one by which the drying process occurs first and then the grinding process. In this investigation both processes will occur simultaneously to take advantage of the newly exposed surfaces to give a faster drying rate.

The extent of this work was limited to the variation of three factors:

size of alfalfa;

temperature at which drying took place;

the percent moisture in the feed.

The range in modified Reynold's number varied from 20 to 125.

HISTORY

To the author's knowledge no investigation has been made on the simultaneous drying and grinding of alfalfa. There is much publicized information on the drying of alfalfa both in the field and in the barn. There is also information concerning the drying of chopped alfalfa. At present there are two firms manufacturing equipment for the drying of chopped alfalfa, namely the Heil Company, and the Arid-Aire Manufacturing Company.

Kettenring, Manderfield, and Smith (7) did some work on mass transfer in fluidized beds, and made the following correlation:

(1) $$k_g = \frac{.00180}{p_m M_m G} \left(\frac{D_p G}{\mu}\right)^{0.30}$$

This correlation varies somewhat with the work done by Gamson, Thodos, and Hougen (5). This work was for mass transfer in a fixed bed.

(2) $$k_g = \frac{16.8 G}{p_{gf} M_m} \left(\frac{D_p G}{\mu}\right)^{-1.0} \left(\frac{\mu}{\rho D_v}\right)^{-\frac{2}{3}}$$

Both of these correlations are for laminar flow $Re < 60$.

These two correlations indicate that the farther away from a fixed bed the system becomes, the more positive is the exponent for the Reynold's number.

McCune and Wilhelm's (9) investigation indicates that it is not the high transfer coefficient but rather the great drying surface that gives a rapid rate of drying in fluidized bed.

Chilton and Colburn (2) have formulated a method of correlating mass transfer. This is by the use of the J_D and the Reynold's number where:

(3) $$J_D = \frac{k_g \, p_{gf} \, M_m}{G} \left[\frac{\mu}{\rho \, D_v} \right]^{\frac{2}{3}}$$

In this paper the same method of correlation will be used.

EQUIPMENT

The equipment used in this work is as follows:

McCormick-Deering Hammer Mill No. 4-E complete with motor.

Specifications for Hammer Mill

Speed, full load	2980
Diameter of rotor, hammers extended	12 in.
Power	7.5 H. P.
Grinding plate area	123 sq. in.
Screen area	148 sq. in.
Total grinding area	271 sq. in.
Blower fan	10 3/8" diameter, 5 wings, 3 1/16" wide
Pipe size	4" diameter
Cyclone	diameter 14.5 in., overall height 36 in.

Surface Combustion Burner taking 35 psi propane

Orsat analyser

Temperature recording galvanometer

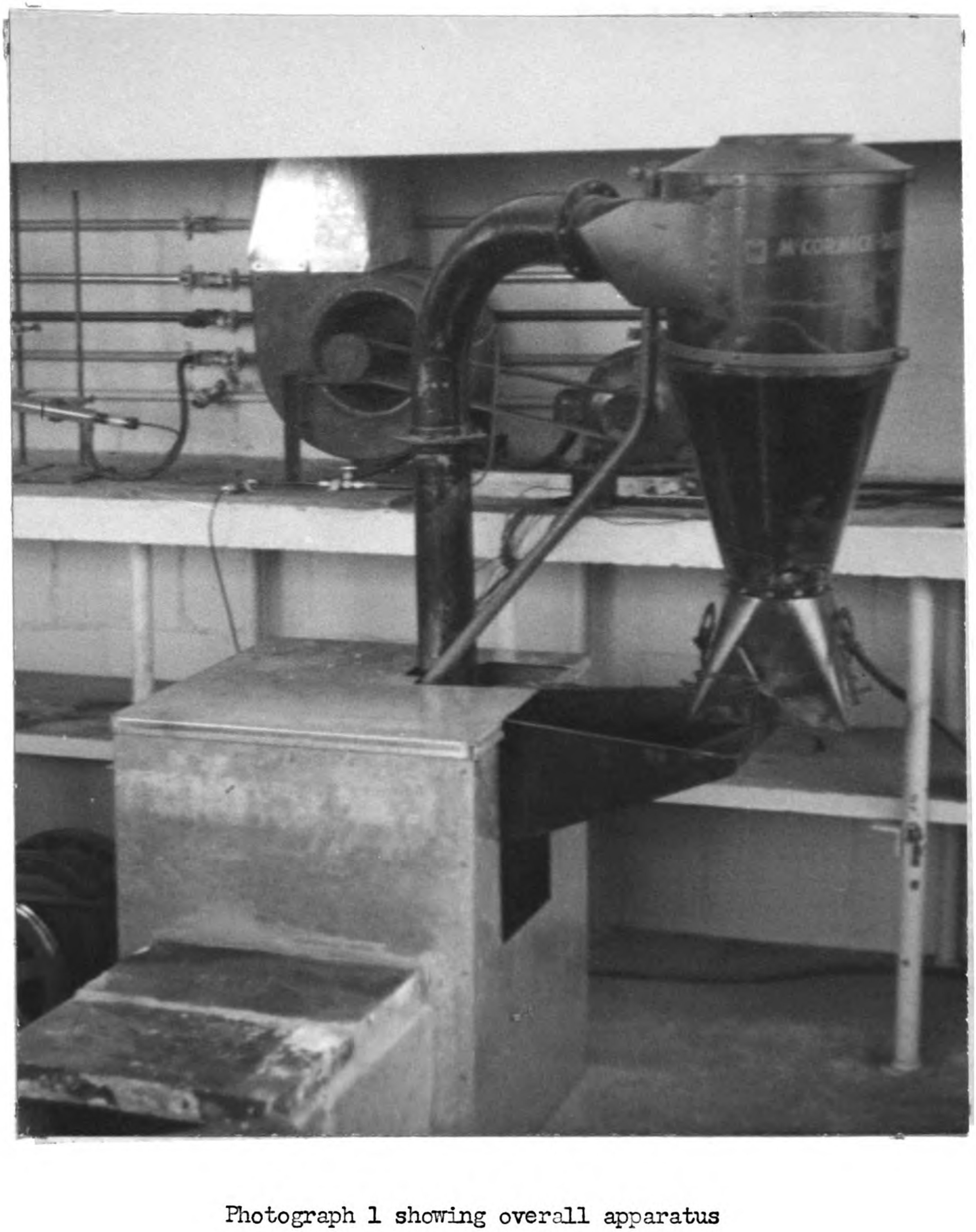
Chromel-alumel thermocouples

Westinghouse type T. A. Industrial Analyser, P. F., volts, amperes, kilowatt meter

Scales to weigh the feed and propane used per run

Cenco Analytical Balance CM - 777

Drying oven at 120° C.



Photograph 1 showing overall apparatus

This equipment was revised to draw in hot flue gases below the screen. These hot gases picked up the ground alfalfa and carried it to the cyclone where the alfalfa meal was separated from the hot gases. During this time the drying took place.

Photograph No. 1 shows the entire equipment layout. The hammer mill was enclosed to safeguard against damage to the building or personnel working with the apparatus.

Photograph 2 showing Burner,

Hammer Mill and Cyclone

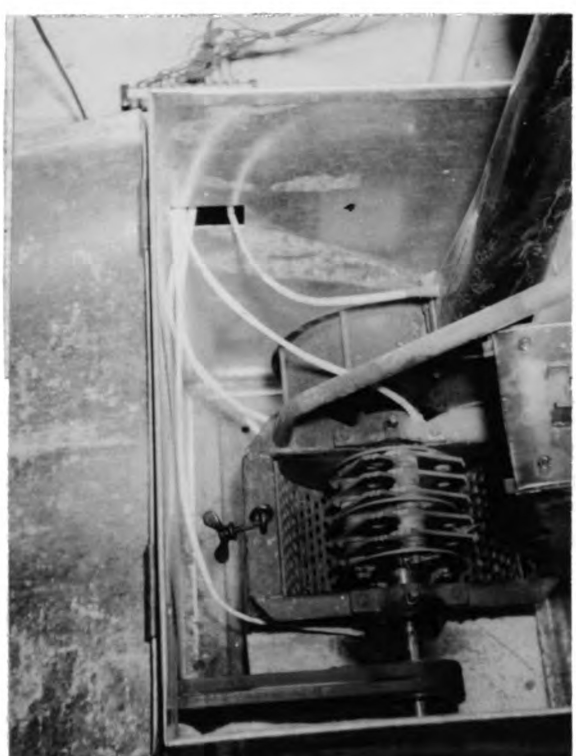
In the foreground of photograph No. 2 is the burner and burner chamber. The open space in the top of the burner chamber could be adjusted to vary the excess air; thus varying the temperature of the entering gases.

