專論

空氣流量對於澳洲胡桃單層乾燥速率之影響

The Effect of Airflow Rate on Single Layer Drying Rate of Macadamia Nuts

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中文摘要

澳洲胡桃（Macadamia nut）原產於澳洲南昆士蘭及新南威爾斯北部，約在1885年引進夏威夷羣島，直到1916年開始大量種植，逐漸成爲夏威夷之主要特產，行銷世界各地。臺灣自1954年亦自澳洲及夏威夷引進種子試種，種植地區遍及中、南及東部各地，但目前產量極爲有限，如能積極推廣繁殖，外銷前途甚爲可觀。

澳洲胡桃之調製加工方法，最早係由 Moltzan 及 Ripperton 兩氏所研究發明，因澳洲胡桃果實成熟後，自樹上自然落下，必須以人力自地面上拾起，在雨季及成熟盛期時需每隔一至三週收集一次，但旱季時可能每隔五至六週始收穫一次，成熟之果實在收穫後一週內，必須脫去外殼（Husk），以防其生熱而變質，經過脫殼但尚未脫莢（Shell）之果實可利用通風，日晒或加熱等方式加以乾燥。含水率約 10 %左右之莢果可安全儲藏數月，而風味不致變劣。

加熱乾燥現已爲一般澳洲胡桃加工業所普遍採用，但乾燥步驟因工廠之需要而有相當程度之差異，例如乾燥時間可能由數日延至數月，乾燥溫度之差別亦可達 40°F 之多，一般來說，果實多在收穫後二至三個月內予以加工，首先將帶莢之果仁乾燥至含水率在3-5%後予以脫莢，乾燥溫度在120-150°F 之間，乾燥時間約爲24-72小時，然後果仁經分選後更進一步乾燥至含水率 1-1½%，再置於椰子油中加以烘焙，然後將多餘的油濾去，再加粘着劑後上鹽，即可眞空封罐包裝。

根據前人研究所得，在乾燥初期以使用較低溫度較爲經濟，但在乾燥末期利用高溫可加速乾燥之完成，例如莢果可用通風方式進行乾燥兩週，然後再用加熱空氣（110°F）予以乾燥一週，另外一法爲先用110°F 之熱空氣乾燥五天，接着以150°F 乾燥一天，即可完成乾燥作業，但乾燥時如使用溫度過高，在烘製時果仁中心部份會變爲深棕色，影響品質。Prichavudhi 及 Yamamoto 兩氏曾研究乾燥條件對於澳洲胡桃化學組成及品質關係，他們試驗在各種溫度下，由室內溫度至 160°F，在烤箱內以強制通風乾燥莢果，發現在室溫及 100°F 以下時，乾燥溫度對於莢果無顯著之影響，但建議 125°F 及 140°F 之高溫只有在果仁之含水率已經降低至 8 %及 6 %時使用，方始安全。

過去有關澳洲胡桃之研究大都集中於種植技術及改良品種方面，直到近年其他問題如儲藏，加工以及可能影響果仁風味及化學成份的因素才逐漸受到重視。加熱乾燥雖已普遍使用，但這方面的研究工作仍然很少，如欲增加機械乾燥之作業效率以及保存或維持果仁之品質，吾人需要有更多準確的有關乾燥速率與其影響因子間之試驗資料。本研究之目的卽爲探討空氣流量對於澳洲胡桃乾燥速率之影響，其他可能影響乾燥速率之因子，如乾燥空氣之溫度與濕度，胡桃之含水量及其物理性質等均不在本研究範圍之內。

ABSTRACT

The effect of air flow rates from 25 to 300 cfm/ft^2 on the drying rate of macadamia nuts was investigated. In conducting the tests, a laboratory drier was employed. A single-layer of macadamia nuts was dried with constant air temperature of 120°F and humidity of 33 per cent. Samples of 90-95 fresh husked nuts with initial moisture contents in the range from 15 to 24 per cent dry basis were used. The lowest air flow rate used was 27 cfm/ft^2, and the highest was 290 cfm/ft^2 in accordance with the maximum capacity of the heater.

Samples were weighed at 2 hour intervals for the first 12 hour period, and then increased to 4 hours as the drying rate decreased. Drying rates were analysed by plotting the moisture ratio against time on semi-logrithmic paper. It was found that the logrithmic drying equation did not adequately represent the drying curves for the full drying period, except for the straight line portion of the curves after drying had continued for about 36 hours. Since all the straight line portion of the drying curves when extended across the vertical axis nearly at the same point, which is 0.3 on the vertical axis. Therefore, a modified equation for this drying period can be obtained as follows:

$$\frac{M - M_e}{M_o - M_e} = 0.3\, e^{-K\Theta}$$

The equilibrium moisture content M_e is 3.5 per cent, which was determined by drying macadamia nuts under dynamic conditions of 120°F and 33 per cent humidity until a constant moisture content was reached.

The drying rate constant K was then examined to see if it were an identifiable function of air flow conditions. Such an analysis was made by plotting the K value against air flow rate on logrithmic coordinates. The result shows that the drying rate constant will approach a maximum value of 0.027 when the air flow rate is about 300 cfm/ft^2. This implies that an increase in the air flow rate beyond this limit would not increase the drying rate. It may be recommended as the highest air flow rate that could be used for drying macadamia nuts in single layer with air temperature at 120°F.

A linear relationship between drying rate constant and air flow rate was observed for the range from 50 to 200 cfm/ft^2. The following equation can be developed for this case:

$$K = 0.0062\, V^{0.27}$$

For predicting the single layer drying rate of macadamia nuts under air conditions as follows: a) temperature at 120°F; b) relative humidity at 33 per cent; and c) air flow rates in the range from 50 to 200 cfm/ft^2, the following equation may be used for this purpose for the 36 to 72 hour period after the drying started:

$$\frac{M - 3.5}{M_o - 3.5} = 0.3\, e^{-0.0062\, V^{0.27}\theta}$$

INTRODUCTION

The macadamia nut was introduced into the Hawaiian Islands from Australia about 1885. It has since become an important orchard crop in the Islands, ranking second only to coffee in acreage and value. The importance of the macadamia nuts in Hawaii's agricultural economy has increased greatly in recent years. There are several reasons for the rise of macadamia nut production to a prominent position in the agriculture of Hawaii. The tree thrives in the Island's climate on a wide variety of soils. It can be grown in many areas which, because of climate, soil types, location or topography, are not suited to the culture of sugar cane, pineapples, bananas, papayas and other important Island crops.

Processing of macadamia nuts was pioneered and developed by Moltzau and Ripperton.[11] Briefly, macadamia nuts which have fallen on the ground are harvested and then mechanically husked. The husked nuts are then dried and, when the moisture in the kernels has been reduced to approximately 3-5 per cent, the nuts are cracked. After an extensive separation and sorting operation, the kernels are further dried to approximately 1-1½ per cent moisture and roasted in coconut oil. After roasting, excess oil is removed, adhesive and salt are added, and the nuts are vacuum packed.

