THE PACKED BED DRYING CHARACTERISTICS OF COCOA BEANS

by

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SUMMARY

Experiments were carried out on the drying of cocoa beans in a packed bed, in order to determine their drying characteristics. The air temperature used in the experiments 135°F, was the maximum possible, consistent with the desired biochemical changes. Superficial bed air velocities, V, were varied in the range 8 to 18ft/minute, and bed depths, h, in the range 2 to 10 inches. The following relationship was derived from the results, this being an equation for the time required to dry cocoa beans to 6.4% moisture, dry basis, θ_T, in terms of the initial moisture content, X_o, dry basis and the variables quoted:-

$$\theta_T = \frac{(X_o - 0.3)}{\exp(-2.8482 + 0.0277V - 0.1154h)} + 22$$

An optimisation calculation was carried out, on the basis of this equation, which showed that the running costs reduced progressively with reducing air velocity. The optimum bed depth was ten inches.

INTRODUCTION

The most common type of artificial cocoa drier in the Caribbean region is the packed bed drier. This is a very simple piece of equipment in which the drying compartment consists of a cylindrical or rectangular vessel, with a perforated plate at the bottom, on which the bed of beans is placed. Air from a fan is ducted to the drying chamber and blown up through the perforated plate and bed of beans. The air is heated in some way, e.g. electrically, between the fan and the drying chamber.

Now, although this is a standard technique there is little available information on its use as a cocoa drier, and no relationships have yet been reported for the rate of drying of cocoa in this type of equipment. The object of this work was to derive a relationship between the rate of drying and the various variables. This relationship could be used

(a) To predict the required drying time under given conditions
(b) To optimise the operating conditions for minimum running cost

It is possible to apply a theoretical approach to the problem of heat and mass transfer in a static packed bed, which can be satisfactorily solved by computer techniques. Unfortunately, however, in the case of cocoa drying, there is the practical necessity of manually turning the beans over during the first few hours of drying, because of the tendency of the beans to stick together. This renders the assumption of a static packed bed inapplicable. Since the only other theoretical approach possible would be to assume perfect mixing, an empirical approach to the problem was necessary. The approach used was to carry out a series of drying tests on suitable equipment, these being used to find the required relationship by curve fitting and regression analysis.

APPARATUS

The drier used in the experiments consisted of a 12" long, 6" diameter QVF glass section, through which heated air was passed. The air was distributed over the section by a mild steel perforated plate containing 0.073 inch diameter holes and of 8% open area. The beans to be dried were placed in a wire mesh basket, suitably constructed to fit very closely to the walls of the QVF section, and which could be easily removed for weighing during drying.

The air was supplied to the drier from a centrifugal fan through a 2-inch nominal bore pipe. The pipe was expanded into the drier by use of a cone piece of about 60^{0} angle. A gate valve on the output side of the fan controlled the air flow rate. The air was heated by an in-line electrical heater supplemented by heating tape surrounding the delivery pipe, the temperature being controlled with a variac.

The air flow rate was measured with an orifice plate in the delivery line, the calibration being in accordance with British Standards BS 1042. Air temperatures were measured just under the bed and just above the bed with mercury in glass thermometers, estimated accuracy $\pm 1^{o}$F. During each experiment the total bed weight was measured at intervals, by removing the basket, weighing on a triple beam balance, and returning to the bed. This operation was complete in a few seconds and the accuracy of the balance was ±0.1 gms. The humidity of the inlet air was measured using wet and dry bulb thermometers, and the outlet air by using a 'Humeter' instrument consisting of a suitably impregnated plastic probe, together with its associated measuring circuit, which gave an indicated output in the range 0 - 100% relative humidity. The moisture content of the initial wet beans was calculated from measurement of the change in weight, while in an oven at 105^{o}C for 12 to 15 hrs.

