Research papers

Investigation of the characteristics of a traditional natural convection cocoa dryer

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A production scale, natural convection, wood fired dryer for cocoa was tested during the six month period of the 1978 cocoa harvest in the Bahia region, Brazil. The object of the test sequence was to determine and investigate the operational parameters of the drying unit with a view to the subsequent development of improvements which could be applied in the field to the existing 25 000 dryers of this type. The design of dryer used was, for the most part, that recommended by the Extension Department of CEPLAC, while care was taken to ensure that the operational procedure was as near as possible to that normally used on farms. The performance of the dryer with different cocoa and wood loadings and with varying plenum chamber heights was investigated. The effect of ambient wind speed and direction was also considered. **Keywords: Cocoa beans; Driers (heating equipment); Wood**

The most common forms of artificial dryer for cocoa are those of the platform type, which consists simply of four walls forming a rectangle, or square, supporting a perforated floor onto which the cocoa is loaded. The enclosed volume beneath the drying floor (known as the plenum chamber) serves to distribute the drying air flow evenly over the area of the drying floor. This airflow can be achieved by forced convection (Wood, 1961; McDonald and Freire, 1981) or, more commonly, by natural convection.

Natural convection dryers usually have set horizontally into the plenum chamber a single, large diameter, metal tube, through which pass the combustion gases from a wood-fired furnace. The air surrounding this tube is heated, its density is reduced and buoyancy currents are formed which force the air upwards (McAdams, 1954) and through the cocoa. The higher is the plenum chamber, the more efficient will be the conversion of dynamic to static pressure and hence the larger will be the overall flow of air through the crop.

Natural convection currents cannot generate very strong air flows; therefore the cocoa bed must be shallow so as to minimise the air-flow resistance of the system. In the event of a peak in the harvest, the dryer can become overloaded. The farmer's only recourse then is to pile more wood onto the furnace, resulting in overheating of the beans and reduced quality of the end-product.

Inherently then, natural convection dryers should have large drying floors (low throughput per unit area) and high plenum chambers, the combination of which results in large and hence costly installations. On the other hand, operating and maintainance costs are low; in spite of this, however, servicing of the dryer is commonly neglected until long after wear or corrosion of the heater tube or furnace is such that wood smoke is being passed directly into the plenum chamber. Installations in this condition will still successfully dry the cocoa but the end product will be contaminated and of low quality.

Natural convection cocoa dryers

Natural convection drying of cocoa has been practised for many years, although many of the earlier designs were of the 'drying house' type, the air flowing over, rather than through, the cocoa, which was spread on several trays rather than on a single platform (Oliviera, 1903).

One of the earliest throughflow natural convection dryers was a converted, raised, sun drying platform in Trinidad (Fauchere, 1906). The drying floor was drilled to allow the passage of air, while the space beneath was provided with brick walls to give a plenum chamber. Into this was set a system of heating tubes through which hot water circulated by thermosyphon, heat being supplied by a wood-fired furnace. Operating at 46 °C a dryer of this type had a throughput of 9 kg/m²‡ per three days (Oliviera, 1903). Steam heating was later adopted with greater success (Hart, 1911).

The Martin dryer, developed in the Far East, has a large drying floor (of up to 105 m²) with primary heat derived from a wood-fired furnace connected to a U-shaped heating flue set into the plenum chamber. Drying air enters the plenum chamber not simply by holes in the walls but by ducts leading

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‡ Dryer throughput, production or loading is referred to throughout this paper as kg of dry beans at 7 per cent. moisture content wet basis per m² of drying floor area.

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directly to the underside of the heater tube. For a throughput of 25 kg/m² a drying time of only 20 h is claimed (Urquart, 1956). This is so rapid a dry when compared with that reported with other similar equipment that it must be presumed to apply to pre-dried cocoa.

The Samoan dryer is a smaller version of the Martin dryer, developed as a low investment installation for the smaller farmer (Anon, 1963). The construction is based entirely upon locally available materials and provision is even made for the once-through heater tube to be manufactured from discarded oil drums. Drying floors of 11 m² are typical and with a loading of 24 kg/m² a drying time of 40-44 h is possible (Urquart, 1956). For drying air temperatures in the range of 60-80 °C a wood consumption of 1.5 kg/kg dry beans is required (Anon, 1963) which represents an overall thermal efficiency of approximately nine per cent. (see below, *Analysis of the data)*.

