Development and Testing of

A Forced Air Dryer
For Fiber Flax
(Linum usitatissimum)

Norman R. Brandenburg

Jesse E. Harmond

Agricultural Experiment Station
Oregon State College
Corvallis

Contents

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Summary

In an effort to assist the domestic fiber flax industry, the United States Department of Agriculture and the Oregon Agricultural Experiment Station cooperated in a program of engineering and agronomic research. This paper discusses one of the engineering investigations concerning the design, construction, and test operation of a semicommercial size dryer for retted fiber flax straw.

The dryer is a continuous, conveyor-type structure with three exposure zones. It uses diluted combustion products from an oil-fired furnace as the drying medium. A squeeze-roll unit is employed to remove some moisture mechanically before flax enters the dryer.

Specific objectives of the study were to:
1. Determine maximum production of dried straw;
2. Study the effects of various drying exposures upon straw yields, fiber yields, and fiber quality; and
3. Evaluate dryer operation from an engineering standpoint.

In a commercial production trial, the maximum dried straw rate was found to be 730 pounds per hour obtained with a loose flax bed 6 to 10 inches thick, and the average rate for a 35-hour run was 520 pounds per hour.

In a study of drying exposures, the highest drying rates were obtained with squeeze-rolling, thick beds, and the test's highest drying temperatures. Temperatures of circulating air entering the flax bed varied from about 180° F. to 270° F. for zone 1, and about 140° F. to 190° F. for zone 2. Typical flax moisture contents were 350% entering the squeeze-rolls, 245% entering the dryer, and 10% leaving the dryer—all expressed on the dry basis. On the wet basis, these moisture contents would be 77.8, 71.0, and 9.1% respectively. Because of a modulating control system, the supply of heated air to the dryer was variable and, for a selected run, ranged from 2,050 to 4,160 c.f.m. at 650° F. (zone 1), and from 2,380 to 3,000 c.f.m. at 250° F. (zone 2). Firing rates for most of the tests varied between 12 and 18 g.p.h. when using diesel oil. Total measured power requirement for the drying operation was approximately 26 hp.

In comparing fiber from force-drying exposures with fiber from control lots, average line fiber yields and wax contents appeared similar, but force-dried material showed greater fiber strength and higher grade. Type of force-drying exposure had little effect upon fiber quality.

In evaluating this drying operation, dryer efficiency was found to range between 49% and 81% for a test run with modulated heat supplies. Overall efficiencies, considering furnace and dryer operations together, varied from 39% to 65%, where highest efficiencies were found related to highest evaporation rates. An Orsat analysis of the combustion gas-air mixture as it entered the dryer revealed that the CO_2 content was only about 1%, and that for this direct-fired system the "excess air" was approximately 1,000%. Limited comparison of this dryer's production with published results of several European units—all on the same basis of pounds of dry straw per hour per square foot of conveyor area—showed a favorable performance for the USDA dryer.

From results of one year's study, it appears that forced-air drying of retted fiber flax straw is entirely feasible and offers great possibilities in the mechanized production of good quality flax fiber.

FIGURE 1. Setting up retted flax bundles to dry in the field.

Introduction

Flax and its processing

Flax—one of man's oldest crops—is grown and processed to provide fiber for linen products, seed for linseed oil, and pulp for paper. As a textile source, there has been a small fiber flax industry in the United States since colonial days, and during recent years this activity has centered in the Willamette Valley of Oregon. Although now small, the industry has a potentially large market since annual imports to this country include raw fiber and manufactured flax products worth many millions of dollars.

In an effort to assist the domestic fiber flax industry, the United States Department of Agriculture and the Oregon Agricultural Experiment Station have cooperated in engineering and agronomic research investigations. This paper treats one of the engineering developments stemming from the research—a forced-air dryer for retted fiber flax straw.

Fiber flax processing, as now performed, consists of harvesting, deseeding, retting, drying, and scutching. During retting, bundles of flax straw are immersed in warm water for 3 to 7 days after which the stalks are dried to prepare the material for storage or further processing. Although field or sun-drying (figure 1) has been practiced for thousands of years, certain advantages result from a satisfactory forced-air drying operation. It will:

1. Provide control of the drying process.
2. Permit year-round retting and drying independent of weather.
3. Help establish a continuous, straight-line, factory type of production.
4. Improve subsequent processing by delivering straight, untangled straw conditioned to the optimum moisture content for scutching.
5. Reduce the straw-to-fiber processing cycle from the current 18 months to a few weeks.

Little information is available concerning forced-air drying of retted straw, even though some dryers are now operating in flax regions of Europe. Generally, heated air is forced through or across a flax layer that is conveyed through a tunnel-type chamber. Air movement within the tunnel may be counter-flow, parallel-flow, or a modification of either.

In considering heat supply for a forced-air flax dryer, several factors favor a direct application of furnace gases. A relatively high efficiency is possible in the utilization of heat available in the fuel,

and the maintenance associated with steam boilers may be eliminated. Also, the initial cost of a direct heating system will generally be lower. Loose shives and other waste material from flax processing may be used to fire a direct heat unit, but some means should be provided for entrapping embers from the gases. Canadian investigators compressed flax shive into briquettes and determined a heat content of 7,554 B.t.u. per pound as contrasted to about 8,500 for wood refuse (1)[1]. Compared with shive as a fuel, oil produces cleaner gases, requires less storage space, and demands less attention. Although representing an added cost, the use of oil makes available quantities of shive which have potential value in the manufacture of pressed hardboard or insulating board. Sample boards prepared from Oregon flax shive have demonstrated good structural properties, an interesting surface texture, and a thermal conductivity of 0.462 B.t.u.-in./ft.^{2}-hr.-°F.[2]

There is considerable disagreement among research workers as to the effect of forced-air drying on fiber strength of flax. Conflicting opinions are illustrated by fiber studies in the Netherlands where mechanically dried flax was reported superior to field-dried flax in some cases, and inferior in others (2). In an American study flax was dried at atmospheric temperatures, 120° F., 180° F., and 220° F., and tensile strength tests were performed on the fiber. A statistical analysis of results found no significant differences attributable to forced-air drying (3).