CHOICE OF OPERATING CONDITIONS

In accordance with normal drier operation it was decided to operate at the highest temperature consistent with a satisfactory product quality. The main criterion in terms of product quality is that of flavour. The characteristic chocolate flavour has been found to be derived mainly from the phenolic constituent of the bean.[1] The flavour development[2] is enzymic in nature and is associated with the oxidation of a polyphenol by a polyphenol oxidase. Quesnel and Jugmohansingh[3] found that the optimum temperature for enzyme activity was 94^{o}F but this activity was lost altogether after 4 hours at 167^{o}F. In experiments whereby polyphenolic material was extracted from beans treated at various temperatures, both Phillips and Quesnel and Lopez[5] extracted much less polyphenolic material at temperatures greater than 140^{o}F. Raelofsen through Rohan[6] has also found that bean temperatures in excess of 140^{o}F adversely affected both the flavour and colour of the beans. In view of this evidence it was decided to carry out the experiments at a drying temperature slightly less than 140^{o}F and the figure of 135^{o}F was used.

Because of the size of the bean it is likely that the drying operates mainly with a diffusion mechanism, thus making low air flow rates more applicable. The range of superficial air velocities investigated was 8 ft/min to 18 ft/min, these values being of the order of those used in previous reported work[7,8] on artificial cocoa drying.

The normal bed depth is just a few inches, so the range of bed depths investigated was 2 inches to 10 inches.

EXPERIMENTAL RESULTS

The results were plotted as characteristic drying curves, which are plots of moisture content, dry basis, X, against time θ. A typical plot is given in Figure 1. Also shown in Figure 1 are the plots of exit air temperature and humidity against time, for the same experiment. An examination of these curves showed that they could be split up in each case into two separate sections. The first section was linear, indicating a constant rate of drying, the second section however was one of falling rate drying. The cross-over point between sections was found in each case to occur at a moisture content $X_1 = 0.3$. When plotted on a semi logarithmic basis however, the second section became linear as shown by typical curves in Figure 2.

In the first period, the constant rate of drying $(dX/d\theta)$, was a function of both air velocity and bed depth as shown in Table 1. Regression analysis was supplied to these results and the following equation was found between the rate of drying, air velocity and bed depth in this period.

$$\ln m_1 = \ln\left(\frac{dX}{d\theta}\right)_1 = -2.8482 + 0.0277 \quad -0.1154h \qquad \text{.. (1)}$$

Thus for the first period, the time of drying may be obtained from:

$$\theta_1 = \frac{X_0 - X_1}{m_1} \qquad \text{.. .. (2)}$$

In the second period of drying however, the slope of the semi logarithmic plot, $\left(\frac{d\ \ln X}{d\theta}\right)_2$ was independent of both air flow rate and temperature, the value of the slope being found to be 0.07 ± 0.003 over the rangeof variables examined.