Photograph 3 showing temperature recorder

and exhaust fan in background.

Photograph No. 3 shows the exhause fan in the background. This fan was installed to prevent a large dust accumulation in the room.

Photograph 4 showing propane
tank and scales.



Photograph 5 showing hammers,
screen in place, and thermocouples.

Photograph No. 5 shows the hammers and screen in place. This photograph also shows the location of several of the thermocouples. The thermocouples were located as follow:

#1 in the inlet gas stream.

#2 on the roller bearing opposite the inlet gases. This was used to keep a check on the bearings so they would not burn out.

#3 in the chamber just below the screen.

#4 in the chamber just below the screen opposite #3.

#5 in the gas stream at the outlet of the blower.

#6 on the outside of the pipe leading to the cyclone. This was to indicate the temperature of the wall so a radiation correction could be made for the thermocouples.

#0 in the cyclone.

Samples for the orsat analysis were drawn from two points; one from the inlet stream and one from the pipe connecting the hammer mill with the cyclone — spots #01 and #02 respectively. These samples were cooled by means of a water cooled condenser before being analysed.

Precaution was taken to prevent damage to the building or equipment by using asbestos sheets where the temperature might be too high.

PROCEDURE

Preparation of alfalfa:

The alfalfa was cut into lengths that averaged one inch. This chopped alfalfa contained between 70 and 80 percent moisture. This alfalfa was mixed with pre-dried alfalfa meal which contained approximately 10% moisture.

The hammer mill was first started; then the burner was lighted. Time was allowed for the burner chamber and hammer mill to come to temperature before the run was made. After constant temperature was reached, readings were taken at all of the indicated locations. The temperatures were also read during the run and at the end of each run.

An orsat analysis was made for each of the check points before the run and during the run.

The ready mixed feed was fed at the same time recording the weight of propane and also the time. The alfalfa was fed as fast as possible without causing an overload on the heat coils which would turn off the motor. This happened twice. An ampere meter was placed in the line to indicate the degree of loading placed on the hammer mill and motor. At the end of the run the time and weight of propane were again recorded.

Moisture determination:

The moisture contents of the dry feed, wet feed and product were determined by accurately weighing approximately 10 gram samples of each, and then drying these samples at 120° C. until they came to constant weight. Since the ratio of dry feed to wet feed was known, the moisture content of the feed was determined.

Density determination:

The absolute densities for the different runs were determined by placing a weighed amount of the ground alfalfa in a measured volume of kerosene. The increase in volume was recorded which enabled the density calculation. Kerosene was used instead of water because the alfalfa will absorb water giving an erroneous density.

Col. 1 Run No.	Col. 2 Wt. of Alfalfa Feed (lbs.)	Col. 3 Length of run (min.)	Col. 4 Feed Rate (#/min.)	Col. 5 Moisture in feed ($\frac{\# H_2O}{\# \text{dry alfalfa}}$)
1	No good. The % moisture was too high and the screen plugged.			
2	30	25	1.2	.585
3	15	20	.75	.590
4	15	14	1.06	.601
5	20	13	1.539	.369
6	20	9	2.222	.364
7	20	10	2.00	.334
8	20	8	2.5	.302
9	30	4.5	6.67	.246
10	25	5.5	4.55	.288
11	20	4.0	5.0	.368
12	12	3.5	3.43	.490
13	30	6	5.0	.252
14	25	4.5	5.56	.271
15	20	5.0	4.00	.311
16	No good. The hammer mill motor stopped because the alfalfa was being fed too fast. The screen did not plug.			
17	30	6.2	4.84	.282
18	25	5.0	5.0	.315
19	20	5.5	3.64	.339
20	30	7.0	4.29	.252
21	25	5.0834	4.92	.264
22	20	5.917	3.38	.300
23	10.5	4.5	2.335	.411

Col. 1 Run No.	Col. 6 Moisture in product ($\frac{\text{\# water}}{\text{\# dry alfalfa}}$)	Col. 7 (Col. 5 minus Col. 6)	Col. 8 w' ($\frac{\text{\# water}}{\text{\# dry alfalfa - min.}}$)
2	.128	.457	21.1
3	.0590	.531	24.55
4	.0808	.5202	24.05
5	.0928	.2762	12.77
6	.05	.314	14.52
7	.0192	.3144	14.50
8	.0477	.2543	11.73
9	.0894	.1566	7.23
10	.1032	.1848	8.54
11	.1091	.2589	11.97
12	.100	.390	18.01
13	.0703	.1817	8.39
14	.0528	.2182	10.10
15	.0737	.2373	10.97
17	.1075	.1745	8.05
18	.0729	.2421	11.19
19	.0538	.2852	13.15
20	.068	.184	8.49
21	.045	.219	10.10
22	.043	.257	11.85
23	.0244	.3866	17.80

Col. 1 Run No.	Col. 9 w $\left(\frac{\#\ \text{mols.}}{\text{hr.}}\right)$	Col. 10 (1 - wt. fr. H_2O in feed)	Col. 11 Absolute Density of Alfalfa (#/cu.ft.)	Col. 12 Average diameter of particle (ft.)
2	1.155	.6312	68	.001745
3	.834	.62957	68	.001745
4	1.048	.62433	68	.001745
5	1.038	.73095	68	.001745
6	1.705	.73382	68	.001745
7	1.572	.75	68	.001745
8	1.63	.7685	68	.001745
9	2.824	.8108	68	.001745
10	2.125	.7765	68	.001745
11	3.15	.731	68	.001745
12	2.99	.671	68	.001745
13	2.42	.7991	79.1	.001471
14	3.19	.7875	79.1	.001471
15	2.378	.7624	79.1	.001471
17	2.2	.7802	83.5	.001099
18	3.075	.7606	83.5	.001099
19	2.58	.7468	83.5	.001099
20	2.10	.7994	83.5	.000793
21	2.84	.7908	83.5	.000793
22	2.23	.7699	83.5	.000793
23	2.13	.7089	83.5	.000793

Col. 1 Run No.	Col. 13 a $\left(\frac{\text{sq. ft.}}{\text{cu. ft.}}\right)$	Col. 14 Wt. of propane per run (oz.)	Col. 15 Rate propane (#/min.)	Col. 16 $\frac{\text{\# air}}{\text{\# propane}}$
2	.508	30	.075	91.2
3	.317	33	.103	67.7
4	.448	22	.0983	56.1
5	.65	12	.0578	100.4
6	.941	20	.139	29.17
7	.846	45	.281	23.15
8	1.059	12	.0939	35.8
9	2.82	4.0	.0556	47.0
10	1.927	8.0	.091	47.0
11	2.118	3.0	.0459	47.0
12	1.45	4.0	.0715	47.0
13	2.158	9.0	.0939	37.9
14	2.4	6.0	.0833	37.9
15	1.725	8.0	.100	37.9
17	2.65	10	.1007	30.4
18	2.74	9.0	.1125	30.4
19	1.991	10	.1135	30.4
20	3.25	11	.0983	26.95
21	3.73	8.0	.0983	26.95
22	2.56	10	.1055	26.95
23	1.77	8.0	.111	26.95

Col. 1 Run No.	Col. 17 Total wt. rate of flue gas (#/min.)	Col. 18 Mol. % H_2O in gas	Col. 19 G' (#/min. sq. ft.)	Col. 20 G (#/hr. sq. ft.)
2	6.92	2.55	79.4	4760
3	7.08	3.217	81.0	4860
4	5.61	3.358	64.25	3855
5	5.86	2.485	67.1	4030
6	4.19	4.10	48.0	2880
7	6.79	4.95	78.9	4740
8	3.45	3.32	39.5	2370
9	2.662	3.125	30.5	1830
10	4.36	3.125	49.9	2995
11	2.25	3.125	25.75	1545
12	3.43	3.125	39.25	2360
13	3.655	3.139	41.8	2510
14	3.24	3.139	37.1	2225
15	3.89	3.139	44.5	2670
17	3.165	3.49	36.25	2178
18	3.54	3.49	40.50	2430
19	3.56	3.49	40.80	2450
20	2.745	3.52	31.42	1889
21	2.745	3.52	31.42	1889
22	2.945	3.52	33.75	2023
23	3.10	3.52	35.5	2130