Scope of this investigation

This investigation consisted of the design, construction, and test operation of a semicommercial size dryer for retted flax straw. The primary aim, in general, was to demonstrate the feasibility of forced-air drying in processing fiber flax. Specific objectives included determining maximum production of dried straw, studying the effect of various drying exposures upon straw yield, fiber yield, and fiber quality, and evaluating dryer operation from an engineering standpoint.

Preliminary studies were made to gain basic knowledge concerning forced-air drying of retted flax straw. Factors investigated were: relation of drying temperatures and fiber quality; influence of air volume and temperature on drying rates; and equilibrium moisture contents and moisture regain rates of straw in various air conditions (3). This pertinent information was used to design a continuous, conveyor-type dryer which was constructed in prefabricated form. It was assembled with a direct heat, oil-fired furnace for pilot plant test operation at a commercial processing mill.

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1 Numbers in parentheses refer to literature cited.
2 Value determined by Measurements Section, Physics Department, Oregon State College.

Although planned primarily for flax processing, the dryer was designed as a flexible research tool suitable for other agricultural products.

Maximum capacity figures were obtained by drying a commercial tank load of retted flax to provide a substantial run of approximately 10 tons (dry weight) of typical, mill-run straw. Studies of drying exposures and the dryer evaluation were carried out in a series of controlled tests which employed various temperatures, humidities, flax-bed thicknesses, conveyor speeds, and combinations of washing and squeeze-rolling. These variables were recorded, together with dried straw capacities, moisture evaporated, moisture removed by squeezing, oil consumption, electrical power, static pressures, and air volumes. Dried straw from each test was scutched to determine fiber yields, to compare forced-dried fiber with air-dried controls, and to permit a fiber quality analysis consisting of tensile strength, strength uniformity, wax content, and fiber grade determination.

The mechanism of drying

The characteristic drying cycle for most hygroscopic materials can be divided into three basic parts: the constant rate period, the uniform falling rate period, and the varying falling rate period. One or more of the components may be missing under certain conditions. During the constant rate period, evaporation takes place at a rate comparable to that of a free-water surface, and moisture is supplied by diffusion or capillarity at a rate equal to or greater than the evaporation rate. In the uniform falling rate period, moisture is still evaporating from the surface, but the area of wetted surface is steadily diminishing. During the varying falling rate period, all surface moisture is gone, and evaporation is dependent upon rate of moisture flow inside the material to the surface. According to Van Arsdel, this rate of moisture diffusion is only imperfectly understood but, more than any other single factor, determines the ease or difficulty of drying products to a low moisture content (4).

In the constant rate part of the cycle, most wet material theoretically assumes the wet-bulb temperature of the air, acting much the same as wicking of a wet-bulb thermometer. As the material dries, temperatures rise and approach the dry-bulb temperature of the air. This typical action was investigated for flax straw by inserting thermocouples in the stalk centers and observing temperatures during drying. Figure 2 shows temperatures at the top and bottom of a flax bed when air flow was up through the bed. Straw temperatures at bed top exhibit the previously mentioned characteristic, while bottom tem-
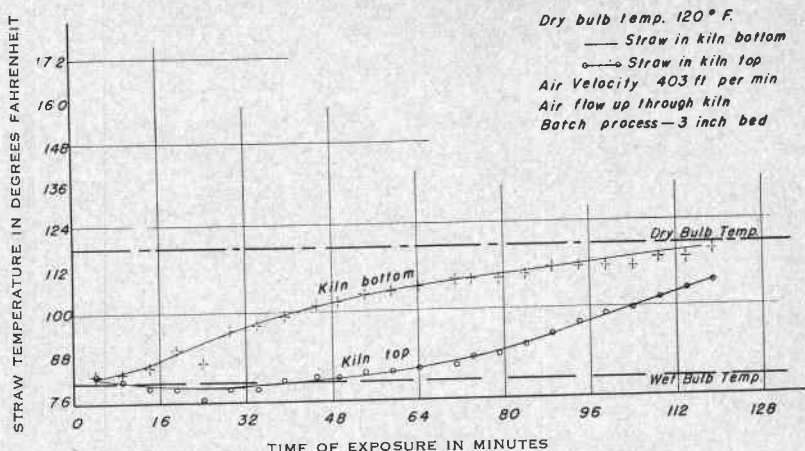
FIGURE 2. Flax straw temperature during drying. (Air velocity based on flow through total kiln area.)

peratures indicate a more rapid drying and a faster approach to the dry-bulb temperature of the air.

As the moisture content of an organic material decreases, the remaining moisture becomes increasingly difficult to remove, and diffusion rates and evaporation rates therefore decrease. Small amounts of moisture are very firmly adsorbed in the molecular structure of the substance. This firmness of binding is reflected not only by the low diffusivity of the remaining moisture, but also by a lower vapor pressure than would be exerted by pure water at the same temperature (4). Reduced evaporation rate, associated with low moisture content, is characteristic of flax, as shown in figure 3. The 180° curve, for example, indicates about half the total drying time is required for the final 10% of evaporation.

Drying rates may be influenced by several different factors. During the first two periods of the drying cycle, when surface evaporation is taking place, drying rates may be increased with an increase of air velocity. Air flow directed perpendicularly to the drying surface exhibits the best efficiency in dispersing a dead air film (5). Increased air velocities have little effect in the third period of the drying cycle, since moisture diffusion rates are the main factors controlling drying. Higher temperatures are beneficial here by increasing diffusion rates and, therefore, subsurface drying (4) (6).

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Generally speaking, the driving force for evaporation is proportional to the difference between vapor pressure of the liquid being removed and partial pressure of vapor in the air. This differential may be increased in several ways: by a temperature rise, since vapor pressure of the liquid will then increase; by lowering specific humidity of the drying medium, since this decreases partial pressure of the vapor; or by a combination of these methods. Another factor helpful in drying is an increase in the surface area-volume ratio for the material being dried. This expedites heat transfer to the center of the mass, shortens the diffusing path, and provides more evaporating surface.

