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EXPERIMENTAL ANALYSIS OF DRYING OF AGRICULTURAL PRODUCT

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A thesis submitted to the School of Graduate Studies of Addis Ababa University in partial fulfillment of the Degree of Masters of Science in Mechanical Engineering (Thermal Engineering stream.)

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Abstract

An experimental system set up has been developed to investigate the drying rate of the selected material, the drying air temperature and relative humidity and moisture content profiles developed with the food materials during forced convective air drying. The moisture content profile was determined by employing the technique of oven drying method. Embedded thermocouples were used to sense temperature at different locations, and the embedded digital relative humidity measuring instruments were used to sense the relative humidity and recording the values manually at different locations of the drying chamber. A data logger and a computer front end were implemented for data acquisition.

Temperature, relative humidity, moisture and drying rate profiles are presented as function of the drying time. All profiles described the drying phenomena inside each trays of the drying chamber. The close relations of overall drying rate and profiles of moisture content, drying air temperature and relative humidity are discussed. Finally correlations are formulated from the experimental data to relate the drying parameters; drying air temperature, relative humidity, velocity, initial moisture content of material to be dried and drying time that predict the moisture content on wet basis.

Chapter One

Introduction

1.1 Objective and Scope of the Project

Drying is an operation in which a volatile liquid is separated from a solid or semisolid material by vaporization. In dehydration, vegetable and animal products are dried to lower their moisture contents or water of crystallization is removed from chemical compounds. In freeze drying, the wet material is cooled to freeze the liquid; vaporization then occurred by sublimation of ice.

Reasons for drying include customer convenience or preference, reduction of shipping cost, maintenance of product stability and removal of toxic or noxious liquids and the need for storing the material for long time. Waste recycling and disposal are growing applications.

Drying of moist materials is a complicated process involving simultaneous, coupled heat and mass transfer phenomena which occurs inside the material being dried. These coupled phenomena make the analysis of the drying mechanism so complicated that there is no commonly accepted theoretical model of heat and mass transfer to describe the drying phenomena in the biological materials. In addition, lack of good experimental data which provide the moisture and temperature profiles during drying process make model verification difficult, if not impossible. In most studies currently being published, the data presented to validate a given work is using a method similar to the work of Beard, et al by checking the profiles of the drying parameters and the average moisture content [8].

In drying process, parameters that influence the drying rate are properties of the drying material, drying air temperature, relative humidity, and the air flow rate. Changing any of these parameters can affect the drying process and quality of the dried product.

Equilibrium moisture content (EMC) also directly related to the drying process and storage of selected commodities. The equilibrium moisture content is the only parameter that indicates whether the product will loss or re-absorb moisture at the temperature and relative humidity of the drying air. Thus, the information on the equilibrium moisture content of the selected agricultural product will be also determined from the experiment.

Determination of the time needed for drying is difficult, especially in solar drying, due to the continuous variation in solar radiation, drying air temperature and humidity, and the continuous change in the moisture content of the drying agricultural product. However, this can be simplified if the drying rate is expressed as function of these continuously changing affecting factors.

So, the problem of the present research work is to deal with the continuous changing of the affecting parameters during the period of the drying process. These conditions also change through the different locations along the dryer. The drying rate does not have a constant value; it starts with a rising value, and then a falling value. All these facts make it difficult to determine the volume of the air needed for any drying process, the energy requirement for the process, the time duration of the process, and the most suitable values of the affecting factors to accomplish a successful drying process.

It was found that it is better to utilize a locally designed and fabricated especial apparatus in the *Addis Ababa University, Faculty of Technology, Mechanical Engineering Department,* which can be used as an experimental apparatus to determine the impact of factors affecting the drying process of agricultural products. Using this experimental apparatus, the drying parameters may be controlled to give all the expected variations during the drying process.

The main objective of this thesis is to see the behavior of drying of certain selected agricultural product by varying the main drying parameters. These parameters are the drying air temperature, the drying air relative humidity and drying air mass velocity flux. Specifically it is aimed at analyzing:

- The behavior of drying of selected agricultural product by varying the drying air temperature
- The behavior of drying of selected agricultural product by varying the drying air relative humidity
- The behavior of drying of selected agricultural product by varying the drying air mass velocity flux and
- Develop a correlation from the experimental data that predicts the moisture content of potato as function of the drying parameters.

1.2 Organization of the Thesis

The first three chapters focus on the literature survey of different drying theories, drying experiments and drying air properties. Chapter four focuses on different equipment and instruments applicable for drying process which include air conditioner with convective batch dryer, AMB 310 Moisture Balance, Data Logger and Thermocouples. Chapter five deal with the discussion of the different experiments. Finally, Chapter six focuses on conclusions and recommendations of the experimental study.

1.3 Literature Review

Drying is an important factor in the economics of the handling and storage of agricultural products. The need for the process is greatly felt when harvesting moisture content of the product is higher than the safe moisture content. Also, when the weather conditions are such that they promote the growth of the micro-organisms, drying of crop would be necessary to prevent spoilage. Historically, kilns for drying corn were used in the humid areas of Europe after the Iron Age. At present, the most common method of drying such type of agricultural products is by using oil (or gas) burning dryers to obtain hot air which is then passed through the drying material resulting in a reduced moisture content of the crop. This type of drying works basically in the same way as that of the Iron Age kilns [9].

The use of air as heat and mass transfer medium in agricultural product drying is common because air is easy to handle and is unlikely to contaminate the agricultural product. However, as stated in [9] using air as the only drying medium results in an inefficient process because the air will reach saturation before all of the sensible heat in the air can be utilized. As indicated in [9], Chancellor developed a simple conductive grain dryer which worked on the principle of conductive heat transfer. The procedure used consists mainly of placing the grain on heated steel plate and stirring it for a specified time. Khan et al. [9] suggested the use of heated granular medium to reduce excessive localized heating of the grain caused by the hot plate while enhancing the conductive heat transfer.

Researchers have been working to find an optimum solid medium and operating conditions for grain drying. Although the use of salt and steel balls has been reported [9], sand appears in several works as the common choice for heated granular medium.

Some researchers have used a different approach; keeping the grain in intimate contact with some desiccant material at ambient temperature. Danziger, et al.[9], and Sturton, et al., [9] have worked with Silica gel and Bentonite, respectively. Although reasonable results were obtained, the time required for the grain and the desiccant to reach the equilibrium was very long [9].

It is generally accepted that moisture flow takes place by liquid or vapor diffusion. Newman [11] derived an equation based on Fick's second law, which states that at any section the rate of decrease inflow in the x-direction will be equal to the rate of increase in water content, in that direction. He derived equations for three basic shapes: a plane sheet or slap, a sphere and a cylinder.

The typical solution for spherical body shape is described as:

$$m_r = \frac{6}{\Pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} e^{-\frac{\Pi^2 D t n^2}{r^2}} \tag{1.1}$$

where

m_r = moisture ratio
D = hygroscopic diffusivity, cm^2/s
t = time in sec
r = radius in cm

$$m_r = \frac{m_{do} - m_d}{m_{do} - m_{eq}} \tag{1.2}$$

where

m_{do} = Initial moisture content (d.b)

m_{eq} = Equilibrium moisture content (d.b)

m_d = moisture content at time “t”(d.b)

The general equation of the moisture-time relationship proposed by Newman expressed in the form:

$$m_r = Ae^{-akt} + Be^{-bkt} + Ce^{-ckt} + ... \tag{1.3}$$

where

k = diffusivity, cm/s

A, B, C, a, b, c. etc. = characteristic constants of the drying product.

Newman [11] reports that the series converges rapidly and after a period of time it is represented by:

$$m_r = Ae^{-kt} \tag{1.4}$$

Lewis [11] determined a relationship similar to equation (1.3) that is analogous to Newton’s law of cooling. He suggested that the rate of removal of moisture from a product was proportional to the difference between the average moisture content and equilibrium moisture content, and could be expressed as:

$$\frac{dm_d}{dt} = K(m_d - m_{eq}) \tag{1.5}$$

where

K = drying constant

He derived this equation on the assumption that the resistance to the moisture flow is concentrated at the surface of the material. The equation may be integrated to give:

$$m_r = Ae^{-kt} \tag{1.6}$$

This equation is commonly known as the exponential or logarithmic model. If the constant “A” in equation (1.6) is equal to unity the equation is reduced to the same form as the Newton's law of cooling model.

A modified form of logarithmic drying equation is often used to describe the drying rate of biological products. Page [11] found that the drying rate of shelled corn during the falling rate period could be described by an equation of the form:

$$m_r = e^{-kt^n} \tag{1.7}$$

where

n = dimensionless drying exponent

Chen and Johnson [11] consider the kinetics of moisture movement in hygroscopic materials during drying, and have presented the following model:

$$\frac{dm_d}{dt} = k\left(m_d - m_{eq}\right)^n \tag{1.8}$$

where

k, n = experimental constants

They assumed that diffusion was the mechanism of internal flow of moisture in the material.

Single grain drying theory consists of a constant rate period followed by a falling rate period with sharp discontinuity in the rate at critical moisture contents Brooker et al. [11]. Since most biological materials do not exhibit a constant rate drying period, diffusion is the most likely physical mechanism governing the moisture movement in these materials L.R.Verma and A.Noomhorm [11].

Chapter Two

Drying

Drying is an operation in which a volatile liquid is separated from a solid or semisolid material by vaporization. In dehydration, vegetable and animal products are dried to lower their moisture contents or water of crystallization is removed from chemical compounds. In freeze drying the wet material is cooled to freeze the liquid; vaporization then occurred by sublimation of ice. Evaporation differs from drying in that feed and product are both pump-able fluids.

Reasons for drying include customer convenience or preference, reduction of shipping cost, maintenance of product stability and removal of toxic or noxious liquids and the need for storing the material for long time.

When material dries, heat is transferred to evaporate the liquid and mass is transferred in the form of liquid and vapor. Heat is transferred first to the surface of material and then into the interior. The usual heat transfer mechanisms are:

1. Convection from a hot gas that is brought in contact with the material.
2. Conduction from a hot surface that contacts the material
3. Radiation from a hot gas or hot surfaces which are either in contact or in close proximity to the material.

Mass transfer during drying involves the removal of vapor from the material surface and the movement of internal moisture to the surface. Material structure and the mechanisms of internal liquid and vapor flow usually control the drying rate when the internal moisture is removed during drying.

Before drying can begin a wet material must be heated to a temperature such that the vapor pressure of the liquid content exceeds the partial pressure of vapor already present in the surrounding atmosphere.

2.1 Drying Operation

Drying operations can be broadly classified according to whether they are batch or continuous. This term are applied specially from the point of view of the substance being dried. Thus, the operation termed batch drying is usually in fact a semi-batch process where in quantity of substance to be dried is exposed to a continuously flowing stream of air into which the moisture evaporates. In continuous operations, the substance to be dried as well as the gas passes continuously through the equipment. No typical stage wise methods are ordinarily used, and all operations involve continuous contact of the gas and the drying substance.

Classification of drying operation based on theories of drying and methods of design:

I. Method of operation, i.e. *batch, or semi-batch*: Equipment is operated intermittently or continuously under unsteady state conditions. The drier is charged with the substance, which remains in the equipment until dry, and then the drier is emptied and recharged with a fresh batch. Continuous driers are usually operated in steady state fashion.