Col. 1 Run No.	Col. 21 Mol. wt. of gas	Col. 22 Temp. of TC # 5 (^{o}F)	Col. 23 True gas temp. (^{o}F)	Col. 24 Density of gas (#/cu.ft.)	Col. 25 Viscosity of gas (#/ft.hr.)
2	28.00	270	279	.0520	.0537
3	28.02	310	320	.0493	.0562
4	28.00	370	386	.0454	.0593
5	27.95	300	310	.0499	.0556
6	27.90	410	430	.0432	.0629
7	27.93	530	563	.0375	.0682
8	27.94	400	419	.04375	.0607
9	27.93	390	408	.0443	.0605
10	27.93	400	419	.04375	.0607
11	27.93	390	408	.0443	.0605
12	27.93	390	408	.0443	.0605
13	27.89	370	386	.0454	.0593
14	27.89	375	391	.0451	.060
15	27.89	365	380	.04575	.0593
17	28.00	380	397	.0448	.0603
18	28.00	390	408	.0443	.0605
19	28.00	395	413	.0440	.0605
20	28.00	420	441	.0427	.063
21	28.00	420	441	.0427	.063
22	28.00	400	419	.0438	.0612
23	28.00	405	424	.0435	.0617

Col. 1 Run No.	Col. 26 D_v (sq.ft./hr.)	Col. 27 p_{gf} (atm.)	Col. 28 p_g (atm.)	Col. 29 p_{se} in entering alfalfa (atm.)	Col. 30 p_{sl} in leaving alfalfa (atm.)
2	1.26	.9745	.0255	.0345	.132
3	1.368	.96783	.03217	.0345	.196
4	1.525	.96642	.03358	.0345	.510
5	1.305	.97515	.02485	.0345	.151
6	1.74	.959	.0410	.0345	.818
7	2.45	.9505	.0495	.0345	1.41
8	1.67	.9668	.0332	.0345	.785
9	1.67	.96875	.03125	.0345	.635
10	1.67	.96875	.03125	.322	.785
11	1.67	.96875	.03125	.407	.635
12	1.67	.96875	.03125	.322	.635
13	1.518	.96861	.03139	.0345	.510
14	1.59	.96861	.03139	.252	.407
15	1.518	.96861	.03139	.191	.322
17	1.525	.9651	.0349	.322	.570
18	1.67	.9651	.0349	.286	.635
19	1.67	.9651	.0349	.322	.706
20	1.82	.9648	.0352	.0345	.887
21	1.82	.9648	.0352	.372	.887
22	1.67	.9648	.0352	.372	.785
23	1.745	.9648	.0352	.322	.785

Col. 1 Run No.	Col. 31 p_m (atm.)	Col. 32 k_g $\left(\frac{\# \text{ mol.}}{\text{hr.-sq.ft.-atm.}}\right)$	Col. 33 $k_g a$	Col. 34 $\left[\frac{\mu}{\rho \quad D_v}\right]_f^{\frac{2}{3}}$
2	.0394	22.3	11.32	.8775
3	.0379	26.8	8.5	.886
4	.1205	7.5	3.36	.902
5	.0453	13.6	8.83	.902
6	.3852	1.818	1.71	.888
7	.678	1.06	.898	.819
8	.118	5.05	5.34	.885
9	.115	3.36	9.47	.875
10	.486	.876	1.685	.885
11	.480	1.198	2.53	.875
12	.433	1.84	2.67	.875
13	.0945	4.59	9.9	.9083
14	.292	1.755	4.21	.888
15	.2175	2.445	4.22	.9028
17	.396	.81	2.14	.8725
18	.400	1.08	2.96	.875
19	.454	1.10	2.195	.879
20	.425	.587	1.908	.8705
21	.554	.532	1.98	.8705
22	.517	.651	1.67	.889
23	.482	.965	1.708	.871

Col. 1 Run No.	Col. 35 $\frac{k_g\, p_{gf}\, M_m}{G}$	Col. 36 J_D	Col. 37 $\frac{D_p\, G}{\mu}$
2	.1279	.112	155
3	.1495	.132	172
4	.0526	.0475	113.4
5	.0922	.0831	126.5
6	.0169	.0150	80.1
7	.00598	.0049	121.3
8	.0576	.051	68.2
9	.0498	.0435	52.6
10	.00795	.00704	86.1
11	.0210	.01839	44.6
12	.0212	.01855	68.3
13	.0495	.0450	62.4
14	.0224	.0199	54.7
15	.0248	.0224	66.3
17	.0101	.00881	39.6
18	.012	.0105	44.1
19	.0121	.01064	44.5
20	.00839	.0073	23.75
21	.00761	.00663	23.75
22	.00868	.00771	26.3
23	.01225	.01068	27.35

Col. 1 Run No.	Col 2 Wt. of Alfalfa Feed (lbs.)	Col. 3 Length of run (min.)	Col. 4 Feed Rate (#/min.)	Col. 5 Moisture in feed $\left(\frac{\#\ H_2O}{\#\ \text{dry alfalfa}}\right)$
24	The motor stopped. The alfalfa was being fed too fast. The screen did not plug.			
25	15	5.584	2.69	.258
26	25	8.0	3.125	.28
27	20	4.5	4.45	.434
28	20	4.75	4.21	.434
29	7.5	4.0	1.875	.862

Col. 1 Run No.	Col. 6 Moisture in product $\left(\frac{\text{\# water}}{\text{\# dry alfalfa}}\right)$	Col. 7 (Col. 5 minus Col. 6)	Col. 8 w' $\left(\frac{\text{\# water}}{\text{\# dry alfalfa - min.}}\right)$
25	.0337	.2243	10.38
26	.0206	.2594	11.95
27	.182	.252	11.62
28	.132	.302	13.92
29	.195	.667	30.8

Col. 1 Run No.	Col. 9 $\left(\frac{\#\ \text{mols.}}{\text{hr.}}\right)$	Col. 10 (1 - wt. fr. H_2O in feed)	Col. 11 Absolute Density of Alfalfa (#/cu.ft.)	Col. 12 Average diameter of particle (ft.)
25	1.6	.795	69.6	.000779
26	2.11	.7812	69.6	.000779
27	2.6	.6977	68	.00256
28	2.955	.6977	68	.00256
29	2.24	.5369	68	.00256

Col. 1 Run No.	Col. 13 a $\left(\frac{\text{sq. ft.}}{\text{cu. ft.}}\right)$	Col. 14 Wt. of propane per run (oz.)	Col. 15 Rate propane (#/min.)	Col. 16 $\frac{\text{\# air}}{\text{\# propane}}$	Col. 17 Total wt. rate of flue gas (#/min.)
25	2.49	10	.1118	23.1	2.695
26	2.90	12	.0939	23.1	2.26
27	1.282	7	.0972	23.7	2.40
28	1.215	7	.0920	23.7	2.27
29	.829	5	.0781	23.7	1.93

Col. 1 Run No.	Col. 18 Mol. % H_2O in gas	Col. 19 G' (#/min. sq. ft.)	Col. 20 G (#/hr. sq. ft.)	Col. 21 Mol. wt. of gas
25	3.54	30.8	1848	28.0
26	3.54	25.85	1550	28.0
27	3.385	27.40	1703	28.0
28	3.385	26.0	1560	28.0
29	3.385	22.1	1325	28.0

Col. 1 Run No.	Col. 22 Temp. of TC # 5 (° F.)	Col. 23 True gas temp. (° F.)	Col. 24 Density of gas (#/cu. ft.)	Col. 25 Viscosity of gas (#/ft. hr.)
25	415	435	.0429	.063
26	425	447	.0423	.062
27	365	380	.0457	.0593
28	380	397	.0448	.0603
29	400	419	.0437	.063

Col. 1 Run No.	Col. 26 D_v (sq. ft./hr.)	Col. 27 p_{gf} (atm.)	Col. 28 p_g (atm.)	Col. 29 p_{se} in entering alfalfa (atm.)	Col. 30 p_{sl} in leaving alfalfa (atm.)
25	1.672	.9646	.0354	.0345	2.88
26	1.749	.9646	.0354	.785	4.13
27	1.508	.96615	.03385	.0345	4.13
28	1.598	.96615	.03385	.0345	.2525
29	1.639	.96615	.03385	.0345	.2525

Col. 1 Run No.	Col. 26 D_v (sq. ft./hr.)	Col. 27 p_{gf} (atm.)	Col. 28 p_g (atm.)	Col. 29 p_{se} in entering alfalfa (atm.)	Col. 30 p_{sl} in leaving alfalfa (atm.)
25	1.672	.9646	.0354	.0345	2.88
26	1.749	.9646	.0354	.785	4.13
27	1.508	.96615	.03385	.0345	4.13
28	1.598	.96615	.03385	.0345	.2525
29	1.639	.96615	.03385	.0345	.2525