Moisture content of a material may be expressed as a percentage of total weight or dry-material weight. Use of the latter "dry basis" facilitates computations in drying work since the base (weight of dry matter) remains constant throughout the process. All expressions of moisture percentage in this study are on the dry basis; for example, 250% moisture represents 2.5 pounds of water per pound of bone dry material. This would be 71.4% moisture on the wet or total basis.
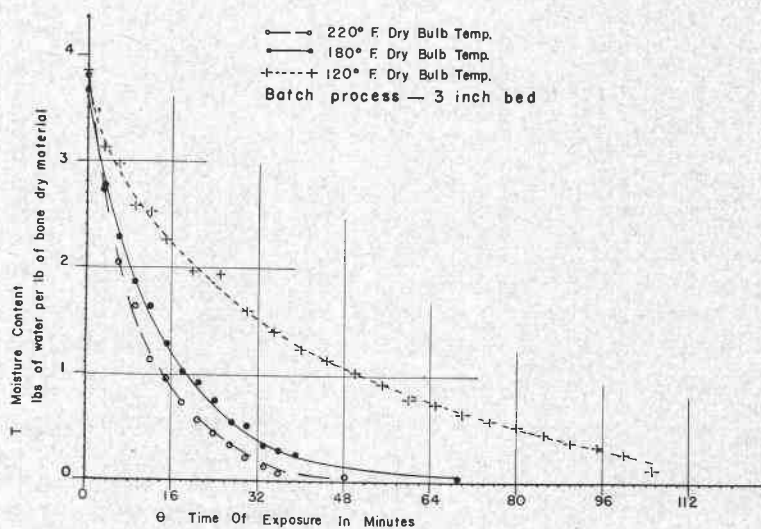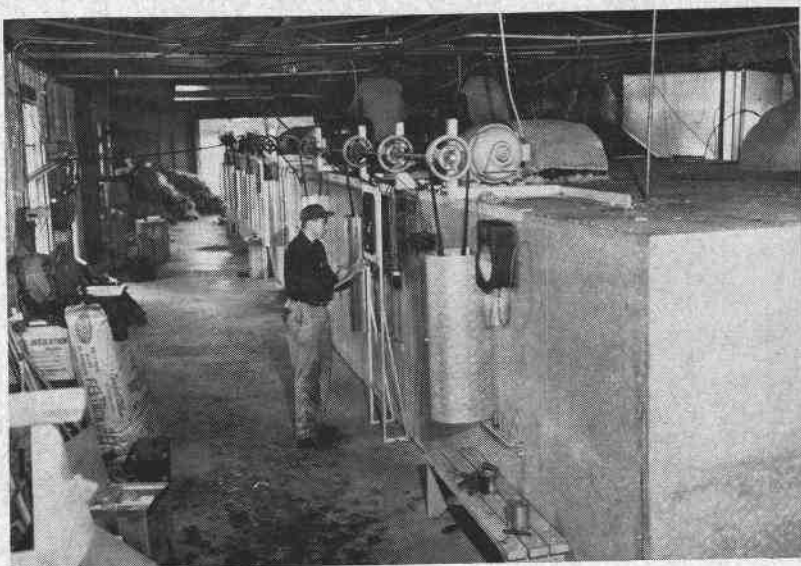

FIGURE 3. Moisture content of retted flax straw during drying.

FIGURE 4. General view showing line shaft drives for circulating fans and hot air supply system on top of dryer.

Equipment

Dryer

The dryer is a continuous, conveyor, tunnel-type unit composed of three exposure zones—each independently controlled. The first two zones are used for drying while the third may serve either as a conditioning section or as an additional drying zone. When zone 3 is used to condition freshly dried flax, warm water is sprayed into the circulating air to provide an atmosphere necessary for the desired equilibrium moisture content of the material. Figure 4 shows a general view of the dryer which is 74 ft. long, 12 ft. wide, and 6 ft. high. A modular design was employed, and the dryer was prefabricated in 10-ft. panels for easy assembly and dismantling. Construction consists of structural iron framework, fiber board and fiber-glass blanket insulation, and galvanized sheet metal sheathing.

Wet flax is spread on a wire mesh belt and slowly conveyed through the dryer while heated air is circulated up through the bed by eight axial-flow fans housed within the dryer, but driven by outside line shafts and $\frac{1}{4}$ turn V-belts. The 5 ft. wide conveyor belt is driven by a canvas-lagged pulley constructed from 24 in. steel pipe.

A feature of the reduction drive is its overall speed ratio of about 11,000:1, provided by a combination of variable speed transmission, worm gear reducer, V-belts, chains, and gears.

Squeeze-rolls

This unit extracts water and residual retting substances mechanically from retted flax preliminary to forced-air drying. As shown in figure 5, the machine employs two sets of rubber-faced rolls with the two drums of each set tending to stay in contact by adjustable spring pressure. In operation, flax is squeezed in the first set of rolls, washed in a clean water spray, and then squeezed in the second set of rolls. The lower roll in each set is driven by use of a roller chain, speed reducer, and electric motor. The 36 in. rolls are constructed of 8 in. steel pipe faced with $\frac{1}{2}$ in. of rubber to help minimize straw damage.

Furnace and heat distribution system

Heat requirements for the dryer are supplied by use of the direct heat principle, where products of combustion are mixed with diluting air, filtered, and distributed to several dryer inlets as the drying medium (figure 6). The furnace designed and constructed to produce
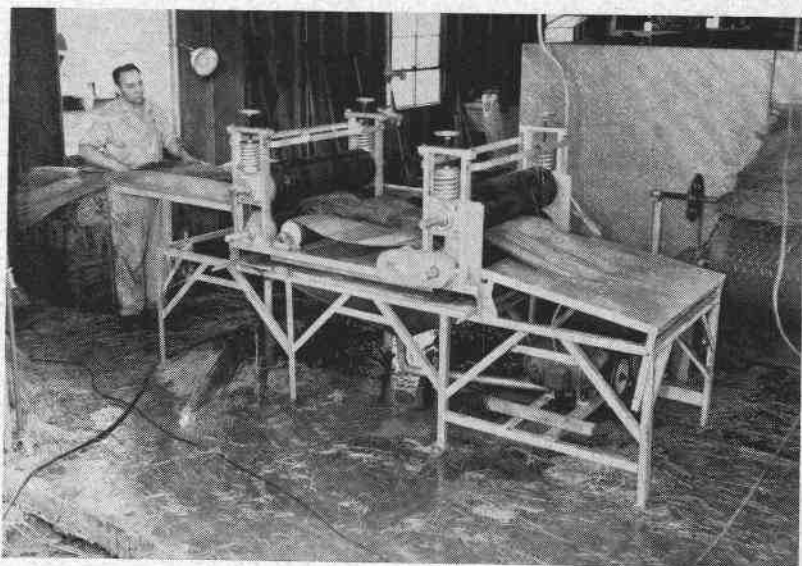
FIGURE 5. Squeeze-rolls which remove some water from retted flax before drying. Flax is also shown entering the dryer.
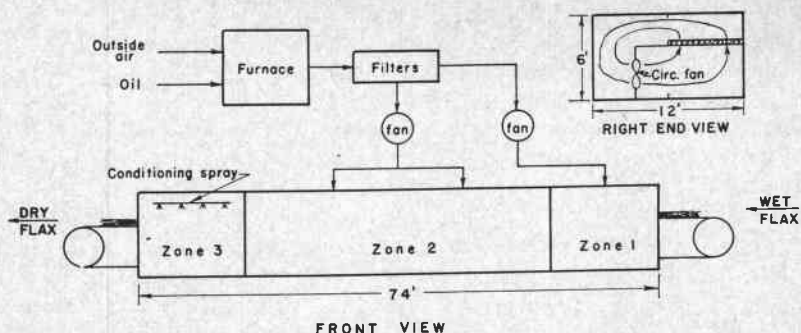
FIGURE 6. Schematic sketch of flax dryer showing direct-heat supply and air circulation.