Bahia is one of those cocoa growing regions which suffers from a high incidence of rainfall during the harvest season and consequently artificial drying has been necessary since plantings first began (Torrend, 1918). Though these early dryers were based upon the 'drying house' principle (Bondar, 1924), through-flow, platform type units were soon developed (Schmidt, 1932). The dimensions of this type of dryer, known locally as the 'secador tubular' have been standardized (Sobral, nd) and now account for nearly all artificial drying in the region. At a loading equivalent to 37.5 kg/m² the drying of freshly fermented cocoa can be completed in less than two days. It is usual practice, however, to pre-dry on a sun drying platform and after two days in good sun only one subsequent day of artificial drying is necessary. A dryer of this type forms the basis of the test sequence described in the present paper.

Drying by natural convection

The drying of individual cocoa beans has been shown to consist of three distinct phases (Bravo and McGaw, 1974):

(i) evaporation of surface moisture (down to 40 per cent. mc*).

(ii) drying of the seed coat (down to 23 per cent. mc); and

(iii) drying of the cotyledon (down to 7 per cent. mc).

When being dried in deep beds, however, these phases become less distinct and Shelton (1967) has observed an initial temperature and air flow rate controlled period, followed by a temperature only controlled period with a critical moisture content of 23 per cent.

With a natural convection dryer of the type under study here, the two important drying rate determining variables, air flow and temperature, are themselves related by a complex mutual interdependency upon the dryer operating parameters: the rate of firewood used, the rate of combustion air to the furnace, the load of cocoa on the dryer floor, and to a lesser extent, the scheme adopted for mixing the cocoa. The first two of these parameters combine to determine the instantaneous rate of heat generated in the furnace. This, through the heat transfer properties of the heater tube, determines the drying air temperature which in turn determines the rate of drying air flow. The maximum possible air flow for a given dryer system, then, is determined by the maximum drying air temperature permissible which for cocoa is quoted variously as lying between 60 °C and 80 °C (Quesnel and Jugmohunsingh, 1970, Howat *et al.*, 1957, Vincent *et al.*, 1980).

Unlike with forced convection dryers the drying air flow rate is not an independent operating parameter that can be manipulated at will to improve drying speed or efficiency. Its magnitude is especially dependent upon the system resistance to flow and hence to the depth of cocoa on the drying floor. The ventilating effects of ambient wind will also be important. In any event, the air flow rates likely to be developed will be low. Shelton (1967), studying the efficiency of deep bed drying (with loadings up to 120 kg/m²) of cocoa, found that the lowest air flow tested (0.051 m/s) gave the highest efficiency and from this concluded that, because of their inherently low air flows, natural convection dryers should be advocated.

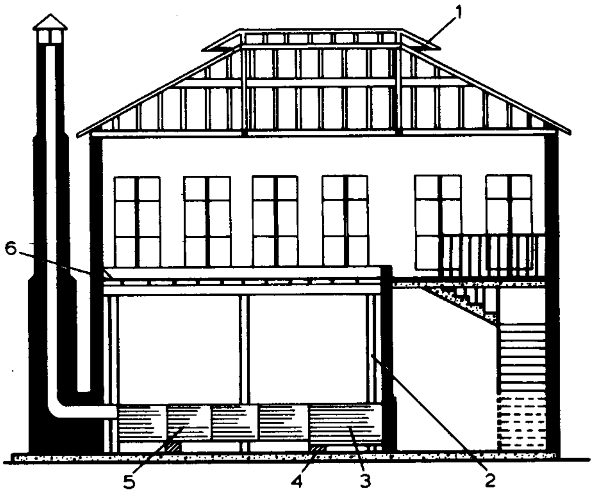

Fig. 1 Cross section of the test drier. 1, Lantern roof; 2, drying floor supports, 3, furnace; 4, drying air inlet, 5, heat exchange tube; 6, drying floor

Materials and methods

Description of the test dryer

The test dryer (Fig. 1) was of brick construction with a drying floor (6 m x 6 m in area) consisting of a perforated mild steel sheet on a framework of angle iron. The floor was supported on stilts, sections of which could be removed to allow variation in plenum chamber height. Traditionally, the plenum chamber height, as measured from the centre of the heater tube, is half the length of one of its sides, ie, in this case, 3 m.

Drying air entered the plenum chamber at ground level by a total of four inlets of approximately 0.1 m² (two on each of the two longitudinal walls), and, having passed through the cocoa, left the dryer either by the windows around the drying floor or by a ridge vent in the roof.

Set into the plenum chamber was the furnace/heat exchange unit. The furnace consisted of a horizontal cylinder of diameter 0.8 m and length

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* Bean moisture content, wet basis to be assumed throughout

1.35 m. The grate was of cast-iron fire bars set into the lower part of this cylinder and had a free area of 19 per cent. For the most part, air entered the furnace via the grate. There was no inlet for secondary air, although sufficient probably entered by leakage around the fire-box door. The combustion gases then passed directly into the heat exchange tube. This consisted of four sections, 1.03 m in length and 0.64 m in diameter, joined by bolted flanges. The final tube section reduced by a sharp contraction to a diameter of 0.2 m which projected into the chimney brickwork. Within this short run was located a simple damper for regulating the flow of combustion air. The damper was moved by a push-pull rod operated from the front of the furnace.