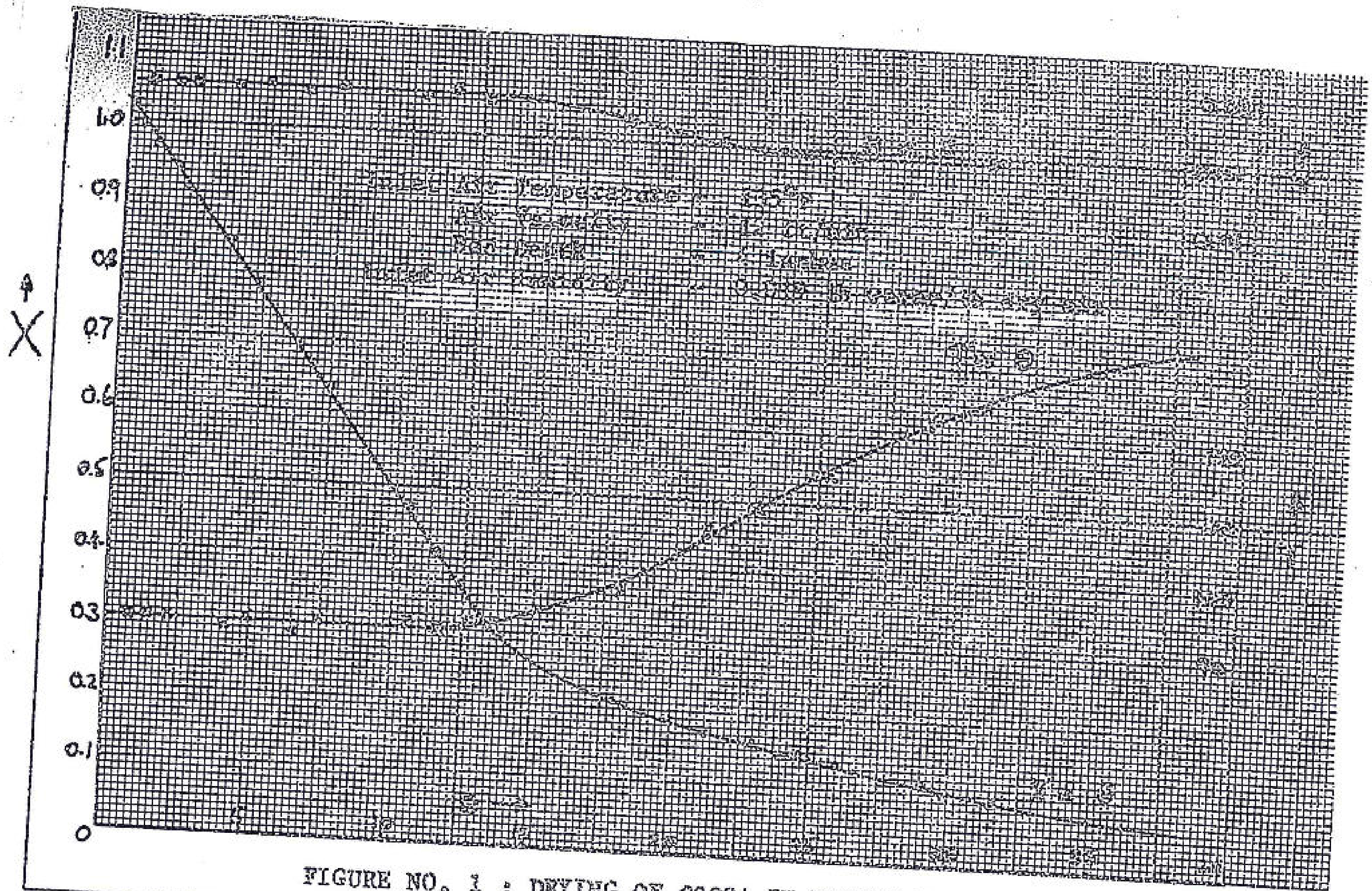

FIGURE NO. 1 : DRYING OF COCOA IN PACKED BEDS

Exit Air Humidity H, Exit Air Temperature T, Moisture Content X curves vs. Time θ

