RELATIONSHIPS IN THE PNEUMATIC DEHYDRATION OF ALFALFA

by

WILLIAM ARTHUR HANEY

B. S., University of Colorado, 1949

A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Chemical Engineering

KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1950

TABLE OF CONTENTS

INTRODUCTION

The purpose of this work is to present data and relationships gathered from the construction and operation of a pneumatic alfalfa dehydrator.

Alfalfa is artificially dehydrated to preserve, insofar as possible, the nutritive constituents. Sun-cured alfalfa does not possess the high carotene and protein content that is found in the artificially dried product. Dehydrated alfalfa meal is finding an ever-increasing use in livestock feeds; in fact, practically all feeds contain some alfalfa meal; for this reason alfalfa dehydration equipment and procedures have been receiving more attention now than ever before.

The pneumatic dehydrator, constructed and erected in the Chemical Engineering Building at Kansas State College, was originally intended to serve as a partial dryer to precede a rotary drum-type dryer. In the partial dryer, it was anticipated that chopped field-run alfalfa would be dried to a moisture content of about forty-five per cent (wet basis). The partially dried alfalfa product from the pre-dryer was to be fed to a rotary dryer for final drying to less than ten per cent moisture. At the present time the rotary dryer is used for practically all alfalfa dehydration.

After the pneumatic dryer was put into operation as a predryer it became apparent that a product having a lower moisture content than was expected could be obtained; therefore, the operation as a pre-dryer was discontinued, and attention was directed toward the total drying to less than ten per cent moisture content in the pneumatic unit, thereby eliminating all need for the rotary drum-type dryer.

Although the operation of drying is one of the oldest unit operations, the origin of flash or pneumatic conveying drying dates back to about 1930 (2). Several commercial makes of dryers are available for general purchase. The Combustion-Engineering Raymond Flash Dryer manufactured in the United States has been successfully used to dry materials such as pulverized coal, chemical salts, and sewage sludge. The Pherson Pneumatic Dryer which is manufactured by a Swedish concern, and the Bamag Spiral Flotation Dryer (a pneumatic dryer) have been reported to be very successful in the dehydration of grain, seed, lucerne, and other forage crops. Buttner, a German company, manufactures a dryer in which a high-temperature drum dryer is followed by a medium-temperature pneumatic dryer (4). Although no references were found as to the successful use of these dryers with alfalfa, there was reason to believe that results similar to those achieved with other forage crops could be obtained with alfalfa.

THEORY OF PNEUMATIC DRYING

The fundamental theory of pneumatic drying is simple and easily understood. The dryer itself is an insulated, vertical duct through which heated air and combustion gases are passed at a high linear velocity. Combustion gases cannot be used as a drying medium when the material to be dried is sensitive to the combustion products. Alternatively, when the material is subject to high temperature deterioration by oxidation, the quantity of air used for conveying must be reduced, and the quantity of combustion products increased. The material to be dried is introduced into the gas stream and conveyed up the drying section, losing moisture during the movement upward. Since the weight of the material decreases greatly with little change in the volume, its density also decreases, and a lower gas rate is required to keep the particle suspended. The lower gas rate is achieved by increasing the diameter of the duct near the top of the vertical section. The particle will float in the gas stream losing moisture until its density decreases to a value which will allow it to be carried out of the drying section and into a cyclone separator where it is removed from the gas stream and collected as a dry product.

Lorenzi (2) lists four fundamental factors which govern flash drying. They are:

1. Moisture dispersion.
2. Temperature differential.
3. Agitation.
4. Particle size.

A material which has most of the moisture close to the surface will dry more rapidly than the same material with the water uniformly dispersed or present in the interior of the material. Unfortunately the latter condition usually exists, and it is the water present in the interior of the material which offers the greatest resistance to removal not only by flash drying, but by other drying methods.

There are two stages in the drying of a wet solid, the first stage or "constant-rate period", and the second stage or "falling-rate period". The surface of the material is completely wetted during the constant-rate period, and evaporation occurs as it would from a free liquid surface. At a certain moisture content, termed the "critical moisture content", the rate of drying decreases, and the range from there to dryness is termed the falling-rate period. Moisture on or near the surface of the material is evaporated during the constant-rate period, and the moisture in the interior of the material is evaporated during the falling-rate period of drying.

High gas temperatures are essential for rapid drying and for high thermal efficiency. The fundamental equation for heat transfer states that the rate of heat transfer is proportional to the temperature difference between the gas and the surface of the material being dried. As long as the material contains a considerable amount of moisture which can move freely to the surface by capillarity, the evaporation of water is rapid, and the temperature of the gas is decreased without a corresponding increase in the temperature of the moist material which remains at the original wet-bulb temperature of the gas. During this period in the process it is possible to apply directly to the material gases of very high temperature without risk of over-heating. When the moisture content of the material has decreased to the critical moisture content, moisture movement by capillarity ceases and the rate of diffusion of water from the inner cells to the surface controls the evaporation rate. During this falling-rate period, evaporation becomes progressively slower with an accompanying rise in surface temperature; therefore, over-heating of heat sensitive materials becomes possible. Drying of alfalfa in the falling-rate period, when it contains a small percentage of moisture, should be carried out at relatively low temperatures to avoid charring.

A large difference in the relative movement of the material being dried and the drying medium increases the drying rate. When a particle of alfalfa gives up its moisture to the conveying gas an envelope of vapor is formed around it. Local equilibrium would be established, and continued vaporization would be retarded were it not for the fact that the rapid movement of the gas past the particle continuously destroys the vapor envelope.

Particles of small diameter will dry faster than those of large diameter since in the smaller internal moisture has a shorter distance to travel to reach the surface; hence, a shorter period of time to travel the distance is required. Large pieces of material, such as alfalfa leaf, that have at least one small dimension will also dry quickly.

Pneumatic conveying dryers are suitable for almost all substances that can be dispersed in a gas stream and conveyed. According to Perry (3) dryers of this type are especially suited for handling large quantities of material and are usually the more economical type of dryer for evaporation capacities above two thousand pounds of water per hour. Evaporation capacities of commercial alfalfa dehydrators are above this figure.

EXPERIMENTAL STUDIES

Equipment

Furnace. Heat for the drying system was supplied by the combustion of a mixture of natural gas and air in the furnace 9 feet long, 4 feet wide, and 3 feet high. The furnace was constructed of firebrick and contained a combustion tube, 4 feet long and 1 foot square, also constructed of firebrick. Natural gas at a pressure of about 5 pounds per square inch and the air at a pressure of about 60 pounds per square inch passed through regulating valves and were fed into a nozzle where they were mixed and ignited. The products passed into the combustion tube, where unburned natural gas came into contact with the hot firebrick and was ignited. Since the products of combustion constituted only a small part of the gases required by the dryer, air drawn in through the firebrick checkerwork in the front of the furnace was mixed with the flue gases to obtain a mixture which was at the temperature desired for the drying operation. A period of from ten to fifteen minutes was required for the furnace to reach operating temperatures. The furnace was not insulated.

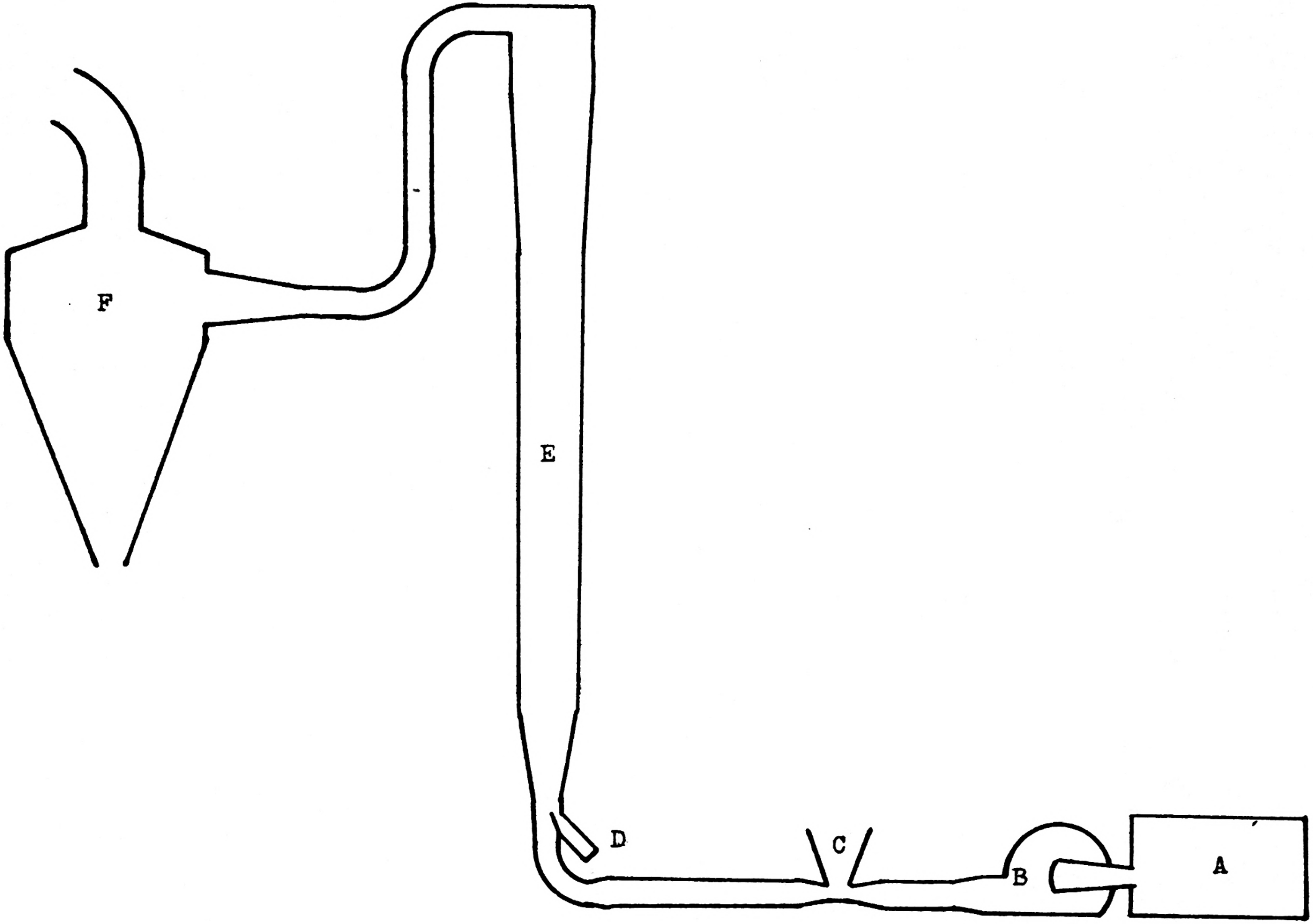
Blower. A Clarage No. 15 exhaustor fan equipped with long-shaving blades was used to exhaust the hot gases from the furnace into the dryer. The blower was equipped with an improvised

EXPLANATION OF PLATE I

Pneumatic alfalfa dehydrator

A. Furnace
B. Blower
C. Feed hopper
D. Stem separator
E. Drying section
F. Cyclone separator

PLATE I



water-cooling system to protect the shaft bearings from the effects of high temperature operation. A 10 horsepower, 1750 R. P. M., Allis-Chalmers induction motor furnished power for operating the blower; a six-inch pulley on the motor shaft drove a pulley of the same size on the fan shaft by four one-half inch V-belts. The blower was connected to the back of the furnace by a 2 foot section of 24 gauge iron duct, 8 inches in diameter at the furnace and 15 inches in diameter at the blower inlet. A slot in the duct at the enlarged end and perpendicular to the direction of flow allowed orifice plates to be inserted for the control of the gas rate. The sizes of the orifices used were 3-7/8, 4-1/2, 5-1/8, 6, 7-7/8, and 10 inches in diameter, and when no plate was used the diameter of the opening was the same as that of the blower inlet. The blower outlet was 13 inches square, and was connected to the hopper section by a 6 foot length of duct 8 inches in diameter at the hopper end. The temperature-sensitive element of a Wheelco temperature recorded was inserted in the duct 1 foot from the blower, and a manometer for measuring the static pressure of the gas, and a pitot tube for measuring gas velocity were inserted 4 and 4-1/2 feet, respectively, from the blower.