The chimney was of a height sufficient to project all smoke well above the dryer roof, thereby reducing the risk of smoke contamination of the end-product from this source.

Experimental procedure

Although it is usual practice to pre-dry cocoa in the sun, all tests in this sequence were carried out with freshly fermented cocoa, thereby allowing some control over the initial moisture content. Volumetric control of cocoa loading, which is normal on-farm practice, was applied during early tests but proved erratic. In later tests the cocoa was weighed before drying and a nominal 2.7 tonne loading was aimed at (this being equivalent to approximately 40.3 kg of dry beans per m^2).

The control of the drying air temperature is difficult because of the inherently batch-type loading of the furnace and the depression, which is only slowly restored, of the drying air temperature following the loading of a new charge of wood. In an attempt to minimise these problems and obtain a comparatively constant temperature, the furnace was fed at regular one hourly intervals with a weighed quantity of wood that had been chopped as necessary to ensure that each log was no more than one metre in length or 0.15 m in major cross-sectional dimension. Spot checks on wood moisture content showed a range of between 25-35 per cent. Fuel moisture content was not controlled closely, although obviously green wood was rejected. Sampling of the beans was carried out every two hours at two specified locations on the drying floor (for sampling technique see McDonald and Freire, 1981). Moisture content determination was carried out by drying to constant weight in a ventilated laboratory oven at 105 °C.

Mixing of the drying bed was carried out manually every four hours, immediately after sampling.

Drying air flow and temperature measurement

Attempts to measure the rates of air actually flowing through the crop by means of funnelled hot wire and vane anemometers proved unsuccessful and overall air flow had to be characterised by flow readings taken at the inlets to the plenum chamber. Nine point scans of flow over the area of the inlet with a hot wire anemometer resulted in average readings which were comparable with those obtained using a vane anemometer centrally located on an aluminium stand of negligible projected area. The two available vane anemometers were calibrated against a sensitive cup anemometer (CF Cassella and Co., London).

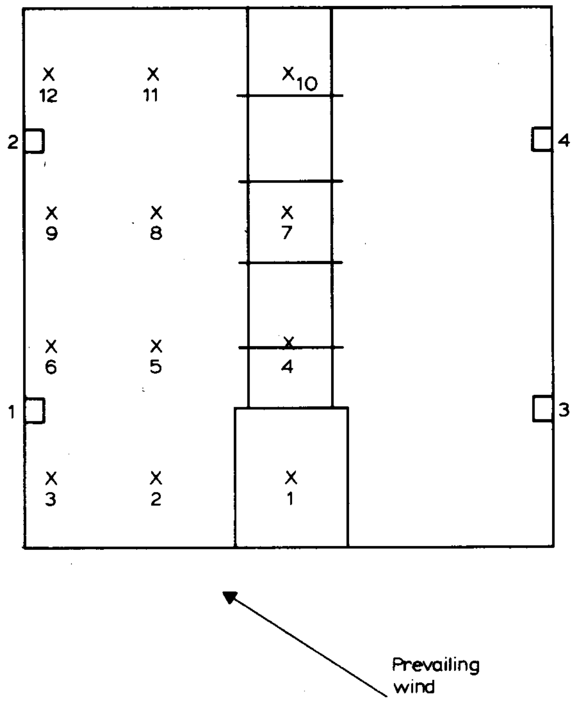

Fig. 2 Secador tubular showing numbering of air outlets and position of thermocouples for tests ST/07 to ST/14 inclusive. Arrow indicates direction of prevailing wind

Wind speed and direction readings were taken with a sensitive cup anemometer and a wind vane both located at a height of 4 m and about 25 m upwind of the dryer. The ground around the dryer was quite flat and for the most part free from obstructions to a distance of 300-400 m. Wind in the test region invariably followed a set pattern, being strong during the daytime and almost non-existent at night. Readings with a reasonable span of wind speed could often be obtained during the period 1700 to 1800 h.

Continuous monitoring of the drying air temperature in the form of half-hourly readings was achieved by means of a single mercury-in-steel thermometer located in the dryer wall some 1.15 m above the furnace. It was shielded from direct radiation by being set into a small alcove. An accurate measure of the distribution of air temperature beneath the drying floor was obtained by chromal/alumel thermocouples set into double radiation shields of aluminium foil on plastic tubing. Unfortunately, insufficient thermocouple wire prevented thermocouples being distributed evenly over the whole area of the dryer; the distribution adopted is shown in Fig. 2. Temperatures were monitored on a 12 point chart recorder (Foster-Cambridge Ltd., UK). The average values of these 12 readings compared well with the wall mounted thermometer described above, the two often being within 1 °C.