Col. 1 Run No.	Col. 31 p_m (atm.)	Col. 32 k_g $\left(\frac{\# \text{ mol.}}{\text{hr.-sq. ft.-atm.}}\right)$	Col. 33 $k_g a$	Col. 34 $\left[\frac{\mu}{\rho D_v}\right]_f^{\frac{2}{3}}$
25	1.422	.174	.436	.917
26	1.975	.1422	.413	.8905
27	.457	1.71	2.195	.9058
28	.375	2.50	3.04	.8923
29	.375	2.785	2.31	.9182

Col. 1 Run No.	Col. 35 $\frac{k_g P_{gf} M_m}{G}$	Col. 36 J_D	Col. 37 $\frac{D_p G}{\mu}$
25	.0254	.02325	22.8
26	.0247	.022	19.47
27	.0271	.0246	73.6
28	.0433	.0336	66.3
29	.0569	.0522	53.9

Col. 1 Run No.	Col. 35 $\frac{k_g \, p_{gf} \, M_m}{G}$	Col. 36 J_D	Col. 37 $\frac{D_p \, G}{\mu}$
25	.0254	.02325	22.8
26	.0247	.022	19.47
27	.0271	.0246	73.6
28	.0433	.0386	66.3
29	.0569	.0522	53.9

Col. 1 Run No.	Col. 35 $\frac{k_g\, p_{gf}\, M_m}{G}$	Col. 36 J_D	Col. 37 $\frac{D_p\, G}{\mu}$
25	.0254	.02325	22.8
26	.0247	.022	19.47
27	.0271	.0246	73.6
28	.0433	.0386	66.3
29	.0569	.0522	53.9

CALCULATIONS

The calculations will be presented showing how each of the columns of data was derived.

Col. 1 Run No.

Indicates number of runs made.

Col. 2 Weight of alfalfa

Measured.

Col. 3 Length of run (time)

Measured

Col. 4 Feed rate

$$\frac{\#\ \text{feed}}{\text{time}} = \frac{\#}{\text{min.}}$$

Col. 5 Moisture in feed

Example: Run #8

3 parts dry @ 4.06% moisture

1 part wet @ 80.4% moisture

% moisture in feed 23.15%

$$\frac{\#\ \text{water}}{\#\ \text{dry alfalfa}} = \frac{23.15}{100 - 23.15} = .302$$

Col. 6 Moisture in product

Example: Run #8

% moisture in product 4.55

$$\frac{\#\ \text{water}}{\#\ \text{dry alfalfa}} = \frac{4.55}{100 - 4.55} = .0477$$

Col. 7 Col. 5 minus Col. 6

$$\frac{\#\ \text{water evaporated}}{\#\ \text{dry alfalfa}}$$

Col. 8 w'

$$\frac{\#\ \text{water evaporated}}{\#\ \text{dry alfalfa - min. of contact time}} = \frac{\text{Col. 7}}{1.3\ \text{sec.}} \frac{60\ \text{sec.}}{\text{min.}}$$

$$= (46.1)(\text{Col. 7})$$

The contact time was determined by averaging six different checks. It was 1.3 sec.

Col. 9 w

$$\frac{\#\ \text{moles water evaporated}}{\text{hr.}}$$

$$w = \frac{\#\ (1 - \text{wt. fr. } H_2O)(\text{Col. 7})}{\text{min.}}\left(\frac{\#\ \text{mol.}}{18\ \#}\right)\left(\frac{60\ \text{min.}}{\text{hr.}}\right)$$

Col. 10 (1 - wt. fr. H_2O in feed)

Col. 11 Absolute density of alfalfa ρ_A

$$\left(\frac{\text{gm.}}{\text{cc}}\right)(62.4) = \frac{\#}{\text{Cu. ft.}}$$

Col. 12 Average diameter of particle

This was calculated by a screen analysis of the product and then a weighted average taken. Two analyses were made for each size screen used in the hammer mill.

Col. 13 a

$$a = \frac{\#}{\text{min.}\ \rho_A} \frac{6}{D_P} \frac{1.3\ \text{sec.}}{60\ \text{sec.}} \frac{\text{min.}}{V}$$

V = vol. chamber below screen + vol. fan + vol. pipe + vol. cyclone = 2.5895 cu. ft.

$$a = \frac{\#}{\text{min.}} \frac{.0502}{D_P\ \rho_A}$$

Col. 14 Weight of propane

Measured

Col. 15 Weight rate of propane

$$\frac{\text{Col. 14}}{\text{Col. 3}}$$

Col. 16 $\dfrac{\#\ \text{air}}{\#\ \text{propane}}$

In calculating this column it was assumed that the air came in at 50% relative humidity and 77° F. This gave a moisture content of the air as:

$$\frac{.01\ \#\ H_2O}{\#\ \text{dry air}} = \frac{.0204\ \text{mol. } H_2O}{\text{mol. } N_2}$$

The over-all equation for the burning of propane:

$$C_3H_8 + 5O_2 + \underset{\text{Excess}}{O_2} + \underset{\substack{\text{in}\\ \text{air}}}{H_2O} + \underset{\substack{\text{in}\\ \text{air}}}{N_2} = 3CO_2 + 4H_2O + \underset{\substack{\text{in}\\ \text{air}}}{H_2O} + \underset{\text{Excess}}{O_2} + N_2$$

$$\frac{\text{mols. } H_2O}{100 \text{ mols. dry flue gas}} = \frac{4}{3} \text{ mols. } CO_2 + .0204 \text{ mols. } N_2$$

$$\frac{\text{mols. air}}{\text{mol. propane}} = \left(\frac{5}{3}\ \%\ CO_2 + \%\ O_2\right) \frac{1}{.21} \frac{3}{\%\ CO_2}$$

$$\frac{\#\ \text{air}}{\#\ \text{propane}} = \frac{29}{44} \frac{\text{mols. air}}{\text{mol. propane}} = \frac{(29)(3)}{(.21)(44)} \frac{\left(\frac{5}{3} CO_2 + O_2\right)}{CO_2}$$

$$= \frac{9.41 \left(\frac{5}{3} CO_2 + O_2\right)}{CO_2}$$

Col. 17 Total weight rate flue gas

$$\frac{\#\ \text{propane}}{\text{min.}} \left(1 + \frac{\#\ \text{air}}{\#\ \text{propane}}\right) \text{ or Col. 15 (1 + Col. 16)}$$

Col. 18 Mol. % H_2O in gas

Measured from flue gas analysis as described under Col. 16 calculations.

Col. 15 Weight rate of propane

$$\frac{\text{Col. 14}}{\text{Col. 3}}$$

Col. 16 $\frac{\#\ \text{air}}{\#\ \text{propane}}$

In calculating this column it was assumed that the air came in at 50% relative humidity and 77° F. This gave a moisture content of the air as:

$$\frac{.01\ \#\ H_2O}{\#\ \text{dry air}} = \frac{.0204\ \text{mol. } H_2O}{\text{mol. } N_2}$$

The over-all equation for the burning of propane:

$$C_3H_8 + 5O_2 + \underset{\text{Excess}}{O_2} + \underset{\text{in air}}{H_2O} + \underset{\text{in air}}{N_2} = 3CO_2 + 4H_2O + \underset{\text{in air}}{H_2O} + \underset{\text{Excess}}{O_2} + N_2$$

$$\frac{\text{mols. } H_2O}{100\ \text{mols. dry flue gas}} = \frac{4}{3}\ \text{mols. } CO_2 + .0204\ \text{mols. } N_2$$

$$\frac{\text{mols. air}}{\text{mol. propane}} = \left(\frac{5}{3}\ \%\ CO_2 + \%\ O_2\right) \frac{1}{.21}\ \frac{3}{\%\ CO_2}$$

$$\frac{\#\ \text{air}}{\#\ \text{propane}} = \frac{29}{44}\ \frac{\text{mols. air}}{\text{mol. propane}} = \frac{(29)(3)}{(.21)(44)}\ \frac{\left(\frac{5}{3}\ CO_2 + O_2\right)}{CO_2}$$

$$= \frac{9.41\ \left(\frac{5}{3}\ CO_2 + O_2\right)}{CO_2}$$

Col. 17 Total weight rate flue gas

$$\frac{\#\ \text{propane}}{\text{min.}}\left(1 + \frac{\#\ \text{air}}{\#\ \text{propane}}\right) \text{ or Col. 15 (1 + Col. 16)}$$

Col. 18 Mol. % H_2O in gas

Measured from flue gas analysis as described under Col. 16 calculations.