this type of mixture is fired with a horizontal, rotary oil burner capable of modulated firing from 7 to 35 gallons per hour. The burner has automatic gas-electric ignition, an attached oil meter, and a stack switch combustion control.

Effectively, the furnace is under induced draft since two high-temperature centrifugal fans continuously exhaust the gas-air mixture and supply it to the intake side of circulating fans within the dryer. A large damper above the furnace hood is positioned manually to direct gases to the stack during the fire-up period and to the dryer when operating. Beyond the damper, the mixture passes through fiber-glass filters to entrap any embers or burning particles as a fire precaution, after which it divides into two ducts, passes through the fans, and enters the dryer in both zones 1 and 2. The filter bank, hot-gas fans, and ducts are insulated with rock wool batts.

Process controls and measuring instruments

Control is provided for temperature and humidity of the circulated drying air, temperature of diluted furnace gases, oil firing rate, and the conditioning spray of zone 3.

Furnace gas temperature is controlled by a recording temperature controller which pneumatically modulates oil flow to the burner. Hygrometers record and control temperature and humidity of the circulating drying air in zones 1 and 2. Dry-bulb control is obtained by positioning dampers pneumatically in the two supply ducts, thus regulating the amount of gas-air mixture the high-temperature fans deliver to the zones. Wet-bulb measurement tends to control humidity of the circulating air by regulating dampers in special vents which permit atmospheric air to be drawn into the high temperature fan and

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supplied to the zone. The zone 3 conditioning spray is controlled by wet-bulb measurement made by a recording temperature controller. Deviations from the set point cause the controller to operate a diaphragm valve in the line which introduces moisture to the circulating air.

Temperatures are measured at various stations in the dryer system with the instruments already mentioned plus a 12-point pyrometer with iron-constantan thermocouples, and mercury thermometers. An Orsat flue gas analyzer is used to determine percentages and constituents of the diluted furnace gases, and static and velocity pressures are measured with a pitot tube and an inclined draft gage. Moisture contents of wet and dry straw are obtained by the oven-drying method.

Scutcher

Fiber was extracted from each test lot of dried straw using a commercial size scutching machine developed by this project. A description of this unit is available in report form and has been published by the U. S. Department of Agriculture (7).

Fiber tensile strength testing apparatus

Tensile strengths were determined for representative fiber samples of each test lot by using a power-driven Scott Tensile Tester, Model D. H., pendulum type, with a 50 kilogram maximum load. This standard test unit was verified for accuracy and was found in conformance with the pertinent requirements of the Standard Specifications for Textile Testing Machines, D 76-49, American Society for Testing Materials. All samples were made up, conditioned, weighed, and tested in a room with controlled atmosphere. Fiber moisture contents were readily checked throughout the testing with a special quick-reading moisture indicator in which a prepared fiber sample of 100 grams, bone dry weight, was exposed to the atmosphere and weighed periodically. The weight in excess of 100 grams directly indicated moisture percentage on the dry basis.

Procedure

The dryer test operation was conducted in two phases: one, a maximum production trial striving for high capacities typical of commercial operations; the other, a controlled study of drying exposures.

Maximum production trial

Wet flax bundles were passed through the squeeze rolls without washing and fed into the dryer which utilized zone 3 as a supple-

mental drying zone rather than a conditioning section. Progressively thicker layers of flax were employed throughout the run from an overlap bed 3 inches thick to a cross-hatched bed 10 inches thick. In this manner, 10 tons of dry retted straw were obtained with a test crew of 4 men. One man fed the squeeze-roll, one man removed bundles at the squeeze-roll and fed the pressed flax to the dryer, one man removed flax discharged from the dryer and bound the dry bundles, and one man supervised and recorded test data.

Controlled exposure study

Test lots were dried using various temperatures and relative humidities of drying air, constructions and thicknesses of flax bed, combinations of squeeze-rolling and washing, and operations of the zone 3 conditioning spray. Control groups were also selected from the wet test lots and air-dried for comparison with force-dried material from the various exposures.

During a typical drying test, straw moisture samples were taken before squeeze-rolling, after squeeze-rolling, and after drying. Electric power, conveyor speeds, and oil consumptions were recorded for the interval that each test lot was discharged from the dryer. Periodic determinations were made of the range of supply air volumes, static pressures, temperature drops across the flax bed, and supply air temperatures at various points in the duct system.

After drying, the bundles of each test lot were bound, weighed, and stored. Control groups for each lot were placed to dry in the conventional "wigwam" or cone position in a large storage shed with open sides and concrete floor, since rain prevented normal field drying. An additional control group that was sun-dried and fully typical of commercial practice was provided by analyzing fiber samples from the original field which supplied the test material.

Fiber was obtained from the test lots and control groups using this project's scutcher and its auxiliaries. Each straw lot was weighed and sampled for moisture content, and scutching intensity was adjusted as needed to deliver clean fiber. Line and tow fiber from each lot was weighed as discharged, and four or more fiber hanks were selected randomly from each lot for evaluation in the fiber quality analysis.