Analysis of the data

The assessment of dryer operation was quantified in terms of the overall thermal efficiency, which is defined as that proportion of the heat generated in the furnace which is actually used for evaporation of water. The calculation of this factor is described elsewhere (McDonald and Freire, 1981); the final form of the equation for wood fired installations is given below:

$$\eta = 4.187\, L/t_c F$$

where L = Loading of dry cocoa (at 7 per cent. mc), kg/m²

t_c = Drying time corrected to that required to pass from 50 to seven per cent. mc rounded up to the nearest integer, h.

F = Rate of consumption of wood, assumed to be of calorific value 16,680 kJ/kg, kg/h.

By rounding up the drying time, the product $t_c F$ represents the total quantity of wood actually used when a scheme of hourly charging of the funace is rigidly applied throughout.

Discussion of results

Overall drying performance

A resumé of the tests carried out is presented in Table 1 in which the various runs are arranged in terms of plenum height, wood rate and drying air temperature respectively. The air temperature quoted is the average of the half-hourly operational readings. The quality of the drying air temperature control achieved can be judged in Fig. 3, which shows a typical operating temperature profile.

Of those tests carried out with 30 kg/h of wood at a plenum chamber height of 2.9 m, only 5 tests had wet cocoa loadings in the region of the required 40.3 kg/m² (tests 18, 14, 16, 15 and 21). Of these five tests all but one resulted in overall average temperatures within the range 59.3-61.6 °C (with overall standard deviations of 6.5-7.6 °C). Yet in spite of these ostensibly controlled conditions, the corrected drying time for these four tests varied from 32.2 to 43.8 h. This is thought to be due to variations in the drying air flow, which was neither directly controlable nor continuously monitored. Such variations must be due to external factors which, as will be seen, are probably wind speed and direction.

Overall thermal efficiency for the five tests considered above lies in the range 11.6-17.5 per cent., which is fairly typical for most modes of operation. The exceptions are tests 10, 23 and 24, of which the last two were carried out with all windows closed throughout. During such tests much condensation occurred on the corrugated iron roof, especially during the first night of drying, showing that the ridge vent alone was not sufficient to allow adequate passage for the humid spent air.

As opposed to Shelton's proposals, the efficiency of this dryer is seen to be low compared to similar results with forced convection, ie, 18.5-29.9 per cent. for platform drying (Wood, 1961; McDonald and Freire 1981).

Effect of plenum chamber height

Reducing plenum chamber height would reduce the capital cost of the dryer and should increase thermal efficiency by reducing wall heat losses. On the other hand increased non-uniformity of drying and a decrease in drying air flow would also be likely to occur.

Several pairs of tests with similar temperatures and cocoa loadings but different plenum heights can be extracted from Table 1 (ie, tests 3 with 15, 8 with 19, 14 with 11, and 21 with 12). Among these, there seems to be no direct relationship between plenum height and either drying rate or overall efficiency, and it concluded that the effects of the applied changes in plenum height are small in comparison