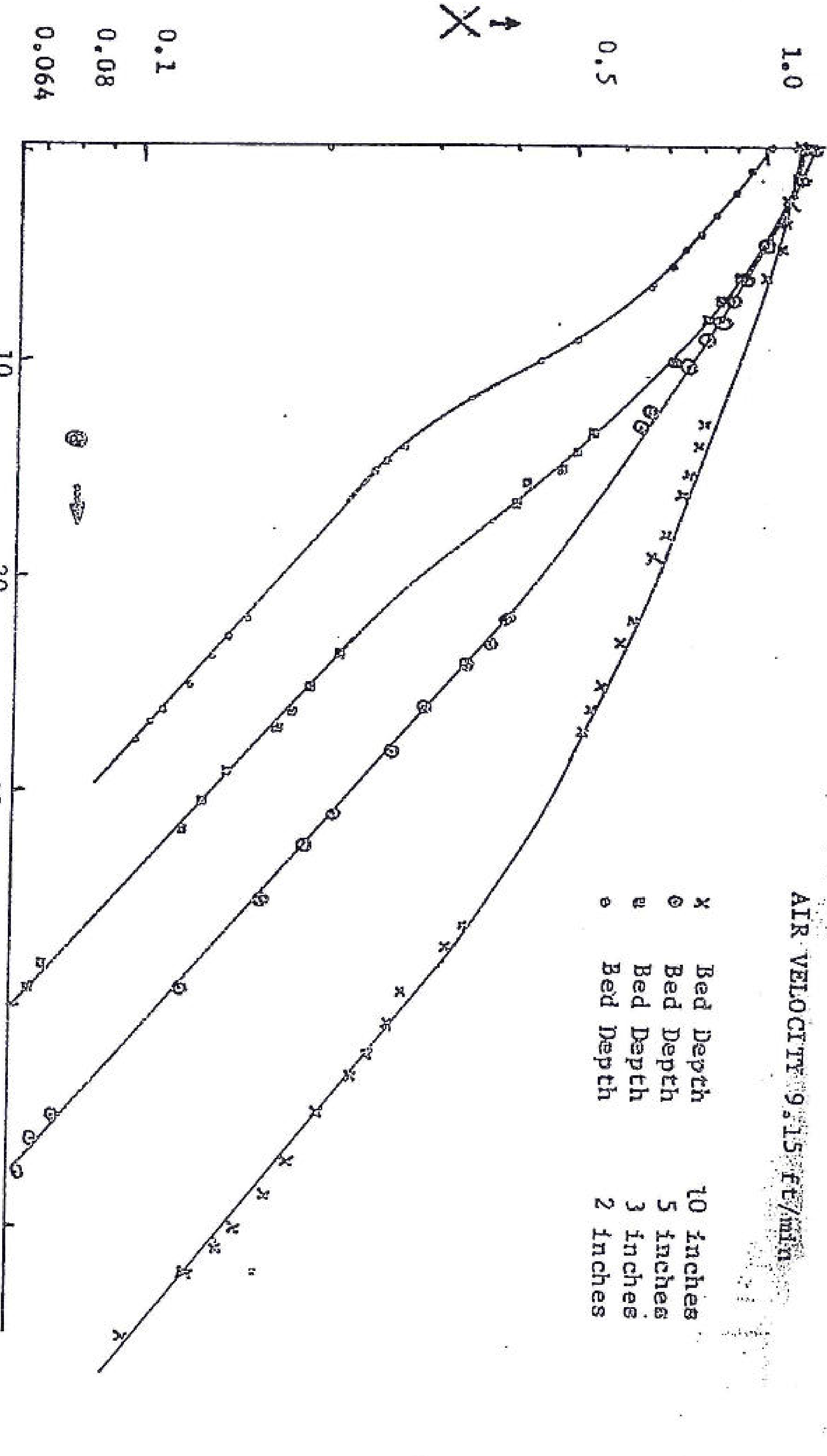

FIGURE NO. 2. SEMILOGARITHMIC DRYING CURVES

Thus

$$\left(\frac{d \ln X}{d\theta}\right)_2 = 0.07 = m_2 \qquad (3)$$

and the time of drying in this period may be obtained from

$$\theta_2 = \frac{1}{m_2} \cdot \ln \frac{X_1}{X_2} \qquad (4)$$

This now gives a basis for determining the total time of drying. If the end of the first period occurs at a moisture content $X_1 = 0.3$ and the final moisture content required is $X_2 = 0.064$ (6% wet basis) then the total drying time may be given by:-

$$\theta_T = \frac{(X_o - 0.3)}{\exp(-2.8482 + 0.0277v - 0.1154h)} + 22 \qquad (5)$$

Reference to Figure 1 shows that the exit air temperature and humidity remained constant over most of the first period. It is worthwhile noting that these values of temperature 33°C and humidity 0.027 lb water per lb dry air did not vary significantly from experiment to experiment, and are close to saturation conditions. In the second period the air temperature rose and the humidity dropped gradually until they began to approach the inlet conditions.

In spite of the turning of the beans, a stratication of bean moisture contents was noticed. In order to determine the effect of this on the final distribution of moisture contents, an experiment was carried out whereby samples were taken periodically for moisture content analysis, from the following locations in the bed.

(i) At the top of the bed
(ii) In the centre of the bed
(iii) At the bottom of the bed

The results are shown in Figure 3, where it is seen that the bottom layer dried off to X = 0.1 in 15 hours whereas the top layer required 27 hours to reach the same moisture content. By the time the top layer had reached X = 0.1 the bottom layer had almost reached an equilibrium moisture content at X = 0.06. The distribution of moisture contents was quite large to start with, but reduced considerably in the later stages.