II. Method of supplying the heat necessary for evaporation of the moisture: In *direct dryers,* the heat is supplied entirely by direct contact of the substance with the hot gas into which evaporation takes place. In *indirect driers,* the heat is supplied quite independently of the gas used to carry away the vaporized moisture. For example, heat may be supplied by conduction through a metal wall in contact with the substance, or less frequently by exposure of the substance to infrared radiation or by dielectric heating. With the last, the heat is generated inside the solid by a high frequency electric field.

III. Nature of the substance to be dried. The substance may be rigid solid such as wood or fiber board, a flexible material such as cloth or paper, a granular solid such as a mass of crystals, a thick paste or thin slurry, or a solution. If it is a solid, it may be fragile or sturdy. The physical form of the substance and the diverse methods of the handling have perhaps the greatest influence on the type of drier used.

2.2 Batch Drying

Drying in batch is relatively expensive operation and is consequently limited to small scale operation, to pilot plant and development work, and to drying valuable materials whose total cost will be little influenced by added expense in the drying operation.

2.3 Direct Driers

The constructions of such driers depend greatly upon the nature of substance being dried. *Tray driers* also called cabinet, compartment, or shelf driers, are used for drying solids, which must be spread on trays, and similar materials. Examples are pasty materials such as wet flicker cakes from filter pressures or lumpy solids. After loading, the cabinet is closed, and stream of heated air is blown across and between the trays to evaporate the moisture. When the solid has reached the desired degree of dryness, the cabinet is opened and the trays replaced with a new batch.

With granular materials, the solid can be arranged in thin beds supported on screens so that the air or other gas can be passed through the beds. This results in a much more rapid drying.

One of the most important difficulties in the use of driers of the type described is the non-uniformity of moisture content found in the finished product taken from various parts of the drier. This is largely the result of inadequate and non-uniform air movement inside the drier. It is important to eliminate stagnant air pockets and to maintain reasonably uniform air humidity and temperature through out the drier. In order to do this, large volume of air must be blown over the trays, if possible at velocity ranging up to 3 or 4 m/s if the solid does not blow from the trays at these rates. But this is done at the expense of the loss of large quantities of heated fresh air. The loss of heat in the discharge air will then usually be prohibitive in cost. Instead, it is the practice to admit only relatively small quantities of fresh air and to re-circulate the bulk of it. Generally, the greater the gas velocity over, through or impinging upon a material the greater is the convective heat transfer co-efficient [12]. Furthermore; the better the solids are dispersed in a gas for a surface exposure, the greater is the heat transfer rate [6]. In direct heat dryers more gas is needed to transport heat than to purge vapor.

2.4 Rate of Batch Drying

In order to set up drying schedules and to determine the size of equipment, it is necessary to know the time required to dry a substance from particular moisture content to another under specified conditions. We shall also wish to estimate the influence of different drying conditions on the time of drying. Our knowledge of mechanism of drying is so incomplete that it is necessary, with few exceptions, to relay upon at least some experimental measurements for these purposes. Measurements of the rate of batch drying are relatively simple to make and provide much information not only for batch but also for continuous operation.

2.5 Drying Test

The rate of drying can be determined for a sample of substance by suspending it from a balance in the cabinet or duct in a stream of air. The weight of drying sample can then be measured as a function of time. Certain precautions must be observed if the data are to be of maximum utility. The sample should not be too small. Further, the following conditions should be resembled as closely as possible.

1.) The sample should be similarly supported in a tray of frame
2.) It should have the same ratio of drying to non-drying surface
3.) It should be subjected to similar conditions of radiant heat transfer
4.) The air should have the same temperature, humidity and velocity (both speed and direction with respect to the sample).

If possible several tests should be made on samples of different thickness. The dry weight of sample should also be obtained.

The exposure of the sample to air of constant temperature, humidity and velocity constitutes drying under constant drying conditions.

2.6 Rate of Drying

From the data obtained during the test, a curve of moisture content as function of time can be plotted. This will be useful directly in determining the time required for drying large batches under the same drying conditions. Mach information can be obtained if the data are converted into rates (or fluxes) of drying, expressed as N mass/[(area)(time)], and plotted against moisture content. This is done by determining from the curve small changes in moisture content Δm_d or corresponding small changes in time Δt and calculating the rate as:

$$N = -w_o \frac{\Delta m_d}{A \Delta t} \qquad Or \qquad Drying\ rate = -\frac{\Delta m_d}{\Delta t} \tag{2.1}$$

where

m_d = moisture content on dry basis at time “t”

w_o = the mass of dry solid

A = wet surface over which the gas blows and through which evaporation takes place/ it is the cross-section of the bed measured at right angle to the direction of the gas flow.

If a solid is initially very wet, the surface will be covered with a thin film of liquid, which we shall assume is entirely-unbound moisture. When it is exposed to relatively dry air, evaporation will takes place from the surface.

2.7 Drying Mechanisms

2.7.1 Drying Period

Although some times it is possible to select a suitable drying method simply by evaluating variables such as humidity. The goal of many operations is not only to separate a volatile liquid, but also to produce a dry solid of specific size, shape, porosity, density, texture, color, or flavor; an understanding of liquid and vapor mass transfer mechanisms is essential for quality control. Measuring drying time and drying rate behavior under controlled conditions best identifies mass transfer mechanisms.

Several distinct periods occur during drying; refer to Figure (2.1) and (2.2)

1. An initial period, during which the wet material is heated to drying temperature.
2. A period of constant rate drying and can be seen as horizontal portions of the rate profiles during which the drying rate per unit area is constant.
3. A period of decreasing rate can be seen sloping portion of rate profile. During which the drying rate appears proportional to moisture content.
4. A period of decreasing rate during which the drying rate is evidently a more complex function of moisture content than simple proportionality.

The moisture content obtained at the end of constant rate drying period is designated as critical moisture content.

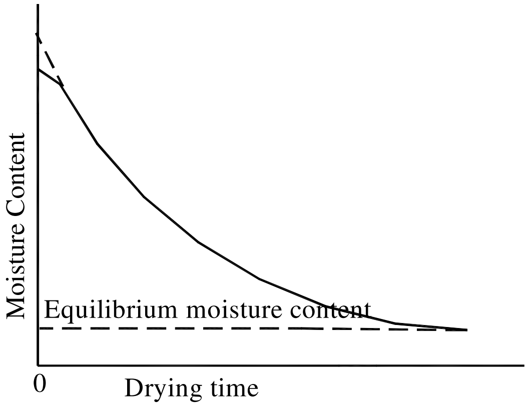


Figure 2. 1 Rate of moisture loss

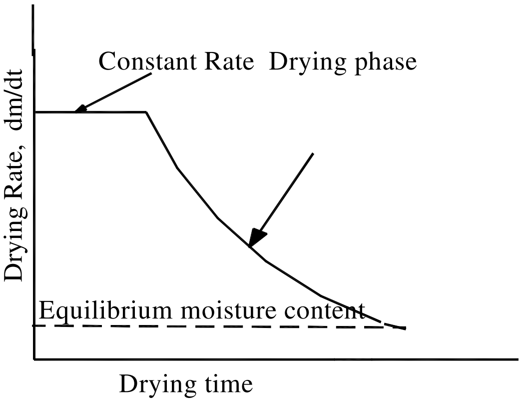


Figure 2. 2 Drying rate with time curve

2.7.1.1 Constant Rate Drying

During the constant rate period, vaporization occurs as a free liquid surface of constant composition and vapor pressure; Material structure has no influence. In an atmospheric-pressure dryer, drying proceeds by diffusion of vapor from the wet surface through a gas film into the environment. Moisture movement from within the material is fast enough to maintain a completely wet surface. The vaporization rate is controlled by the heat transfer rate to the evaporating surface; the mass transfer rate adjusts to the heat transfer rate and the liquid surface reaches a steady state temperature. The drying rate is, therefore, constant as long as the heat transfer rate is held constant by external conditions. If heat transfer is solely by convection from a gas the steady state surface temperature is the gas wet-bulb temperature. When conduction or radiation contributes to heat transfer, for example, the material rests on the warm surface or receives radiation from a warm enclosure, a surface temperature some where between the wet-bulb temperature and the liquids boiling point is obtained. In indirect-heat and radiant heat dryers where there are high rates of conduction and radiation heat transfer, the surface liquid may boil as in a pan of water on a stove regardless of humidity or temperature in the environment. During constant rate drying, therefore, a material temperature can more easily be controlled in a direct heat dryer than in an indirect or radiant heat dryer because in a direct heat dryer the material temperature doesn’t exceed the gas wet-bulb temperature as long as all surfaces are wet.

All principles relating to simultaneous heat and mass transfer between gases and liquids apply to constant rate drying. The steady-state relationship obtained between heat transfer and mass transfer at the liquid surface can be represented in the following manner [6].

$$-\frac{dm_d}{dt} = \frac{h_t A}{\lambda_s}(T - T_s) = K_a' A(p_s - p_v) \tag{2.2}$$

where

$-\frac{dm_d}{dt}$ = drying rate [kg/s]

h_t = the sum of all conduction, radiation and convection components of heat transfer [kW/m^{2}K]

A = surface area for vaporization and heat transfer [m^2]

λ_s = latent heat of vaporization and at T_s [kJ/kg]

K'_a = mass transfer coefficient [kg/sm^{2}kPa]

T = average source temperature for all components of heat transfer [K]

T_s = liquid surface temperature [K]

p_s = Saturation pressure at T_s [kPa]

p = partial pressure of vapor in the gas environment [kPa]

It is sometimes useful to express this relationship in terms of moisture change rather than the liquid quantity evaporated. For vaporization from a layer of wet material

$$-\frac{dm_d}{dt} = \frac{h_t}{\rho_m d_m \lambda'_s}(T - T_s) \tag{2.3}$$

where

$-\frac{dm_d}{dt}$ = Drying rate [kg liquid/s kg dry material]

ρ_m = dry material bulk density [kg/m^3]

d_m = layer thickness [m]

A similar equation can be written for through circulation drying in which gas flows through a deep bed of particles.

The rate of evaporation and the surface temperature can be obtained by a heat balance [12]. If q represents the total heat arriving at the surface, then

$$q = q_c + q_r + q_k \tag{2.4}$$

If we neglect the heat required to supperheat the evaporated moisture to the gas temperature and consider only the latent heat of vaporization λ_s, then flux of evaporation N_c and the flux of heat flow are related as

$$N_c\lambda_s = q \tag{2.5}$$

The heat received at the surface by convection is controlled by appropriate convection heat transfer coefficient h_c.

$$q_c = h_c(T-T_s) \tag{2.6}$$

If a solid is initially very wet, the surface will be covered with a thin film of liquid, which we shall assume is entirely unbound moisture. When it is exposed to relatively dry air, evaporation will takes place from the surface. The rate at which moisture evaporates can be described in terms of gas mass transfer coefficient k_y and the difference in humidity of the gas at the liquid surface y_s and the main stream y.

$$N_c = k_y(y_s - y) \tag{2.7}$$

The coefficient k_y can be expected to remain constant as long as the speed and the direction of gas flow past the surface do not change.