Col. 15 Weight rate of propane

$$\frac{\text{Col. 14}}{\text{Col. 3}}$$

Col. 16 $\frac{\#\ \text{air}}{\#\ \text{propane}}$

In calculating this column it was assumed that the air came in at 50% relative humidity and 77° F. This gave a moisture content of the air as:

$$\frac{.01\ \#\ H_2O}{\#\ \text{dry air}} = \frac{.0204\ \text{mol. } H_2O}{\text{mol. } N_2}$$

The over-all equation for the burning of propane:

$$C_3H_8 + 5O_2 + \underset{\text{Excess}}{O_2} + \underset{\substack{\text{in}\\\text{air}}}{H_2O} + \underset{\substack{\text{in}\\\text{air}}}{N_2} = 3CO_2 + 4H_2O + \underset{\substack{\text{in}\\\text{air}}}{H_2O} + \underset{\text{Excess}}{O_2} + N_2$$

$$\frac{\text{mols. } H_2O}{100\ \text{mols. dry flue gas}} = \frac{4}{3}\ \text{mols. } CO_2 + .0204\ \text{mols. } N_2$$

$$\frac{\text{mols. air}}{\text{mol. propane}} = \left(\frac{5}{3}\ \%\ CO_2 + \%\ O_2\right) \frac{1 \quad 3}{.21\ \%\ CO_2}$$

$$\frac{\#\ \text{air}}{\#\ \text{propane}} = \frac{29}{44}\ \frac{\text{mols. air}}{\text{mol. propane}} = \frac{(29)(3)}{(.21)(44)}\ \frac{\left(\frac{5}{3}\ CO_2 + O_2\right)}{CO_2}$$

$$= \frac{9.41\ \left(\frac{5}{3}\ CO_2 + O_2\right)}{CO_2}$$

Col. 17 Total weight rate flue gas

$$\frac{\#\ \text{propane}}{\text{min.}}\ \left(1 + \frac{\#\ \text{air}}{\#\ \text{propane}}\right) \text{ or Col. 15 (1 + Col. 16)}$$

Col. 18 Mol. % H_2O in gas

Measured from flue gas analysis as described under Col. 16 calculations.

Col. 19 G'

$$\frac{\text{Col. 17}}{\text{Cross sectional area of pipe}}$$

$$A = \frac{4^2}{4\,(144)} = .0874 \text{ sq. ft.}$$

$$G' = \frac{\text{Col. 17}}{.0874}$$

Col. 20 G

$$G = (\text{Col. 19})(60) = \frac{\#}{\text{hr. - sq. ft.}}$$

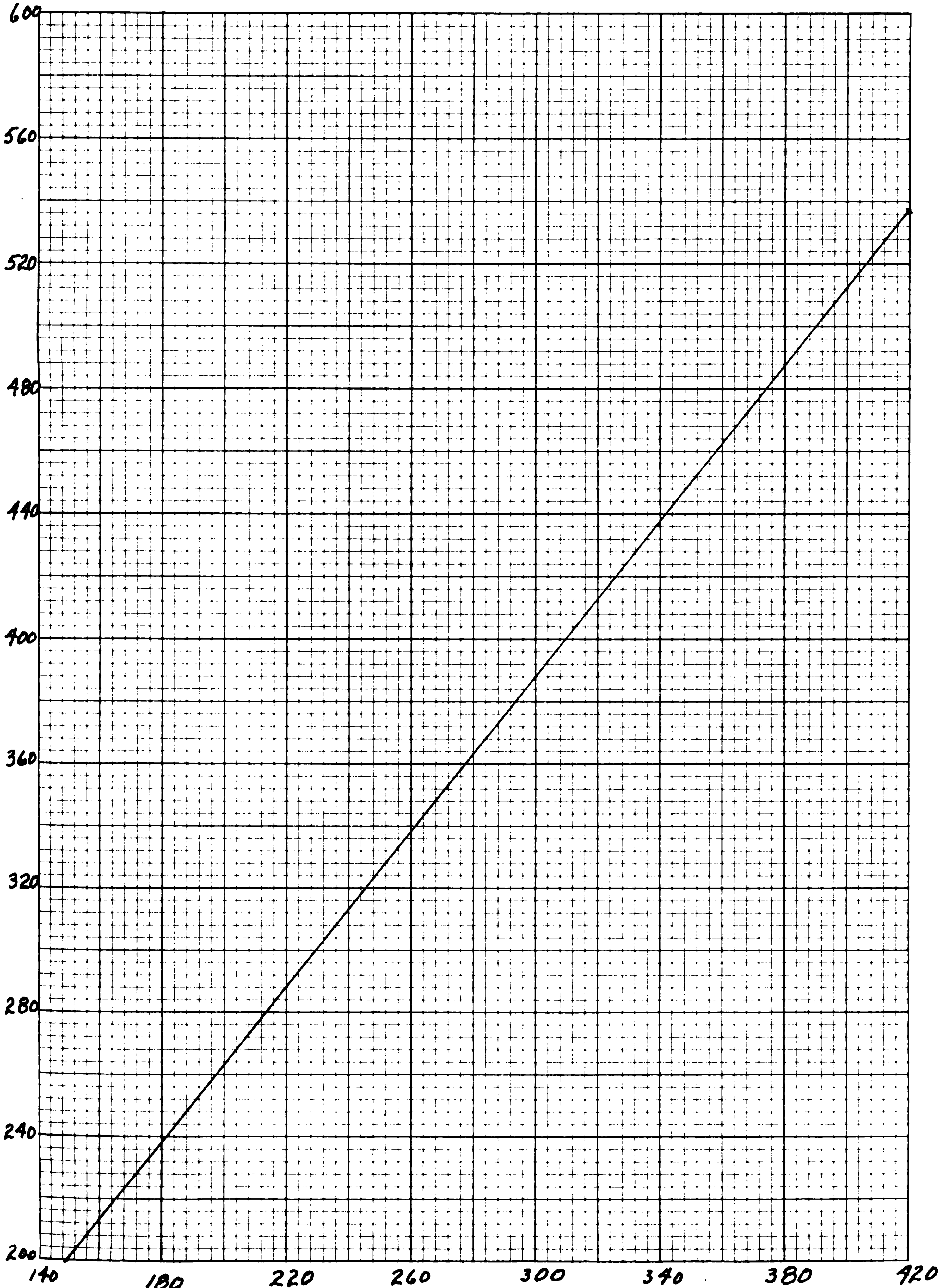
Col. 21 Mol. wt. of flue gas

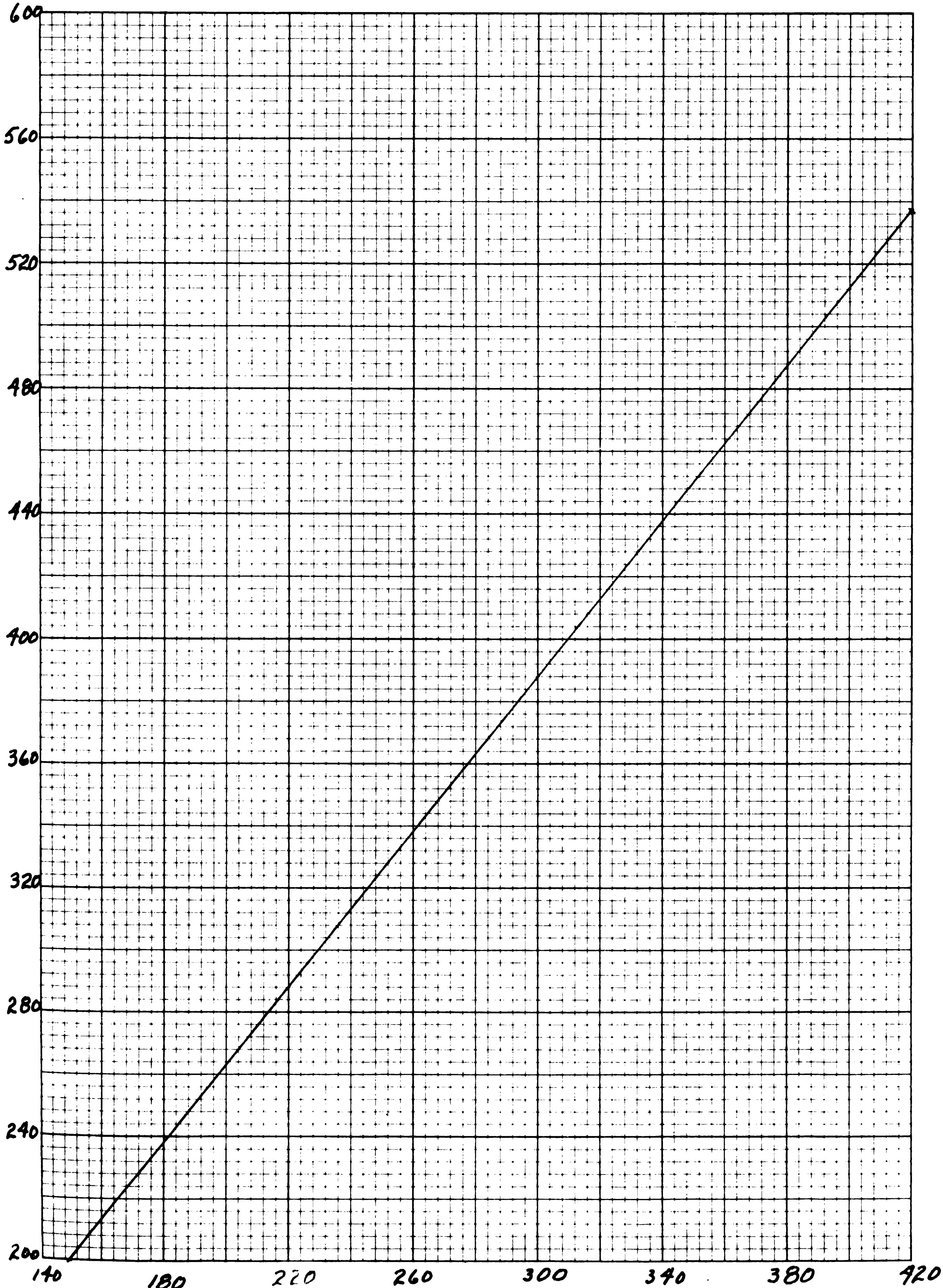
The first 15 runs were calculated from the flue gas analysis. This indicated that the mol. wt. would be very close to 28.0. After the 15th run, the mol. wt. was assumed to be 28.0.