Hopper. The feed hopper consisted of an inverted truncated pyramid 2 feet high, 1-1/2 feet square at the top and 4-1/2 inches square at the point where it was attached to the drying system. At the point of attachment, the duct was narrowed down, over a 16 inch length, from 8 to 5 inches in diameter. This smaller section was to give the gas an increase in velocity as it came into contact with the alfalfa so that there would be little or no danger of the alfalfa clogging the system at this point. A section of 8 inch duct, 10 feet in length, connected the hopper section to a 6 inch square, 90^{o} elbow with an inside radius of 2-1/2 feet. This elbow was of small cross-section to prevent alfalfa from lodging in the elbow at the lower gas rates.

Stem Separator. The larger stems present in alfalfa contain very little nutritive material, and because they are thick and pulpy consume valuable heat in being dried. They also constitute a difficult problem in drying since they char while still containing a considerable amount of moisture in their interior. For this reason removal of the large stems from the alfalfa before they were dried appreciably was desirable.

In the pneumatic dryer, the alfalfa was blown at high velocity, into the transition section of the vertical dryer. The transition section which enlarged from 6 inches to 16 inches in diameter over a length of 5 feet allowed the gas velocity to diminish, and the heavy stems, unable to remain in suspension, fell back into the separator. The separator, a 6 inch duct inclined 45^{o} from the vertical, was inserted 3 inches into the bottom of the transition piece (Plate I). The diameter of the dryer at this point was 8 inches. A damper closed off the other end of the separator, and the stems were removed by opening the damper and allowing the slight positive pressure to blow them out.

Drying Section. Perry (3) states that there are no data available for designing pneumatic dryers; therefore, data imperative to successful design must be obtained experimentally or estimated. Both of these methods were used to obtain data for designing the alfalfa drying section (Appendix).

The drying section consisted of a cylindrical metal duct, 18 feet in length and 16 inches in diameter, suspended vertically. A transition piece 6 feet in length was capped by a section of 18 inch duct 2 feet in length and closed at one end to form the top of the drying section. Two 4-inch glass windows, one 19 feet from the top of the column, and the other 3 feet from the top, were inserted in the side of the drying section so that the movement of the alfalfa could be observed. Three iron-constantan thermocouples were placed along the inside wall of the duct 1, 14, and 25 feet, respectively, from the top of the column, to measure the gas temperature at these three positions. Water-filled manometers were used to indicate the static pressure of the gas 1, 8, and 24 feet, respectively, from the top of the drying section. The drying system was insulated between the blower outlet and the top of the drying section with three-fourths to one inch of asbestos cement. No other parts of the dryer were insulated.

Cyclone Separator. A large cyclone separator was joined to the drying section by 25 feet of uninsulated 8 inch duct. The separator had an overall length of 11-1/2 feet; the conical section, which was 9 feet in length, had a diameter of 6 feet at the top and 6 inches at the bottom. The cylindrical section located above the conical section had a height of 2-1/2 feet. A thermocouple was placed a distance of 1 foot into the 20 inch duct that connected the cyclone separator to the chimney. This duct, which was 30 feet long, was used to exhaust the waste gases to the atmosphere.

Materials and Experimental Methods

Alfalfa Handling. The alfalfa was obtained in mid-morning on the day that the dryer was to be operated. Most of the alfalfa used in the runs was collected directly in the fields by driving a truck alongside a tractor-drawn mower and chopper owned and operated by a commercial dehydration organization. The remainder of the alfalfa was obtained from the feed conveyor at the site of the commercial dehydrator. In no instance had the alfalfa been cut more than an hour before it was collected.

Very little foreign matter, such as weeds and other grasses, was present in any of the material.

Since the experimental dryer was operated in the afternoon, the alfalfa was stored for three or four hours at the Chemical Engineering Building before weighing and drying.

Feeding System. Feed rates of 60 pounds per one-half hour, and 100 pounds per one-half hour were used. At both feed rates the alfalfa was weighed and placed in tubs. The alfalfa was transferred by hand from the tubs to an endless canvas conveyor belt, 18 inches in width, which traveled 8 feet and emptied into the hopper attached to the dryer. For feed rate control, the conveyor belt was geared to a motor through a variable speed drive. Two horizontal cylinders having 6 inch metal prongs revolved above the canvas belt and distributed the alfalfa evenly across the belt.

One of these distributors was located at the hopper end of the feeder, and the other was 4 feet from the hopper end.

By using care considerable accuracy was achieved in feeding, and the feed rate could be considered constant during a given run.

Sampling. Alfalfa samples were collected every 10 minutes during the one-half hour runs. Samples were taken from the feed on the conveyor belt, from the stem separator, from the top of the drying section, and from the stream of dried product issuing from the cyclone separator. The samples, varying between 50 and 100 grams, were placed in labeled metal cans equipped with tight-fitting lids, and except for the moment that the samples were transferred, the lids were kept on the cans so that there would be no change in the moisture content of the alfalfa.

Some difficulty was encountered in obtaining a good representative sample from the top of the drying section, for the alfalfa had to be removed from the gas stream almost instantly so that the sample would not undergo more drying than the alfalfa traveling through the system. This problem was solved by putting a small door in the side of the 8 inch horizontal duct which was attached to the top of the drying section. The door was placed 3 feet from the union of the duct and the drying section, and the sample was obtained by inserting a rectangular piece of metal into the duct so that the gas stream and material were diverted out of the system onto a large floor. The alfalfa sample was immediately collected and placed in the sample can. Not more than a minute elapsed during the sampling procedure, and the moisture content was considered unchanged from the time that the material left the system until it was placed in the sample can.

At the end of each day's run the sample cans with samples were weighed, the lids were removed and the cans were placed in a compartment dryer which was operated at 190°F. The alfalfa samples were dried about 18 hours, and the sample cans with samples were removed and reweighed. From the initial and final weights the percentage moisture contents of the various samples were calculated.

Recording of Data. The following data were recorded every five minutes during each run: pitot tube reading, natural gas and air pressure, static pressure and temperature at the inlet, static pressure and temperature at the bottom, at the middle, and at the top of the drying section, and the temperature at the top of the cyclone separator. The gas meter reading and the dry and wet bulb temperatures at the front of the furnace were recorded at the start of each run, and the gas meter reading and amount of alfalfa fed to the dryer were recorded at the end of the run. The dried product collected from the cyclone separator, and the stems from the stem separator were weighed at the end of the runs and the weights recorded. The temperature of the hot gases from the furnace was recorded on a Wheelco recording thermometer while other temperatures were calculated from millivolt readings obtained by using a Leeds and Northrup potentiometer connected through a selector switch to the four thermocouples on the inside wall of the dryer. A thermos bottle filled with cracked ice served as a cold junction box.

Experimental and Calculated Data

Table 1 shows recorded and calculated data from fifty-six runs. Sixty-three runs were made, but one run was discarded because the air rate was not sufficient to prevent the alfalfa from clogging the system, and six runs were made at an inlet temperature of 560°F. which gave an undesirable product having an excessive moisture content. All of the runs except two were thirty minutes in duration; one run lasted fifteen minutes and one twenty minutes; however, both of these had the same hourly feed rate as the thirty minute runs. Inlet gas temperatures of 900°F., 800°F., and 720°F. were used; these temperatures are listed under the heading T_1 in the table. The other temperatures T_2, T_3, T_4, and T_5 refer to the temperatures of the four thermocouples located in the drying system. It can be noted that a much dryer product, along with fewer stems, was obtained after the twenty-third run; this was attributed to a slight change made in the stem separator which probably changed the path that the gas stream followed, causing it to become more turbulent, thereby affecting the dryness of the product and the stem removal rate. In Table 1, W_0 and W_1 are the pounds of moisture per pound of dry alfalfa in the feed and in the sample taken at the top of the drying section, respectively. Pounds of moisture available is equal to the product of the pounds of alfalfa fed and the moisture content of the feed. Pounds of moisture removed was calculated from the weight and moisture content of the alfalfa leaving the

Table 1. Experimental and calculated data.