Neglecting the effect of radiation and conduction heat transfer and considering equations (2.4) to (2.7) permits calculation of the rate of drying.

$$N_c\lambda_s = h_c(T-T_s) = q$$

$$N_c = \frac{h_c}{\lambda_s}(T - T_s) = k_y(y_s - y) \tag{2.8}$$

The surface temperature must be known in order to use the relationship it can be obtained by consideration of the left hand portion of equation (2.8) and rearranged as follows;

$$\frac{(y_s - y)\lambda_s}{h_c/k_y} = (T - T_s) \tag{2.9}$$

Air flow perpendicular to the surface, for G = 1.08 to 5.04 kg/sm^2 (0.9 to 4.5 m/s) in SI

$$h_c = 24.2G^{0.37} \tag{2.10}$$

where

G is drying air mass velocity flux [kg/sm^2]

The relationship developed in equation (2.8) to (2.10) permit direct estimates of the rate of drying during the constant rate period, but they shouldn't be considered as complete substitute for experimental measurements. Perhaps their greatest value is in conjunction with limited experimental data in order to predict the effect of changing the drying conditions.

Effect of gas velocity: if radiation and conduction are negligible drying rate is proportional to $G^{0.37}$ for perpendicular flow.

Effect of gas temperature: increased air temperature increases the quantity $(T\text{-}T_s)$ and hence, increases the drying rate. In the absence of radiation effects, if the variation of λ over moderate temperature ranges is neglected, the drying rate is proportional to $(T\text{-}T_s)$.

Effect of gas humidity: drying rate varies directly as $(y_s - y)$, and consequently increasing the humidity lowers the rate of drying usually, changes in y and T involve simultaneous change in T_s and y_s, and the effects are best estimated by direct application of equation (2.8).

2.7.1.2 Critical Moisture Content

The critical moisture content which is the average material moisture content at the end of the constant rate of drying period is a function of material properties, the constant drying rate and particle size. The critical moisture content is difficult to determine with out prototype drying test. When drying wet material during the constant rate period, it is assumed that the drying rate increased by increasing the heat transfer rate, for example, by increasing the gas velocity across the surface.

Particle size distribution determines the surface-to-mass ratios and the distance internal moisture must travel to reach the surface. Large pieces have higher critical moisture contents than fine particles of the same material.

2.7.1.3 Falling Drying Rate Period

The principal internal mass transfer mechanisms that control falling rate drying are

1. Liquid diffusion is continuous in homogeneous materials.
2. Capillary in porous and fine granular materials.
3. Gravity flow in granular materials.
4. Vapor diffusion in granular materials.
5. Flow caused by shrinkage induced pressure gradients.
6. Pressure flow of liquid and vapor when a material is heated on one side and vapor escapes from the other.

Liquid flow by diffusion through materials in which the liquid is soluble, movement of bound moisture by liquid diffusion may occur but the mechanism is probably more complicated. Vapor flows by diffusion in the gas phase when liquid is vaporized in isolated pockets in porous and granular materials. Diffusion-controlled mass transfer is assumed when liquid or vapor flow appears to confirm to Fick’s second law of diffusion.

In porous and granular materials, liquid movement may occur by capillary and gravity provided pores are continuous. Capillary applies to liquid that are not held in solution by the material, moisture content greater than fiber saturation in cellular material, unbound moisture in other hydroscopic materials, and all moistures in non-hygroscopic materials.

Only one mass transfer mechanism usually predominates at any given time although several may occur together. In most solids the mechanisms of internal liquid and vapor flow during falling rate drying are complex. Simultaneous heat transfer is an important variable, and falling rate can rarely be described with mathematical precision. In the absence of testes, the falling rate drying periods are usually studied on the assumption that any material is either porous or non-porous, and internal mass transfer is controlled by either capillarity or diffusion.

2.7.1.4 Equilibrium Moisture Content

It is steady-state equilibrium obtained by gain or loss of moisture when a material is exposed to an environment of specific temperature and humidity. This equilibrium condition is independent of drying rate or method but is a material property. Only hygroscopic materials have equilibrium moisture contents. A hygroscopic material retains a fixed percentage of mixture under specific conditions of temperature and humidity. At constant temperature, if the humidity of the atmosphere surrounding the material increases or decreases, in material moisture content will follow. The retained moisture is called equilibrium moisture because it is held in vapor pressure equilibrium with the partial pressure of vapor in the atmosphere. The reason it is retained, even when the atmosphere is quite dry, is that the mechanism of retention reduces the effective liquid vapor pressure. It is bound moisture because it is bound to the material in solution or as an absorbed surface layer. Bound moisture behaves as if the atmosphere were saturated relative to the pure liquid exerting its normal vapor pressure. Because both the partial pressure and vapor in the atmosphere, and its own effective vapor pressure, which varies with temperature, affect equilibrium moisture content, any correlation must take both humidity and temperature into account.

Chapter Three

Air Properties

Air properties are important whether we are ventilating a livestock-housing unit, drying grain, or determining relative humidity in the home. In a livestock building, temperature, moisture, odors, and toxic or noxious gases must be controlled. Since the moisture holding capacity of air increase with increasing temperature, heat may be added in grain drying to aid in removing moisture from the grain kernel. In the home, moisture can either be added to or removed from the air to change the relative humidity. In each case, air provides the link between the controls and the mechanical equipment and air properties influence the results of the process.

Psychometric refers to the properties of moist air. A psychometric chart graphically illustrates the relationships between air temperature and relative humidity as well as other properties. A better understanding of air properties and psychometric chart can aid the selection and management of livestock building ventilation system, in drying system, or home humidifiers.

3.1 Air

a). Atmospheric Air: it contains nitrogen, oxygen, carbon-dioxide, water vapor, other gases and miscellaneous contaminants such as dust, pollen, and smoke. This is the air we breathe and use for ventilation.

b). Dry Air: It exists when all the contaminants and water vapor have been removed from atmospheric air. The following composition has been accepted for dry air;

Oxygen-0.2095; Nitrogen-0.7809; Argon-0.0093; and carbondioxide-0.0003. Molecular weight of air is taken as 28.966kg/kmol.

And the gas constant

$$\begin{aligned} R_a &= \frac{Universal\,Gas\,Cons\tan t}{Mollecular\,Weight} \\ &= \frac{R}{M_R} = \frac{8314}{28.966} J/kgK \qquad (3.1) \\ &= 0.287 kJ/kgK \end{aligned}$$

Since dry air is never found, it may always contain some water vapor. Hence for the term 'air', it is implied as dry air containing moisture in the vapor form.

Standards:

Density of air = *1.293 kg/m*^{3} for dry air at *1.01325 bar* and *0* ^oC

Density of water = *1000 kg/m*^{3} *at 4* ^oC and *998.23 kg/m*^{3} *at 20* ^oC

Barometric pressure = *0.101325 MN/m*^{2} = *760 mmHg*

= *1.01325bar* = *1013.25mbar*

Specific heat of air at constant pressure (C_{pa})

= *1.006 kJ/kgK*

Molecular weight of water (vapor) = *18.02 kg/kmol*

and the gas constant for water vapor using from equation (3.1)

$$\begin{aligned} R_v &= \frac{Universal\,gas\,cons\tan t}{molecular\,weight} \\ &= \frac{8314}{18.02} = 461 J/kgK = 0.461 KJ/kgK \end{aligned}$$

c). Moist Air: It is a mixture of dry air and water vapor. Water vapor present in the air is known as moisture. The determination of the quantity of moisture present in air is a very important factor in air conditioning system and air drying process. Moist air is said to be saturated when it contains maximum amount of water vapor that it can hold.

3.2 Psychometric Chart

The Psychometric chart is a graphical representation of the various thermodynamic properties of moist air. Such a chart helps to determine properties of air and eliminates tedious and time-consuming calculations.

Most charts are prepared for standard atmospheric pressure of 1.031bar. If the atmospheric pressure is different from this, e.g. if the unit is used at high altitude, a chart for the appropriate pressure, should be used. Entering the respective ambient temperature and altitude on computer programs developed for this purpose can give the appropriate psychometric charts for these altitudes.

Given any two independent properties, a state point may be marked on the chart and from this a number of properties may be determined. The properties determined by the chart are: -

i.) Dry bulb temperature
ii.) Wet bulb temperature
iii.) Specific volume
iv.) Specific humidity
v.) Specific enthalpy
vi.) Relative humidity

Chapter Four

Equipment and Procedure

The drying system consists of an air conditioning unit (Helton Re-circulating air conditioning unit model no A771/10834, air flow, humidity, temperature measurement sections and the drying chamber section. Galvanized sheet metal duct connects these sections.

4.1 Description

The air is drawn from the air conditioning unit using the fan inside the air conditioner unit and the exhaust air from the drying section is discharged to the atmosphere.

To determine the initial moisture content of the selected agricultural product in this case potato take a small sample of the sliced potato into an *AMB310 moisture analyzer.* The *AMB310 moisture analyzer* is a precision device for the determination of moisture content in small samples of material by drying the sample with halogen heaters.

The air conditioning unit is connected to the deep-bed drying chamber; 150-cm high drying chamber is constructed, from 60-cm width and 60 cm depth, of galvanized sheet metal. The bottom of the chamber is fitted with wire mesh to hold the agricultural product. The column of the rectangular sectioned drying chamber is constructed to consist of four trays each being 19 cm deep. The dimensions of the tray are shown in Annex E of Figure E.1. A series of 4mm diameter holes are drilled and thermocouple probes are directly inserted 12.2 cm in to the interior of the drying chamber through the provided holes at each inlet and exit of the trays. The thermocouples are to sense the average temperature at the inlet and exit of these individual trays. The data are acquired with the help of a data logger in connection with the Ls2win programming.

An additional set of holes of 4 mm diameter are also drilled for measuring the relative humidity of air at the inlet and exit of each tray. The relative humidity measuring probes are directly inserted 14.5 cm in to the interior of the drying chamber through the provided holes at each inlet and exit of the trays.

The air conditioning unit is started and the desired conditions of the average air temperature, air mass flow rate and humidity are set for each trial. After stabilization for a period of time in this case thirty minute, the drying trays were filled with two kilo grams of fresh sliced potato, which is till the height of the trays are filled with the potato slices, at known moisture content and the trial begins.

Different trials are held in this manner for periods of time ranging from 9 to 12h.
The temperature and relative humidity at each tray inlet and exit is to be recorded automatically at every thirty minute by the data logger and manually, respectively, and samples of the fruits from the drying chamber are also withdrawn every hour for moisture determination.