OPTIMISATION OF RUNNING CONDITIONS

Equation 5 provided the basis from which an optimisation calculation was made. This was carried out by determining the total amount of energy, designated q_T, required by the process, to yield one pound of beans of moisture content, $X = 0.064$, over a range of air velocities and bed depths.

The energy input to the system was considered to be the of the following three components each of which was on the same unit basis as q_T.

1. Energy required to increase the temperature of the air from ambient conditions (80^oF assumed) to 135^oF q_1.

2. Energy required to overcome pressure losses in the supply ducting between the fan and the drying chamber - q_2. This calculation was based on the assumption that the supply ducting used in the experiments was typical.

3. Energy associated with the pressure drop across the bed of beans in the drier - q_3. The relationship between the pressure drop across the plate and bed of beans and the variables (bed depth and air velocity) was obtained experimentally.

The relationship from which q_T was calculated was

$$q_T = q_1 + q_2 + q_3 \qquad (6)$$

$$= \frac{G \Delta H \theta_T}{W} + \frac{C \Delta P Q \theta_T}{\eta W} + \frac{C W_f G \theta_T}{\eta W} \qquad (7)$$

where θ_T was obtained using Equation (5)

The value q_T was calculated for a series of air velocities ranging from 5 ft/min to 30 ft/min and bed depths from 5 to 30 inches. These results are shown in Figure 4 where it is seen that the energy requirement reduced continuously with reducing air velocity. The optimum bed depth was of the order of 10 inches.

DISCUSSION

The splitting up of a drying curve into two sections, the first showing a constant rate of drying, and the second one a falling rate, is in accordance with normal drying theory. Usually, however the constant rate period is associated with evaporation from a saturated surface at its wet bulb temperature. In these experiments, however, a distinct stratification shows up as given in Figure 3, where the moisture content is a function of the bed depth, at any time during the cycle. Visual examination of the bed showed that the bean surface in the bottom layer became visibly dry, i.e. less than saturated, after less than an hour of operation. At the top of the bed, however, the beans look saturated for most of the first period. Thus the normal explanation of the constant rate period was not valid. It was noticed that the outlet air temperature began to rise just before the end of the constant rate period. This indicates that most of the temperature changes in the bed had already taken place and the top layer was beginning to heat up. It is thus likely that the drying process is controlled by the rate of heat transfer to the beans in the first period, this accounting for the fact that the rate of drying was a function of the air flow rate. In this first period different layers are at different stages of the drying process and the fact that a constant rate shows up probably has no physical significance. In the second period the bean surface looks dry throughout the bed, thus the process is probably diffusion controlled, as confirmed by the lack of effect of the bed depth and air velocity. The form of the equation found to fit the results in this period was similar to that found by investigators[9] on the packed bed drying of other materials.

The resultant Equation 5 can be used to predict the drying time for any particular combination of the variables. There is only one reported set of results against which its validity can be checked, but reference to Table 2 shows that Equation 5 gives results which agree quite favourably with those reported. Thus the relationship may be assumed to be valid, and can be used in two ways:-

(i) To determine the drying conditions necessary for a particular quantity of beans to be dried in a given time.

(ii) To optimise the operating conditions for minimum running cost.

When the equation is used to determine the drying conditions, the drying time and bed depth would be given, and an air velocity calculated. It should be noted that if the calculated air velocity is relatively high, > 10 ft/min for example, the possibility exists of reducing the costs by reducing the air flow rate in the second period. Great care should be taken in the use of high air velocities, since quick drying in the initial stages can give rise to unacceptably wrinkled beans.

The optimisation showed that a progressive reduction in the air flow rate resulted in reduced running costs, hence the operating air velocity should be as low as can be conveniently operated. The optimum bed depth was ten inches. Unfortunately this is probably a little too high for practical operation because of the difficulty of turning. Thus the depth of bed should be as deep as can be conveniently operated. Shelton[8] attempted to find the region of minimum running cost based on a factorial experimental design. The results predicted agree reasonably well with Shelton's work, but he did not investigate the region below an air velocity of 10 ft/min.