Run	Length of run, minutes	Gas consumed, ft³/hr.	Alfalfa, lbs./hr.			Alfalfa moisture content, %				Temperatures, °F.							W_o	W_1	$\frac{W_o}{W_1} - 1$	Moisture available, lbs./hr.	Moisture removed, lbs./hr.	Air rate through drying section, lbs./hr./ft²	$\frac{T_1 - T_4}{T_1 - T_{DB}}$	Heat required to vaporize water, B.T.U./lb.
			Feed in	Stems out	Leaf out	Feed in	Stems out	T.D.S.	Leaf out	T_{DB}	T_{WB}	T_1	T_2	T_3	T_4	T_5								
1.	30	2080	200.0	52.0	33.0	74.4	66.4	26.8	16.6	96.5	78.0	904	527	507	463	259	2.91	0.371	6.83	149.0	102.0	2005	0.545	2770
2.	30	1960	200.0	64.4	21.0	76.6	67.0	22.1	17.6	96.5	78.0	898	500	472	433	252	2.36	0.283	10.52	153.0	102.5	1885	0.580	2860
3.	30	1900	206.0	74.6	22.0	71.6	46.8	15.7	14.7	96.5	78.0	901	481	454	418	240	2.53	0.186	12.62	147.5	109.3	1765	0.601	2600
4.	30	2020	194.4	30.0	38.6	69.4	62.0	28.0	18.7	98.0	80.0	903	608	485	475	275	2.27	0.389	4.83	135.0	98.0	2120	0.532	3080
5.	30	2060	200.0	38.0	38.6	72.4	61.5	30.5	13.0	98.0	80.0	909	583	472	456	275	2.61	0.439	4.95	144.8	103.6	2060	0.557	3010
6.	30	--	200.0	30.0	54.0	72.2	65.0	39.5	32.7	98.0	80.0	710	482	402	385	255	2.60	0.652	2.99	144.4	95.9	2535	0.532	2850
7.	30	1920	200.0	20.4	53.0	71.2	57.9	32.8	23.5	101.0	79.0	722	493	419	378	252	2.47	0.487	4.08	142.4	106.8	2265	0.553	2390
8.	30	1760	203.0	31.6	57.6	82.0	59.0	31.3	35.9	101.0	79.0	720	472	392	360	248	4.55	0.457	8.96	167.0	137.8	2160	0.582	1800
9.	30	1700	123.0	12.4	31.0	73.1	56.7	30.4	24.6	101.0	79.0	720	491	427	390	259	2.73	0.436	5.26	90.0	71.0	2145	0.533	3300
10.	30	1780	200.6	56.4	31.0	72.7	62.0	28.1	12.7	98.5	80.0	716	432	364	337	232	2.67	0.392	5.81	146.0	98.0	1910	0.613	2430
11.	30	1700	206.0	60.6	29.0	73.2	60.8	19.2	12.5	98.5	80.0	727	437	373	346	237	2.73	0.238	10.45	151.0	106.8	1850	0.597	2170
12.	30	1680	203.0	102.6	13.0	74.2	60.5	0.0	0.0	98.5	80.0	717	395	345	333	220	2.88	0.0	---	151.0	89.0	1800	0.620	2590
17.	30	1980	200.0	36.0	29.6	82.0	68.5	27.6	25.6	99.0	78.0	903	578	467	440	279	4.54	0.382	10.90	164.0	130.0	2095	0.576	2290
18.	30	--	200.0	38.6	26.0	80.9	65.0	22.4	20.2	99.0	78.0	905	570	468	437	276	4.21	0.289	13.60	162.0	129.8	1970	0.582	2350
21.	30	1840	203.0	36.4	36.4	78.0	63.3	25.5	28.8	97.0	81.0	723	398	362	335	227	3.56	0.342	9.41	158.5	124.0	2010	0.620	2060
22.	30	1800	200.0	56.4	27.0	77.6	60.7	24.5	18.1	97.0	81.0	724	400	357	332	227	3.49	0.325	9.74	155.5	116.3	1800	0.625	1990
23.	30	1740	200.0	18.0	43.0	74.4	62.0	27.5	22.6	97.0	81.0	720	410	378	353	240	2.88	0.379	6.60	149.0	128.1	2140	0.580	1990
24.	30	1900	200.0	20.4	33.0	74.5	52.9	15.2	9.1	97.0	73.0	900	482	426	419	253	2.90	0.178	15.20	149.0	135.4	1780	0.600	2080
25.	30	1880	200.0	10.4	23.0	72.4	51.0	14.8	11.5	97.0	73.0	902	498	442	430	267	2.61	0.173	14.09	145.0	135.3	1900	0.586	2170
26.	30	1880	199.0	6.4	41.6	75.1	51.0	20.9	12.7	97.0	73.0	900	515	452	434	272	3.03	0.264	10.48	149.5	140.9	1980	0.580	2140
27.	30	1820	197.6	10.0	58.4	65.0	11.0	10.6	6.2	97.0	73.0	723	387	347	332	230	1.86	0.118	14.76	128.0	123.3	1990	0.625	2080
28.	30	1750	200.0	5.6	62.4	65.2	18.8	17.7	11.1	97.0	73.0	727	410	360	352	239	1.87	0.214	7.74	130.5	122.3	2100	0.595	2110
29.	30	1660	200.0	1.6	77.0	66.4	25.5	24.2	14.0	97.0	73.0	715	432	390	370	250	1.97	0.320	5.16	132.8	121.6	2280	0.558	2110
30.	30	--	211.0	20.4	51.6	63.3	12.4	7.1	4.1	100.0	75.0	720	355	325	308	213	1.72	0.076	21.63	133.5	128.9	1805	0.665	1890
31.	30	--	220.0	6.0	70.0	64.7	24.6	15.9	13.1	100.0	75.0	718	394	350	330	237	1.83	0.189	8.68	142.3	131.6	2100	0.627	2020
32.	15	--	214.0	0.8	76.0	61.2	25.6	17.9	12.5	100.0	75.0	725	428	384	364	250	1.58	0.218	6.25	131.0	110.8	2240	0.578	2400
33.	30	2000	200.0	21.6	15.6	73.5	52.0	17.6	10.8	89.0	70.0	897	483	418	395	249	2.77	0.213	12.00	147.0	126.7	1750	0.620	--
34.	30	1980	192.0	13.0	40.0	75.2	--	19.2	12.0	89.0	70.0	902	492	430	410	250	3.03	0.238	11.70	125.0	---	1840	0.605	2250
35.	30	1980	198.0	9.0	44.0	74.6	48.4	20.8	11.9	89.0	70.0	898	509	443	418	263	2.96	0.262	10.30	148.0	132.2	1940	0.594	2380
36.	30	1900	200.0	6.0	44.4	70.5	40.6	19.9	6.4	89.0	70.0	808	442	380	365	235	2.39	0.248	8.64	141.0	124.8	1965	0.616	2300

Table 1. (cont.).

Run	Length of run, minutes	Gas consumed, ft³/hr.	Alfalfa, lbs./hr.			Alfalfa moisture content, %				Temperatures, °F.							W_o	W_1	$\frac{W_o}{W_1} - 1$	Moisture available, lbs./hr.	Moisture removed, lbs./hr.	Air rate through drying section, lbs./hr./ft²	$\frac{T_1 - T_4}{T_1 - T_{DB}}$	Heat required to vaporize water, B.T.U./lb.
			Feed in	Stems out	Leaf out	Feed in	Stems out	T.D.S.	Leaf out	T_{DB}	T_{WB}	T_1	T_2	T_3	T_4	T_5								
37.	30	1750	200.0	5.6	56.0	69.9	30.0	23.7	11.0	89.0	70.0	802	457	390	372	243	2.31	0.311	6.43	139.8	120.3	2090	0.604	2470
38.	30	1820	200.0	3.6	58.0	70.8	41.4	25.2	19.6	89.0	70.0	797	467	406	380	250	2.44	0.336	6.26	141.6	121.1	2160	0.589	2460
39.	30	1920	200.0	15.6	35.0	77.0	52.5	21.5	12.3	88.0	70.0	803	430	370	358	230	3.33	0.273	11.20	154.0	135.3	1970	0.622	2140
40.	30	1820	200.0	22.0	29.0	77.5	49.0	9.8	6.3	88.0	70.0	804	383	337	328	204	3.44	0.109	30.56	155.0	140.5	1610	0.665	1790
41.	30	1820	200.0	10.0	52.0	77.8	52.0	25.9	15.4	88.0	70.0	800	449	333	364	240	3.49	0.350	8.97	155.6	136.5	2070	0.613	2220
42.	30	1860	125.0	13.6	23.0	72.0	43.0	8.5	3.7	83.0	62.0	799	437	376	352	225	2.58	0.093	26.74	90.0	81.8	1605	0.625	2900
43.	30	1840	120.0	3.0	26.0	71.5	48.0	17.6	9.8	83.0	62.0	798	492	424	399	258	2.49	0.213	10.69	85.7	77.3	1960	0.559	3460
44.	30	1840	122.0	2.0	32.0	71.5	31.7	25.8	11.2	83.0	62.0	803	505	437	410	270	2.51	0.347	6.23	87.3	75.2	2080	0.545	3650
46.	30	1810	120.0	11.6	21.6	72.8	39.4	9.4	6.7	86.0	72.0	800	452	400	365	230	2.68	0.103	25.02	87.5	80.3	1540	0.609	2780
47.	30	1680	200.0	22.0	35.0	71.5	29.3	8.1	4.9	88.0	70.0	805	395	355	328	213	2.52	0.087	27.96	143.0	132.9	1550	0.663	1570
48.	30	1840	120.0	15.0	17.0	78.0	55.0	24.8	18.4	84.0	76.0	723	409	354	308	200	3.55	0.329	9.80	93.5	78.8	1680	0.650	2980
49.	30	1780	120.0	9.0	26.0	80.0	62.5	41.7	30.1	84.0	76.0	722	436	390	338	220	4.00	0.714	4.63	96.0	75.7	2065	0.602	3520
50.	30	1750	120.0	4.4	27.0	79.3	56.5	40.8	32.2	84.0	76.0	721	445	408	350	230	3.80	0.688	4.52	95.0	76.6	2220	0.582	3600
51.	30	1860	120.0	9.6	23.0	69.0	39.4	13.2	11.6	79.0	58.0	722	406	360	317	205	2.22	0.152	13.60	82.7	74.1	1815	0.630	3330
52.	30	1810	120.0	4.0	29.0	72.0	37.8	21.2	15.3	79.0	58.0	719	440	394	345	232	2.58	0.269	8.59	86.5	76.6	2165	0.585	3540
53.	30	1780	120.0	3.6	34.4	66.5	44.2	24.8	20.1	79.0	58.0	722	457	410	360	238	1.98	0.329	5.02	80.0	67.9	2265	0.563	4060
54.	30	2000	120.0	17.6	20.0	68.9	48.3	5.9	4.2	80.0	64.0	898	464	410	360	220	2.21	0.062	34.64	82.5	72.3	1500	0.657	3770
55.	30	2000	124.0	14.0	35.6	72.0	41.7	17.9	20.0	80.0	64.0	898	472	423	385	230	2.58	0.218	10.80	89.3	77.7	1840	0.627	4150
56.	30	1900	120.0	11.0	19.0	77.0	57.0	4.5	36.2	83.0	64.0	902	514	448	398	247	3.36	0.047	70.48	92.2	84.8	1390	0.615	2750
57.	30	1930	120.0	7.0	24.0	77.2	73.3	20.1	8.7	83.0	64.0	900	532	463	415	264	3.39	0.251	12.50	92.6	81.0	1735	0.594	3510
58.	20	2370	120.0	4.5	22.5	77.2	63.5	23.1	5.4	83.0	64.0	900	548	484	432	272	3.39	0.300	10.30	92.6	82.8	1740	0.573	3310
59.	30	2120	121.0	7.0	27.0	76.5	--	21.4	16.1	64.0	60.0	815	495	440	392	250	3.26	0.271	11.03	92.5	--	1880	0.565	--
60.	30	1900	121.0	1.6	34.0	76.9	36.6	29.5	21.4	64.0	60.0	796	485	426	387	254	3.32	0.418	6.94	93.0	81.8	2020	0.560	3440
61.	30	2000	125.0	1.6	27.6	76.0	55.0	28.8	14.2	64.0	60.0	902	547	468	433	268	3.17	0.404	6.85	95.2	82.5	1970	0.560	3770
62.	30	2060	120.0	14.0	18.0	78.9	64.0	8.4	5.1	82.0	72.0	887	477	420	374	227	3.72	0.095	39.10	94.7	83.8	1500	0.637	3080
63.	30	1950	126.0	5.6	25.6	80.0	65.3	18.0	14.8	82.0	72.0	904	507	450	400	243	4.19	0.220	18.00	101.0	92.4	1635	0.614	2990

See nomenclature for meaning of symbols in column headings.

stem separator and the top of the drying section. The heat required to remove the moisture from the alfalfa was obtained by an enthalpy balance between the gases leaving the blower and the gases leaving the drying section. The gas rate through the drying section was obtained from the pitot tube reading.