4.2 The Helton Re-circulating Air Conditioning Unit

As explained in the introduction part, the Hilton Re-circulating Air Conditioning unit is designed to demonstrate and to evaluate the energy transfers occurring in all the processes which are required in an air conditioning plant. The unit is mounted on a mobile frame, which houses the refrigeration unit and steam generator. The ducting has a clear Perspex front and all the components through the airflows may be seen. The air conditioning set up and the dryer set up are shown in figure 4.1

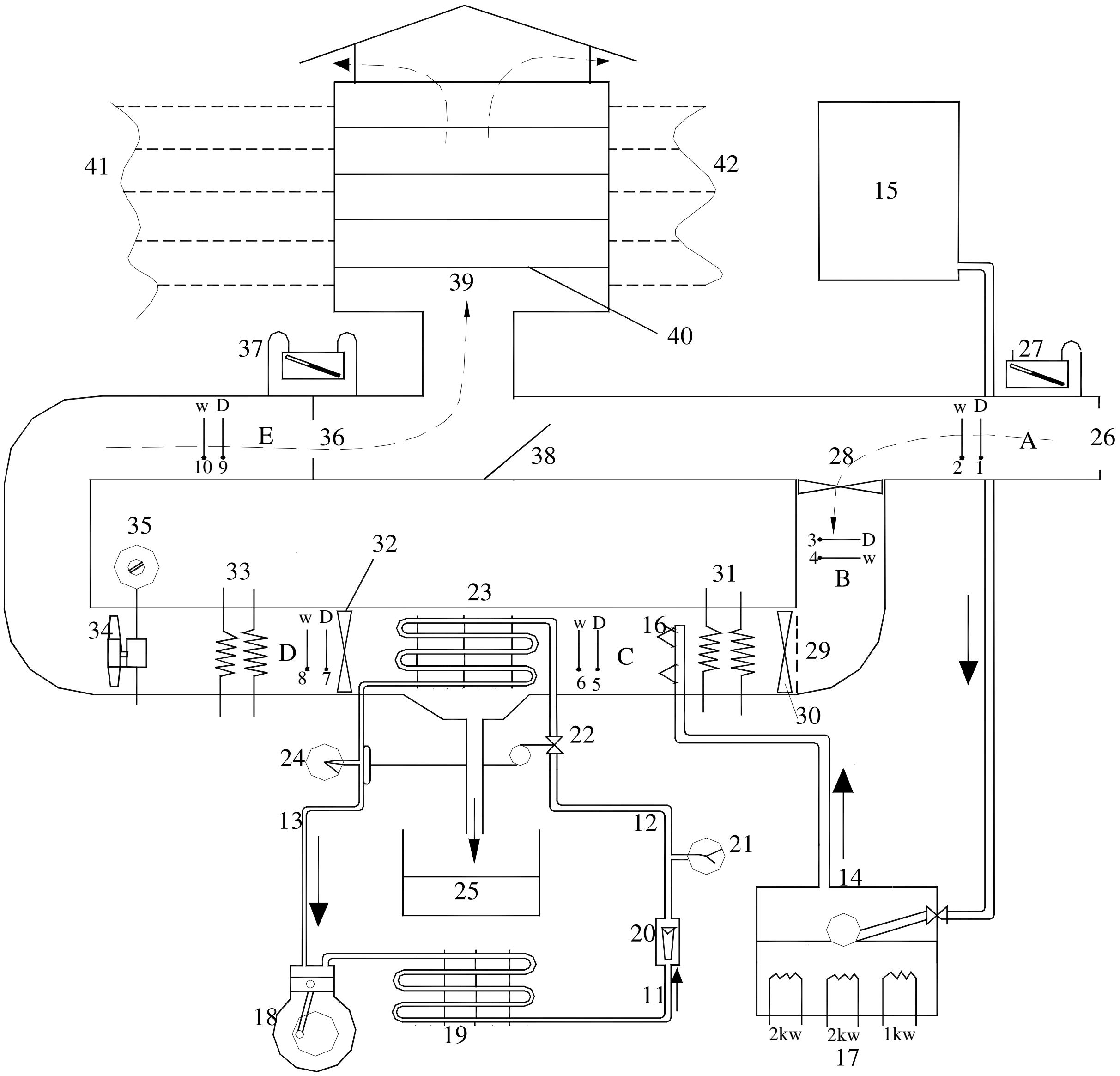


Figure 4. 1 Re-circulating air conditioning and convective batch dryer unit (The drawing is not to scale)

Key

1. Dry bulb Temperature measuring thermocouple of section A
2. Wet bulb Temperature measuring thermocouple of section A

3. Dry bulb Temperature measuring thermocouple of section B
4. Wet bulb Temperature measuring thermocouple of section B
5. Dry bulb Temperature measuring thermocouple of section C
6. Wet bulb Temperature measuring thermocouple of section C
7. Dry bulb Temperature measuring thermocouple of section D
8. Wet bulb Temperature measuring thermocouple of section D
9. Dry bulb Temperature measuring thermocouple of section E
10. Wet bulb Temperature measuring thermocouple of section E
11. Temperature measuring thermocouple of the refrigerant from condenser
12. Temperature measuring thermocouple of the refrigerant to evaporator
13. Temperature measuring thermocouple of the refrigerant from evaporator
14. Boiler
15. Feed water storage
16. Steam injector
17. Water heaters
18. Compressor
19. Condenser
20. Refrigerant flow meter
21. Pressure gauge
22. Thermostatic expansion valve
23. Evaporator
24. Pressure gauge
25. Condensate collector
26. Intake orifice
27. Manometer

28. Mixer

29. Air distributor

30. Mixer

31. Pre-heater

32. Mixer

33. Re-heater

34. Fan

35. Fan speed control

36. Duct office

37. Manometer

38. Damper

39. Drying Chamber

40. Drying trays

41. Location of thermocouples

42. Location of hygrometer

Untreated air entering the ducting passes in series-through

i.) An air measuring intake orifice

ii.) A mixing zone (where it may be mixed with recalculated air)

iii.) A pre-heater: The air after having been cleaned is required to heat in certain cases because the heated air can absorb more water. The heating is carried out in a heater of proper capacity where temperature is controlled manually.

iv.) A humidifier supplied with steam from a generator: These are used to increase the moisture content of the air. Water may be sprayed directly into the air, may be evaporated from a moist surface, or alternatively, steam may be injected into the air.

v.) A cooler /dehumidifier with precipitate water outlet: These are used to reduce the moisture content of the air. This is usually active by cooling the air below its dew point so that the surplus moisture is precipitated. The cooling equipment usually consists of refrigeration coils. The cool and dry air to be conditioned is blown through them. The coils are kept cooled by different refrigeration methods. The refrigeration coils also serve as de-humidifiers as they will remove moisture from the air blowing through them provided the coil surface temperature is below dew point temperature. This will result in condensation of moisture in the air.

vi.) A re-heater

vii.) An axial flow fan with infinitely variable speed control: The function of the fan is to produce air movements through heating, ventilating and air conditioning apparatus.

viii.) An air measuring duct orifice

ix.) A damper, which controls the quantity of air, discharged to the drying chamber.

The following data are readily obtained:

a.) The condition of air before and after the various process

b.) The condition of the air stream before and after mixing and refrigeration unit

c.) The energy transfer rate at each heater, the boiler, fan and refrigeration unit

d.) Air mass velocity flux at the inlet to the conditioner and at the inlet of the drying chamber.

e.) Pressure and temperature of refrigerant

4.2.1 Operation

1. Turn on the water supply to the boiler and check that the water level in the gauge glass stabilizes at a depth which will cover all the heater elements (i.e. about 120 mm from the bottom of the boiler).
2. Rotate the fan speed controller fully clockwise.
3. Switch on the electrical supply at the isolator.
4. Switch on the unit at the main switch.

The following are immediately operative:

- i.) The fan (this should run as soon as the switch is turned on)
- ii.) The mains warming lamp
- iii.) The voltmeter
- iv.) The temperature indicator

As it has seen from the diagram, the lower rows of switches control the adjacent components in the lower duct.

The ammeter switches are biased, and when pressed, the ammeter will indicate the current passing through the component adjacent to the switch. No more than one switch is pressed at a time. If, however, more than one switch is pressed, no damage will occur, but the results will be inaccurate.

If steam is required, the three boiler switches should be closed until steam is seen to issue from the distributor (this takes about 5 minutes). Then the boiler output can be adjusted to the desired rate by switching up to 5 KW in 1 KW increment (240 V), or 4.5 KW in 1.5 KW increment (110 V).

4.2.2 Fan

Its controller on the panel adjusts the fan speed. This must be set to maximum for starting. The controller can not be set below a certain value since it is essential that there is always some air flow through the duct to prevent over heating. (To ensure reliable results from wet bulb thermometers, the airflow should not be less than about 0.07 kg/sm^2.

4.2.3 Damper

The damper may be positioned for no re-circulation. A stop is fitted to the damper to prevent 100% re-circulation since this could cause excessively high or low duct temperatures.

4.2.4 Refrigeration Unit

The *P .A. Hilton Re-circulating air Conditioning Unit employs,* -vapor compression refrigeration system. The refrigerant circuit was correctly charged with approximately *2kg of R134a.*

4.2.5 Calibration of Duct Orifice

In order to keep the Re-circulating Air Conditioning Unit as compact as possible, it has not been possible to provide the necessary of a straight duct orifice, for standard formula to apply.

The duct orifice may be calibrated from the intake orifice, provided the damper is positioned for zero re-circulation. In this condition, the mass flow rate through both orifices will be the same. For the intakes orifice:

$$\dot{m} = 0.075\sqrt{z/\upsilon_A} \quad kg/sm^2 \tag{4.1}$$

where

z is the intake orifice differential pressure [mmHg]

ν_A is the specific volume of the air at the orifice m^3/kg. (from psychometric chart)

and for the duct orifice

$$\dot{m} = 0.083\sqrt{z/\upsilon_E} \quad kg/sm^2 \tag{4.2}$$

4.3 AMB Moisture Balance *(*AMB 50, AMB 110 and AMB 310)

The AMB moisture analyzer is a precision device for the determination of moisture content in small samples of material by drying the sample with halogen heaters.

The AMB moisture balance is easy to use. The user sets the drying parameters into memory, puts the samples into the weighing chamber and then starts the test. The temperature of drying is automatically regulated and the results, elapsed time, current temperature in the chamber and the mode are displayed during the test. The user is told when the test has automatically stopped either due to the sample being dry and the weight no longer changing, or the elapsed time reaching the limit the user has set. The final values are held on the display until the user resets the balance.

The balance can be interfaced to a printer or computer. The results are shown when the test progresses and after the test has finished a summery of the test can be sent to a PC or printer.

At the end of the test the following data are displayed over the digital displays of the *AMB moisture balance*.

i.) Percentage moisture or Percentage Solids

ii.) Initial mass [mg]

iii.) Final mass [mg]

iv.) Drying temperature [^{o}C]

v.) Elapsed drying time [sec]

vi.) Time interval between two successive measurements [sec]

4.3.1 AMB Moisture Balance Description

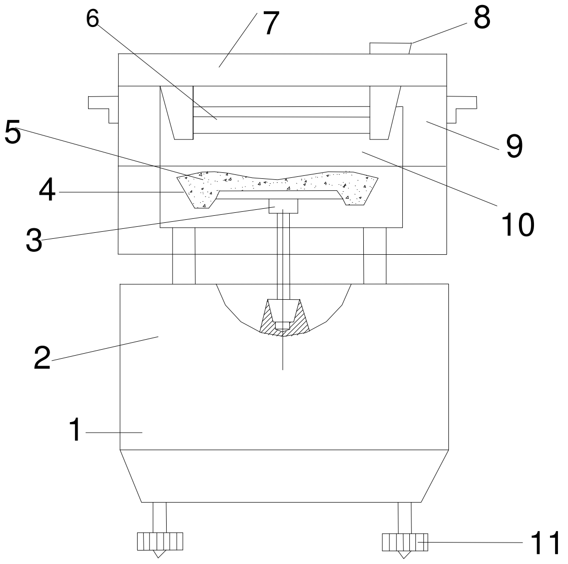
Place the moisture analyzer on stable weighing table

Do not install the balance near warm and cold sources, such as windows, radiators or air conditioners. Protect the balance from vibrations, dust and draughts.