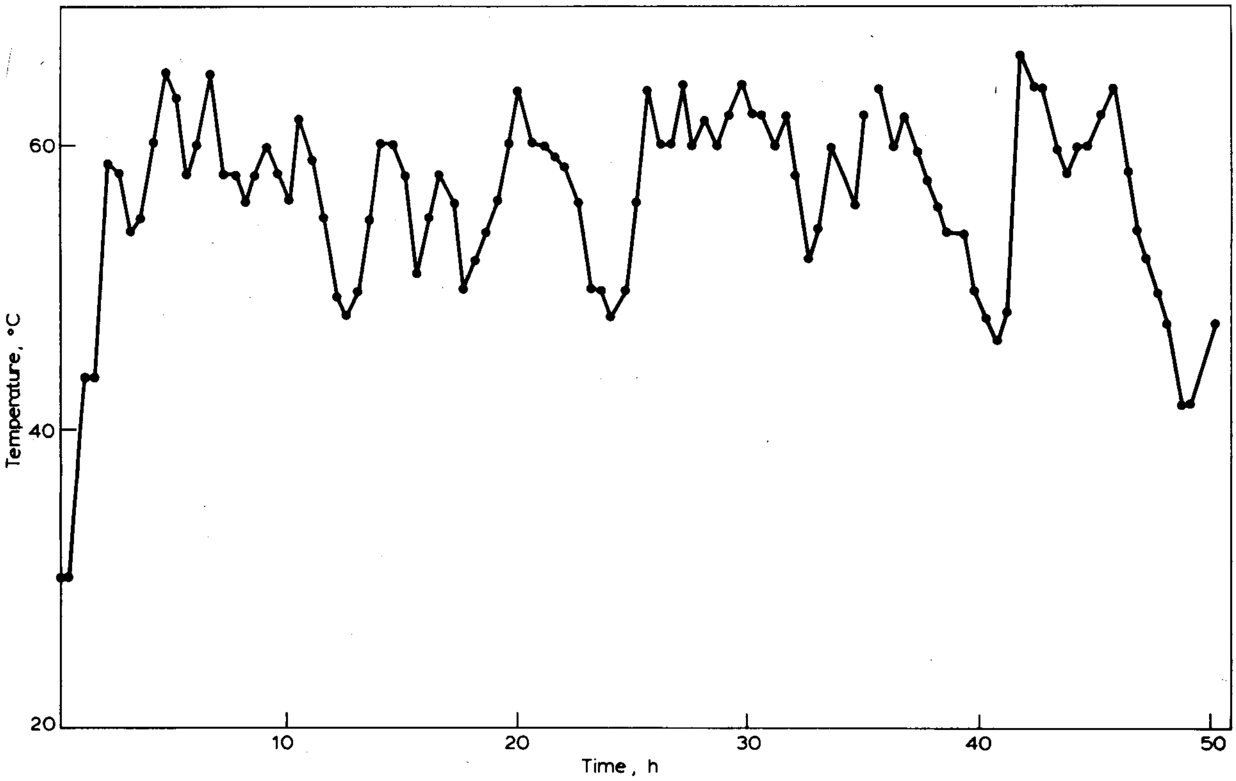

Fig. 3. Drying air temperature operating data of test 7

Table 1 Resume of test conditions

Test number	Height of plenum chamber, m	Rate of wood usage (*F*), kg/h	Average drying temp., °C	Dry wt. loading (at 7% mc) (*L*), kg/m²	Corrected drying time (t_c) h	Overall thermal efficiency, %
8	3.5	40	55.0	33.6	35.9	9.8
3		30	58.5	38.5	41.8	12.8
7			56.3	44.7	51.3	12.0
6			54.1	44.6	53.5	11.5
2		25	60.4	44.1	32.8	22.4
9	2.9	40	62.0	45.6	45.3	10.4
22			57.3	39.1	42.4	9.5
18		30	61.6	40.7	39.6	14.2
14			61.4	41.4	32.2	17.5
16			60.4	41.3	43.8	13.1
25			59.5	35.8	29.5	16.7
15			59.3	40.8	36.9	15.4
19			55.7	37.5	43.6	11.9
10			54.3	31.3	53.9	8.1
23*			54.4	37.7	54.9	9.6
21			54.1	39.2	46.4	11.6
24*			51.3	26.7	52.2	7.0
17		15	46.5	41.6	68.0	17.1
20			39.1	38.4	71.4	14.9
13	2.1	40	63.3	40.4	30.3	13.6
11			61.8	40.0	44.2	9.7
12		30	55.4	38.9	43.4	12.3

with those due to the suspected wind-induced variations in drying air flow. On the other hand the data, which are as yet incomplete, indicate a direct relationship between plenum height and uniformity of drying, though this factor also is affected by wind speed and direction.

Effect of drying air flow rate

The effect of wind on the drying air flow measured at inlet one for dryer operating temperatures in the range 70.3-75 °C is shown in Fig. 4. The wind direction was south-east (that of the prevailing wind, see Fig. 2) and hence inlet one lay on the leeward side of the dryer. It is evident that the natural convection currents formed above the heater tube were not sufficiently strong to completely overcome the wind's suction effect.

The effect of wind upon the distribution of air temperature beneath the drying flow is shown in Fig. 5, where the standard deviation of the 12 drying air temperature readings is plotted against wind speed.

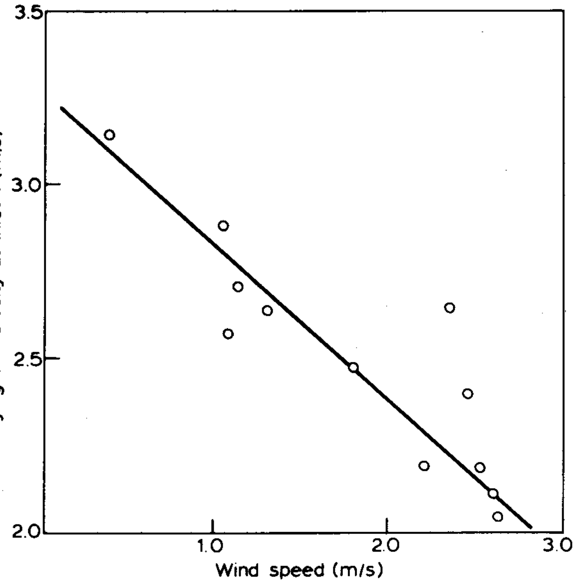

Fig. 4 Variation of drying air velocity at inlet 1 with wind speed data from test 8, mean drying air temperature 70.3 to 75 °C. Correlation coefficient, *r* = 0.869