INTERPRETATION OF DATA

General Discussion

There were essentially four independent variables in each run; they were gas temperature, gas rate, feed rate, and moisture content of the feed. A dependent variable such as the temperature or moisture content at the top of the dryer would be to some extent dependent upon all of the independent variables. It is intended to relate the variables in such a manner that the correlations will be applicable not only to the particular dryer from which the data were obtained but may give an indication of the type of relationships to expect from other pneumatic alfalfa dehydrators. Drying data are usually expressed as a function of the time of drying and of the area of the material being dried; however, in this case it was not practical to measure either the drying time or area of the alfalfa, so other methods of correlation had to be found.

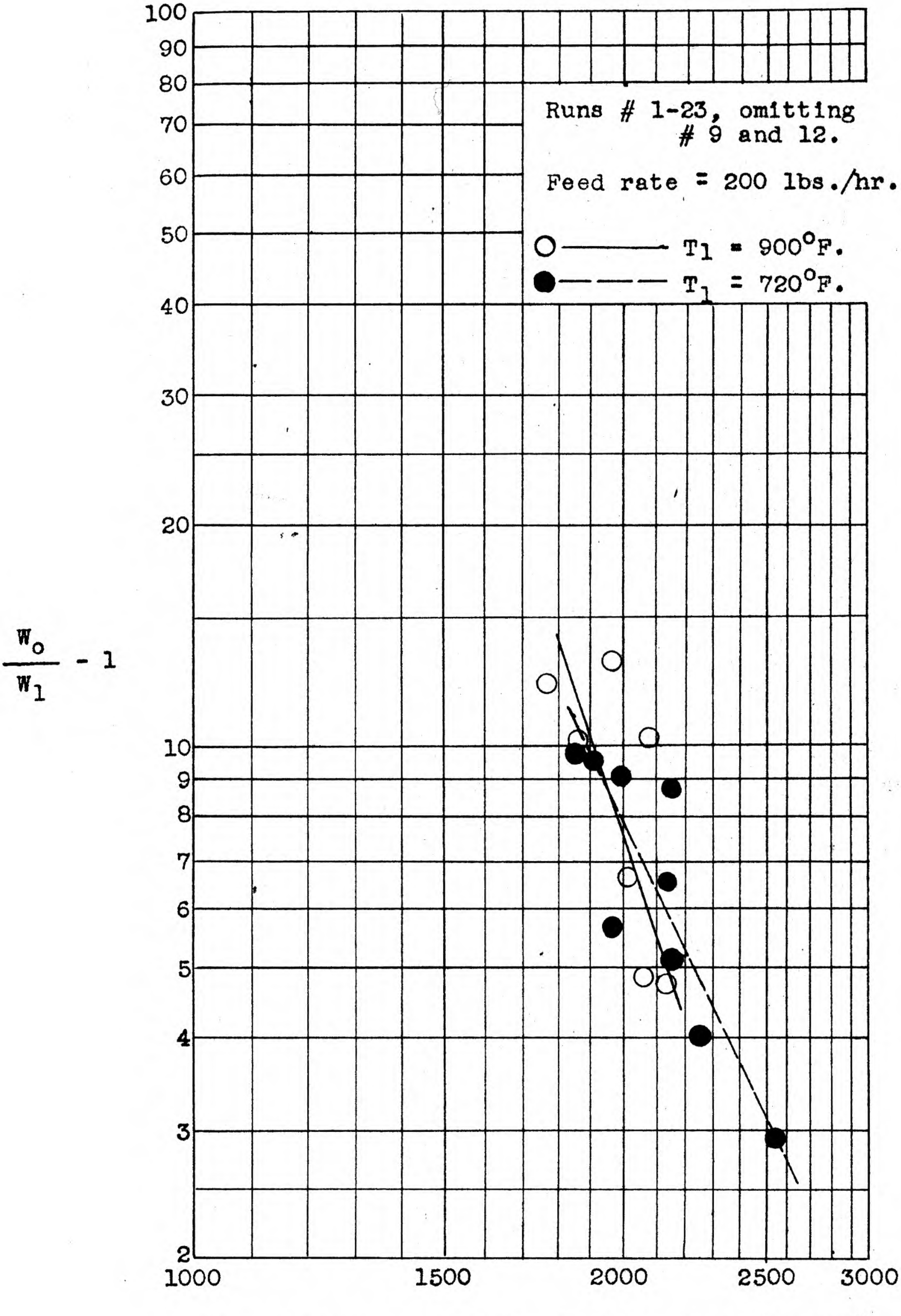
In trying to operate the dryer at a feed rate above 200 pounds per hour it was found that the alfalfa clogged the system at the elbow leading into the drying section. Clogging of the system also occurred when orifice plates having an opening smaller than six inches in diameter were used; therefore, all of the gas rates were obtained by using the 6, 7-7/8, or 10 inch orifice, or no orifice plate. Although 200 pounds per hour was the maximum feed rate that the dryer could handle with aspirating-type feeder and an elbow between the feed and drying sections, it was believed that this did not approach the maximum feed rate insofar as the gas rate and the capacity of the drying section were concerned.

In interpreting the data the runs were divided into three groups, all of the runs in each group having the same feed rate. In the first 41 runs the feed rate was 200 pounds per hour. Since the change made in the stem separator after run No. 23 had such a profound effect on the variables of the system; the runs at a feed rate of 200 pounds per hour were separated into two groups: namely, those runs before the change in the separator was made (No. 1 through 23), and those runs after the change was made (No. 42 through 41 and No. 47). A third group (No. 42 through 63) consisted of runs having a feed rate of 120 pounds per hour. All three of the groups have some relationships in common.

Correlation

In relating the dryer variables, only the drying which took place before the material left the drying section were considered, since it was the drying section which was the principal piece of apparatus under study.

A logistic equation used by Wilke (5) who studied the falling-rate period in the through circulation drying of solids, equates the ratio of the initial moisture content to the moisture content at any time, to several constants which have exponents that are functions of the drying time. In pneumatic drying the time of drying is inversely proportional to the gas rate through the dryer; that is, the alfalfa will lose moisture relatively slow when the gas rate is low. The drying time is also inversely proportional to the gas temperature, for a high temperature gas will effect more rapid evaporation of moisture from alfalfa than will a low temperature gas. Since a relationship exists between the amount of drying accomplished $\left(\frac{W_o}{W_1}\right)$ and the time of drying and also between the drying time, gas temperature, and gas rate; the gas temperature and gas rate can be related to the amount of drying obtained; this relationship is shown in Figs. 1, 2, and 3. Values of $\left(\frac{W_o}{W_1} - 1\right)$ are plotted against the gas rate through the 16 inch drying section at the three inlet temperatures and constant feed rates. A straight line can be drawn through the points plotted on log-log paper where each line represents a constant gas inlet temperature. A comparison of Figs. 1 and 2 shows that higher values of $\left(\frac{W_o}{W_1} - 1\right)$ were obtained for the same gas rate in Fig. 2 (after the change in the stem separator was made), indicating that a dryer product was obtained in the second group of runs. Upon comparing Figs. 2 and 3 in which the feed rates were 200 pounds per hour and 120 pounds per hour respectively, rather close agreement will be noted, especially for an inlet temperature of 800°F. The agreement of the curves of Figs. 2 and 3 indicates that the feed rate, within the range used, exerts little influence on the dryness of the product.



Gas rate through drying section, lbs./hr./ft.^{2}

Fig. 1. Relationship between gas rate and inlet and outlet moisture content.