Although tensile strength is one of the generally accepted measures of flax fiber quality, practically nothing has been published on the subject and no directly applicable standard test procedure is known. A search of literature was made, therefore, in an attempt to establish a sound method for determining fiber strength variations in this study which then might be attributed to drying treatments. A pre-

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liminary survey was also made to study different fiber holding devices, fiber bundle types, and sample preparation. The test procedure, as finally evolved and used, is similar to that of the National Bureau of Standards (8) and the American Society of Testing Materials (9), and includes random selection and compositing of test samples, a controlled atmosphere for weighing and testing, and samples which are constant in length, weight, and twist.

Fiber from each drying exposure was also evaluated in the conventional manner used in industry. This rating method involves knowledge usually acquired by apprenticeship or long practice and considers such fiber characteristics as fineness, color, body, length, cleanliness, and strength as determined by hand breaking. Three fiber experts, who have had many years of experience in flax buying and managing of linen spinning mills, individually graded the samples without knowing the processing history.

Wax content is another quality characteristic of fiber. When flax fiber is being spun, the contained wax tends to accumulate on the spindles or other equipment and cause frequent cleaning and machinery stoppage. In this investigation, wax contents were determined for all test lots to learn if there were any differences that might be assigned to force drying in general, or to a particular drying exposure. The wax was extracted from weighed fiber samples with ether, after which the ether was evaporated.

Results and Discussion

Drying performance

In the maximum production trial the output of dried straw varied from 450 to 730 pounds per hour, and the best drying was observed in the cross-hatched bed 6 to 10 inches thick constructed from 6 or 8 bundles spread one above the other with adjacent layers at right angles to each other. The total drying time for 18,450 pounds of dry retted straw was $35\frac{1}{3}$ hours, which resulted in an average capacity of 522 pounds per hour. The average conditions of drying air after passing through the flax bed of zone 1 were in the range of 165° to 185° F. dry bulb and 40% to 52% relative humidity; zone 2 conditions were 170° to 180° F. dry bulb and 20% to 28% relative humidity; and zone 3 conditions were 150° to 170° F. dry bulb and 23% to 36% relative humidity. The moisture contents of the straw averaged 294% before squeeze-rolling, 209% after squeeze-rolling, and 6.7% after drying. Approximately 3/10 of the straw moisture was, therefore, removed by squeezing.

TABLE 1. RESULTS OF

Test	Zone 1 air		Zone 2 air		Zone 3 air		Bed type	Wash	Squeeze roll[3]
	D.B.	R.H.	D.B.	R.H.	D.B.	R.H.			
	De-gree	Per cent	De-gree	Per cent	De-gree	Per cent			
1A	163	44	142	26	110	70	6" Crosshatch	No	No
1B	163	44	142	26	110	70	6" Crosshatch	No	No
2A	158	57	140	31	115	52	6" Crosshatch	Yes	Yes
2B	158	57	140	31	115	52	6" Crosshatch	No	Yes
3A	176	41	170	11	128	37	6" Crosshatch	Yes	Yes
3B	176	41	170	11	128	37	6" Crosshatch	No	Yes
4A	178	38	170	14	140	29	4" Overlap	No	No
4B	178	38	170	14	140	29	4" Overlap	No	Yes
5A	172	49	186	17	169	23	6" Overlap	No	Yes
5B	172	49	186	17	169	23	9" Crosshatch	No	Yes
6[1]	146	53	146	29	138	32	3" Overlap	No	No
7A	162	45	139	25	124	39	3" Overlap	S.R.—Wash—S.R.	
7B	162	45	139	25	124	39	3" Overlap	S.R.—Wash—S.R. S.R.—S.R.	
7C	162	45	139	25	124	39	6" Crosshatch	(Rerun of wet 7B.)	
7D	162	45	139	25	124	39	3" Overlap	S.R.—Wash—S.R. S.R.—Wash—S.R. S.R.—S.R.	

1 Nontypical straw.
2 Dry-bulb temperatures (°F) and relative humidities are average values (discharge conditions) for time dryer was fully charged with test straw. Zone 3 used as conditioning section in tests 1A, 1B, 3A, and 3B.

General observations during the capacity trial indicated that much of the output was at a lower moisture content than required while a small portion was too wet. Although undesirable, this non-uniform drying is somewhat typical of flax (10) (11), and probably arises since the straw is variable in shape, structure, and moisture content, and does not lend itself to the construction of a constantly dense layer. Because of these inequalities, some parts of the bed are more permeable than others and thus dry at a greater rate.

In the controlled exposure study, 15 different test conditions were employed as shown in table 1. The average relative humidity of zone 1 discharge ranged from about 38% to 57%, and discharge dry-bulb temperatures ranged from 158° to 178° F. In all runs an attempt was made to maintain low relative humidity in the second zone to decrease the partial pressure of vapor in the air and thus accelerate drying rates by the resultant increase in vapor pressure differential or driving force for evaporation. In this zone the average humidities

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Oil consumption	Moisture content[4]—retted straw			Dried straw capacity	Evaporation rate[5]
	Before squeeze roll	After squeeze roll	Out of dryer		
g.p.h.	Per cent	Per cent	Per cent	lbs./hr.	lbs. H_2O/hr.
12.0	330	------	50.4	230	427
9.3	330	------	15.6	273	742
12.9	346	257	6.0	474	1120
12.8	338	248	7.5	389	871
12.5	359	253	7.5	310	706
12.7	347	248	9.8	332	722
13.1	357	------	10.6	430	1349
14.7	348	235	4.9	560	1230
18.0	314	242	3.7	612	1410
13.1	335	235	7.0	572	1220
12.0	355	------	7.1	247	800
12.9	350	255	18.9	307	610
15.0	350	220	52.5	345	379
------	(Redrying of wet 7B.)		3.5	------	------
------	350	208	8.0	------	------

3 S.R. is squeeze roll.
4 Dry basis—average of five bundles.
5 Determined from moisture content change in dryer and excludes moisture removed by squeeze rolls.

varied from about 11% to 31% for all runs while dry-bulb temperatures ranged from 139° to 186° F.