One advantage of the necessity of turning the beans is that it can have some mixing effect, thus reducing the final bean to bean moisture distribution and possible reducing the overall drying time. The use of a slow moving mechanical mixing device in the first period may be worthwhile considering for use with pack bed driers.

Recycling the air is used in a number of drying operations. In this case, however, reference to Figure 1 shows that the air leaving the bed was almost saturated at a temperature very little above ambient, for half the drying time. Thus, recycling does not seem to offer any advantages in this case.

In the optimisation calculation it was found that the cost of fan operation, represented only a small fraction ($\sim 2\%$) of the total cost. Hence the cost of heating the air up is of prime importance and consideration should always be given to the use of cheap energy

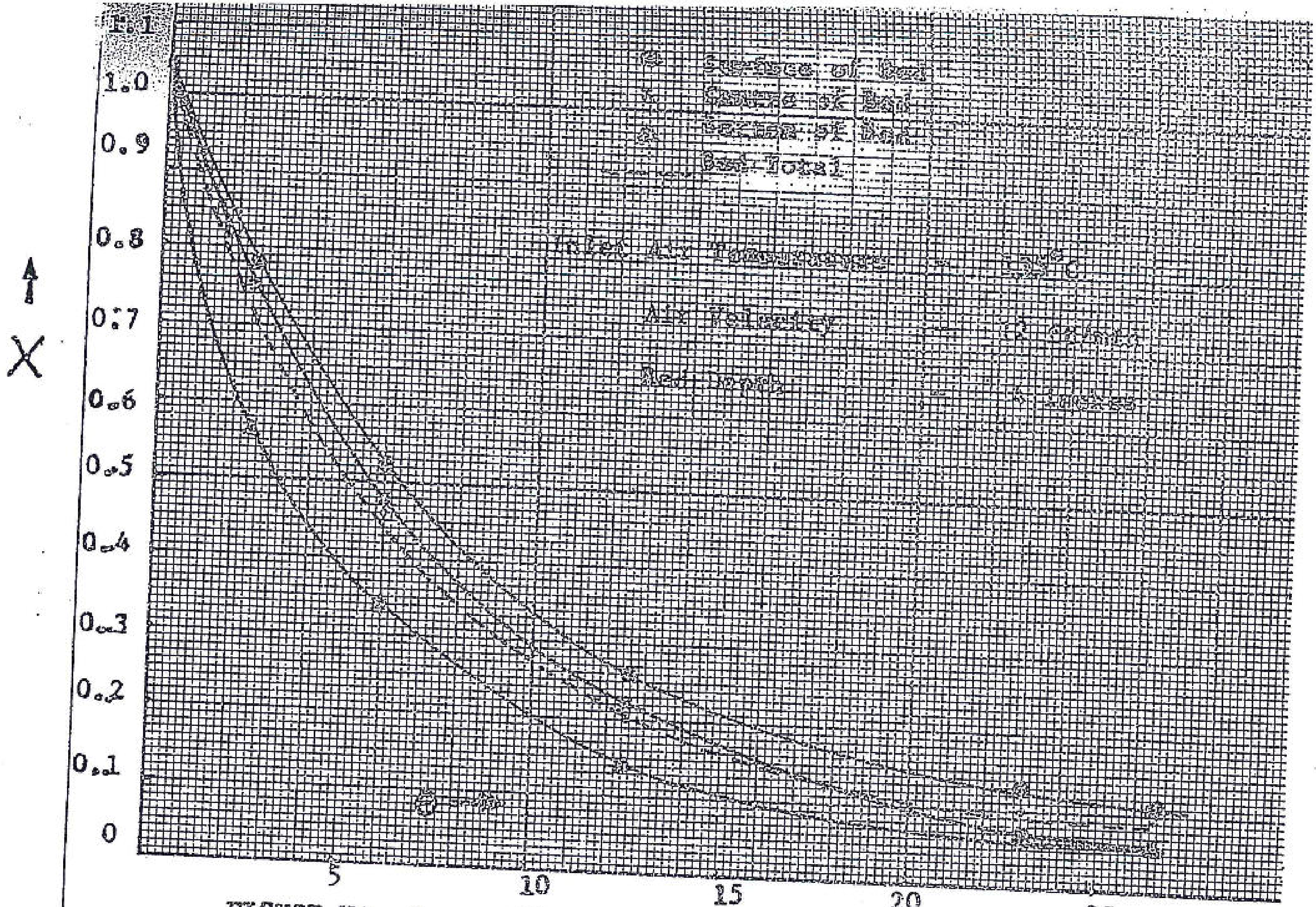

FIGURE NO. 3. DEMONSTRATION OF STRATIFICATION EFFECT

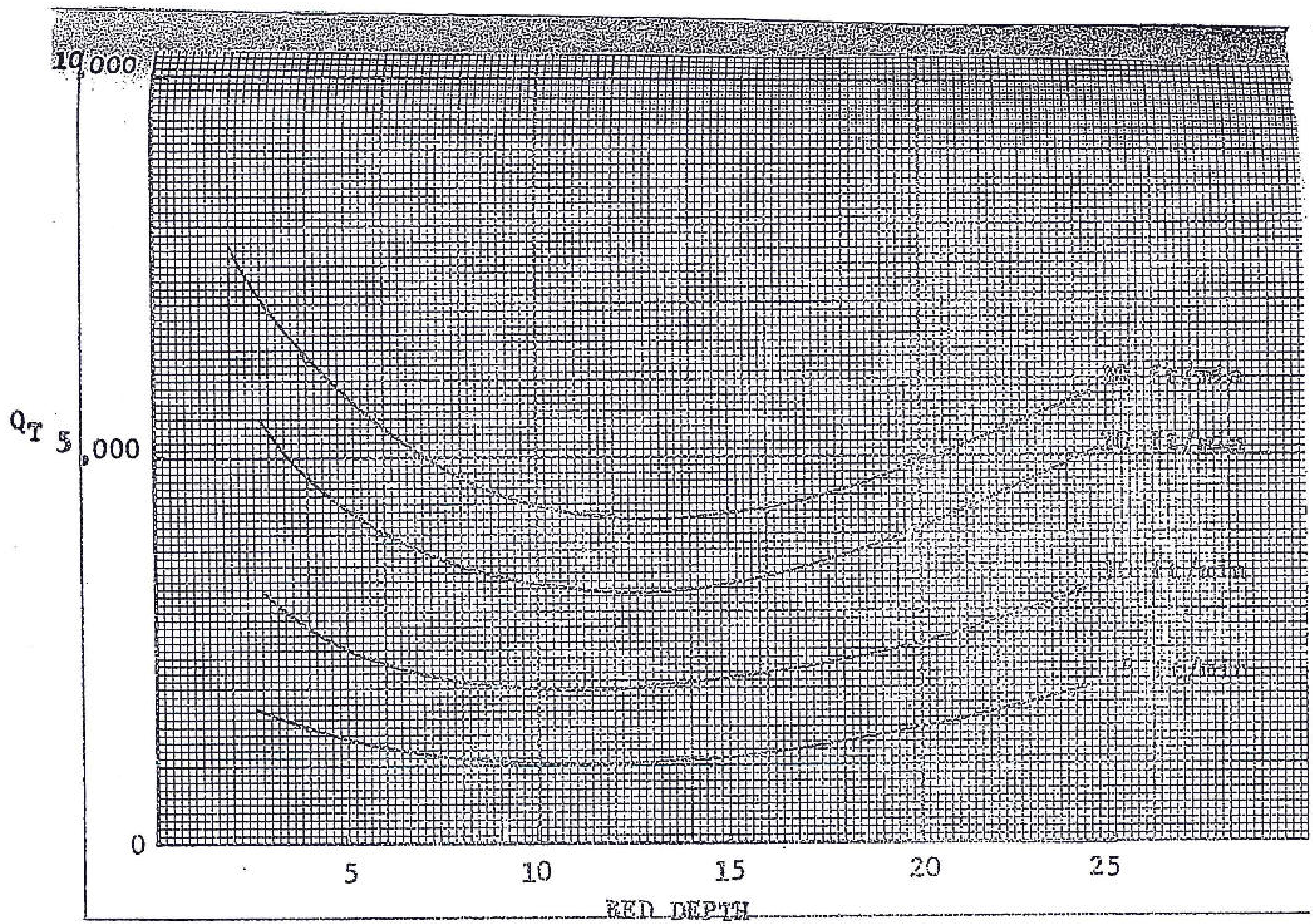

FIGURE NO. 4. OPTIMIZATION OF OPERATING CONDITIONS sources. One possibility is a combined electrical (or gas fired) and solar air heater system, where the solar air heater is used during sunny days, and the other energy source for the rest of the drying time.

CONCLUSIONS

1. There are two separate sections in the characteristic packed bed drying curve for cocoa beans:

   (i) An initial constant rate period, where this rate is a function of both bed depth and air velocity.

   (ii) A falling rate period where a semilogarithmic drying curve shows a constant slope irrespective of bed depth and air velocity.

2. The equation derived to calculate the total drying time for given operating variables compares favourably with reported drying curves in the literature.

3. Optimisation of the variables for minimum running cost showed that such driers should be operated with as low an air velocity and as deep a bed (but not exceeding 10 inches) as can be conveniently operated.

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TABLE I

Values of $(dX/d\theta)_1$ as a function of Bed Depth and Superficial Air Velocity

	Velocity ft/min				
	8.12	9.15	10.5	12.0	17.7
Bed Depth Inches 2	-	0.058	-	-	-
3	- -	0.049	0.057	0.062	0.068
4	0.045	0.047	0.049	0.053	0.059
5	-	0.040	0.041	0.043	0.050
7	-	-	0.032	0.036	0.043
10	-	0.024	-	-	

ABLE 2

Comparison Between Predicted Drying Times and the Experimental Times found by Shelton[8]

Air Velocity ft/min	Bed Depth inches	Time Predicted by Equation 5-hrs. T = 135°F	Shelton's Results in hrs. T = 130°F	T = 140°F
10	6	40.5	-	38
30	6	32.6	-	30.5
10	10	51.2	70	42.5
30	10	38.8	-	28

Nomenclature

C	Energy conversation factor - 0.001285	BTU/ft lbf
G	Air flow rate	lb/hr