Most previous research on macadamia nuts in Hawaii has centered primarily around problems associated with production practices and establishment of improved varieties. During recent years, the problems of storage, processing and factors that may influence the flavor and chemical composition of the nuts were investigated by many researchers.[3,4,5,8,12]

Although forced air drying is commonly used by the Hawaiian macadamia industry, very little research has been done on the drying behavior of the macadamia nuts with heated air. The success of the mechanical drying operations requires more accurate information on the general relation between the drying rate and those possible influencing factors. Such analysis by which the effects of changing conditions can be anticipated is necessary before driers can be designed and operated with full knowledge of how they will perform.

The objective of this study was to investigate the effect of air flow on the rate of drying of macadamia nut. Other factors that may affect the drying rate, such as temperature and humidity of the drying air, moisture content and physical properties of the nut were not within the scope of this study.

THEORY OF SINGLE-LAYER DRYING

Drying in agricultural fields refers to the removal of moisture from a product, usually to some predetermined moisture content. Present theories have firmly indicated that the difference in vapor pressure between the product and the surrounding air is the main driving force in the drying of hygroscopic materials. The adsorbed moisture in the product exerts a moisture vapor pressure which varies with the moisture content and temperature of the material and from material to material. The moisture content of the product when it is in equilibrium with the surrounding air is called the equilibrium moisture content. The equilibrium moisture content is useful to determine whether a product will gain or lose moisture under a given set of temperature and relative humidity conditions. The relative humidity of the air in moisture equilibrium with the product at the particular temperature is known as the equilibrium relative humidity.

The relationship between the moisture content of a particular product and its equilibrium relative humidity at the particular temperature can be expressed by the following equation:[7]

$$1 - \phi_g = e^{-cTM_e^n} \tag{1}$$

where

ϕ_g = equilibrium relative humidity, a decimal
T = absolute temperature, °R
M_e = equilibrium moisture content, dry basis, per cent
c,n = constants varying with materials

By the definition of the relative humidity which is stated as the ratio of the actual pressure of the water vapor in the air to the pressure if the air were saturated with moisture at the same temperature. Thus, if ϕ_g were expressed in terms of vapor pressure at the temperature of the material, the vapor pressure of the moisture in the material could be determined by the following equation:

$$P_g = P_{sg}\phi_g \tag{2}$$

where

P_g = vapor pressure of moisture in the material, lb per sq in
P_{sg} = saturated vapor pressure at the temperature of material, lb per sq in
ϕ_g = equilibrium relative humidity of the material at its temperature, per cent

Thus, if the moisture content and temperature of material are known, the vapor pressure of the material moisture can be determined by the use of Eqns (1) and (2).

The vapor pressure of air surrounding material can be determined in the same manner:

$$P_a = P_{sa}\phi_a \tag{3}$$

where

P_a = vapor pressure of the air, lb per sq in
P_{sa} = saturated vapor pressure at the temperature of the air, lb per sq in
ϕ_a = relative humidity of the air, per cent

The drying potential ($P_g - P_a$) for any condition where material is surrounded by an air-vapor mixture may be determined by substracting the result of Eqn (3) from Eqn (2). When the resulting drying potential is positive, drying will take place. When the drying potential is negative, wetting occurs at a rate usually slower than drying occurred. When the drying potential is zero, a state of equilibrium exists.

The drying potential affects the drying rate, or the flow of moisture from the product in a drying process can be expressed as follows:

$$\frac{dM}{d\Theta} = -c(P_g - P_a) \qquad (4)$$

where

M = moisture content, dry basis, per cent
Θ = time, hr
P_g = vapor pressure of material moisture, lb per sq in
P_a = vapor pressure of air, lb per sq in
c = constant varying with materials

If the temperature of the material and drying air is assumed equal, the P_{sa} equals P_{sg}, and Eqn (4) can be written as follows:

$$\frac{dM}{d\Theta} = -cP_s(\phi_g - \phi_a) \qquad (5)$$

A linear variation of moisture content with equilibrium relative humidity may be assumed, then

$$\Delta M = \Delta\phi \qquad (6)$$

or

$$(\phi_g - \phi_a) = A(M - M_e) \qquad (7)$$

where

A = constant of proportionality
M = moisture content at timeΘ
M_e = equilibrium moisture content of material

Combining Eqns (5) and (7)

$$\frac{dM}{d\Theta} = -cP_sA(M - M_e)$$

for a given set of drying conditions, c, p_s, and A are all constants, let $cP_sA = K$, which is defined as the drying rate constant.
Then

$$\frac{dM}{d\Theta} = -K(M - M_e)$$

and

$$dM = d(M - M_e)$$

therefore

$$\frac{d(M - M_e)}{M - M_e} = -Kd\Theta$$

Integrating between limits of M_o, the initial moisture content, and M, the final moisture content for any given set of air conditions,

$$\int_{M_o}^{M} \frac{d(M - M_e)}{M - M_e} = -K\int_0^{\Theta} d\Theta$$

$$\ln\frac{M - M_e}{M_o - M_e} = -K\Theta$$

or

$$\frac{M - M_e}{M_o - M_e} = e^{-K\Theta} \tag{8}$$

Eqn (8) expresses a relationship between moisture content and time during thin layer drying or drying processes where each part of the material mass is contacted by air of the same condition. There are no temperature or moisture gradients across the layer. In deep layer drying, Eqn (8) does not hold true, because the upper layers are contacted by air which has been humidified by previous layers.

The quantity $\frac{M - M_e}{M_o - M_e}$ is called the moisture ratio (MR), which may be considered equivalent to the decimal part of the drying yet to be done at time θ.

The drying rate constant, K, changes with changes in temperature because of $K = cP_sA$, in which P_s is the variable changing with temperature.

Since $\ln(MR) = -K\Theta$ the value of K may be determined by plotting experimental data as ln(MR) vs Θ on semi-logrithmic paper. The slope of the straight line is the drying rate constant.

With regard to the drying of farm products, Eqn (8) implies that the rate of moisture movement from product to air is limited only by the rate at which moisture can diffuse from the interior to the surface. Thus, the air flow rate through a layer of product must not be a pertinent variable. It means that increase in air flow would not increase drying rate. But additional limited studies have indicated that air velocity and temperature are probably related to the drying rate,[7] thus

$$K = \alpha V^n P_s \tag{9}$$

where

V = air flow rate, cut ft per min per sq ft
P_s = saturated water vapor pressure at the temperature of drying air, lb per sq in
α,n = constants

The velocity exponent n in Eqn (9) is an indication of the relative effect of internal diffusion as compared to surface resistance upon the drying rate. If n is 0.6, there is no internal resistance to moisture movement, and resistance to vapor transfer at the surface controls the drying rate. Small values of n indicate that the internal resistance to flow controls the drying rate and that the surface resistance is minor.[7]

Eqns (8) and (9) when combined for constant temperature, humidity, and velocity give

$$\frac{M - M_e}{M_o - M_e} = e^{-\alpha V^n P_s \Theta} \tag{10}$$

DRYING OF MACADAMIA NUTS

Macadamia nuts fall from the tree when mature and are picked up by hand. During the rainy season and peak ripening period, nuts are picked at intervals of one to three weeks, while during dry period they may be left on ground for five to six weeks.

Mature nuts must be husked within a week after picking to prevent the nuts from heating and spoiling.