Straw moisture contents before the squeezing operation are shown to be relatively uniform in the test lots; all except one fell in the range 330% to 359%. After one pass through the squeezing unit, test lots varied in moisture content from 235% to 257%. Approximately 3/10 of the contained water was, therefore, easily and economically removed before the straw entered the dryer. Lot 7B passed through the squeeze rolls two times and showed a moisture content of 220%, while 7D was squeezed three times and exhibited 208% moisture. In view of this decreasing rate of moisture removal, the value of second or third squeezings seems doubtful.

Most moisture contents of dried flax ranged from about 4% to 18%. Although this moisture range exceeds the optimum span of about 10% to 14%, it is satisfactory from the standpoint of drying requirements. During commercial processing operations, mill-run

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straw has been observed to vary seasonally from about 6% to 18%. The difficulty experienced in holding discharge moisture content within optimum range is attributed mainly to the tendency for non-uniform drying discussed earlier. In a continuous drying-scutching operation, moisture content of discharged straw would be quite important because of its effect on scutching efficiency and fiber yield (12) (13). In a noncontinuous operation, however, it is much less critical since flax straw is hygroscopic and tends to reach a moisture content in equilibrium with the atmosphere.

Evaporation rate is perhaps a better measure of drying than straw discharge rate since it reflects a precise amount of work done and is independent of weight effects of incoming and outgoing straw moisture contents. Evaporation rates, disregarding moisture removed in squeezing, varied from about 400 to 1,400 pounds of water per hour, and as might be expected, high oil-consumption rates were associated with high evaporation rates. Most of the oil rates varied between 12 and 18 gallons per hour. Diesel oil was used in these tests.

Temperatures of the supply air were measured at various positions in the system. At the filter transition near the furnace the temperature was found to range from 860° to 1050° F., and in the zone 1 duct as it entered the dryer the temperature was 600° to 690° F. Zone 2 was supplied with two ducts. In one, the temperature ranged from 170° to 320° F., and in the other, 220° to 360° F. Air temperatures as measured by the furnace control instrument were quite uniform, varying from about 730° to 790° F. Temperature drops as air passed through the flax bed in zone 1 were measured with a probe thermocouple at several stations and ranged from about 35° to 90° F. Zone 2 temperature drops were much smaller—on the order of 5° to 15° F.—indicating a reduced drying rate in this zone. In both zones the temperatures below a bed section increased as that section progressed through the zone. This is logical since there was increasingly less moisture available for evaporative cooling of the air. The maximum recorded temperature of the air impinging on the bed was 295° F. in zone 1; however, the maximum straw temperature was in the vicinity of 145° F.—the wet-bulb temperature. As the straw became dry in zone 2 its temperature rose and approached that of dry-bulb. On this basis, the highest straw temperature of the study was less than 190° F.

Conveyor speeds, which were adjusted as required to discharge dry flax, ranged from 0.50 to 2.00 f.p.m. Maximum static pressure drop as air passed through the zone 1 bed was about 5/10 of an inch of water, reported on a standard air basis.

Because of the control system's modulating characteristic, the

supply air volume to each zone was not constant. Volume determinations were made, therefore, by measuring velocity pressure ranges and calculating flows as the supply damper of each zone duct passed through its cycle. For zone 1, the supply volume varied from 2,050 to 4,160 c.f.m. at 650° F., and for zone 2, 2,380 to 3,000 c.f.m. at 250° F. Air velocities through the flax bed were determined in two ways—by direct measurement with a propeller anemometer and by measuring static pressures in the zones (corrected for temperature) and referring to performance curves for the circulating fans. The anemometer showed erratic velocities as great as 900 f.p.m. through holes and loose parts of the bed, but average velocities through typically uniform sections varied from about 240 to 295 f.p.m. for all runs and all zones, as determined from fan curve data and gross area of the flax bed. By measuring current usage and calculating electrical power consumptions, it was found that the total dryer requirement (excluding the oil burner motor) was 25.2 hp.

Fiber analysis

Analysis of fiber from this study was carried out by scutching the flax straw to obtain fiber yields, grading the fiber as is done commercially, determining fiber wax contents, and performing fiber-strength tests. These results appear in table 2 where "X" lots indicate air-dried controls used for comparison with force-dried material.

In the scutching operation, moisture contents of straw are shown to be relatively high with most values between 15% and 23%, whereas typical moisture contents during commercial winter scutching range from about 10% to 16%. The average moisture content of controls was somewhat greater than that of force-dried material. This may be due to a changed hygroscopic character of the force-dried material, but is more likely a result of incomplete or slow drying of controls due to rainy weather. Of 15 force-drying exposures, those that were squeezed exhibit lower moisture contents, but controls that were squeezed show greater moisture than controls not squeezed. Average line fiber yields for controls is about the same as that for force-dried exposures, and yields from squeezed lots are greater than those from lots not squeezed.

Table 2 indicates, generally, that high moisture contents are related to low fiber yields. Another suggested association is that of high yield and high grade, which has been observed in other flax studies of this project. There is no obvious relationship between strength and yield, or strength and grade; also, no good correlation can be found between quality factors of table 2 and any of the force-drying exposures.

Differences are apparent, however, when comparing force-dried lots and air-dried controls with respect to grade and fiber strength. Results from the three graders indicate the same trend—that force-dried material is generally superior to controls, and the highest rating of each judge is assigned to force-dried fiber. In 12 out of 14 cases,