Turn the adjustable feet (11) until the balance is level (2).

Install the weighing chamber liner on the four supports.

Install the pan support (3) by placing the pan (4) stem in to receptacle in the weighing chamber.



Key
1. Display and Keypad
2. Balance
3. Pan Support
4. Weighing Pan
5. Weighing Sample
6. Halogen Heater (2*200 w)
7. Protection of Temperature Regulation
8. Power Supply switch
9. Cover
10. Sample Chamber
11. Adjustable feet

Figure 4. 2 AMB 310 Moisture Balance description (the drawing is not to scale)

Note: Be careful not to press on the pan as this may damage the balance.

Place an aluminum sample pan on the pan support. The balance may lock-up if this sample pan is not used.

Attach the power cord to the AC power. Verify the AMB power requirements match the service. The AMB balance will use 200 Watts during normal operation.

4.3.2 Drying Parameters

Parameters for drying procedure are set using the front panel keys. Pres [F] key when in the weighing mode to set the parameters test. The parameters control the type of the test to be done (modE), the temperature to do the test (tEmp), the time between RS-232 out puts and verification of results (StropE), the maximum test time (intEr) and a correction factor between the measured temperature of a sample and the set point temperature (SubSt).

4.3.2.1 'SubSt' Substance temperature correction

'SubSt' is a substance temperature correction. This correction allows the user to account for the difference between the temperature measured at the temperature sensor and the temperature of the sample. The balance allows 9 correction factors to be interred into memory in order to match the sample for temperature to the set point temperature.

For most tests the scale will not use this parameter and arrow keys can be used to select SubSt = 0. SubSt 1 to 9 are corrections for up to 9 different types of materials.

Unless values have been entered, select SubSt = 0. This will automatically disable the function.

4.3.2.1.1 Determination of the Correction Factor

The SubSt parameter is a correction between the measured temperature with in a sample and the set temperature (Where the measured temperature is greater). This difference can exist because some materials will absorb more heat than others and different textures will heat more efficiently, thus becoming hotter than the indicated temperature. The balance allows storing 9 correction factors. The effects are stored in permanent memory.

To set the correction factors it will be necessary to dry a sample of the material and measure the temperature on the inside of the sample during the drying process. A small thermometer sensor is suggested for this purpose.

Procedure:

1. With the balance in normal weighing mode, place a sample of material on the sample pan; attach a thermocouple sensor to the sample pan with the active part of the sensor buried in the sample.
2. set the following drying parameters;

SubSt = 0
modE = 7
IntEr = 30:00 minutes or longer
tEmp = typical value for the sample, example 110 °C
StrobE = 20 sec

3. Press the [START] key to display the parameters. Press [START] a second time to begin the test.

4. After the test has run for some time and the temperature in the sample has stabilized, compute the correction factor from the following.

$$Correction = \frac{T_{measure} - T_{set}}{T_{set}} \tag{4.3}$$

For example if the measured temperature is 121°C and the set temperature is 110°C the correction is 0.1.

Record the correction factor. Stop the test by pressing the [TARE] key. Then enter the SubSt parameter menu. Select the SubSt value to enter this correction factor by using the [F] key then [I] to increment the flashing digit.

Press the [F] key to display the current value for the parameter in the temperature display.

Enter the new value in to the window.

The display will show the current value. To change the numbers press the increment arrow key to increment the flashing digit. When the value has been set, press the [F] key as necessary to return to normal weighing.

The scale will display FALSE if a value greater than 0.99 is entered. The temperature display will show again to allow you to change the value.

4.3.2.2 'modE' Mode Select

Select one of seven modes of operation. The modes are identified below.

Mode 1 Percent Moisture determination with respect to initial weight

%moisture = (weight loss/initial weight)*100%

Stop drying when results are the same for 3 consecutive Strobe intervals.

Mode 2 Percent Solids

%Solids = (Current weight/initial weight)*100%

Stop drying when results are the same for 3 consecutive strobe intervals.

Mode 3 Percent Moisture with respect to solids

%Moisture = (weight loss/Final weight)*100%

Stop drying when results are the same for 3 consecutive strobe intervals.

Mode 4 Percent Moisture determination with respect to initial weight

%moisture = (weight loss/initial weight)*100%

Stop drying when results are the same for 3 consecutive Strobe intervals or the maximum time limit have expired.

Mode 5 Percent Solids

%Solids = (Current weight/initial weight)*100%

Stop drying when results are the same for 3 consecutive strobe intervals or the maximum time limit have expired.

Mode 6 Percent Moisture with respect to solids

%Moisture = (weight loss/Final weight)*100%

Stop drying when results are the same for 3 consecutive strobe intervals or the maximum time limit have expired.

Mode 7 Percent Moisture determination with respect to initial weight

%Moisture = (weight loss/initial weight)*100%

Stop drying when the maximum time limit has expired.

4.3.2.3 'tEmp' Drying Temperature

The temperature can be set in the range 50^{o}C to 160^{o}C on standard units, and 50oC to 250^{o}C on the high temperature units.

4.3.2.4 'intEr' Maximum Time

When modes 4, 5, 6 or 7 are selected the maximum time is set. The time can be in the range 10 minute to 9 hours 50 minutes.

4.3.2.5 'StrobE' Strobe Interval Time

The Strobe interval time is the time between one set of results and the next set of results. The interval time sets how often the current results and out put to the RS-232 interface. When using MODE 1,2 or 3 the test will stop when 3 results are the same, indicating the that there is no more moisture to be taken from the sample.

4.3.3 Drying Procedure

The procedure for drying sample can only be done after the parameters are set. The sample must be prepared for the drying procedure. The method of preparation is dependent upon the type of sample to be tested.

In general it is desirable to have the sample of uniform consistency. This may involve a mechanical preparation or a method of spreading the sample over the sample pan evenly.

The sample should spread evenly over the sample pan. Do not allow the sample to extend 10 mm in height above the sample pan.

i.) Place the sample pan with any inert material that may be required on the pan support. Press the [TARE] key to zero the display.

ii.) Place the sample to be tested on the sample pan, as evenly as possible.

iii.) Close the weighing chamber

iv.) Press the [START] key to initiate the test. The display will show the current mode, drying temperature, and the interval time. If these are not correct then reset the parameters.

v.) Press [START] key again to begin the test

The balance will begin the test displaying results as the test progress. The current temperature, elapsed time and computed percentage moisture (or percentage solid) will be displayed.

The test will stop as described for the modes. For mode 1-3 the test will stop if the results do not change for three consecutive strobe intervals time periods.

For modes 4-6 the test will stop if the results do not change for three consecutive strobe intervals time periods or the maximum time is reached.

For mode 7 the test only stops when the maximum time is expired.

At all time it is possible to stop the test by pressing the [TARE] key. The balance will return to normal weighing immediately.

When the test stops automatically the final result are held on the displays. The results can be printed at this time by pressing the [PRINT] key.

4.4 DL2e Data Logger

The DL2e Logger is a programmable data logging device, capable of taking readings and storing data form a wide variety of sources. It is independently powered, capable of operating under wet conditions, and high and low temperatures. The DL2e Logging is therefore, an excellent choice for all classes of logging applications.

Figure 4. 3 Data Logger front panel

PC software LS2win is first used to program the logger, specify what sensors are to be connected to the logger, and how frequently to record data. Once the logger has been set up, the PC can be disconnected and the logger can be left to operate on its own memory, and can be periodically transferred to a PC or to any device which has an RS232 serial port, for example a printer. When the data has been colleted from the logger, it can be cleared from the logger's memory to make room for more data.

Only one PC is needed to operate any number of loggers and it only needs to be connected while setting up the logger and collecting the stored data.

The logger also has a front panel with key pad and display that can be used to check and control logger operation with out using a PC.

The DL2e logger is modular in high design. Depending on the input cards installed, the logger can be record data from up to 62 sensors. Input data are available for analogue and pulse output sensors.

The logger has an initial clock and can be set up to record data at regular intervals. This is known as *timed data.* In addition, it can also record data when events are detected known as *event triggering data*.

The logger can be powered from an external DC power supply, or from its own internal batteries. It has extremely low power consumption and can operate for extended periods on a set of batteries. With rugged weatherproof case, it is equally suited for use as a laboratory instrument or for out door installations in remote locations. Being modular and programmable, it is an extremely flexible tool, and easy adaptable for a wide variety of applications.

4.4.1 Data Logger Software (LS2Win)

Ls2Win enables a PC to communicate with the logger, edit logging programs and collect data. It is supplied on CD-ROM and is not the same as the program in the logger's PROM.

4.4.2 Items Required

To operate the logger from your PC you need the following:

- A PC running windows 95,98,2000 or NT4.0 Service pack 4, or later.
- One free RS232 serial port.
- CD-ROM drive (required for installation)

- At least 16M RAM memory and 5M for hard disk space.
- Logger-PC RS232 cable: Type LRS1 available from Delta-T or you can make up.

Set-up installs a program group named Ls2Win on the program menu, which contains the following items:

- *New DL2 Control Panel,* For creating ’DL2 Control Panels’ which one can use to communicate with the data logger;
- *DL2 Program Editor,* for creating and viewing logging programs;
- *Dataset Viewer,* for inspecting the contents of ’data set’ files (files containing logged data);
- *Dataset Import wizard,* for importing logged data in to Microsoft Excel.

Setup also installs desktop shortcuts that correspond to each item in the Ls2Win program group.

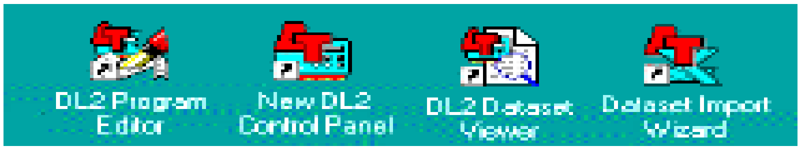
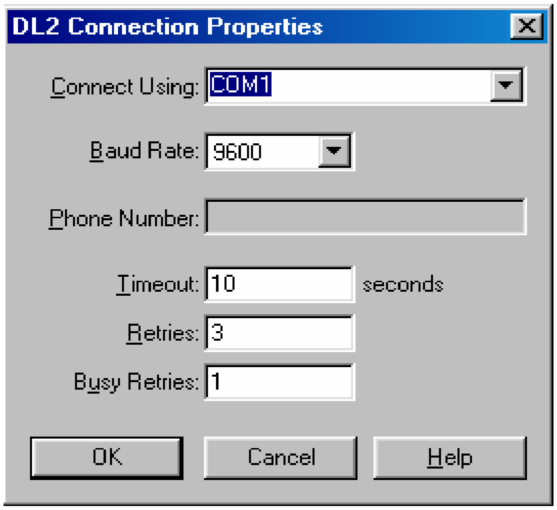


Figure 4. 4 A programming group of the Ls2Win software

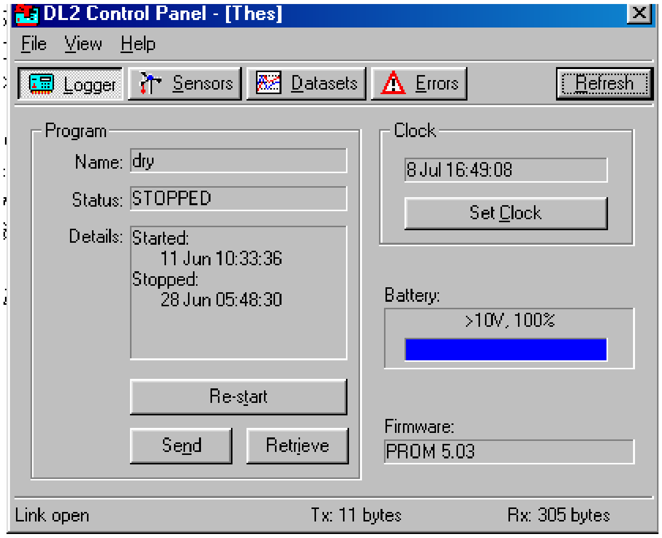
4.4.3 Create a New DL2 Control Panel

Double click The New DL2 control panel desktop icon (or select New DL2 Control panel from the start, programs, Ls2Win menu) this will open the DL2 Control Panel.