Husked, unshelled nuts may be dried by unheated air, sun or heated air. They can keep satisfactorily several months in dry storage, if they have been dried by unheated air or sun to about 10 per cent moisture before storing.[8]

In Hawaii, heated air drying is commonly used. The drying process is adjusted in accordance with facotry demands. There are considerable variations in the drying procedure, for example, drying times may vary from days to weeks, drying temperatures may differ as much as 40°F. Nuts are usually processed within two to three months after harvesting. The first step is to dry the unshelled nuts until the moisture in the kernels has been reduced to approximately 3-5 per cent before cracking. This is accomplished by placing the nuts in a forced draft of air at 120 to 150°F from 24 to 72 hours.[5] After the separating and sorting operations, the kernels are further dried to approximately 1-1½ per moisture for roasting.

Early in the drying process, relatively low temperatures appear to be economical, while higher temperatures will hasten the final drying.[11] For example, one company dries its nuts with unheated air for two weeks and then dries for one week by using 110°F heated air. In another method, the nuts are dried for five days at 110°F and then at 150°F for one day.

It has been found that the nuts dried at high temperatures often developed undesirable dark-brown centers when roasted. Prichavudhi and Yamamoto[12] investigated the effects of drying condition on the chemical composition and quality of macadamia nuts. They dried nuts in forced draft ovens at temperatures ranging from ambient air to 160°F and found that undesirable high temperature effects were lessened by low temperature initial drying at ambient or 100°F. They suggested that 125°F and 140°F should be used only after the moisture of nuts is reduced to approximately 8 and 6 per cent, respectively.

EXPERIMENTAL EQUIPMENT

The apparatus which was used for single layer drying is shown in Figures la and 1b. The 3/4 hp fan is driven through a variable speed control which enables the air to be supplied at various rates. The air flow in the conduit is measured by an orifice plate with an inclined manometer indicating the rate of flow. The air is heated by electric resistance elements when passing through the heater. The temperature sensor is located below the drying chamber to facilitate temperature control. A thermometer is located near the sensor to indicate the temperature. The screened bottom tray was so designed that it could be easily removed and placed on a balance which is supported by a steel stand. The drying tray has the same size as that of the inside diameter of the bin in order to secure uniform air distribution. The upper surface of the bin is open to the atmosphere but shielded from side draughts. The drying chamber was insulated with sponge-rubber to minimize the heat losses from the wall.

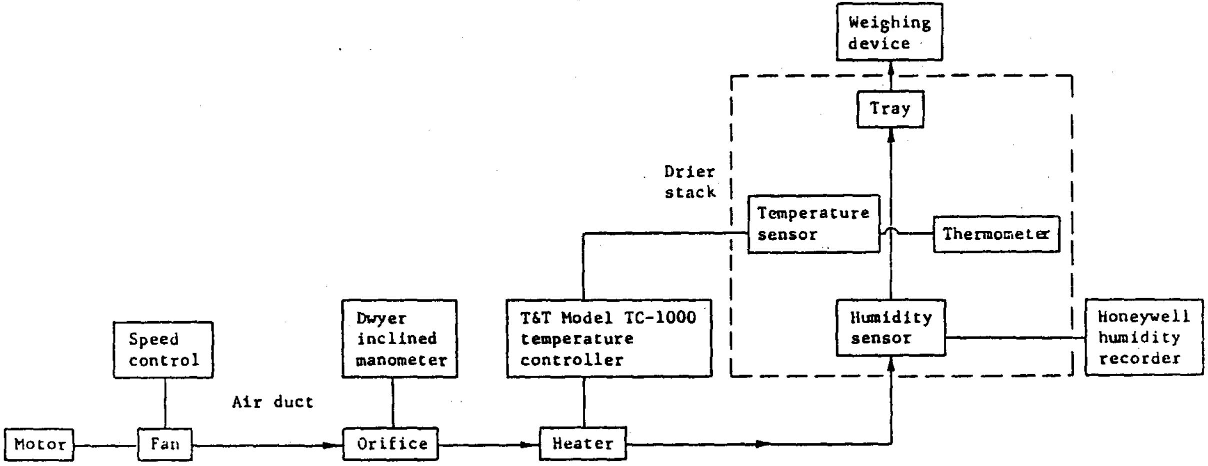

Figure 1a. Schematic Diagram of Single Layer Drying Equipment

Figure 1b. Picture of the Laboratory Drier

EXPERIMENTAL PROCEDURE

1. Material

The variety of macadamia nuts used in this study was Kakea 508 (Figure 2) which were harvested from the Kona Branch Station, Hawaii Agricultural Experiment Station.

The nuts were husked at the Station and shipped by air freight to Honolulu. When the nuts arrived at the laboratory, they were stored in a constant temperature room maintained at 72°F and humidity at 70 per cent. Before each drying run was conducted, the test samples were put into a tightly closed glass container and then taken out of the storage room to allow the nuts to reach the atmospheric temperature.

2. Measurements

A. Weight change

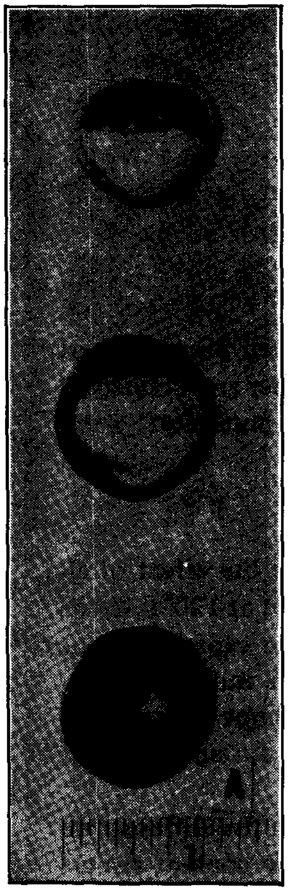

Figure 2. Kakea 508

After the temperature of the drying air was stabilized, the test samples were placed in the drying tray and the tray in turn into the airstreams in the drying chamber. The total weight of the tray and test samples was determined periodically with a balance with an accuracy of 0.1 g. This operation could be carried out rapidly and it was considered such brief interruptions did not interfere with the drying process. The fan was shut off when each weighing was made. During the first 12 hours a weighing was made every two hours. This time interval was increased to four hours as the drying rate decreased.

B. Moisture content

Moisture content determinations were carried out by the vacuum oven method. Samples of 8 nuts were dried in steel containers. The samples were placed in the oven at 212°F and maintained at 25 in Hg of vacuum for 24 hours. The containers were weighed immediately after cooling. All moisture content data are given on a dry basis.

C. Air flow rate

Air flow rates were measured by an orifice plate with D and D/2 flange taps leading off to a Dwyer inclined vertical manometer gauge. The calculation of approximate weight flow rate was based on the equation:[2]

$$Q_w = 359\ CFd^2 \sqrt{h_w f_i} \qquad (11)$$

where

Q_w = weight rate of flow, lb per hr
C = coefficient of discharge
F = velocity of approach factor = $\dfrac{1}{\sqrt{1-\beta^4}}$, in which
β = ratio of orifice diameter to pipe diameter
d = diameter of orifice, in
h_w = differential pressure head, in of water
$h_w = h_f \times \gamma$, in which h_f = manometer reading, in, and
γ = specific gravity of manometer fluid
f_i = specific weight of air at inlet, lb per cu ft

When air flow rate is expressed in terms of cu ft per min per sq ft, the following equation may be used:

$$V = Q_w \times \frac{1}{60 \times A \times f_0} \qquad (12)$$

where

V = air flow rate in cfm per sq ft
A = area of floor, sq ft
f_0 = specific weight of air at drying temperature, lb per sq ft

D. Humidity

Relative humidity of the drying air was recorded by a Honeywell circular chart recorder. Its humidity sensor is mounted underneath the drying chamber and connected to the recorder which gives a direct reading in terms of percent relative humidity.