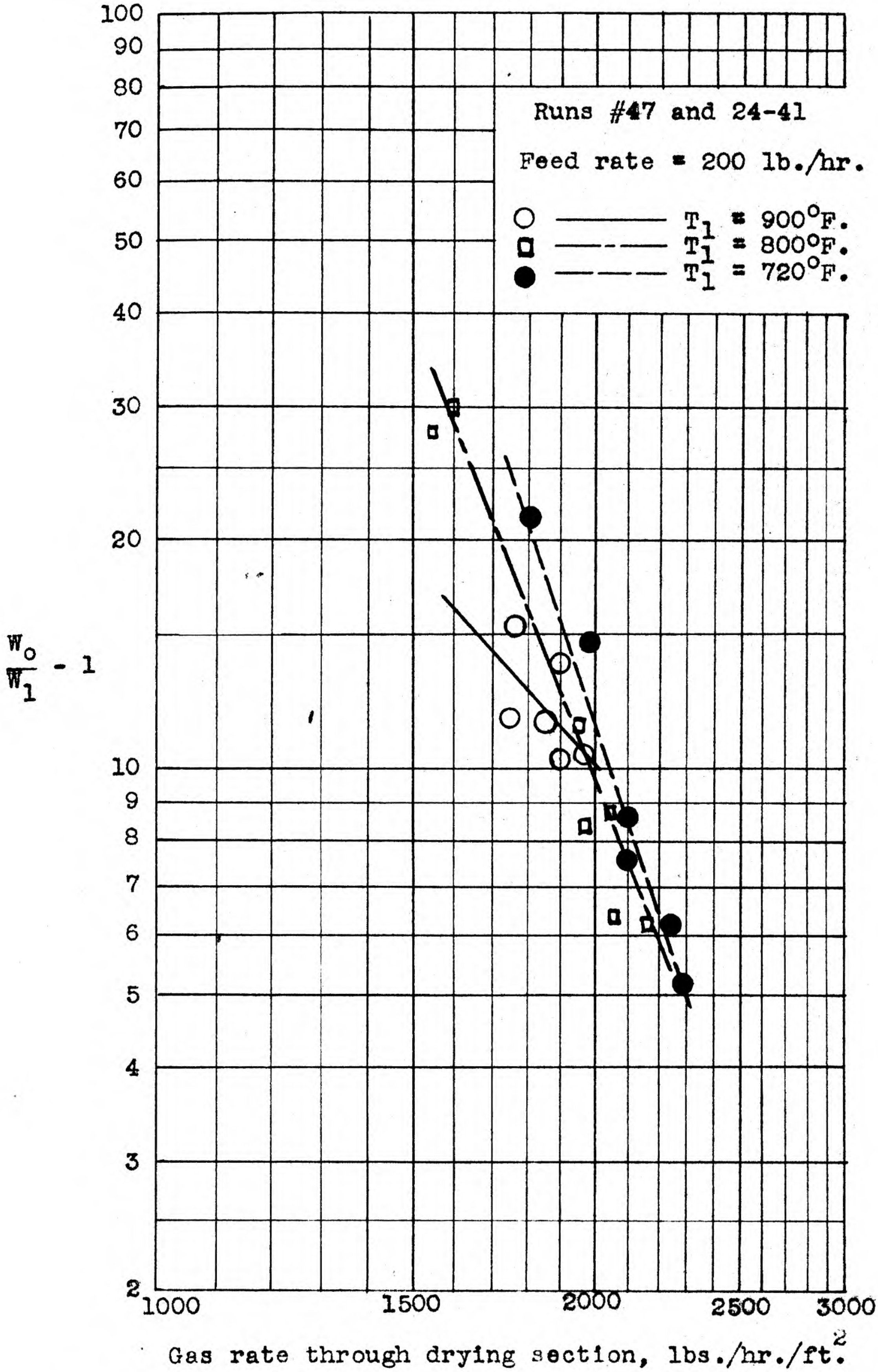
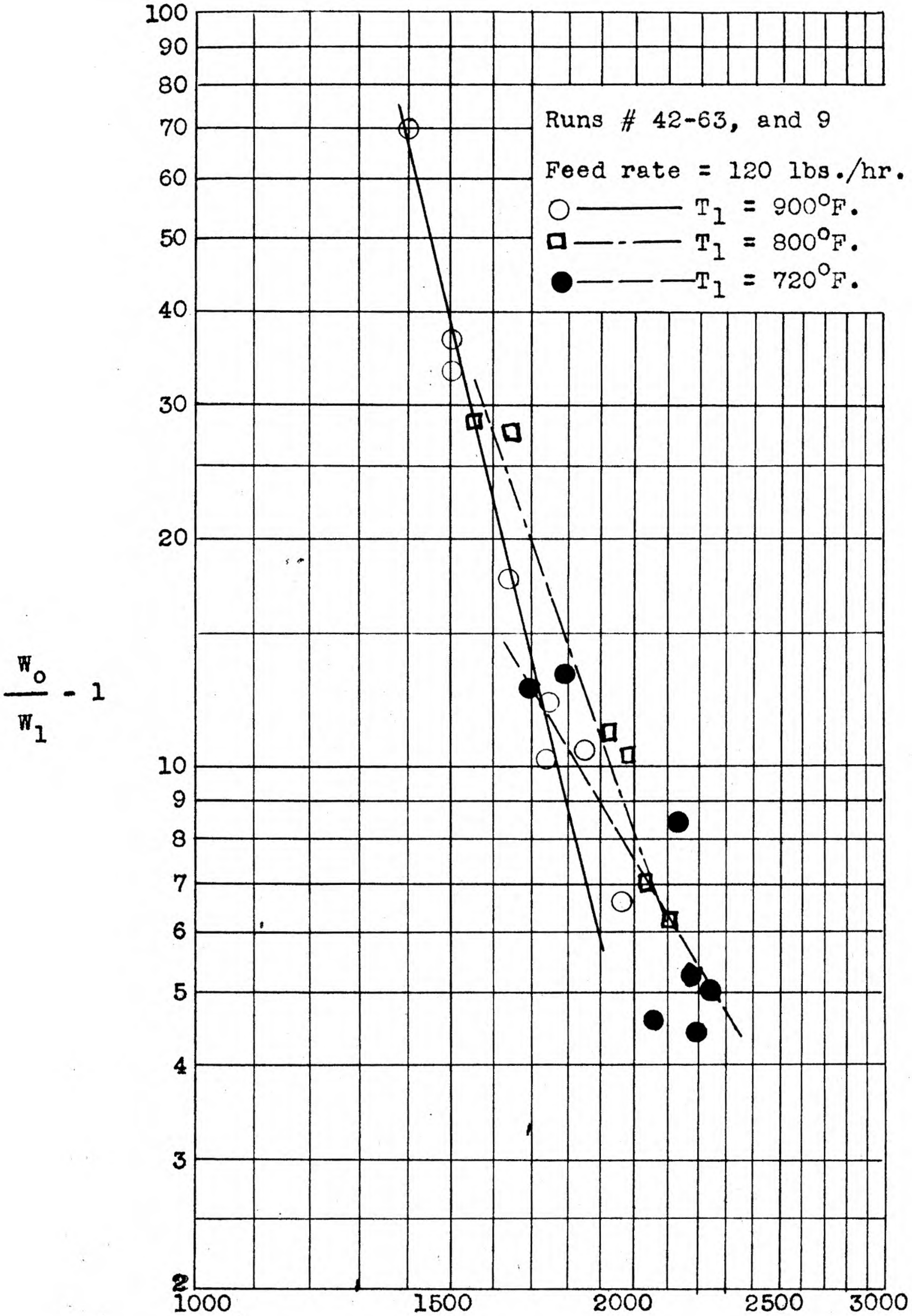


Fig. 2. Relationship between gas rate and inlet and outlet moisture content.



Gas rate through drying section, lbs./hr./ft^2

Fig. 3. Relationship between gas rate and inlet and outlet moisture content.

This relationship may not be valid when the feed rate is greater than 200 pounds per hour or is less than 120 pounds per hour.

Equations have been developed to fit the curves in Figs. 2 and 3. They are:

Inlet temperature	Equation	Average deviation from observed values
900°F.	$\left(\frac{W_o}{W_1} - 1\right) = (1650 - 8.07F)G^{-15.9 + 0.071F}$	12%
800°F.	$\left(\frac{W_o}{W_1} - 1\right) = (80 + 1.28F)G^{-4.42-0.0034F}$	11%
720°F.	$\left(\frac{W_o}{W_1} - 1\right) = (-970 + 8.47F)G^{2.45-0.0423F}$	17%

where; G = gas rate through dryer, lbs./(hr.-ft.^{2}) X 10^{-3}
F = alfalfa feed rate, lbs./hr.

It might be stated here that a variation of 10 per cent between the observed values of $\left(\frac{W_o}{W_1} - 1\right)$ and the values calculated from the equations is equivalent to an error of only from about 3 per cent to 6 per cent in the measurement of W_o or W_1; this would mean that if the gas rate and temperature of operation had been decided upon, and the moisture content of the wet alfalfa was known to within an accuracy of 1 per cent, a product could be obtained with a moisture content of from 3 per cent to 6 per cent of the moisture content predicted by the equations. Any error in measuring the moisture content of the wet alfalfa feed would decrease the percentage error of the dried product. The above equations are applicable only to this particular dryer, for dryers having other shapes would also have different gas stream paths, heat losses, and stem separation from the pneumatic dryer that was used in the investigations; all of these factors exert an influence on the amount of drying that will be accomplished.

Curves such as those of Figs. 1, 2, and 3 are of value in determining the temperature and gas rate required in a dryer if the feed rate and inlet and outlet moisture contents are known. The gas rate and the density of the alfalfa are the factors that should determine when the dried product will be floated from the drying section. The inlet gas temperature should have no effect on the dryness of the alfalfa; however, from an observation of Figs. 1, 2, and 3 it can be seen that a dryer product is consistent with the lower gas temperatures for a given gas rate.

Figures 4, 5, and 6 show the relationship between the thermal efficiency of the dryer, the gas rate, and the inlet gas temperatures. The quantity $T_1 - T_4$ is the temperature difference between the gas leaving the blower and the gas leaving the top of the drying section. $T_1 - T_{DB}$ is the available temperature difference; and represents the heat content available for use in drying were the gas to leave the drying section at the dry bulb temperature of the outside air. Were $T_1 - T_4$ to equal $T_1 - T_{DB}$ the dryer would have a thermal efficiency of 100 per cent.

In actual operation the thermal efficiency of the pneumatic dryer ranged between 50 per cent and 70 per cent with the higher thermal efficiencies being achieved by the lower inlet temperatures and lower gas rates. This is to be expected since at the lower inlet gas temperatures, not only is a dryer product obtained but heat losses through the wall of the column to the surroundings

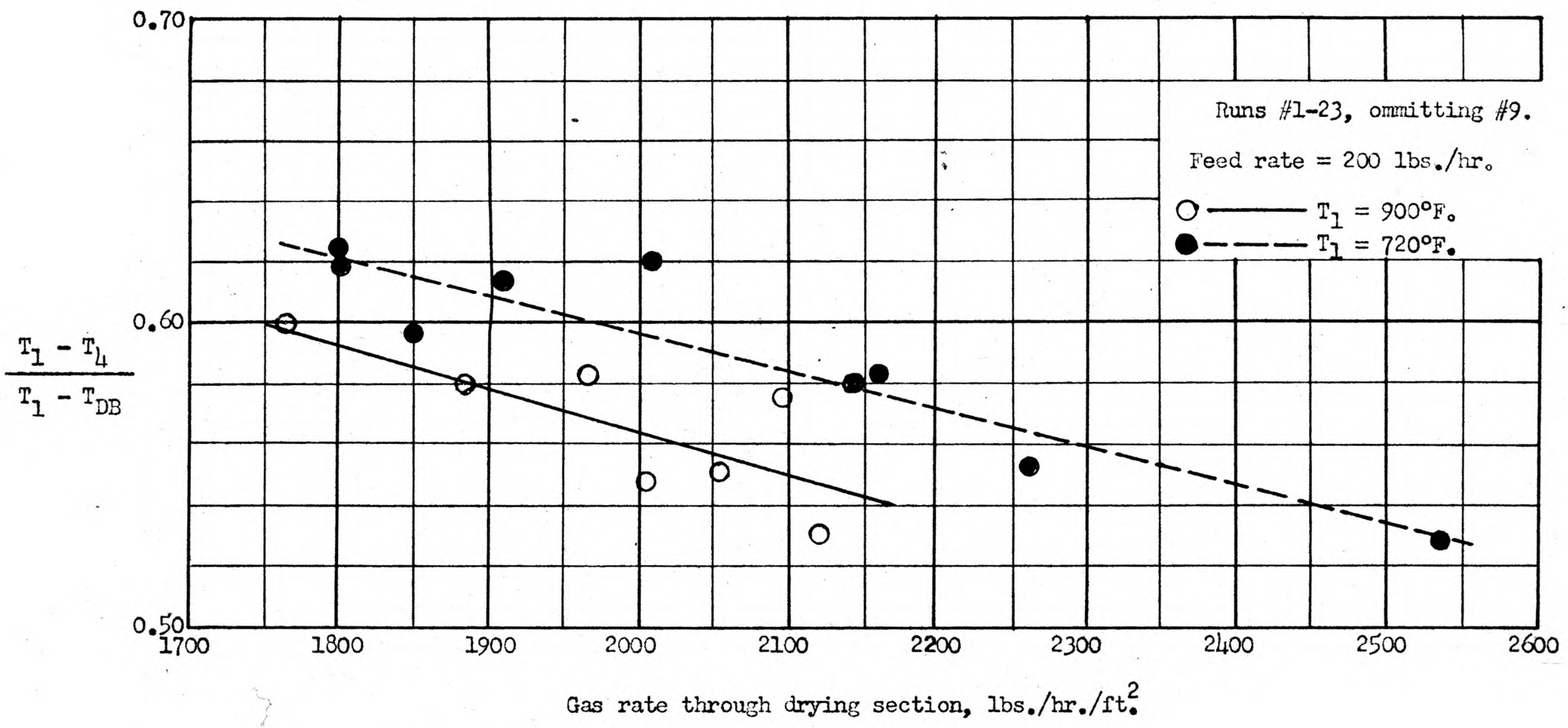


Fig. 4. Relationships between dryer temperatures and gas rate.