TABLE 2. FIBER EVALUATION

Test[1]	Straw moisture content[2] (into scutcher)	Fiber yield[3]	Fiber tensile strength[4]		Fiber grade[5]	Fiber wax content[6]
			$\bar{x}$	c.v.		
	Per cent	*Per cent*	*Per cent*			*Per cent*
1A	23.7	19.2	3,945	6.1	Low B	2.87
1B	19.1	22.0	4,114	7.7	High C	2.84
1X	23.6	19.8	3.306	9.2	Low B	3.11
2A	18.6	24.0	3,766	10.0	Medium B	2.65
2AX	24.1	23.7	3,037	13.2	Medium C	2.65
2B	18.4	22.4	3,629	8.1	Medium B	2.65
2BX	24.8	23.5	3,361	11.2	Medium B	2.59
3A	14.4	22.4	3,485	7.8	High B	2.50
3AX	23.9	21.3	3,522	10.6	High C	2.54
3B	15.5	23.1	3,363	26.5	Medium B	2.50
3BX	31.9	23.0	3,531	11.4	Low B	2.15
4A	17.1	21.0	3,561	11.1	Medium B	2.67
4AX	17.5	17.9	2,933	14.0	Low C	2.66
4B	14.9	21.1	3,664	6.8	High B	2.60
4BX	22.8	20.0	3,234	12.6	Medium C	2.60
5A	14.2	20.8	3,438	9.3	High C	2.56
5AX	17.8	24.4	3,129	14.2	C-1	2.47
5B	20.5	20.2	3,586	5.9	High C	2.62
5BX	16.3	21.3	2,653	10.1	Medium C	2.52
6[7]	15.0	17.6	3,155	10.0	C-1	2.32
7A	20.2	20.5	3,321	10.8	High B	2.88
7B	......	22.0	3,240	9.6	Medium B	2.58
7C	9.8	22.3	3,197	11.1	High B	2.83
7D	22.9	17.9	3,285	11.6	C-1	2.79
7X	23.3	17.0	3,193	12.3	Low B	2.53
8X[8]	......	21.0	2,966	14.4	High C	2.96

1 X lots are air-dried controls.
2 Dry basis.
3 Retted straw basis.
4 $\bar{x}$ is arithmetic mean of 20 determinations (kg. per gm.-cm.), and c.v. is coefficient of variation in per cent.
5 High B is highest, and C-1 is lowest.
6 Fiber basis.
7 Nontypical straw.
8 Commercially processed control from same field as test straw.

the fiber from any particular force-drying exposure has greater strength than its air-dried control. Overall average of force-dried strengths is 3,542 kilograms per gram-centimeter as compared to an average strength of 3,190 for shed-dried controls and 2,966 for sun-dried control. Also, indicated coefficients of variation determined in a statistical analysis of strength results strongly suggest that fiber going through the dryer was more uniform in strength characteristics than controls.

To summarize, most force-dried material shows greater fiber strength and higher grade than air-dried controls, but relatively little difference is seen as to the effect of specific force-drying exposures.

Engineering evaluation of dryer

The dryer operation was evaluated from an engineering stand-point by calculating thermal efficiencies, analyzing the products of combustion, and comparing performance with other existing flax dryers.

Thermal efficiencies were calculated for the dryer alone and as overall figures for the combined operation of furnace and dryer. Values for the dryer represent ratios of heat for evaporation to heat content of gas-air mixture supplied to the dryer, and overall figures stem from heat for evaporation and heat content of the fuel. Since the control system, supply volumes, and oil combustion rates were modulating, dryer efficiencies were computed for a range varying from the condition of minimum supply flow to that of maximum, assuming a constant evaporation load. The analysis was made of test 5B where the velocity pressure of zone 1 supply air cycled from about 0.10 in. to 0.42 in. H_2O at 650° F., and zone 2 cycled from about 0.25 in. to 0.40 in H_2O at 370° F., both determined by pitot tube traverses in straight duct runs. Air velocities were calculated using the formula:

$$V = 1096.5 \left(\frac{P_v}{w} \right)^{\frac{1}{2}}$$

where V = Velocity, f.p.m.

P_v = Velocity pressure, in. H_2O

w = Air density, lbs. per cu. ft.

Velocities, duct sizes, and densities were then used in arriving at the following weight rates of hot air flow: zone 1—71.4 to 146.5 lbs. dry air per min.; and zone 2—119.0 to 150.8 lbs. dry air per min. Heat contents of the hot air supply, as determined from a high tem-

perature psychrometric table (14) that employs a datum temperature of 32° F., were: zone 1—178.4 B.t.u. per lb. dry air; and zone 2—106.2 B.t.u. per lb. dry air. Then, total heat supply to the dryer = zone 1 supply + zone 2 supply.

$$\text{Total} = \left(\frac{71.4 \text{ to } 146.5 \text{ lbs. dry air}}{\text{min.}}\right)\left(178.4 \ \frac{\text{B.t.u.}}{\text{lb. dry air}}\right)\frac{60 \text{ min.}}{\text{hr.}} +$$

$$\left(119.0 \text{ to } 150.8 \ \frac{\text{lbs. dry air}}{\text{min.}}\right)\left(106.2 \ \frac{\text{B.t.u.}}{\text{lb. dry air}}\right)\frac{60 \text{ min.}}{\text{hr.}}$$

Total heat supply = 1,527,000 to 2,529,000 B.t.u. per hr.

In figuring evaporation load, evaporating temperature was taken as the average wet-bulb temperature of zone 1.

$$\text{Then, the evaporation load} = \left(\frac{1220 \text{ lbs. } H_2O}{\text{hr.}}\right)\left(1011 \ \frac{\text{B.t.u.}}{\text{lb. } H_2O}\right)$$

$$= 1,234,000 \text{ B.t.u. per hr.}$$

$$\text{Dryer efficiency} = \frac{\text{evaporation load}}{\text{heat supply to dryer}}$$

$$= \frac{1,234,000 \text{ B.t.u. per hr.}}{1,527,000 \text{ to } 2,529,000 \text{ B.t.u. per hr.}}$$