EXPERIMENTAL RESULTS

A series of single layer drying tests were carried out to investigate the effect of air flow on drying rate of macadamia nuts. Drying air temperature was kept at 120°F for all runs and air flow rates varied between 27 and 290 cfm/ft^2 within the capacity of the drier. Samples of 90-95 nuts, weighing about 700-760 grams, with initial moisture content ranging from 15 to 24 per cent dry basis were dried. No attempt was made to control the relative humidity, it was 33 per cent and varied very little during the drying tests.

Drying curves for samples of macadamia nuts in a single layer with five different air flow rates are illustrated in Figure 3 as plotting reduction of moisture content against drying time. It was noted that macadamia nuts with initial moisture content within the range tested dried rapidly when drying started and more than half of the moisture was removed during the first ten hours. All the drying curves approach the equilibrium boundary condition at long drying periods. As far as drying time is concerned, the initial drying period can be considered minor due to its short duration when comparing to the final drying period. Since the drying tests started at different initial conditions, it is difficult to evaluate the effect of air flow rate on the drying rate of macadamia nut from Figure 3.

The drying rates were determined by plotting the moisture ratio against drying time on semi-logirthmic paper. The moisture ratio is a dimensionless parameter, the variation of initial moisture content is then considered to be eliminated. In figure 4, it is obvious that the simple exponential drying equation did not adequately represent the experimental results over the full drying period. The straight line portion of the drying curves, however, may be expressed by the equation as used by Henderson:[6]

$$\frac{M - M_e}{M_o - M_e} = Ce^{-K\Theta} \qquad (13)$$

Where C is the intercept at the vertical axis. It should be noted that the drying rate curves at all air flow rates across the vertical axis nearly at the same point, which is

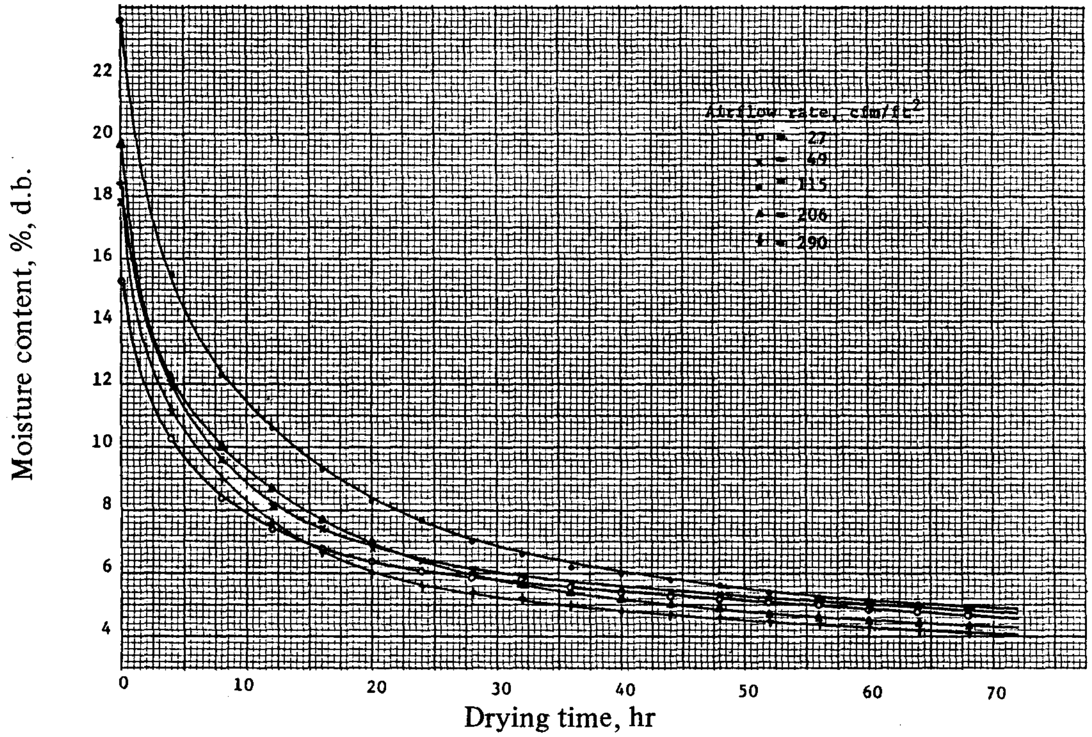

Figure 3. Reduction in Moisture Content as a Single Layer of Macadamia Nut is Dried

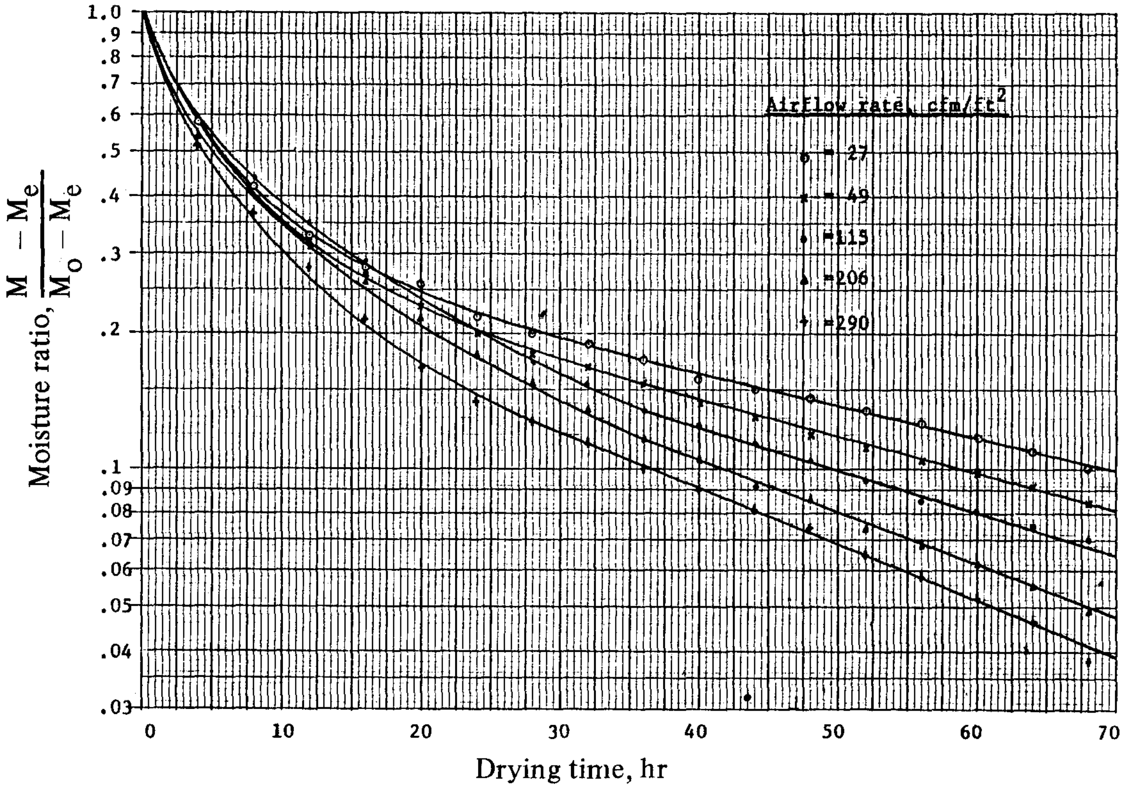

Figure 4. Moisture Ratio Plotted against Time for the Data of Figure 3

0.3 on the vertical axis. Therefore, Eqn (14) may be obtained for the 36 to 72 hour period after the drying started as follows:

$$\frac{M - M_e}{M_o - M_e} = 0.3\ e^{-K\Theta} \tag{14}$$

for drying of macadamia nuts with air temperature at 120°F and air flow rate up to 300 cfm/ft².