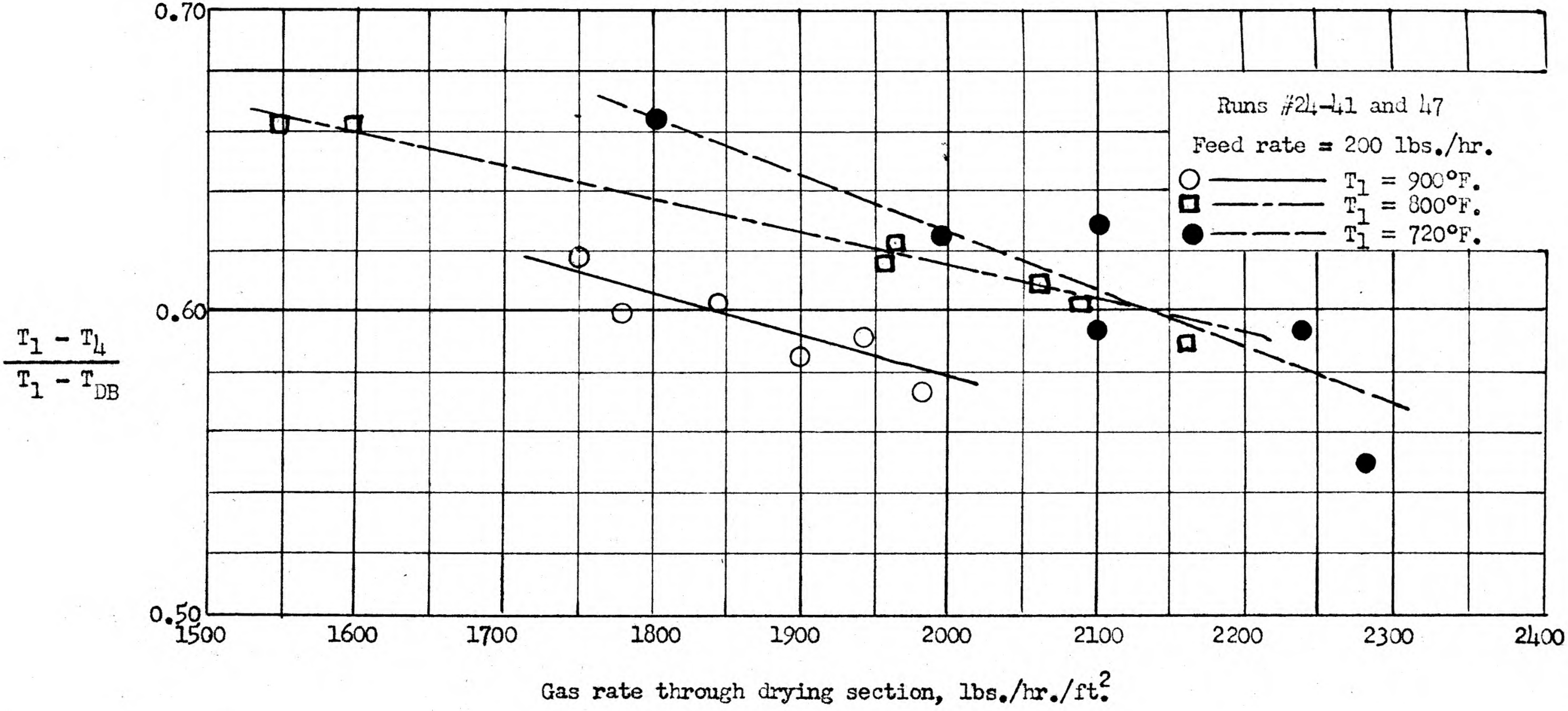


Fig. 5. Relationships between dryer temperatures and gas rate.

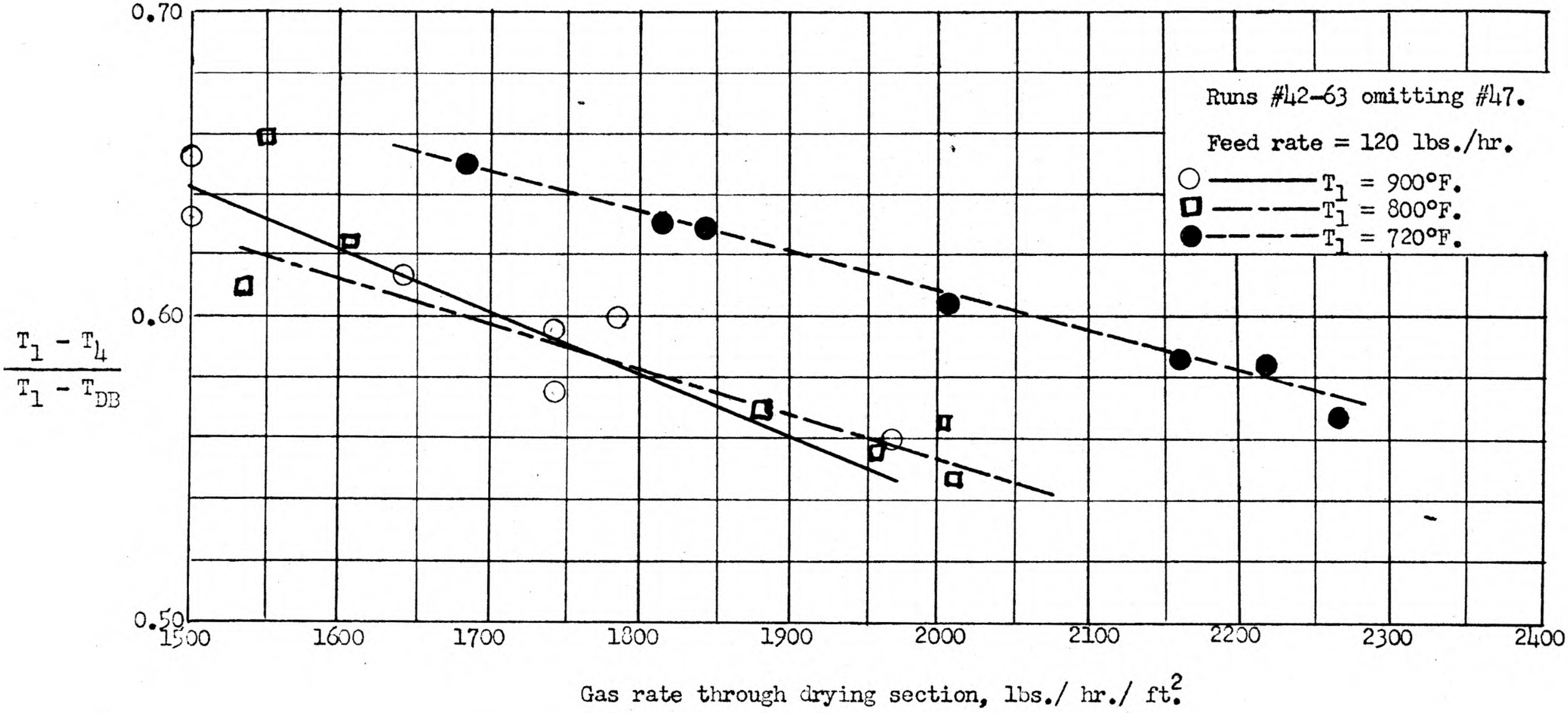


Fig. 6. Relationships between dryer temperatures and gas rate.

are less. The lower thermal efficiencies at the higher gas temperatures are contrary to the theory of pneumatic drying which predicts high thermal efficiencies with high temperature operation. If the dryer had been operated at feed rates greater than 200 pounds per hour, more moisture would have been removed by gases at the higher temperatures, and the temperature drop through the dryer would have been greater and higher thermal efficiencies would have been noted. For example, from the curves of Figs. 4, 5, and 6 it can be noted that at the lower gas rates the efficiencies at the high inlet temperatures tend to become greater than those at the lower inlet temperatures. For this comparison, a decrease in the gas rate is equivalent to an increase in the feed rate.

Consistent with the behavior of the thermal efficiency is the manner in which the heat required to evaporate a pound of water varies with the inlet temperature and gas rate. The last column in Table I shows the heat energy removed from the gas stream per pound of water evaporated. These values vary in the same manner as the thermal efficiencies since they are both a measure of the efficiency of the dryer. From Table I it is evident that operation of the dryer at a feed rate of 120 pounds per hour is uneconomical as a large amount of heat is wasted in obtaining a product that is only slightly drier than that obtained when the feed rate is 200 pounds per hour.

The weight of stems taken from the stem separator is inversely proportional to the air rate since the higher air rate will carry more of the lighter stems up the drying column and over into the cyclone separator. In most of the runs too many stems were separated from the alfalfa. Stem removal should be held within one or two pounds of stems for every 100 pounds of alfalfa fed to the dryer.

Goldberg and Bertelli (1) stated that the difference in specific gravity between grasses with 8 per cent moisture and that with 17 per cent moisture is only 3 per cent to 4 per cent; therefore, very careful control of the gas rate must be maintained in order to obtain selective ejection from the drying section. This statement is supported by the experimental data presented here, which shows that a change of about 1 per cent in the gas rate will affect a change of from 1 per cent to 2 per cent in the dryness of the alfalfa.