h	Bed depth	inches
ΔH	Change in enthalpy when air is heated from 80°F to 135°F	Btu/lb
m_1	Slope of drying curve in constant rate period	-
m_2	Slope of semi logarithmic drying curve in bed of beans	–
q_T	Total amount of energy required by the process to yield 1lb of beans at $X = 0.064$	BTU/lb dried beans
q_1	Energy required to increase the air temperature from 80°F to 135°F per 1 lb dried beans at $X = 0.064$	BTU/lb dried beans
q_2	Energy required to overcome the pressure drop in the drier per 1 lb dried beans at $X = 0.064$	BTU/lb dried beans
q_3	Energy required to overcome pressure losses in supply ducting per 1 lb dried beans at $X = 0.064$	BTU/lb dried beans
Q	Volumetric air flow rate	ft^3/hr
V	Superficial air velocity in drier	ft/min
W	Wt. of dried beans	lb dried beans
W_f	Energy losses in ductwork per lb air	ft lb_f/lb_{air}
P	Pressure drop through distribution plate and bed of beans	lb/ft^2

X	-	Moisture content dry basis	lb moisture/lb dry bean
X_o	-	Initial moisture content - dry basis	lb moisture/lb dry bean
X_1	-	Moisture content at crossover point between periods - dry basis	lb moisture/lb dry bean
X_2	-	Final moisture content - dry basis	lb moisture/lb dry bean
[illegible]	-	Time	hrs
$_1$	-	Length of time in constant rate period	hrs
$_2$	-	Length of time in falling rate period	hrs
Γ	-	Total drying time	hrs
[illegible]	-	Fan efficiency	-