The values of the moisture ratio at particular times in Eqn (13) depend on the equilibrium moisture content M_e. This value has been experimentally determined by drying samples at specified air conditions until a constant weight was reached. The experimentally obtained value of 3.5 per cent was then employed as a boundary condition for drying unshelled macadamia nuts with temperature at 120°F and relative humidity at 33 per cent.

The values of the drying rate constant K, i.e. the slope of the straight line portion of the drying curves, can be calculated after the moisture ratio values at any two points on the straight line have been determined. Values of K for five different air flow rates tested are given in Table 1.

Table 1. Drying Rate Constants

Air flow rate, V cfm/ft²	Drying rate constant, K hr^{-1}
27	0.0160
49	0.0177
115	0.0244
206	0.0262
290	0.0268

Consequently, the following equations may be written to express the drying rate of macadamia nuts with the five different air flow rates which were tested.

For V = 27 cfm/ft²:

$$\frac{M - M_e}{Mo - M_e} = 0.3\ e^{-0.0160\Theta} \tag{15}$$

For V = 49 cfm/ft²:

$$\frac{M - M_e}{M_o - M_e} = 0.3\ e^{-0.0177\Theta} \tag{16}$$

For V = 115 cfm/ft²:

$$\frac{M - M_e}{M_o - M_e} = 0.3\ e^{-0.0224\Theta} \tag{17}$$

For V = 206 cfm/ft²:

diameter and the velocity was $ft^3sec^{-1}ft^{-2}$ of cross-sectional area of the chamber. Note that air rate of 27 cfm/ft^2 can probably be considered laminar, with air rates of 115 cfm/ft^2 and above being turbulent. Air rate of 49 cfm/ft^2 may be considered as transient flow. If Reynolds number of 4000 is accepted as turbulent,[7] the velocity in this case is 53 cfm/ft^2 for turbulent flow. It was noted in Figure 6 that the K value holds a straight line relation for turbulent flows ranging from 50 to 200 cfm/ft^2 and will have approximately 0.027 as its limiting value while air flow rate is about 300 cfm/ft^2.

In applying Eqn (9) to this case, the following equation may be obtained to express the linear relation between the drying rate constant of macadamia nut and air flow rate ranging from 50 to 200 cfm/ft^2 with air temperature at 120°F:

$$K = 0.0062\ V^{0.27} \qquad (20)$$

Therefore, the resultant equation for drying macadamia nuts in single layers with air conditions as follows:

Temperature: 120°F
Relative humidity: 33 per cent
Flow rate: 50 – 200 $ft^3/min\text{-}ft^2$

Table 2. Reynolds Numbers

Air flow rate, V cfm/ft²	Reynolds number, Re*
27	2,033
49	3,690
115	8,661
206	15;515
290	21,841

*$Re = \frac{DV}{v}$, D= diameter of pipe = 0.8541 ft, v = kinematic viscosity of air at 120°F = 1.89×10^{-4} ft^2/sec.

may be written for the 36 to 72 hour period after drying started:

$$\frac{M - 3.5}{M_o - 3.5} = 0.3\ e^{-0.0062\ V^{0.27}\ \Theta} \qquad (21)$$

DISCUSSION OF RESULTS

1. The equilibrium moisture content of solid materials is usually considered to be dependent upon the temperature and humidity of the surrounding air as well as the particular material considered. In order to solve the exponential drying equations (8) or (13), the initial condition and the boundary conditions of the drying product have to be