Col. 22 Temp. of TC 5

Measured.

This temperature was the one used and considered to be the most indicative of the temperature at which drying took place. There would be some drying before this location at a higher temperature, and some drying after this location at a lower temperature. These two variations tend to offset each other.


600
560
520
480
440
400
360
320
280
240
200
140
180
220
260
300
340
380
420


600
560
520
480
440
400
360
320
280
240
200
140
180
220
260
300
340
380
420

Col. 23 True gas temp. in chamber, cyclone, and pipe

Since the thermocouple will radiate to the colder walls, the true gas temperature will be a little higher than the thermocouple will indicate. This true gas temperature can be calculated from the equation below:

$$q = h\,A(T_g - T_{TC}) = .173\,A\,\epsilon\left[\left(\frac{T_{TC}}{100}\right)^4 - \left(\frac{T_W}{100}\right)^4\right]$$

Assume ϵ for all surfaces = 0.9

$$h = .026\,\frac{G_{av.}^{\,.6}}{D^{.4}}$$ page 223 (7)

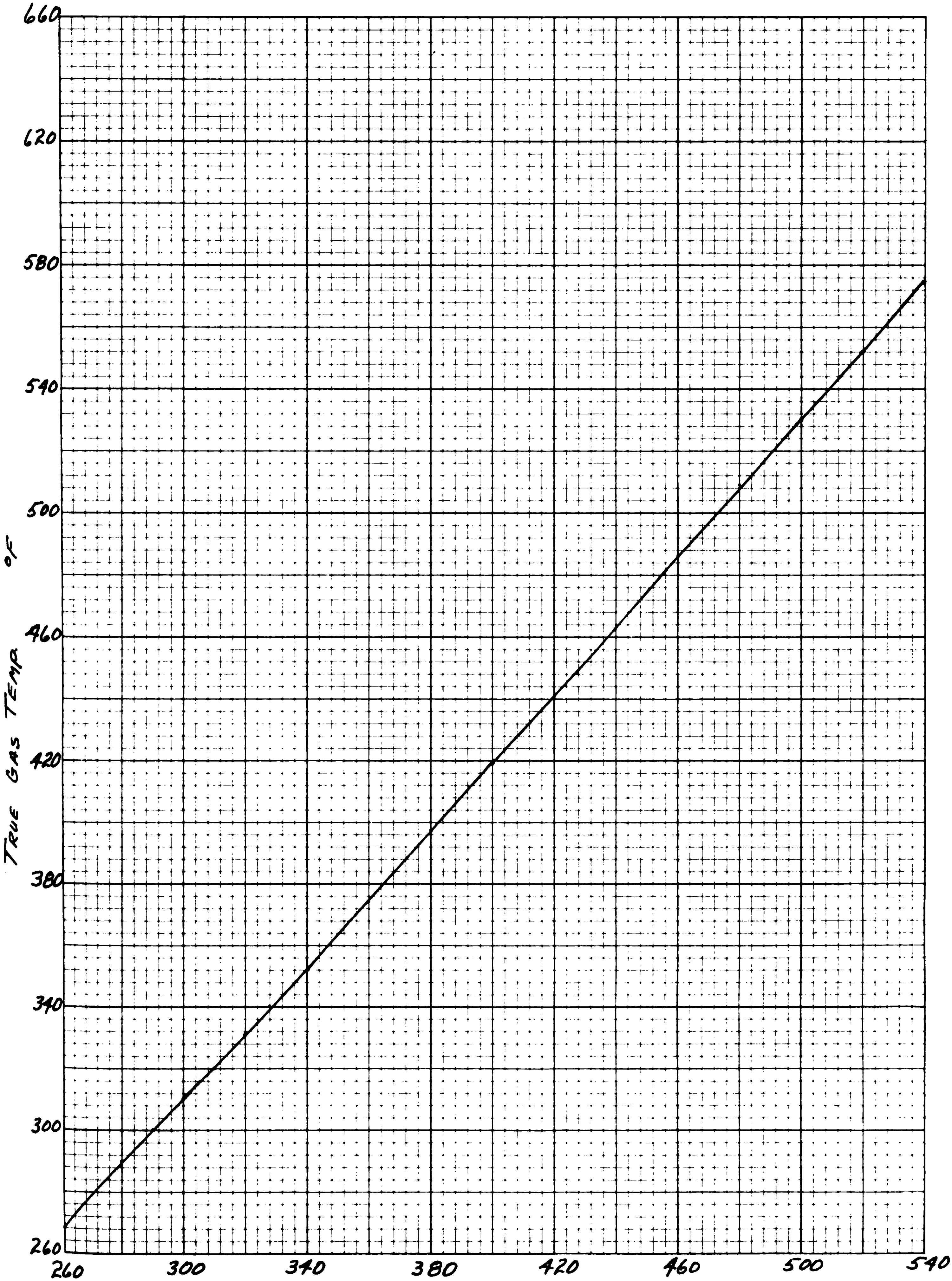
D_{TC} = .0105 ft.

$G_{av.} = 3111 \dfrac{\#}{\text{hr.-sq. ft.}}$

$$h = \frac{(.026)(3111)^{.6}}{(.0105)^{.4}} = 16.25\ \frac{\text{BTU}}{\text{hr. - sq. ft.-}\ \Delta t}$$

$$T_g = .00958\left[\left(\frac{T_{TC}}{100}\right)^4 - \left(\frac{T_W}{100}\right)^4\right] + T_{TC}$$

Using this equation along with figure 1, a new graph was drawn giving the true gas temperature as a function of TC 5. (figure2)


660
620
580
540
500
460
420
380
340
300
260
TRUE GAS TEMP °F
260
300
340
380
420
460
500
540

Col. 24 Density of gas

PVT relationships were used to calculate the density of the gas.

$$\frac{w}{V} \quad \frac{P\,M}{Z\,RT} \quad \frac{(14.7)(144)}{Z\,1546} \quad \frac{M}{T}$$

$$Z = \frac{Z_A N_A + Z_B N_B + Z_C N_C + Z_D N_D}{N_t}$$

$M = .28$

	N_2	CO_2	H_2O	O_2
Critical temp. ($^oF.$)	-232.6	87.8	705.2	-181.8
Critical press. (atm.)	33.5	73.	217.7	49.7
Reduced press. $P_r = \frac{P}{P_c}$	.0299	.0137	.0046	.0201
Reduced temp. $T_r = \frac{T}{T_c}$	$\frac{T}{229.4}$	$\frac{T}{547.8}$	$\frac{T}{1165.2}$	$\frac{T}{278.2}$

Since T_r is large and P_r is very small, the gas obeys the perfect gas law which was used in calculating the density.

$$\rho = \frac{38.4}{T}$$

Col. 25 Viscosity of gas

Taken from a nomograph (4)

Col. 26 D_v

The following equation was used: (11)

$$D_v' = .0043 \frac{T_K}{P(V_A^{1/3} + V_B^{1/3})^2} \sqrt{\frac{1}{M_A} + \frac{1}{M_B}}$$

$$= .0043 \frac{T_K}{1(2.45 + 3.14)^2} \sqrt{\frac{1}{18} + \frac{1}{28}}$$

$$= 3.92 \times 10^{-5}\ T_K \qquad cm^2/sec.$$

$$D_v = (D_v')(3.88 \frac{sq.\ ft./hr.}{cm^2/sec.})$$

Col. 27 p_{gf}

(1 - mol. fr. H_2O in flue gas)

Col. 28 p_g

(mol. fr. H_2O in flue gas)

Col. 29 p_{se}

Vapor press. of water in the entering alfalfa.

p_{se} = vapor press. of water at the temp. of the alfalfa (6).