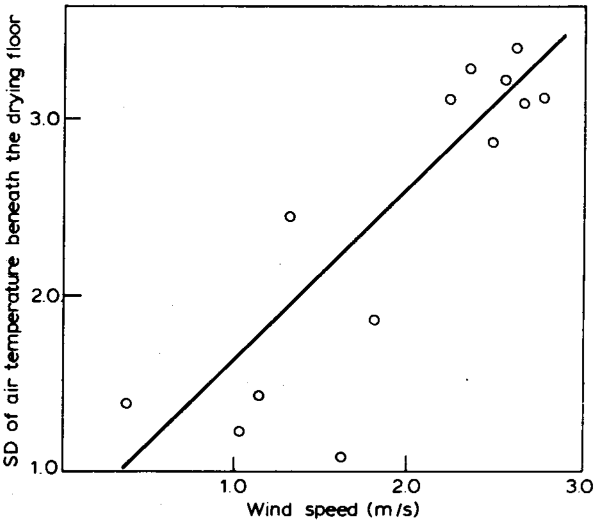

Fig. 5 Variation of standard deviation (SD) of air temperature beneath the drying floor with wind speed. Data from test 8, mean drying temperature 70.3 to 75 °C. Correlation coefficient, *r* = 0.913

Table 2 Drying air flow—the effect of wind. Test ST/12, 8 Sept. 1978. Wood rate 30 kg/h, bean moisture content 27% wb

Time	Drying Air		Wind, m/s	Drying air flow at inlets				Air flow in the cocoa,	Comments
	Mean temp., °C	Standard deviation		Inlet no.	m/s	Inlet no.	m/s	m/s	
15-40	50.82	10.27	2.49	3	2.44	1	0.08	0.014	All inlets open
15-45	50.89	10.29	2.93		2.29		−1.71	0.003	
15-50	48.12	10.33	3.53		2.07		−1.05	0.006	
15-55	46.97	10.89	2.73		3.03		−1.18	0.010	
16-00	46.23	10.95	2.56		2.37		−0.53	0.010	
16-05	47.33	11.00	3.45		2.83		−1.51	0.007	
16-10	47.69	11.94	2.54		2.18		−0.42	0.010	
16-15	49.83	10.04	2.68		2.81		−0.58	0.012	
16-20	48.80	10.86	2.81		2.23		0.13	0.012	
16-25	49.09	11.07	3.45		1.80		−1.63	0.001	
16-30	48.69	9.57	2.39	3	3.07	4	2.97	0.017	Inlets 1, 2 closed
16-35	47.38	8.90	3.16		3.13		2.71	0.016	
16-40	48.57	9.62	1.76		2.87		2.76	0.016	
16-45	47.72	9.66	2.56		2.68		2.42	0.014	
16-50	48.38	8.98	2.26		2.57		2.43	0.014	
17-10	49.15	8.60	—	2	−1.54	1	1.33	−0.001	Inlets 3, 4 closed
17-15	51.05	8.21	1.82		1.21		0.89	0.006	
17-20	51.71	8.20	2.31		2.14		0.41	0.007	
17-25	52.63	7.92	2.55		0.73		0.50	0.003	
17-30	52.74	7.81	1.47		1.45		1.15	0.007	
17-35	53.88	8.93	1.74		1.44		1.00	0.008	
17-40	52.99	7.98	1.81		1.31		0.98	0.006	
17-45	53.54	7.91	1.46		1.70		1.18	0.008	
17-50	55.19	8.22	1.11		1.73		1.37	0.007	
17-55	56.18	8.07	1.38		1.60		1.32	0.008	

It can be seen that increased wind speed causes a worsening of the temperature distribution which will increase nonuniformity of drying.

Table 2 shows three sequences of air flow data for average plenum temperatures in the range 46-56 °C. With all inlets open it can be seen that the dryer operated with negative flow on the leeward side during almost the whole of the measurement period. The high standard deviation values under these conditions should be noted. In the second set of data it can be seen that the closure of the leeward inlets does not significantly increase air flow on the windward side. However, a sudden drop in temperature standard deviation was noted signifying an improvement in the homogeneity of drying. In the third set of readings, the two windward side inlets were closed, the full effect of the natural convection being applied exclusively to the leeward side inlets. This, combined with the reduced wind speed and increased drying air temperature for this data set, resulted in inlet air flows which, though very low, remained positive. The standard deviation values were low, suggesting that the observed jump in drying air temperature homogeneity was a discontinuity that occurred on the reversal of direction of air flow at the leeward side inlets.