There would be little use in drying alfalfa artificially if a high content of nutritive material were not maintained. Samples of dried alfalfa were taken from eight of the runs which yielded products of acceptable moisture content. The samples were analyzed for carotene, and they were found to contain between 100,000 and 250,000 units per pound of dry alfalfa. These values were consistently higher than those obtained from the same alfalfa dehydrated in a conventional rotary dryer.

SUMMARY OF RESULTS

A pneumatic dehydrator was constructed and operated in the Chemical Engineering Building of Kansas State College for the purpose of determining its adaptability for drying alfalfa. The dehydrator consisted essentially of a 16 inch diameter vertical duct 24 feet in height into which a dry hot gas carrying moist alfalfa was blown. Provision was made at the bottom of the drying column for the separation and removal of coarse stems. The dried alfalfa and moist gas were separated in a cyclone separator, and the dried alfalfa was recovered.

Gas rates were varied between 1500 and 2500 pounds per hour per square foot of drying column cross-section, and inlet gas temperatures of 900°F., 800°F., and 720°F. were studied. Because of limitations in the method used for feeding moist alfalfa, feed rates of 120 pounds per hour and 200 pounds per hour only were investigated.

The results from 62 experimental runs are summarized as follows:

1. A relatively drier alfalfa product was obtained at the lower hot gas rates.

2. For a given hot gas and feed rate, the dryness of the product was inversely proportional to the temperature of the hot inlet gas.

3. No effect of feed rate on the dryness of the product was evident over the narrow range of feed rates used.

4. Gas temperatures between 720°F. and 800°F. and gas rates between 1600 and 1900 pounds per hour per square foot of dryer cross-section favored the carotene content of the dried product.

5. Thermal efficiencies of the drying column were 50 per cent and 70 per cent; the higher efficiencies corresponded to the lower inlet gas temperatures and lower gas rates.

Some of the larger stems issuing from the cyclone separator were charred, and it would have been more desirable had the charring been eliminated, although this had little or no effect on the nutrient content of the dried alfalfa. The charring could probably have been eliminated by lowering the temperature of operation which would also lower the drying capacity or increase the moisture content of the product.

The results obtained in operating the dryer give definite indications of the adaptability of the pneumatic dryer for dehydrating alfalfa.

RECOMMENDATIONS FOR FUTURE WORK

A large number of improvements can be made to the pneumatic alfalfa dehydrator used in this work. Further investigations are suggested for evaluating the effect of different gas rates, and gas temperatures, with special attention directed toward locating an operating point at which the small dry alfalfa stems will not char. Alterations to produce a lower gas temperature during the falling-rate drying period where charring occurs appear necessary. Recycling of low temperature waste gases from the cyclone separator is one method of achieving low temperature operation in the upper part of the drying section (the zone of falling-rate period drying), and at the same time economizing on the heat requirements.

An interesting study could be made on the effect of different shapes and sizes of drying sections on the quality of the product.

The method of introducing the feed into a horizontal section should be modified since clogging of the system occurred with the present system of feeding at feed rates greater than 200 pounds per hour. A feed rate of 200 pounds per hour did not appear to approach the potential drying capacity of the drying section; therefore, the dryer was not operated at a point which could be considered the most efficient. Introducing the feed by injection into the side of the drying section would allow feed rates greater than 200 pounds per hour to be used.

The stem separator was not entirely satisfactory for the efficient removal of large stems, as the amount of stems removed varied appreciably with changes of gas rate.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to the Kansas Industrial Development Commission for the generous financial assistance given to the project, and to:

Dr. Henry T. Ward for awarding the graduate research assistantship that made this research work possible.

Dr. Rollin G. Taecker for his encouragement and counsel.

Mr. Melville Marnix, who deserves a major share of the credit for this experimental work, for contributing his advice, time, and labor in constructing and operating the experimental dryer.

LITERATURE CITED

(1) Goldberg, A., and A. C. Bertelli.
Grass drying-engineering aspects.
Trans. of the British Inst. of Chem. Eng. 22: 89-99. 1944.

(2) de Lorenzi, Otto.
Combustion engineering, 1st ed. New York: Combustion.
Engineering-Superheater Inc. Chapter 29. 1949.

(3) Perry, John H., Editor.
Chemical engineers handbook, 3rd ed. New York:
McGraw-Hill Book Company. 800-838. 1950.

(4) Slade, R. E.
Grass driers. Green Crop Dryers' Assn. Year Book.
London: Farmers Weekly. 65-72. 1949.

(5) Wilke, Charles R.
The falling-rate period in the through circulation
drying of solids. Ph. D. thesis, University of
Wisconsin, Madison, Wisconsin, 1944.

APPENDIX

DRYER DESIGN

The following calculations were used to determine the specifications for the experimental pneumatic dryer:

Basis: 200 pounds of alfalfa per hour, (75% moisture content)

(1).

wt. of bone-dry alfalfa = 0.25(200) = 50 lbs.
wt. of moisture = 0.75(200) = 150 lbs.

Assuming 10% moisture in dried alfalfa,

$$\text{wt. of moisture} = \frac{10}{(100-10)}(50) = 5.6 \text{ lbs.}$$

wt. of moisture evaporated = 150 - 5.6 = 144.4 lbs.

(2).

Assuming that the falling rate period starts at 0.75 pounds of moisture per pound of dry alfalfa,

$$\text{wt. moisture evaporated during constant-rate period} = \left(\frac{75}{25} - 0.75\right)(50) = 112.5 \text{ pounds}$$

wt. moisture evaporated during falling-rate period = 144.4 - 112.5 = 31.9 pounds

(3).

Assuming specific heat of wet alfalfa (75%) = 0.8 B.T.U./lb./°F.
" " " " dry " (10%) = 0.15 " " "
" alfalfa enters dryer at 70°F.

heat required to heat wet alfalfa from 70°F. to 212°F. = (200) (0.8) (212-70) = 22,700 B.T.U.

Assuming an air rate of 2600 pounds per hour, and C_p of air = 0.25 + 0.47 (Humidity) B.T.U./°F.

$$\text{temperature drop of air} = \frac{22{,}700}{(2600)\ (0.25)} = 35^{\circ}\text{F.}$$

(4).

$$\text{humidity of air leaving constant rate zone of drying} = \frac{112.5}{2600} = 0.045 \ \frac{\text{lb. } H_2O}{\text{lb. B.D.A.}}$$

$$\text{average humidity during constant rate period of drying} = \frac{0.045 + 0}{2} = 0.0225 \ \frac{\text{lb. } H_2O}{\text{lb. B.D.A.}}$$

λ of water at 212°F. = 970 B.T.U./lb.
(wet bulb temp. of air)

heat absorbed in drying alfalfa = (112.5) (970) = 109,000 B.T.U.

$$\text{temperature drop of air} = \frac{109{,}000}{2600\,[0.25 + 0.47(0.0225)]} = 161^\circ\text{F.}$$

(5). Heat required to vaporize water during the falling-rate period, and to heat alfalfa to an outlet temperature of 350°F.

humidity of air leaving the falling-rate zone =

$$\frac{144.4}{2600} = 0.0556\ \frac{\text{lb. } H_2O}{\text{lb. B.D.A.}}$$

$$\text{average humidity of air in falling-rate zone,} = \frac{0.0556 + 0.045}{2} = 0.050\ \frac{\text{lb. } H_2O}{\text{lb. B.D.A.}}$$

heat absorbed in drying = (31.9) (970) = 31,000 B.T.U.

heat absorbed to heat alfalfa from 212°F. to 350°F. = (200) (0.15) (350-212) = 4,150 B.T.U.

$$\text{temperature drop of air} = \frac{35{,}150}{2600\,[0.27 + 0.47(0.050)]} = 49.3^\circ\text{F.}$$

(6). It was noted from earlier investigations on a drying section somewhat similar to the one under design that the lower section of the dryer was only 30% efficient, and the constant-rate and falling-rate drying sections were 70% efficient; therefore, corrections for temperature drops were made.

	temp. drop	temp.
1) Drop in heating alfalfa to 212°F.	117°F	603°F.
2) Drop in vaporizing water during constant-rate period	228°F.	375°F.
3) Drop in vaporizing water during falling-rate period, and in heating alfalfa to 350°F.	70°F.	305°F.

(7). The following alfalfa particle densities were determined by the displacement of mercury:

density of wet alfalfa (70%) = 45.5 lb./ft.^{3}
" " dry " (0%) = 26.8 "

density of 10% moisture alfalfa = 29.5 lb./ft.^{3}
estimated density of alfalfa at the end of the constant-rate period (43%) = 38.3 lb./ft.^{3}

(8). density of dry air at 603°F. = 0.0374 lb./ft.^{3}
density of wet air at 375°F. = 0.0462 "
(humidity = 0.045 lb./lb.)
density of wet air at 305°F. = 0.0505 "
(humidity = 0.056 lb./lb.)

(9). Using a form of Stokes Law where K_e is a constant which includes a shape factor, U is the free falling velocity of a particle and ρ_s and ρ are the densities of the alfalfa and air, respectively:

$$U = K_e\sqrt{\frac{\rho s - \rho}{\rho}}$$

$$U_0 = K_e\sqrt{\frac{45.4 - 0.0374}{0.0374}} = 34.8\ K_e$$

$$U_1 = K_e\sqrt{\frac{38.3 - 0.0462}{0.0462}} = 28.8\ K_e$$

$$U_2 = K_e\sqrt{\frac{29.5 - 0.0505}{0.0505}} = 24.2\ K_e$$

(10). Calculation of the diameter,

Previous investigations showed that a 16 inch diameter column using a gas rate of 2600 lbs./hr. would give a gas velocity that would keep the particles suspended.

G_0 = 2600 lbs./hr.
ρ_0 = 0.0374 lbs./ft.^{3}
U_0 = 830 ft./min., $U_0 = 34.8K_e$, $K_e = \frac{830}{34.8} = 23.8$

G_1 = 2600 + 112.5 = 2712.5 lbs./hr.
ρ_1 = 0.0462 lbs./ft.^{3}

$$U_1 = \frac{2712.5}{(0.0462)\left(\frac{\pi D_1^2}{4}\right)}$$, but $U_1 = 28.8\ K_e$, U_1 = 687 ft./min.

therefore D_1 = 16.12 inches.

G_2 = 2600 + 144.4 = 2744.4 lbs./hr.
ρ_2 = 0.0505 lbs./ft.^{3}

$$U_2 = \frac{2744.4}{(0.0505)\left(\frac{D_2^2}{4}\right)}, \text{ but } U_2 = 24.2\ K_e,\ U_2 = 575 \text{ ft./min.}$$

therefore $D_2 = 16.97$ or 17 inches.