Col. 30 p_{sl} in leaving ground alfalfa

Same as Col. 29.

Col. 31 Δp_m

$$\Delta p_m = \frac{p_{sl} - p_{se}}{\ln \dfrac{p_{sl} - p_g}{p_{se} - p_g}}$$

Col. 32 k_g

$$k_g = \frac{w}{a\ V\ \Delta p_m}$$

Col. 33 $k_g a$

(Col. 32)(Col. 13)

Col. 34 $\left[\frac{\mu}{\rho D_v}\right]_f^{\frac{2}{3}}$

Calculated from the various columns.

Col. 35 $\frac{k_g P_{gf} M_m}{G}$

Calculated as indicated.

Col. 36 J_D

$$J_D = \frac{k_g P_{gf} M_m}{G} \left[\frac{\mu}{\rho D_v}\right]_f^{\frac{2}{3}} = (\text{Col. } 34)(\text{Col. } 35)$$

Col. 37 **Reynold's** number

$\frac{D_p G}{\mu}$ Calculated as indicated.

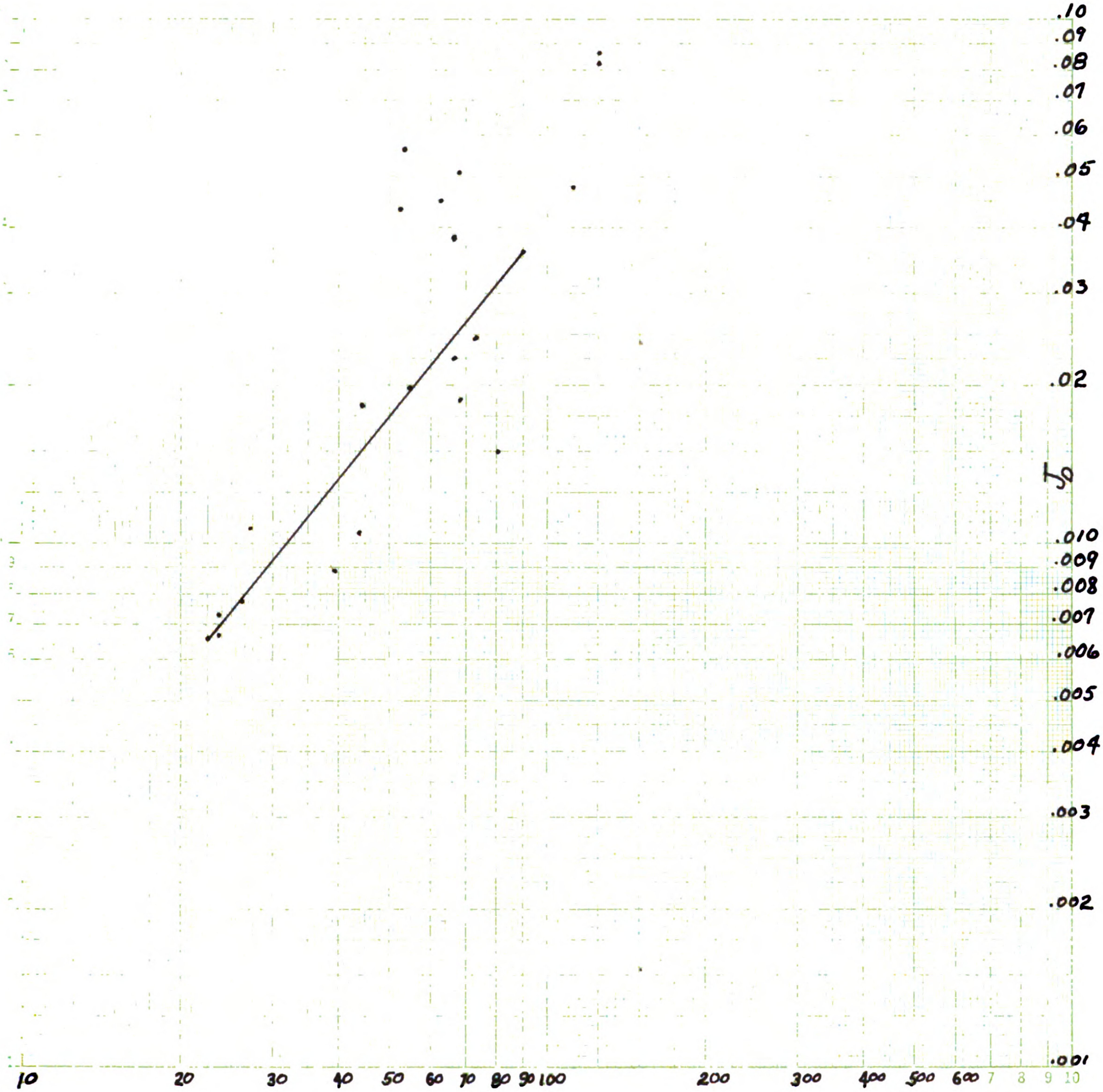
DISCUSSION

The data obtained from this investigation would indicate that the size of the particle was one of the main factors in mass transfer. This is in agreement with two sets of investigators while in disagreement with two other sets of investigators (9). The effect of particle size was indicated by the lower moisture content in the product runs 25 and 26.

To vary the particle size of the product a different screen was used in the hammer mill. A 1/2" round hole screen was used for runs 1 - 12 inclusive and runs 27 - 29 inclusive; a 1/4" round hole screen was used for runs 13 - 15 inclusive; a 1/8" screen for 16 - 19 inclusive; a 1/16" screen for 20 - 23 inclusive; a 1/32" screen for 24 - 26 inclusive.

The motor driving the hammer mill stopped on runs 16 and 24. This was due to an overloading of the heat coils protecting the motor. It was found that 10 amperes was the maximum current the motor would handle for any length of time. This fact was used as an indicator to the capacity of the mill.

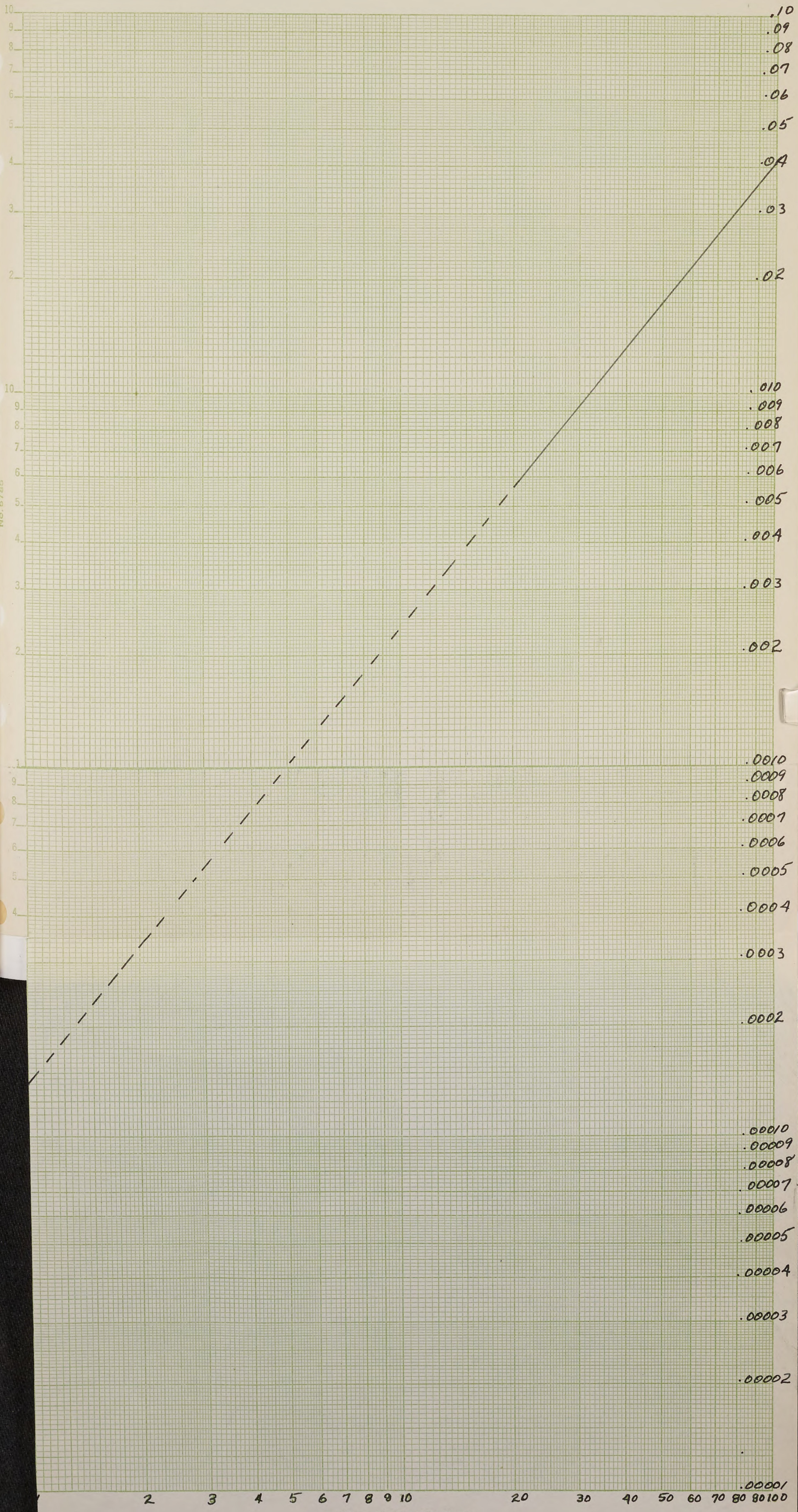
The drying of alfalfa usually takes a long time, since after the evaporation of the water from the outside surface, the remainder of the water must come by capillary action to the surface. By simultaneously drying and grinding the alfalfa, this difficulty is avoided. As soon as the surface is dried,