Connect Using: COM1
Baud Rate: 9600
Phone Number:
Timeout: 10 seconds
Retries: 3
Busy Retries: 1

Figure 4. 5 Connections properties dialog box

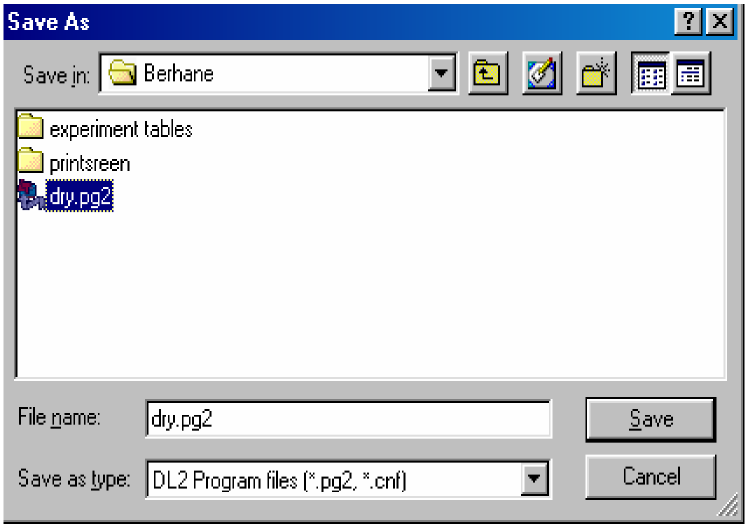


Name: dry
Status: STOPPED
Details: Started:
11 Jun 10:33:36
Stopped:
28 Jun 05:48:30
8 Jul 16:49:08
Battery:
>10V, 100%
Firmware:
PROM 5.03
Link open
Tx: 11 bytes
Rx: 305 bytes

Figure 4. 6 Logger Panel on the DL2 Control panel

This figure shows the final box of the control panel after communicating with the logger.

Before proceeding first must save the connection properties as a DL2 control panel file. A save DL2 control panel as dialog will now appear as shown below. Write the file name in this case “dry” *and click OK* to accept the file name.



Save in: Berhane

File name: dry.pg2

Save as type: DL2 Program files (*.pg2, *.cnf)

Figure 4. 7 Save DL2 control panel dialog

DL2 control panel now creates a short cut icon to it self on the disk top and retrieves and displays states of information from the logger. You have now established communication with the logger. If you select the incorrect connection setting, select properties from the file menu, change the setting in the DL2 connection properties dialog, and click Refresh to refresh DL2 control panel.

There are four panels of information in the DL2 control panel: you switch between them by clicking the Logger, Sensors, Datasets and Error buttons. The current panel –Logger- shows the general information about the state of the logger.

4.4.3.1 Logger Panel

Inspects the logger status and start logging

Program *Name* is the name of the logging program currently stored in the DL2. The program *states* can be:

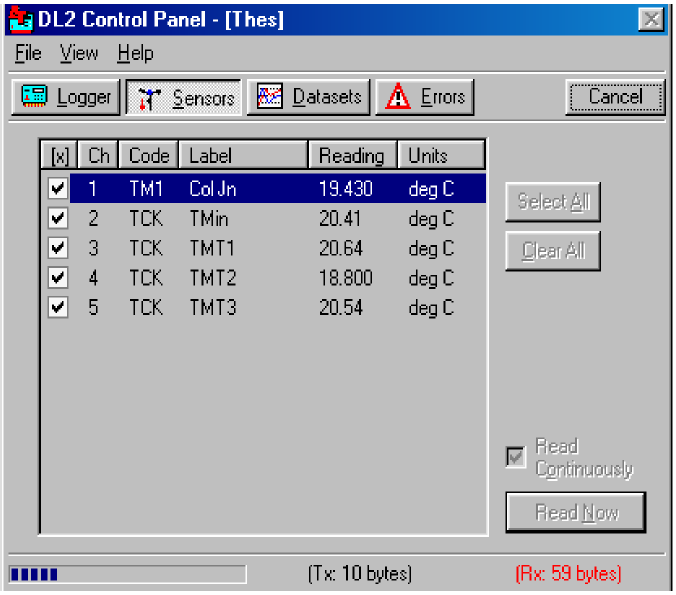
- *Standing by:* not logging, not logged data
- *Armed:* Awaiting a start trigger, but NOT awaiting first TIMED data
- *Logging:* actively recording data (or awaiting first TIMED data)
- *Stopping:* not logging logged data exists.

These all shown in Figure 4.6

4.4.3.2 Sensors Panel

Watch the sensor readings

Click the sensors button. Enable Read *continuously* and click *Select All* and *Read Now*:



[x]	Ch	Code	Label	Reading	Units
☑	1	TM1	Col Jn	19.430	deg C
☑	2	TCK	TMin	20.41	deg C
☑	3	TCK	TMT1	20.64	deg C
☑	4	TCK	TMT2	18.800	deg C
☑	5	TCK	TMT3	20.54	deg C

☑ Read Continuously

(Tx: 10 bytes) (Rx: 59 bytes)

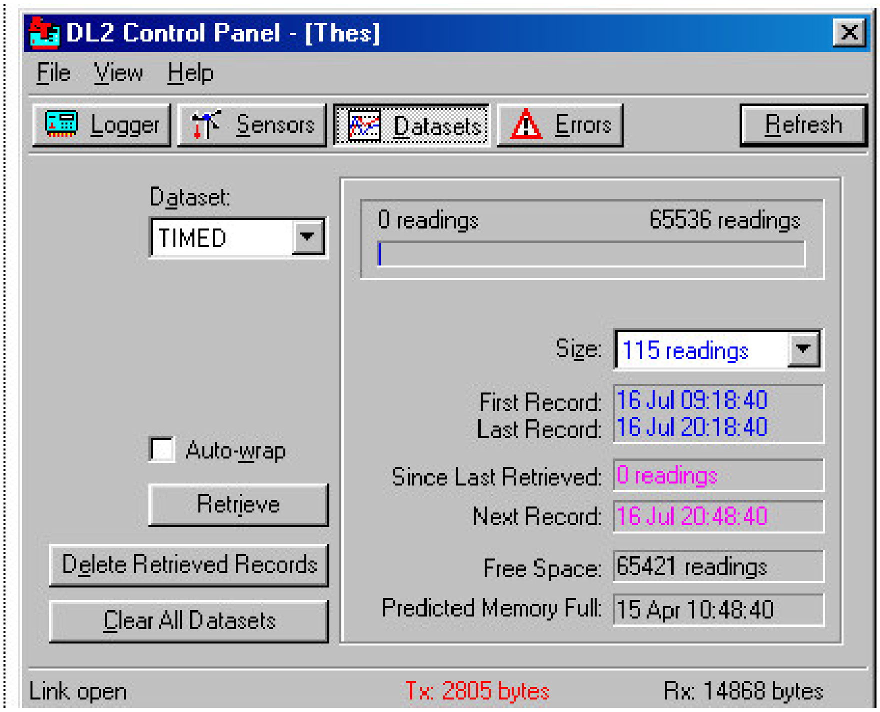
Figure 4. 8 Sensors panel showing real time readings from the thermocouples used in the project using the "dry" logging program

The display shows the sensors being read continuously. You can see this whether or not the logger is logging. This is useful for inspecting the sensors before logging starts.

4.4.3.2 Dataset Panel

Retrieve the dataset. The dataset panel displays the information about readings stored in the logger.

Click *Datasets* and then *Refresh*:



Dataset: TIMED

☐ Auto-wrap

0 readings 65536 readings

Size: 115 readings

First Record: 16 Jul 09:18:40
Last Record: 16 Jul 20:18:40

Since Last Retrieved: 0 readings
Next Record: 16 Jul 20:48:40

Free Space: 65421 readings
Predicted Memory Full: 15 Apr 10:48:40

Link open Tx: 2805 bytes Rx: 14868 bytes

Figure 4. 9 Dataset control panel, display the information about the readings stored in the DL2

Inspect the dialog; most of the indicated values should be self-explanatory.

- *Dataset:* A logger program can generate up to three datasets: the TIMED dataset contains data recorded at regular recording intervals, and TRIG/61 and TRIG/62 datasets which contain data recorded on detection of events on digital input channels 61 and 62 respectively.
- *Auto-warp:* If selected, when memory is full, the most recent data overwrites the oldest readings. The most recent data are retained; the oldest

data are overwritten by new data. This option is only available for TIMED dataset.

- *Retrieve*: Retrieves the selected dataset to a PC disk file.
- *Delete retrieved Records:* Delete the most recently retrieved dataset records from the logger's memory. This option is only available for the TIMED dataset. For TRIG/61 and TRIG/62 datasets, the alternative command is *Delete All Records*, which deletes the entire contents of the selected dataset from the logger's memory.
- *Clear All Dataset:* Deletes the contents of all datasets from the logger's memory. This command is only enabled when the logger is not logging.
- *Size:* Determines how used and available memory is played from a large drop down list of options.