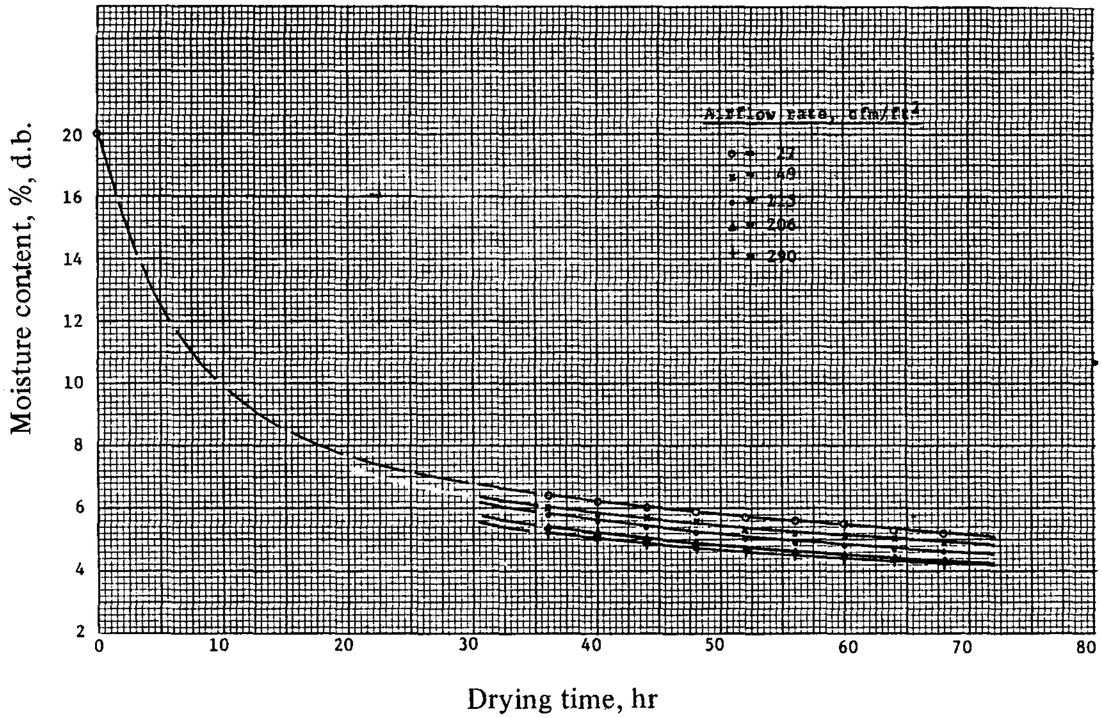

Figure 7. Drying Curves for Standardized Initial Moisture Content of 20%

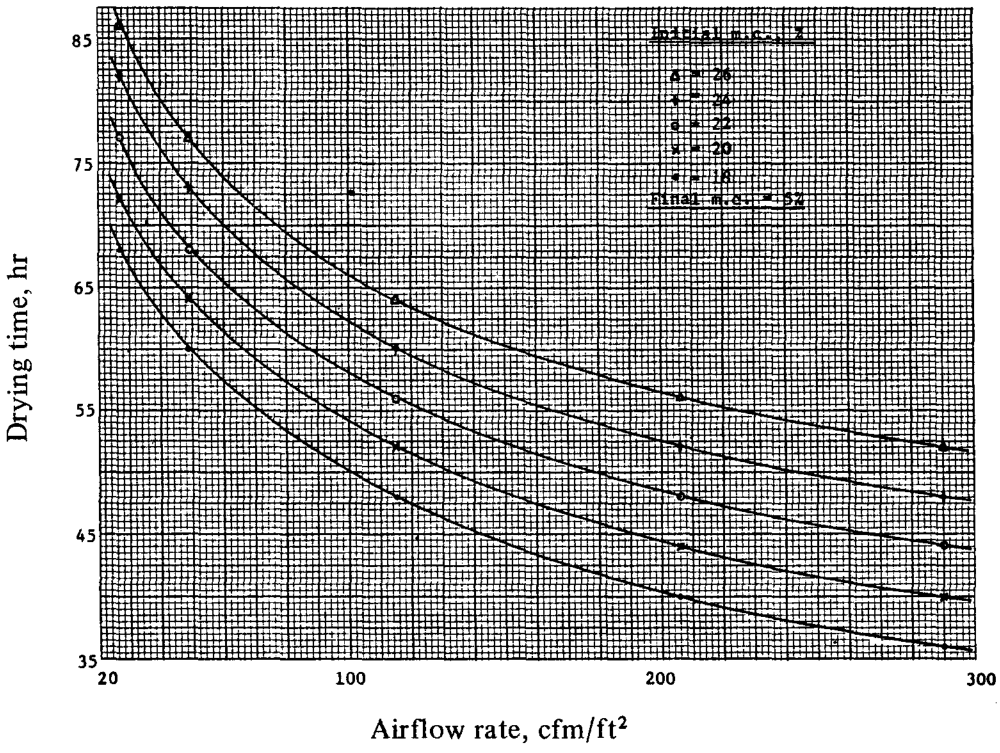

Figure 8. Variation of Drying Time with Airflow Rate

$$\frac{M - M_e}{M_o - M_e} = 0.3\, e^{-0.0262\Theta} \tag{18}$$

For V =290 cfm/ft²:

$$\frac{M - M_e}{M_o - M_e} = 0.3\, e^{-0.0268\Theta} \tag{19}$$

That the drying rate constant is related to air flow rate was illustrated in Figure 5, which is a plot of K against V for all the tests. The value of the drying constant is obviously influenced by the magnitude of air flow. As shown in Figure 5, it appears that K increases as air rate increases and approaches a maximum value when air rate reaches about 300 cfm/ft². It implies that an increase in the air flow rate beyond this limit would not increase the drying rate.

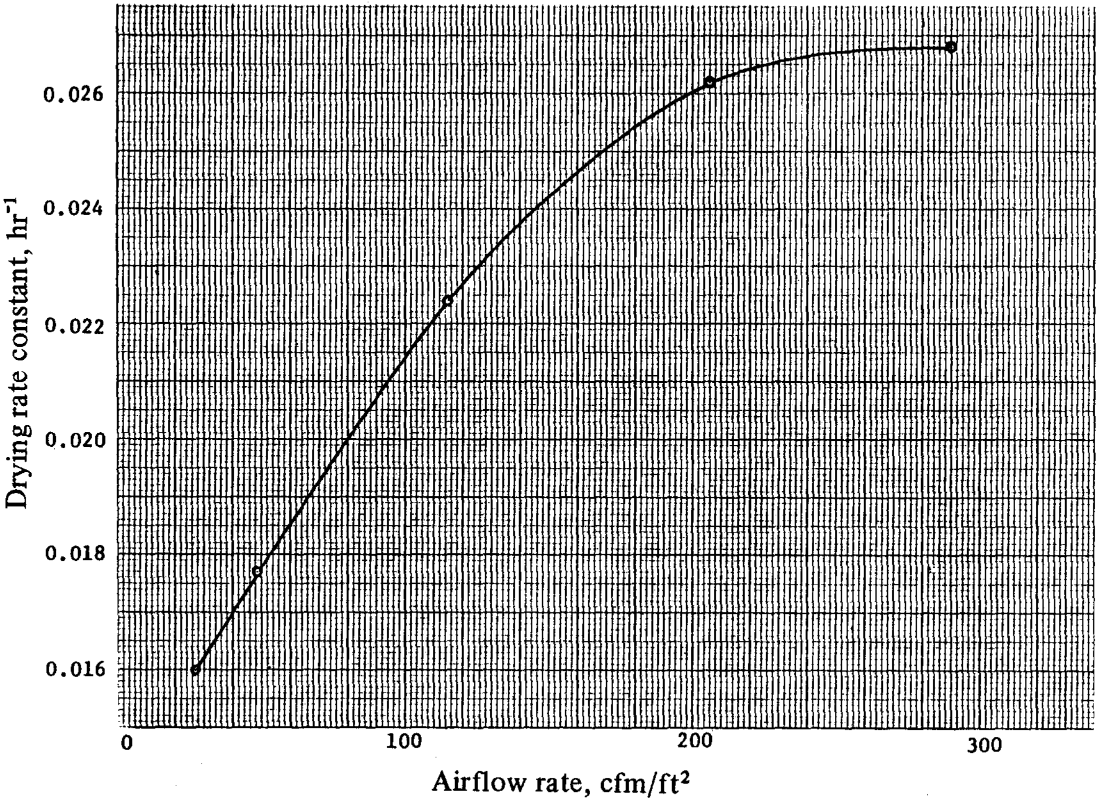

Figure 5. Effect of Airflow Rate on Drying Rate Constant

Further, these empirical values of the drying constant were examined by plotting them against V on logrithmic coordinates to see if they were an identifiable function of air flow conditions. An attempt was also made to investigate the relation between drying rate constant and Reynolds number. The results of such a calculation are given in Table 2 for five air rates. The diameter as used in Reynolds number was the drying chamber