$$= 81\% \text{ to } 49\%$$

The 49% figure represents a condition of maximum hot air flow to both zones and the 81% that of minimum flow, but in operation the modulated flow varied between these extremes. While not specific, this determination gives some idea of the dryer's effectiveness. In a study of textile drying practices in mills of five states, the Institute of Textile Technology, Charlottesville, Virginia, found that 44 stock dryers showed an average efficiency of 50%, and 57 tenter dryers—46% (15).
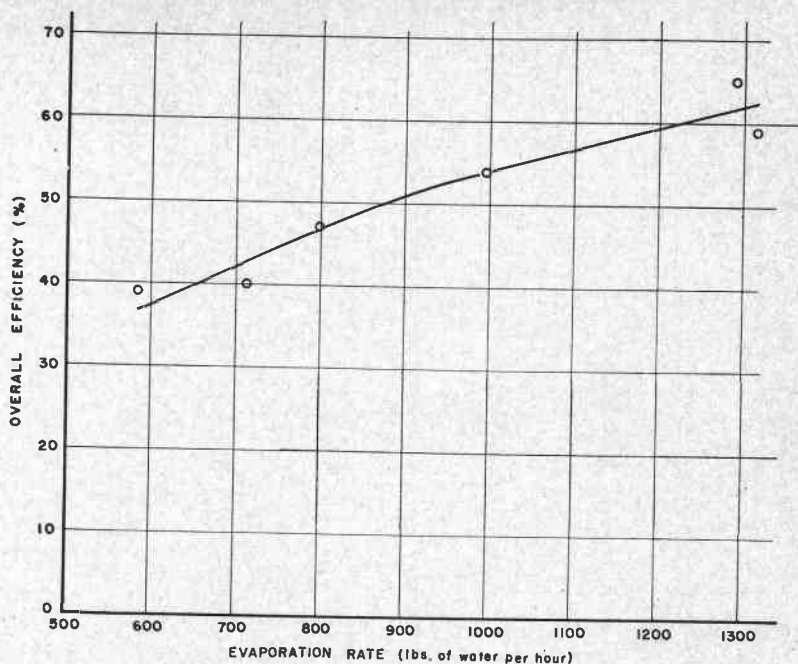
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Figure 7. The relationship of over-all efficiency and evaporation rate in a direct-heat flax dryer.

Overall efficiency figures for combined operation of furnace and dryer were computed by assuming an oil heating value of 145,000 B.t.u. per gallon and an evaporating temperature equal to the average wet-bulb temperature of zone 1. Six different operations showed an efficiency range of 39% to 65% which compares favorably with figures for similar operations in Great Britain where direct-fired dryers have been studied. A comprehensive analysis of English drying methods and mediums showed typical efficiencies of 45% to 70% for horizontal conveyor dryers with direct heating and recirculation (16). In the USDA test program there was strong indication that overall efficiencies were directly related to firing rates and evaporation rates. Figure 7 shows a substantial change in efficiency as evaporation rate increases.

A good measurement of furnace efficiency was not obtained but in theory, the efficiency of a direct heat furnace may be very high. One English study reported figures of 85% to 90% for hot gas production by a direct system (17). In a well-insulated and properly ad-

justed oil-fired unit, about the only significant heat loss would be that represented by small amounts of water vapor in the gas resulting from hydrogen in the fuel and atmospheric moisture in the combustion air. Radiation heat losses, however, may be relatively great in a noninsulated unit of this type because high air-gas temperature is involved and radiation is a function of the fourth power of absolute temperature.

A commonly used indicator of combustion efficiency is the CO_2 content in stack gases. In this study, the combustion gas-air mixture was analyzed near its entrance to the dryer by use of an Orsat apparatus with the following results:

	CO_2	O_2
	Per cent	*Per cent*
Zone 1...	1.0	19.2
	1.2	19.8
Zone 2...	0.1	20.1
	0.1	19.9

Although low CO_2 readings are usually associated with low efficiencies, values shown here are not the result of poor combustion, but indicate instead the great dilution of furnace gas that has taken place with tempering air. In view of the extremely low order of CO_2, the air-gas mixture may, for all practical purposes, be considered air and thus requires no weighted, mean specific heat figure in heat content calculations. Another value of the readings is to give a general idea of the amount of excess air in the mixture. Such low CO_2 values as these indicate a great deal of excess air—perhaps in the neighborhood of 1,000% (18). It should be emphasized that in the direct-fired heating system these extremely high figures of excess air do not represent losses inasmuch as the total mixture is used as the drying medium.

A sensible comparison of dryer performance with that of other existing dryers is rather difficult because operation data are scarce and dryer sizes vary. In the attempt to present a logical evaluation, production figures of several European dryers are compared with the USDA unit in table 3—all on the same basis of unit conveyor area.

Operations in table 3 may not be similar with respect to squeezing, drying temperature, and moisture content of straw entering and leaving the dryer—all of which influence production. In the general comparison indicated, however, the USDA unit is shown to perform very favorably.

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TABLE 3. A COMPARISON OF SEVERAL CONVEYOR FLAX DRYERS

Dryer	Production of dry retted straw	Conveyor area	Production/area
	(lbs./hr.)	(sq. ft.)	(lbs./hr./sq. ft.)
German[1]	660—1,100	665	1.0—1.6
English[2]	1,000	788	1.3
Irish[3]	500	470	1.1
USDA	450—730	370	1.2—2.0

[1] German single conveyor drying chamber (2, pp. 70-71).
[2] English machine using five tiers of conveyors (19, p. 19).
[3] Irish single conveyor unit (11, pp. 14-16).

Conclusions

Considering the maximum production trial as well as the controlled exposure study of this semicommercial size dryer, the following conclusions may be drawn:

1. Forced-air drying of retted straw is feasible in processing fiber flax.

2. Maximum production of dried straw was 730 pounds per hour.

3. Squeeze-rolling of flax before drying removed about 30% of the contained water.

4. Oil consumption varied from about 12 to 18 gallons per hour.

5. Test conditions appearing most influential in achieving highest production rates were squeeze-rolling, a fairly loose flax layer 6 to 10 inches thick, and drying temperatures of about 230°—280° F. in zone 1 and 180°—195° F. in zone 2.

6. In almost every test condition, forced-dried flax was found superior to its air-dried control with respect to fiber grade, fiber strength, and strength uniformity.

7. In 6 out of 9 tests, line fiber yields of force-dried flax lots were greater than yields of air-dried controls; however, average moisture content of controls was relatively high and may have influenced fiber yields.

8. Squeeze-rolling appeared to improve average fiber yields about 2%, and 5 out of 6 force-dried lots that were squeeze-rolled and washed received high fiber grades.

9. A direct relationship was indicated between fiber yield and fiber grade for force-dried lots.

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10. No definite fiber correlation was found between strength and yield, or strength and grade, for force-dried material.

11. No definite correlation was found between any of the force-drying exposures and fiber strength, wax content, or grade.

12. Dryer efficiency was found to range between 49% and 81% for a modulating run with variable heat supply.

13. Overall efficiencies, considering furnace and dryer together, ranged between 39% and 65% for 6 of the operations, and high efficiencies were associated with high evaporation rates.

14. In a limited comparison with performances of several European flax dryers, the USDA unit showed greater dry straw production per unit of conveyor area.

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