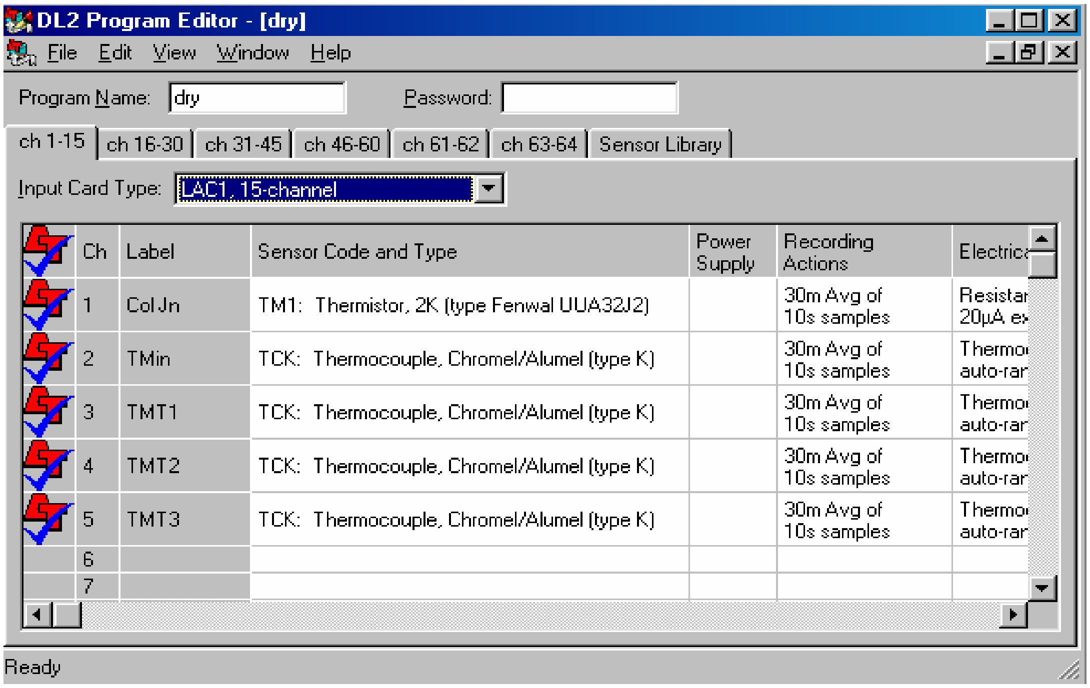
4.4.4 Programming the DL2e Logger

For real logging applications you need your own logging program. A logging program specifies some or all of the following:

- What sensor types will be connected to each of the logger's channels,
- How frequently readings are to be logged from each channel,
- What type of units the raw readings are converted to,
- When or how logging should start,
- What happens when memory is full,
- How long a sensor receives power before taking a reading

4.4.4.1 The DL2 Program Editor

Select the logger panel in the DL2 control panel and click retrieve. The program will appear, laid out as a table in a row of tab sheets, in the DL2 program Editor.



Program Name: dry

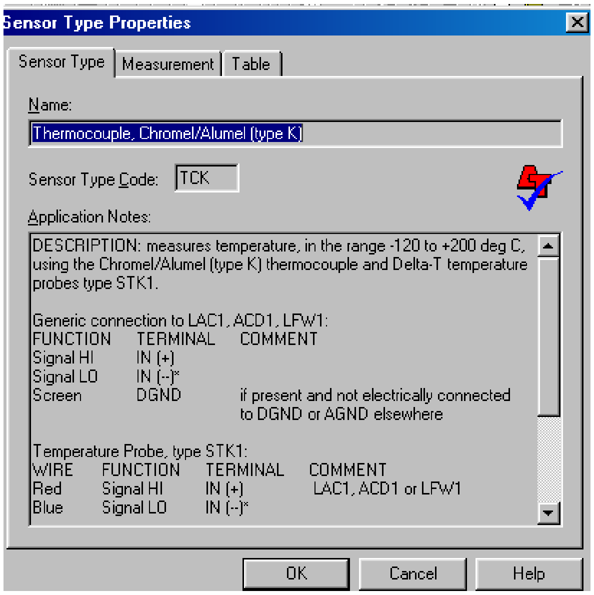
Password:

Input Card Type: LAC1, 15-channel

Ch	Label	Sensor Code and Type	Power Supply	Recording Actions	Electric
1	Col Jn	TM1: Thermistor, 2K (type Fenwal UUA32J2)		30m Avg of 10s samples	Resistar 20µA ex
2	TMin	TCK: Thermocouple, Chromel/Alumel (type K)		30m Avg of 10s samples	Thermo auto-rar
3	TMT1	TCK: Thermocouple, Chromel/Alumel (type K)		30m Avg of 10s samples	Thermo auto-rar
4	TMT2	TCK: Thermocouple, Chromel/Alumel (type K)		30m Avg of 10s samples	Thermo auto-rar
5	TMT3	TCK: Thermocouple, Chromel/Alumel (type K)		30m Avg of 10s samples	Thermo auto-rar
6					
7					

Figure 4. 10 A copy of the "dry"-logging program in the DL2 is retrieved and displayed in the program Editor

A single click on any row displays application notes in a separate window. You can find wiring instructions here where appropriate. Double click on sensor type in the sensor library tab pops up the sensor type properties dialog, which contains a collection of tab sheets.



Name: Thermocouple, Chromel/Alumel (type K)

Sensor Type Code: TCK

Application Notes:

```
DESCRIPTION: measures temperature, in the range -120 to +200 deg C,
using the Chromel/Alumel (type K) thermocouple and Delta-T temperature
probes type STK1.

Generic connection to LAC1, ACD1, LFW1:
FUNCTION     TERMINAL     COMMENT
Signal HI    IN (+)
Signal LO    IN (--)*
Screen       DGND         if present and not electrically connected
                          to DGND or AGND elsewhere

Temperature Probe, type STK1:
WIRE     FUNCTION     TERMINAL     COMMENT
Red      Signal HI    IN (+)        LAC1, ACD1 or LFW1
Blue     Signal LO    IN (--)*
```

Figure 4. 11 Sensor type properties include detailed applications notes on each sensor, including wiring instruction

4.4.5 Retrieving Logged Data to PC

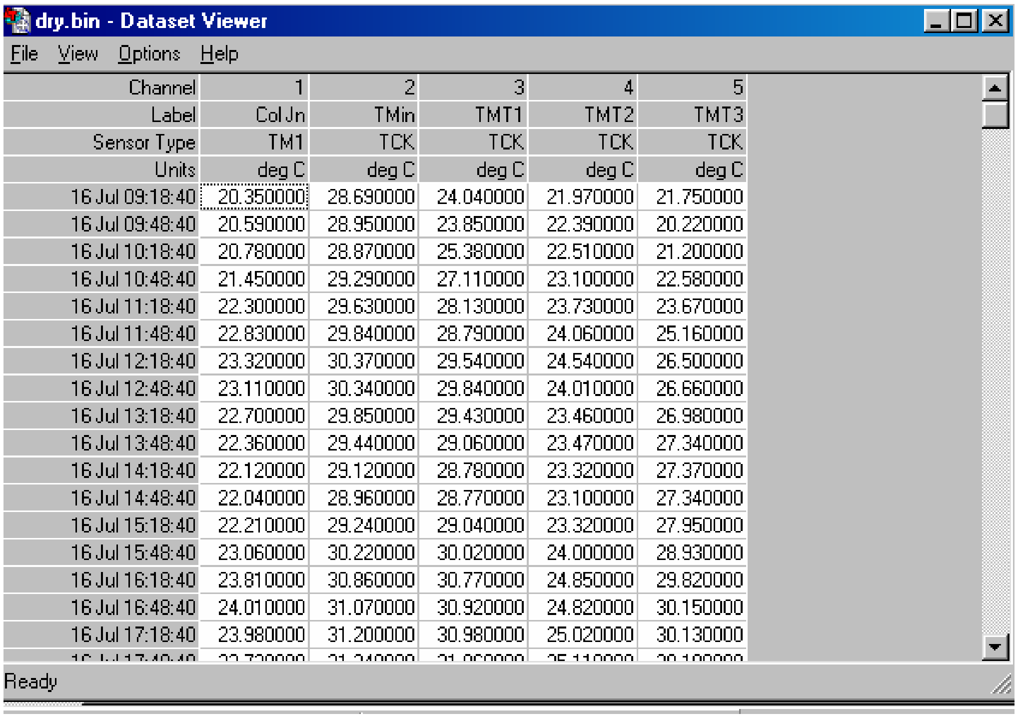
The Ls2Win program called DL2 control panel to:

- Display information about the logger and its datasets
- Display data settings in real-time
- Retrieved logged data from the logger data from the logger to a PC disk file
- Display the data on your PC screen

4.4.5.1 Dataset Viewer

This is a separate program that automatically opens on your disk top when you retrieve a dataset via the DL2 control panel.

This shows the reading of Temperature from the dryer at different location an at every 30 minutes. The binary format dataset is displayed in the dataset Viewer.



Channel	1	2	3	4	5
Label	Col Jn	TMin	TMT1	TMT2	TMT3
Sensor Type	TM1	TCK	TCK	TCK	TCK
Units	deg C	deg C	deg C	deg C	deg C
16 Jul 09:18:40	20.350000	28.690000	24.040000	21.970000	21.750000
16 Jul 09:48:40	20.590000	28.950000	23.850000	22.390000	20.220000
16 Jul 10:18:40	20.780000	28.870000	25.380000	22.510000	21.200000
16 Jul 10:48:40	21.450000	29.290000	27.110000	23.100000	22.580000
16 Jul 11:18:40	22.300000	29.630000	28.130000	23.730000	23.670000
16 Jul 11:48:40	22.830000	29.840000	28.790000	24.060000	25.160000
16 Jul 12:18:40	23.320000	30.370000	29.540000	24.540000	26.500000
16 Jul 12:48:40	23.110000	30.340000	29.840000	24.010000	26.660000
16 Jul 13:18:40	22.700000	29.850000	29.430000	23.460000	26.980000
16 Jul 13:48:40	22.360000	29.440000	29.060000	23.470000	27.340000
16 Jul 14:18:40	22.120000	29.120000	28.780000	23.320000	27.370000
16 Jul 14:48:40	22.040000	28.960000	28.770000	23.100000	27.340000
16 Jul 15:18:40	22.210000	29.240000	29.040000	23.320000	27.950000
16 Jul 15:48:40	23.060000	30.220000	30.020000	24.000000	28.930000
16 Jul 16:18:40	23.810000	30.860000	30.770000	24.850000	29.820000
16 Jul 16:48:40	24.010000	31.070000	30.920000	24.820000	30.150000
16 Jul 17:18:40	23.980000	31.200000	30.980000	25.020000	30.130000

Figure 4. 12 Dataset retrieved from the logger to file and also displayed from the logger

The dataset viewer is also available as an icon on your disk top. The Dataset viewer offers the following commands:

Open: Command (file menu) opens and displays a DL2e dataset file.

Save As: command (file menu) saves the dataset, which is currently open in the dataset viewer as a data format file- a comma to separated ASCII format, which is compatible with most data processing applications.

Data Format: Command (View menu) allows you to select the Day/Month order for interpreting ambiguous data file timestamps.

Chapter Five

Results and Discussions

5.1 Characteristics of Potato Used In the Experiments

For determination of the characteristics of potato, 10 sliced potatoes have been taken.

Table 5. 1 Characteristics of fresh Potato ready for drying purpose

Characteristics	***Average Value***
Shape	Rectangular
Potato kg weight per square meter per tray[kg/m^2]	6.213
Slice length[mm]	49.78
Slice height [mm]	10
Slice width [mm]	7
Surface area [cm^2]	18.32
Average weight of each slice [g]	3.3
Average volume of each slice [cm^3]	3.48
Average density [g/cm^3]	0.947
Moisture content fresh potato (wet basis), m_{wo}	79-83%
Moisture content fresh potato (dry basis), m_{do}	380-450%
Dried material of the potato (wet basis)	8.8-19.2%
Dried material of the potato (dry basis)	48.1-97.5%

For determination of the characteristics of potato, 10 slices are taken as an average for all potato. These characteristics of the potato will surely affect the rate of moisture loss during the drying process. To ensure this an experiment is conducted by increasing the surface area two times by adjusting the supper-slicer cutting edges and the result show that the duration of time for drying process is reduced by half. This shows that as the surface area increase the drying rate increases. Sample of the potato slice diagram is shown in Figure E.1 of Annex E.