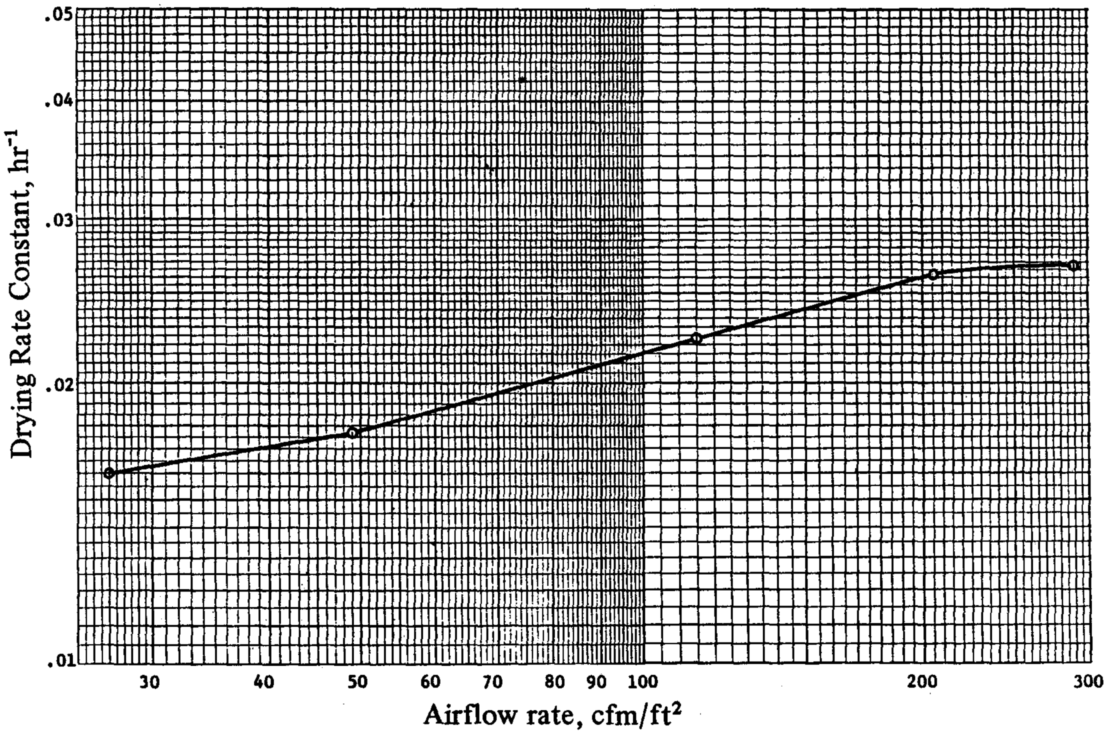

Figure 6, Full-logrithmic Plot of Drying Rate Constant against Airflow Rate

known. The choice of the boundary conditions affects not only the shape of the theoretical drying plot but also the calculated value of the drying rate constant of the drying product. Many researchers applied the static moisture equilibrium for solving the equation but found that the theoretical and experimental curves did not coincide over the full drying period. Jones[10] originated the idea of a dynamic moisture equilibrium. He postulated that during the falling drying period the surface moisture concentration of a hygroscopic product remain a value above the static equilibrium moisture content as long as the "more loosely" held water has not been removed. Simmons et al[13] accepting Jones' hypothesis, speculated that the static and dynamic moisture equilibrium of a biological product are different because of the living nature of such a product. However, Allen[1] suggested that the concept of a dynamic moisture equilibrium appealed to many researchers because it offered the possibility of obtaining a straight line relationship when the moisture ratio was plotted against time.

The equilibrium moisture content of macadamia nut was determined under dynamic conditions by drying samples in heated airstreams. When two successive weighings show the same moisture content, it is assumed that equilibrium is reached. It should be noted that "constant weight" really proves only that the change in weight, if any, was less than could be detected with the balance that was used. Whether further change in weight is underway can only be observed directly by continued drying for periods that may be considered impractical.

2. It is assumed that there may have been some error in measuring the initial moisture and consequently in the estimate of the initial dry weight for each test. Basic methods of measuring moisture content may not be entirely satisfactory, since they

depend on the assumption that all the moisture, and nothing but moisture, is driven off. This is doubtful in drying of macadamia nuts at high temperatures becaue of a) extremely slow rates of drying as dryness is approached, and b) the possibility of simultaneous loss of other materials, such as oil component in the kernel, which may result in an inaccurate value of moisture content.

In handling the data, the observed weight at each successive reading was used in studying the rate of drying.

3. In conducting the drying tests the samples were stored in a constant temperature room until the test was conducted. It is assumed that a) samples in each test have same initial moisture content, and b) samples were stored long enough so that the moisture content is uniform throughout the kernel. If it had not been, then the drying rate, particularly during the initial drying period, would undoubtedly be different.

4. The variation of size and shape of the nut might have some effects on the basic drying characteristic of the individual nut, but it was outside the range included in this study.

5. In Figure 4, it is very evident that the moisture decreases rapidly after the start of drying, and Eqn (8) failed to describe the relation. The following explanation, as illustrated by Hukil and Schmidt,[9] might account for the existence of this phenomenon:

At the start of drying, a moisture gradient is established within the kernel. Early in the drying period the gradient extends inward from the surface only a short distance, and points near the center of the kernel have not lost any moisture at all. As drying continues, the inner end of the gradient moves closer to the center of the kernel. At any time during this period there is a point on the radius of the kernel, outward from which the moisture is changing and inward from which the moisture content is still at its initial level. Finally, the inner end of the gradient reaches the center of the kernel and from that time on the moisture content continues to drop at all points within the kernel. The period during which the inner end of the gradient is advancing toward the center of the kernel might be interpreted as the initial drying period. The latter period, after the advancing of the gradient no longer influences the drying rate, might be interpreted as the final drying period. In other words, during the final drying period the flow of moisture at any point in the kernel is proportional to the moisture gradient at that point, and then Eqn (13) represents the relation.

6. In Figure 4, the straight line portion of the drying curves follows the equation: $MR = Ce^{-K\Theta}$. This equation contains the three adjustable constants M_e, K and M_o. Therefore, if M_e and K are known, the drying rates may be compared by comparing the values of the constant M_o. Let M_{01}, M_1 represent the experimental values of initial moisture content and the moisture at any time Θ during the process of drying, and M_{02}, M_2 represent the standarized initial moisture content and the moisture at the same time, respectively. Using Eqn (13), the following equations may be written:

$$\frac{M_1 - M_e}{M_{01} - M_e} = R(K,\Theta) \qquad (22)$$

$$\frac{M_2 \; - M_e}{M_{02} - M_e} = R(K,\Theta) \tag{23}$$

with M_e, K and Θ the same in equations (22) and (23), then

$$M_2 = (M_1 \; - M_e) \frac{M_{02} - M_e}{M_{01} - M_e} + M_e \tag{24}$$

With M_1, M_e, M_{01}, and M_{02} known, M_2 at any specified time can be computed. Then a set of drying curves with the same initial moisture content for five different air flow rates can be established. For example, Figure 7 shows the drying curves for standardized initial moisture content of 20 per cent.

As mentioned previously, the macadamia nuts are usually dried to 3-5 per cent moisture in the kernel before cracking. Let the time required to dry macadamia nuts at different air flow rates from an initial moisture content, M_o, to the same end point, say 5 per cent, be $\Theta = \Theta_1, \Theta_2, \ldots\ldots \Theta_5$, the relation between drying time and air flow rate is then shown in Figure 8 for different initial moisture contents ranging from 18 to 26 per cent.