Reynold's Number

Figure 3

Original plot from data and calculations.



Reynold's Number

Figure 4

Extension of figure 3 to calculate coefficient and exponent.

new surfaces are exposed to the drying medium. This prolongs the constant drying rate period.

A correlation of the data was obtained by the use of Colburn and Chilton's J factor. This J factor is derived from dimensional analysis where k_g is considered to be a function of M_m, p_{gf}, G, μ, ρ, D_v. Written in equation form this is:

$$k_g = \int p^a M_m^b G^c \mu^d \rho^e D_v^f$$

Solving this:

$$J_D = \left(\frac{k_g M_m p_{gf}}{G}\right)\left(\frac{\mu}{\rho D_v}\right)^x$$

Colburn and Chilton found that the value of x was 2/3.

The J in the above equation is a function of the modified Reynold's number. Stated in equation form it is:

(4) $$J_D = C\left(\frac{D_p G}{\mu}\right)^{a'}$$

The original correlation is given in figure 4. This graph was enlarged to enable the calculation of the values of C and a'. The following relationship is obtained.

(5) $$J_D = .00014 \left(\frac{D_p G}{\mu}\right)^{1.24}$$

Combining equation (5) with equation (3) will give a means of calculating the mass transfer coefficient.

(6) $$k_g = \frac{.00014\ G}{p_{gf}\ M_m}\left(\frac{D_p G}{\mu}\right)^{1.24}\left(\frac{\rho D_v}{\mu}\right)_f^{\frac{2}{3}}$$

The variation between this correlation and those found in the literature can be attributed to the fact that the mass transfer took place neither in a fixed bed nor in a fluidized bed. In this investigation such things as total volume of mass transfer space and the cross sectional area were not so easily obtained nor clearly defined as they are in a fixed or fluidized bed.

In the author's opinion the reason for the group of points in figure 3 lying above the line is that this group was calculated from the first runs and the equipment did not have sufficient time to come up to constant temperature before each run was made. This gave erroneous data for calculations.

There is a region of transition from laminar flow to turbulent flow which is the reason the curve tends to slope upward above Re = 90.

CONCLUSION

1. The mass transfer rate of water from small particles of alfalfa to the carrying medium may be expressed as follows:

$$w = \frac{.00014\ G\ a\ V\ \Delta p_m}{p_{gf}\ M_m} \left(\frac{D_p\ G}{\mu}\right)^{1.24} \left(\frac{\rho\ D_v}{\mu}\right)^{\frac{2}{3}}$$

2. The average diameter of the particle is a contributing factor in determining the mass transfer coefficient.
3. The feed must be below a certain moisture content. If this is not the case, the screen will plug. This limit varies with the size of screen.

   46% for 1/2" round screen

   32% for 1/4" round screen

   30.0% for 1/8" round screen

   29.11% for 1/16" round screen

   24% for 1/32" round screen
4. The drying rate is proportional to moisture content of the feed.
5. The temperature has little or no effect on the drying only as it varies the density, viscosity, and diffusivity of the drying medium. This, as such, has no reference to Δ p.

NOMENCLATURE

a = effective area of mass transfer/unit volume of bed sq. ft./cu. ft.

a' = experimental constant

C = constant of proportionality

D = diameter - feet

D_v = diffusivity of gas in the film - sq. ft./hr.

G = mass velocity #/ft.^{2} hr.

G' = #/ft.^{2} min.

J_D = J transfer factor postulated by Chilton and Colburn to correlate the mass transfer coefficient with the modified Reynold's number.

k_g = mass transfer coefficient # moles/hr. sq. ft. atm.

M_A = mol. wt. of gas that is passing from one phase to another.

M_B = mol. wt. of gas that is absorbing gas A.

M_m = mean molecular wt. of the gas stream.

P = total pressure (atm.)

p = partial pressure (atm.)

Δp_m = log mean partial pressure difference at the terminals (atm.)

p_{gf} = log mean partial pressure of the non-transferred gases in the gas film (atm.)

R = universal gas constant.

t = temperature $^{\circ}$F.

T_K = absolute temp. $^{\circ}$K.

T_R = absolute temp. $^{\circ}$R.

TC = thermocouple

V = volume of mass transfer space - cu. ft.

w = rate of mass transfer # mols./hr.

w' = # H_2O evaporated/# dry solid - min.

Z = compressibility factor

$\frac{D_p G}{\mu}$ = Reynold's number

$\frac{\mu}{\rho D_v}$ = Schmidt's number

ρ = density of the gas stream #/cu. ft.

ρ_A = absolute density of Alfalfa

μ = viscosity of gas #/hr. ft.

λ = molal heat of vaporization

ϵ = emissivity factor

BIBLIOGRAPHY

(1) Badger and McCabe, Elements of Chemical Engineering, 2nd edition, 16th impression, McGraw-Hill Book Co., Inc., New York and London (1936).

(2) Chilton, T. H., and Colburn, A. P., "Mass Transfer Coefficients," Industrial and Engineering Chemistry, Vol. 26, 1183 (1934).

(3) Colburn, A. P., "A Method of Correlating Forced Convection Heat Transfer Data," transactions of American Institute of Chemical Engineers, Vol. 29, 174 (1933).

(4) Davis, D. S., Chemical Engineers' Nomographs, 1st edition, 2nd impression, McGraw-Hill Book Co., Inc., New York and London (1944), page 249.

(5) Gamson, B. W., Thodos, G., and Hougen, O. A., "Heat Mass and Momentum Transfer in the Flow of Gases through Granular Solids," American Institute of Chemical Engineering Transactions, Vol. 39, 1 (1943).

(6) Keeman and Keyes, Thermodynamic Properties of Steam, 1st edition, John Wiley and Sons, Inc., New York (1936).

(7) Kettenring, K. N., Manderfield, E. L., and Smith, J. M., "Heat and Mass Transfer in Fluidized Systems," Chemical Engineering Progress, Vol. 46, 139 (1950).

(8) McAdams, W. H., Heat Transmission, 2nd edition, 8th impression, McGraw-Hill Book Co., Inc., New York and London (1941).

(9) McCune, L. K., and Wilhelm, R. H., "Mass and Momentum Transfer in Solid-Liquid System," Industrial and Engineering Chemistry, Vol. 41, 1124 (1949).

(10) Perry, John, Chemical Engineers' Handbook, 2nd edition 5th impression, McGraw-Hill Book Co., Inc., New York and London (1941).

(11) Sherwood, T. K., Absorption and Extraction, 1st edition, 3rd impression, McGraw-Hill Book Co., Inc., New York and London (1937), page 21.

(12) *The Refrigerating Data Book*, 6th edition, The American Society of Refrigerating Engineers.

(13) Walker, Lewis, McAdams, Gilliland, *Principles of Chemical Engineering*, 3rd edition, 15th impression, McGraw-Hill Book Co., Inc., New York and London (1927), page 613.