(11). A previous investigation on the rates of water removal during the constant-rate and falling-rate periods showed that water was removed 1.75 times faster in the constant-rate period than in the falling-rate period.

relative time to remove water during the constant-rate period $= \frac{112.5}{1.75} = 64.3$

relative time to remove water during the falling-rate period $= \frac{31.9}{1.00} = 31.9$

If the mean temperature driving force were the same;

length of constant-rate drying section $= \frac{64.3}{96.2} = 0.67$

length of falling-rate drying section $= \frac{31.9}{96.2} = 0.33$

(12). The actual length of the drying sections could theoretically be any length; however, if they were very short the momentum of the alfalfa would carry it through and out of the system with little drying taking place. The falling-rate section was arbitrarily made 8 feet long, this would make the constant-rate section 16 feet long.

(13). Since a certain amount of alfalfa would be held up in the falling-rate section, causing an increase in the superficial gas velocity; the diameter of the top of the drying section was increased from 17 to 18 inches.

SPECIFIC HEAT OF GRASSES

Goldberg (1) gives a chart relating the specific heat of grass to its moisture content. This graph is reproduced in following Fig. 7.

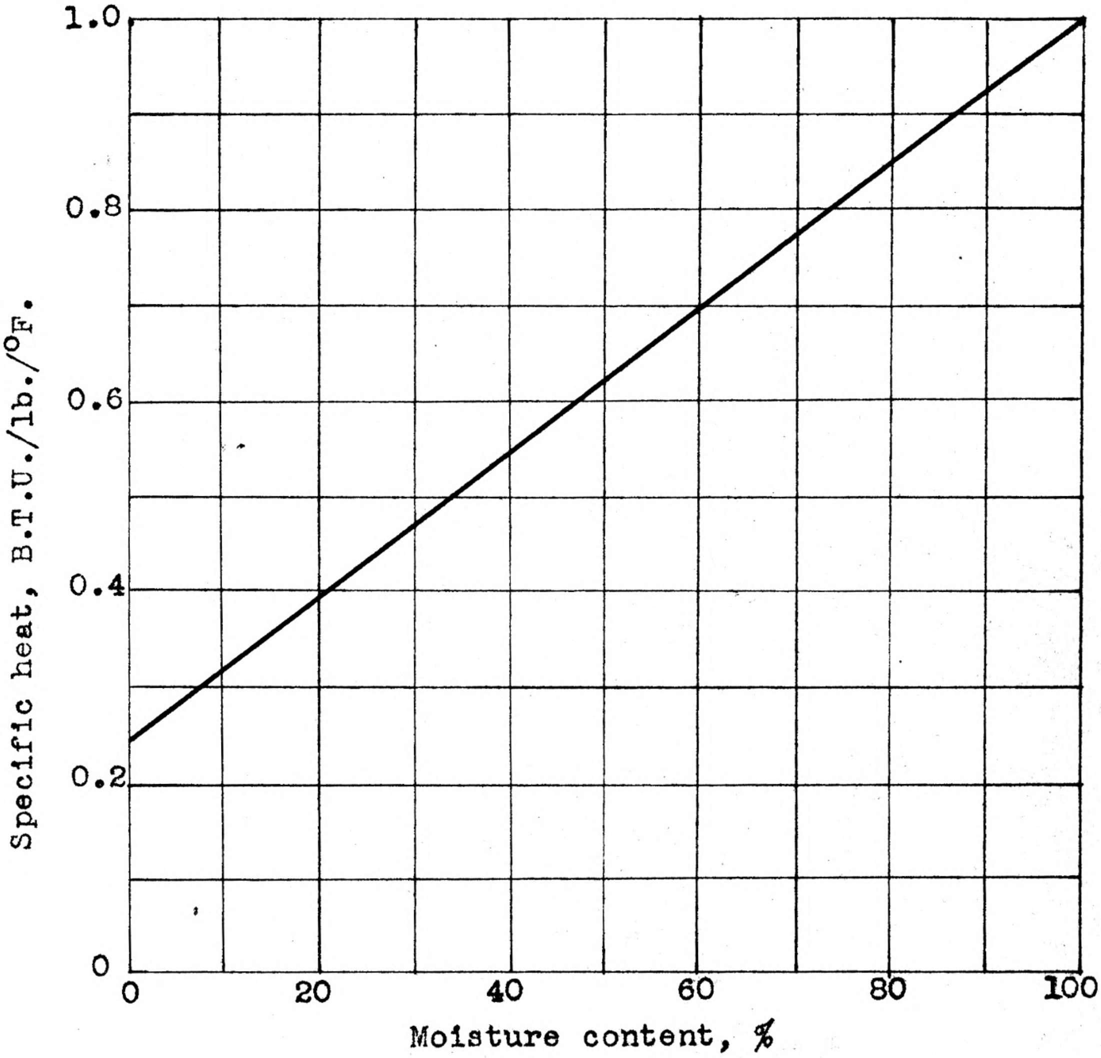


Fig. 7. Relationship between the specific heat and moisture content of grasses.

SAMPLE CALCULATIONS

Run #3

Recorded Data

period of run 30 min.
natural gas consumed 950 ft.^{3} (s.c.)
lbs. of feed in 103.0 lbs.
lbs. of stems out 37.3 lbs.
lbs. of leaf out 11.0 lbs.
moisture content of feed 71.6%
" " " stems 46.8%
" " T.D.S. 15.7%
" " leaf out 14.7%

T_{DB} 96.5°F.
T_{WB} 78°F.
T_1 901°F.
T_2 481°F.
T_3 454°F.
T_4 418°F.
T_5 240°F.

Calculated Data

$$W_o = \frac{71.6}{100 - 71.6} = 2.53 \text{ lbs. water/lbs. dry alfalfa}$$

$$W_1 = \frac{15.7}{100 - 15.7} = 0.186 \text{ lbs. water/lbs. dry alfalfa}$$

$$\frac{W_o}{W_1} - 1 = \frac{2.53}{0.186} - 1 = 12.62$$

moisture available = 2(103) (0.716) = 147.5 lbs./hr.

wt. bone dry alfalfa = 206 - 147.7 = 58.3 lbs./hr.

wt. moisture in stems = 37.3(.468)2 = 34.90 " "

wt. B.D. alfalfa in stems = 75.4-34.9 =40.5 " "

wt. B.D. alfalfa in leaf = 58.3-40.5 = 17.8 " "

wt. moisture in leaf = (17.8)(0.186) = 3.3 " "

wt. moisture out in leaf and stems = 3.3 + 34.9 = 38.2 lbs.

wt. moisture removed by dryer = 147.5 - 38.2 = 109.3 lbs.

pitot tube reading = 0.414 inches water

gas density assumed at $903^{\circ}F.$ = 0.0278 $lb./ft.^3$

$$\text{velocity head in 8" duct} = \frac{0.414(62.3 - 0.0278)}{(12) \quad (0.0278)} = 77.3 \text{ ft.}$$

$$\text{for pitot tube, } \frac{U_{max}}{U_{ave}} = 1.0$$

$$\text{velocity through 8" duct} = \sqrt{(64.3)(77.3)} = 70.5 \text{ ft./sec.}$$

gas rate through column = (70.5)(.349)(3600)(0.0278) = 2460 lbs./hr.

cross-section area of 16" drying section = 1.395 $ft.^2$

$$\text{gas rate through drying section} = \frac{2460}{1.395} = 1765 \text{ lb.}/(\text{hr.-ft.}^2)$$

$$\frac{T_1 - T_4}{T_1 - T_{DB}} = \frac{903 - 418}{903 - 96.5} = 0.601$$

Assuming hot gas to have same composition as pure air in order to simplify a heat balance;

Datum plane = $65^{\circ}F$,

Heat Input

from 2460 pounds of air at $903^{\circ}F.$ (85 pound moles).
C_p = 7.20 B.T.U./lb.mole/$^{\circ}F.$

$$H_1 = (85)(7.2)(903-65) = 512{,}000 \text{ B.T.U./hr.}$$

from 206 lbs. of alfalfa 71.6% moisture at the wet bulb temperature of the air ($78^{\circ}F.$)
specific heat from Fig. 7. = 0.79 B.T.U./lb./$^{\circ}F.$

$$H_2 = (206)(0.79)(78-65) = 2{,}100 \text{ B.T.U./hr.}$$

$$\text{Total heat input} = H_1 + H_2 = 514{,}100 \text{ B.T.U.}$$

Heat Output

from 2460 pounds of air at $418^{\circ}F.$
C_p = 7.02 B.T.U./lb. mole/$^{\circ}F.$

$$H_3 = (85)(7.02)(418-65) = 211{,}000 \text{ B.T.U./hr.}$$

from 109.3 lbs. of water vapor removed from alfalfa, temperature = 418°F., 6.1 pound moles, C_p = 8.14 B.T.U.

$$H_4 = (6.1)(8.14)(418-65) = 17,500 \text{ B.T.U.}$$

from 74.6 lbs. of stems out of separator at 46.8% moisture. temperature = adiabatic saturation temperature of gas = 250°F. specific heat = 0.64 B.T.U./lb.

$$H_5 = (74.6)(0.64)(250-65) = 8,830 \text{ B.T.U.}$$

from 22 lbs. of leaf out of T.D.S. at 15.7% moisture, and temperature of 418°F., specific heat = 0.37 B.T.U./lb.

$$H_6 = (22)(0.37)(418-65) = 2,900 \text{ B.T.U.}$$

Total heat out = $H_3 + H_4 + H_5 + H_6$ = 230,200 B.T.U.

Heat absorbed in vaporizing water =

$$514,100 - 230,200 = 283,900 \text{ B.T.U.}$$

Heat required to evaporate one pound of water $= \frac{283,900}{109.3} = 2600$ B.T.U.

NOMENCLATURE

B.D.A.	Bone dry air.
D	Column diameter, inches.
F	Feed rate, lbs./hr.
G	Gas rate through drying section, lbs./(hr.-ft.^{2}) X 10.$^{-3}$
H	Enthalpy, B.T.U. above datum plane of 65°F.
K_e	Shape factor constant in Stokes equation.
T_1	Temperature of gas at blower outlet, $^{\circ}$F.
T_2	Temperature of gas 25 feet from top of column, $^{\circ}$F.
T_3	Temperature of gas 14 feet from top of column, $^{\circ}$F.
T_4	Temperature of gas 1 foot from top of column, $^{\circ}$F.
T_5	Temperature of gas leaving cyclone separator, $^{\circ}$F.
T_{DB}	Dry bulb temperature of outside air, $^{\circ}$F.
T_{WB}	Wet bulb temperature of outside air, $^{\circ}$F.
U	Free falling velocity in Stokes equation, ft./min.
W_o	lbs. water/lb. dry alfalfa in feed.
W_1	lbs. water/lb. dry alfalfa at top of drying section.
λ	Latent heat of vaporization of water, B.T.U./lb.
ρ_s	Particle density of alfalfa, lbs./ft.^{3}
ρ	Density of air, lbs./ft.^{3}