This relationship was further examined by plotting the drying time against air flow rate on logrithmic coordinates to see if it were an identifiable function of air flow conditions. Such a plot is given in Figure 9 for macadamia nuts with initial moisture content in the range from 18 to 26 per cent. An approximate straight line relationship can be observed for the air flow rates in the range of 50-300 cfm/ft^2. Therefore, the following equation can be suggested to estimate the drying time required to dry the

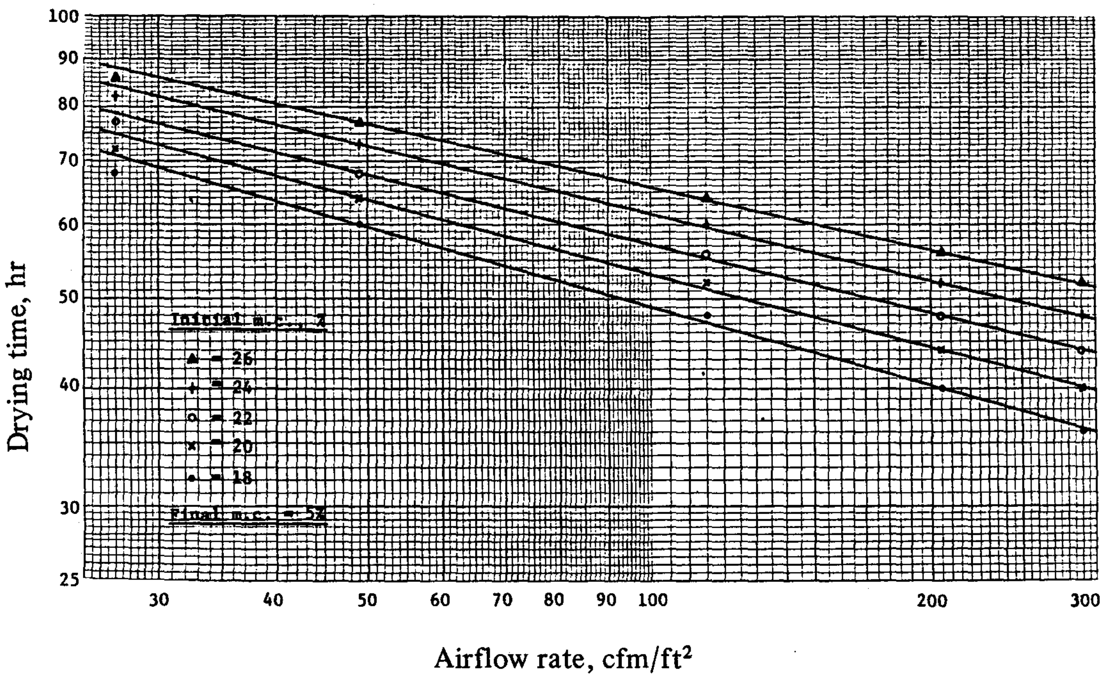

Figure 9. Full-logrithmic Plot of Drying Time against Airflow Rate

macadamia nuts with initial moisture contents in the range from 18 to 26 per cent to the final moisture content of 5 per cent with air temperature at 120°F and relative humidity at 33 per cent.

$$\Theta = 180 \, V^{m} \tag{25}$$

As shown in Table 3, it should be noted that m changes with the initial moisture content of macadamia nuts.

Table 3. Values of m for Various Initial Moisture Contents

Initial moisture content %, d.b.	m
18	-0.279
20	-0.265
22	-0.244
24	-0.237
26	-0.223

CONCLUSIONS

From the results of experimental work on drying of macadamia nuts in single layers, it has been found that the drying rate was affected by the air flow rates in the range from 25 to 300 cfm/ft². It is indicated that the internal resistance to moisture movement controls the drying rate and the surface resistance to vapor transfer can be considered minor during the final drying period.

The logrithmic drying equation, Eqn (8), did not adequately represent the single layer drying rate of macadamia nuts over the full drying period. However, a modified exponential equation, Eqn (14), was found to express the straight line portion of the drying curve for the 36 to 72 hr period after the drying started.

Based upon the results of experimental work carried out on single layer drying of macadamia nuts, an analysis was made which produced an approximate equation, Eqn (20), for evaluating the drying rate constant within the range of turbulent flows. The results also showed that drying rate in the laminar flow range needs further investigations.

Finally, combined Eqns (14) and (20), the resultant empirical equation was obtained as Eqn (21) for drying macadamia nuts in single layers with air temperature at 120°F and air flow rates in the range from 50 to 200 cfm/ft².

REFERENCES

1. Allen, J. R. Application of Grain Drying Theory to the Drying of Maize and Rice. J. Agric. Engng. Res. 5(4). 1960.

2. ASME Power Test Codes. Chapter 4, Flow Measurement. 1959.
3. Cavaletto, C. A., Dela Cruz, A., Ross, E., and Yamamoto, H. Y. Factors Affecting Macadamia Nut Stability. Food Technology. 20(8). 1966.
4. Dela Cruz, A., Cavaletto, C. A., Yamamoto, H. Y., and Ross, E. Factors Affecting Macadamia Nut Stability. Food Technology. 20(9). 1966.
5. Hamilton, R. A. and Storey, W. B. Macadamia Nut Production in the Hawaiian Islands. Economic Botany. 10(1). 1956.
6. Henderson, J. M. and Henderson, S. M. A Computational Procedure for Deep-bed Drying Analysis. ASAE 6th Meeting Transcript No. 67-316. 1967.
7. Henderson, S. M. and Perry, R. L. Agricultural Process Engineering. John Wiley & Sons. New York. 1955.
8. Higaki, T. and Dedolph, R. R. The Storage of Macadamia Nuts. Proceedings of the America Society for Horticultural Science. 10(1). 1956.
9. Hukill, W. V. and Schmidt, J. L. Drying Rate of Fully Exposed Grain Kernels. ASAE Transactions. 1960.
10. Jones, C. R. Evaporation in Low Vacuum from Warm Granular Material (wheat) during the Falling Rate Period. J. Sci. Fd. Agric., 2. 1951.
11. Moltzau, R. H. and Ripperton, J. C. Processing of Macadamia. Hawaii Agr. Expt. Sta. Bul. No. 83. 1939.
12. Prichavudhi, K. and Yamamoto, H. Y. Effect of Drying Temperature on Chemical Composition and Quality of Macadamia Nuts. Food Technology. 19(5). 1965.
13. Simmons, W.H. C., Ward, G. T., and McEwen, E. The Drying of Wheat Grain. Trans. Instn. Chem. Engrs. 31. 1953.

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管線或分散集水區等方法，用模式分析取易行之方法用之。

參考文獻

1.臺北市政府工務局新建工程處：
「臺北市原市區雨水下水道系統檢討報告」，73.
「臺北市雨水下水道系統規劃 規劃報告」，58.12.
2.臺北市政府工務局養護工程處：
「72年度臺北市地盤下陷調查測量成果」，72.5.
「地層沉陷對排水系統排水能力影響之研究」，68.8.
3.臺北市政府環境保護局：
「臺北市幹支線排水溝73年度清理計劃」，
4.臺北市政府建設局：
「臺北市山坡地水土保持工程整體性調查規劃研究報告」，73.4.
5.臺北市政府主計處：
「73年臺北市施政統計摘要」，
6.臺北市政府工務局都市計劃處：
「臺北市山坡地開發之研究——山坡地住宅區開發之檢討73年度研究報告」，
7.「72年度水土保持訓練班參考資料」，
8.「下水道工程實務研討會論文集」，72.6.3.—4.
9.歐陽嶠暉：「下水道工程學」（增訂版）
10.雷萬清：「臺北市區地水探討」
11.曹以松：「臺北市區過渡抽取地下水所引起之地層沉陷及其補救方法之研究」，
12.劉長齡：「論都市水災及地盤沉陷之防止」，
13.「臺灣水利第78卷第4期」，
14.「自由中國之工業第39卷第5期」，
15.「臺灣礦業第30卷第4期」，
16.臺灣省水利局編印：「防洪工程規劃」
「灌溉排水工程設計上、下册」