Also shown in Table 2 are estimates of the actual air flow passing through the cocoa, calculated on the assumption of perfect air flow distribution. In the case of the first data set, the sum of the two available readings was taken to represent half of the total flow. The advantage of having only the windward side inlets open is clear and higher air flow still might well be possible if extra inlets were to be located there. However, it should be noted that a reversal in wind direction will result in a total flow lower than that which would be obtained with the existing distribution of air flow inlets.

Investigation of the drying curves

In Fig. 6 is shown a fairly typical pair of drying and drying rate curves (for drying rate estimation, see McDonald and Freire, 1981). The slight fall off in drying rate immediately after start-up should be noted. This is common behaviour and is often much more accentuated than in the example shown here. The peak in drying rate was, however, common to all runs except those carried out with only 15 kg/h of wood, in which case the drying rate remained low throughout.

The effects of air flow on the drying rate profile can be judged in Fig. 7 where the results of test 7 are compared with data from two high air flow runs (on forced convection equipment). All three tests had similar dryer loadings (46 kg/m²) and air temperatures (54-63 °C) while of the two forced convection runs one was carried out on the laboratory scale with an air-flow of 0.17 m/s, the other on a field-scale platform operating at 0.03 m/s (see McDonald and Freire, 1981, run 4), both flows being significantly higher than the nominal 0.01 m/s of the natural convection dryer.

The laboratory test was typical of the throughflow drying of a porous material of high initial moisture content (Keey, 1972). A rapid rise in drying rate during the warm-up period was followed by a barely discernible constant rate period. Soon after 40 per cent. mc, the drying rate began to fall off and continued to do so without interruption throughout the remainder of the test.

The form of the drying rate profile of the platform dryer run has been explained as being due to the glutinous nature of the freshly fermented cocoa hindering the throughflow of the drying air (McDonald and Freire, 1981). The resultant low air flow in itself inhibits high drying rates but it is also thought to be sufficiently low as to result in condensation within the cocoa bed, this causing a further reduction in drying speed. This effect begins to diminish as skin dry conditions are approached and it can be seen that the drying rate picks up rapidly beyond the 40 per cent. mc point. Although from then on theoretically independent of the drying air flow rate, the drying rate only intersects the high air flow curve at some 22.5 per cent. mc. Thereafter, however, the fall of the two curves is almost coincident.

The drying rate curve for the natural convection run, apart from being lower throughout, is of practically the same form as that of the platform dryer and can be interpreted in a similar way. The major difference between the two is the fact that the natural convection curve only intersects the other two at about 11 per cent. mc and the drying can be taken to the air-flow rate controlled almost throughout.

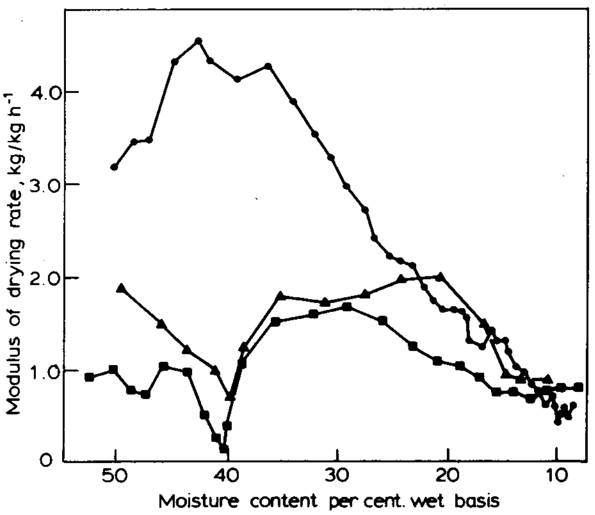

Fig. 7 Comparison of the drying rate curves at various drying air rates:

Nominal air flow, m/s	η	t_c
● 0.17	—	28.0
▲ 0.03	27.5	36.2
■ <0.01	12.0	51.3

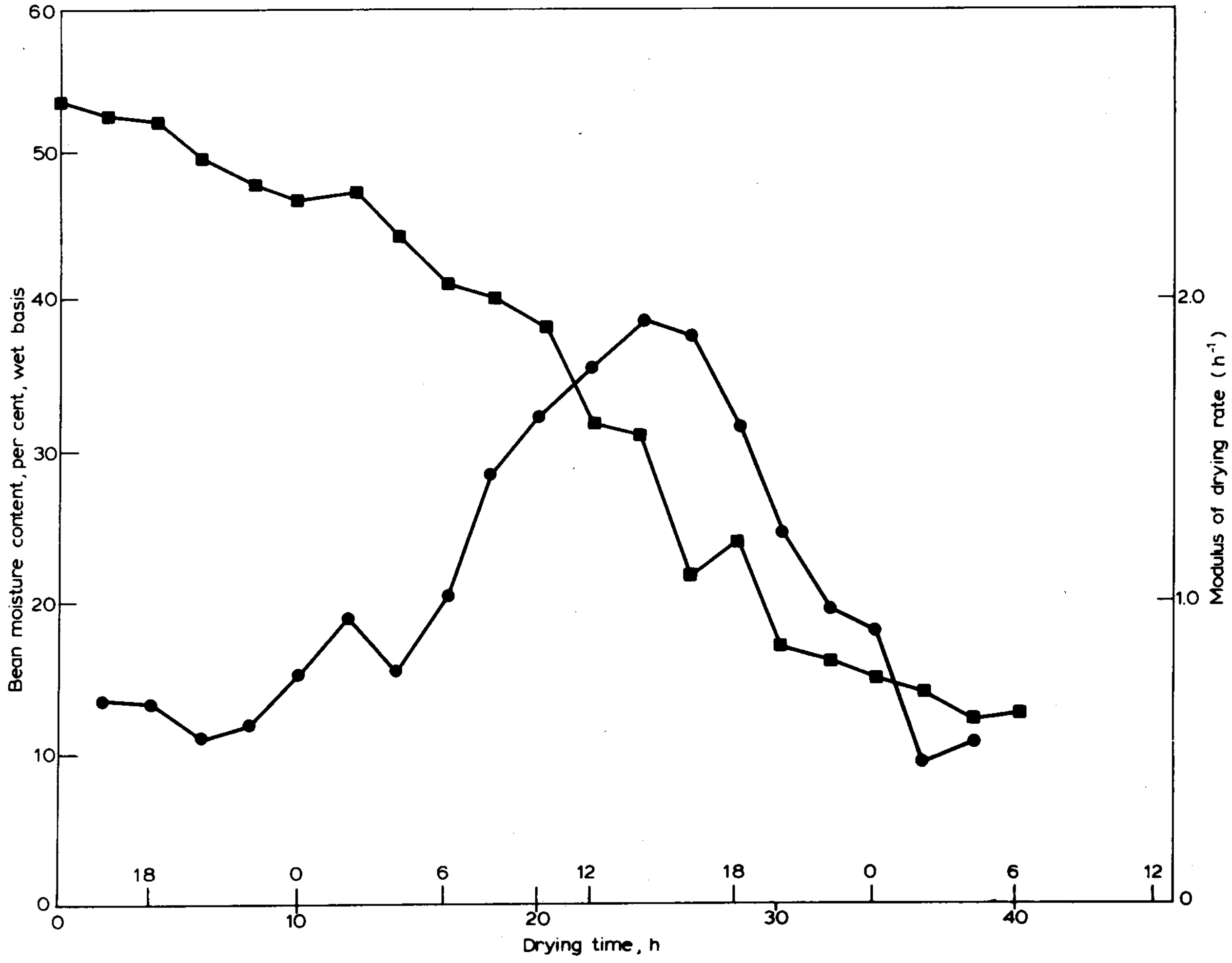

Fig. 6 Drying (■) and rate of drying (●) curves for test 3

From the results shown on Fig. 7 it can be seen that both drying time and efficiency can be improved by limited increases in air-flow, which could probably be achieved by taking advantage of the wind's effect to increase ventilation. As a last resort forced ventilation could be applied.

Condensation effects can be minimized by increased mixing during the early hours of drying, though it must be pointed out that it is precisely during this period that the glutinous nature of the crop and the evaporation of acetic acid make mixing arduous and uncomfortable. The problems associated with the early period of drying are largely overcome by pre-drying in the sun to less than 40 per cent. mc.

Conclusions

1. The average overall thermal efficiency of the test dryer under normal operation was of the order of 14 per cent., which proved to be about half that of forced convection drying with air-flows some three times greater.
2. The forms of the drying rate profiles obtained were similar to those in the literature for field-scale forced convection drying and were similarly interpreted. The low initial drying rates are thought to be due to the high resistance to air flow of the wet cocoa and the occurrence of condensation within the bean mass during this period. There is evidence to show that the drying is air-flow rate controlled almost throughout.
3. Significant increases in drying air-flow were noted when air inlets were opened on the windward side of the dryer only. Further wind induced increases in air flow are thought to be possible.
4. With air inlets on the leeward side of the dryer under medium to high wind conditions, hot air was sucked from the plenum chamber. This was accompanied by a sharp decrease in the uniformity of drying.

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