Since the selected vegetable slice for conducting the experiments has almost the same size, weight and characteristics shown in Table (5.1), the change in the behavior of the drying process is due to change in the drying parameters such as the drying air temperature, relative humidity and drying air mass velocity flux for all variations recorded.

5.2 Experimental Work for Drying Potato

It was shown that the readings of the moisture content of the drying fruit corresponding to the passing time through the drying process are the main important data in the eight experiments as shown in the Table (5.2) and Annex (B). From these data, the results dealing with loss of moisture content of potato, and the instantaneous drying rate could be all calculated and related to the time. Also, the duration of drying time and the range of potato moisture content through each of rising rate, and the falling drying rate occurred could be determined.

Table 5. 2 Test Treatment of drying air conditions for studying their effects on the drying process of Potato

Treatment Number	Drying Controlling Variables at the inlet of drying chamber		
	Drying Air Velocity [kg/m^2 s]	Mean Drying Air Relative Humidity [%]	Mean Drying Air Temperature [^{o}C]
1	0.19	8.084	50.173
2	0.187	12.349	38.242
3	0.183	18.6	26.496
4	0.19	14.681	50.881
5	0.191	23.201	51.401
6	0.193	25.85	54.06
7	0.176	18.681	40.203
8	0.146	13.776	48.536
9	0.191	15.13	50.6

Table 5. 3 All air property measurements taken from the air conditioner In the preparation of the experiment

Treatment number	1	2	3	4	5	6	7	8	9
Dry bulb temperature T_{db} [^oC]	50.1	38.2	26.5	50.9	51.45	54	40.2	48.53	50.6
relative humidity RH [%]	8.08	12.35	18.6	14.68	23.2	25.85	18.7	13.8	15.13
Orifice differential (Duct)[mmH_2O]	4.4	4.4	4.4	4.4	4.4	4.4	3.9	2.6	4.4
Voltage [V]	220	220	220	220	220	220	220	225	230
Pre-heater current (0.5kw) I_p [A]	-	-	-	2.5	2.5	2.5	2.4	2.4	2.4
Pre-heater current (1 kw)I_p [A]	4.4	-	-	4.4	4.5	4.6	-	-	4.9
Boiler Current (1 kw) I_b [A]	-	-	-	8.4	8.6	8.6	-	-	-
Boiler Current (2 kw) I_b [A]	-	-	-	-	8.8	8.6	-	-	-
Boiler Current (2 kw) I_b [A]	-	-	-	-	-	4.4	-	-	-
Re-heater current (1 kw) I_r [A]	4.5	4.6	-	4.6	5	4.8	4.8	4.8	4.8
Re-heater current (0.5 kw) I_r [A]	2.4	2.4	-	2.6	2.6	2.4	2.4	2.4	2.4
Fan current I_f [A]	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6
Air specific Volume near the duct [kg/^{3}m]	0.84	0.872	0.907	0.837	0.828	0.818	0.864	0.841	0.835
Mass velocity flux [kg/m^{2}s]	0.19	0.187	0.183	0.19	0.191	0.193	0.176	0.146	0.191
Total power consumed [KW]	2.618	1.672	0.132	5.082	7.172	8.03	2.244	2.244	3.473
Energy Consumed [KWh]	23.562	16.72	1.584	50.82	71.72	88.33	22.44	22.44	17.365

Altitude: 2250m
Ambient Temperature: 23^{o}C
Relative Humidity: 45%

5.3 The Moisture Content and Drying Rate of Material

The moisture content of fresh potato used in the experimental work was ranging between 380% and 450% or from 79% to 83% moisture content on dry basis and on wet basis, respectively. The original moisture content, dry basis, "m_{do} " of fresh potato of weight "w_{in}" were dried in an electrical drier called AMB (AMB 310) moisture balance at 160°C until the weight w_o of the dried sample became stable or until the results were the same for three consecutive strobe intervals. According to Robert E.Treybal [12], the moisture content, on dry basis, m_{do} of the fresh potato is expressed as:

$$m_{do} = \frac{w_{in} - w_o}{w_o} 100\% \tag{5.1}$$

For moisture content on wet basis, m_{wo} of fresh potato is determined from:

$$m_{wo} = \frac{w_{in} - w_o}{w_{in}} 100\% \tag{5.2}$$

For determination of the moisture content, on dry basis, "m_d" of potato at any time "t" during the process, the following equation could be used.

$$\begin{gathered} m_d = \frac{w \ - w_o}{w_o} 100\% \\ or \\ m_d = \frac{w_{is} - w_{os}}{w_{os}} \end{gathered} \tag{5.3}$$

where

w = the weight of the potato at time "t"

w_{is} = initial weight of sample taken at time "t" from the drying chamber to *AMB 310* moisture balance

w_{os} = Final weight of sample weigh that taken from the drying chamber after drying in the *AMB310* moisture balance

Then

$$w = w_o \frac{1 + m_d}{100} \tag{5.4}$$

The determination of the potato moisture content at any time was done by taking a sample at time “t” from the drying chamber to the AMB 310 moisture balance.

For determination of moisture percentage on wet basis, “m_w” at time “t” is:

$$\begin{gathered} m_w = \frac{w_{is} - w_{os}}{w_{is}} 100\% \\ or \\ m_w = \frac{w - w_o}{w_{in}} 100\% \end{gathered} \tag{5.5}$$

For determination of the weight of moisture present in potato at any drying time “t”

$$\begin{gathered} w_{pm} = \frac{w_{in} m_w}{100} \\ or \\ w_{pm} = \frac{m_d w_o}{100} \\ or \\ w_{pm} = w - w_o \end{gathered} \tag{5.6}$$

Moisture percentage on wet basis, at drying time “t”

$$m_w = \frac{w_{pm}}{w_{in}} 100\% \tag{5.7}$$

Moisture percentage on dry basis, at drying time “t”

$$m_d = \frac{w_{pm}}{w_o} 100\% \tag{5.8}$$

For determination of the instantaneous drying rate “dr” (dry basis)

$$dr = -\frac{\Delta w}{w_o \Delta t} = -\frac{w_i - w_{i-1}}{w_o (t_i - t_{i-1})} \qquad kg\, moist / kg\, of\ 100\%\ dried\ mt.\mathrm{min} \quad (5.9)$$

Or

$$dr = -\frac{\Delta m_d}{100\Delta t} = -\frac{m_{di} - m_{di-1}}{100(t_i - t_{i-1})} \quad kg\, moist / kg\, of\ 100\%\ dried\ mt.\mathrm{min} \qquad (5.10)$$

Wet basis:

$$dr = -\frac{\Delta m_w}{100\Delta t} = -\frac{m_{wi} - m_{wi-1}}{100(t_i - t_{i-1})}\ kg\, moist / kg\, in.wt.\mathrm{min} \qquad (5.11)$$

For determination of moisture percentage loss during drying process with respect to the original weight of the drying material (f_{ff}):

$$f_{ff} = \frac{(w_{in} - w_o) - w_{pm}}{w_{in}} 100\% \qquad (5.12)$$

For determination of moisture loss percentage during the drying process of drying materials with respect to the original weight of moisture:

$$f_{fw} = \frac{(w_{in} - w_o) - w_{pm}}{w_{in} - w_o} 100\% \quad = 1 - \frac{w_{pm}}{w_{in} - w_0} \qquad (5.13)$$

5.4 The Experimental Work Treatments

The experimental work is dealt with eight experiment runs. The moisture fraction on wet basis, of the initial and 100 percent dried weight of samples for each tray have been recorded periodically at time intervals of 60 minutes uniformly until the difference of the successive reading of the moisture fractions is very small or zero.

During all periods of the drying process, the values of the drying air temperature and relative humidity are changed and recorded at 30 minutes intervals. As shown in the temperature and relative humidity profiles, in Figure 5.3, Figure 5.4 and Annex C, the inlet temperature, which enters to drying chamber rises during the first five hours of the day then slightly increases or remains constant for the next three or four hours and then starts to decline. On the other hand, the relative humidity profile decreases during the first five hours of the day then decreases slightly or remains constant for some hours and finally starts to increase. These variations are because the inlet drying air is coming from the surrounding environment and the weather condition of the surrounding environment varies through out the day.

In order to conduct the experiment at the required value of the drying parameters, the set point of the parameters should be attained at all points or through-out the drying process. Whenever any slight deviation occurred in any set point value of the drying parameters, there should be suitable adjustments to maintain their values exactly at its set point. But in the experiments conducted it is not possible to control and take action for adjusting the values of the set points. This is because of the nature of the equipment set up does not allow to do the corrections on the deviations occurred. Even if, there exist these limitations it is possible to see the behavior of drying process as function of the drying parameters.

Also, it is shown in the drying air temperature profiles that as one goes from the lower tray to the upper tray, the temperature values of the drying air decreases for the corresponding point in the lower tray or inlet to the drying chamber. This is because the inlet temperature of the drying air for each tray comes from the lower tray. The temperature of drying air coming from the lower tray is used to heat up the potato in the lower tray hence, the drying air temperature decreases. It is also shown in the relative humidity profiles on Figure 5.4 and Annex C that the relative humidity of the drying air increases as we go from the lower tray to the upper tray. This shows that there is moisture loss from the potato and gain of moisture by the drying air. These findings are shown in Figure 5.1, Figure 5.2, Figure 5.4 and Annex C.

From the drying rate profile in Figure 5.1, 5.5, 5.7, 5.10 and Annex C it is shown that the drying rate of potato in Tray 1 and Tray 2 increases and reach a peak drying rate period and then starts to fall. The moisture content at the turning point, which is its peak point, is commonly known as the critical moisture content. From the profiles it is also shown that the duration of the primary rising drying rate period is small compared to the falling drying rate period or for the whole drying process. It is about 22% of the whole duration of drying period.

Before starting the drying process the two trays are filled with similar characteristics of the drying material in this case potato then during drying initially the drying rate of potato in Tray 1 is higher than that of potato in Tray 2. This is due to the fact that the drying air entering the tray one is higher in temperature and relatively dry, which is lower in the value of relative humidity. This is shown in the temperature and relative humidity profiles of Figure 5.3, Figure 5.4, Annex A and Annex C but at some point the drying rate of potato in Tray 2 overtakes the drying rate curve of potato in Tray 1. This is because as drying time goes on the dominant drying characteristic of potato in the two trays vary. That is, the moisture content of potato in Tray 2 is higher than that of the moisture content of potato in Tray 1, this is also shown in the moisture fraction profiles of Figure 5.2, Annex B and Annex C. But the difference in drying air temperature and relative humidity between Tray 1 and Tray 2 became smaller and smaller. The drying air from Tray 1 became relatively dry as drying time goes on relative to the dryness of the drying air from Tray 1 in the initial duration of drying process. This is shown in the temperature and relative humidity profiles of Figure 5.4, Annex A and Annex C. These all show that after certain time the drying rate of potato in Tray 2 is higher than that of potato in Tray 1.

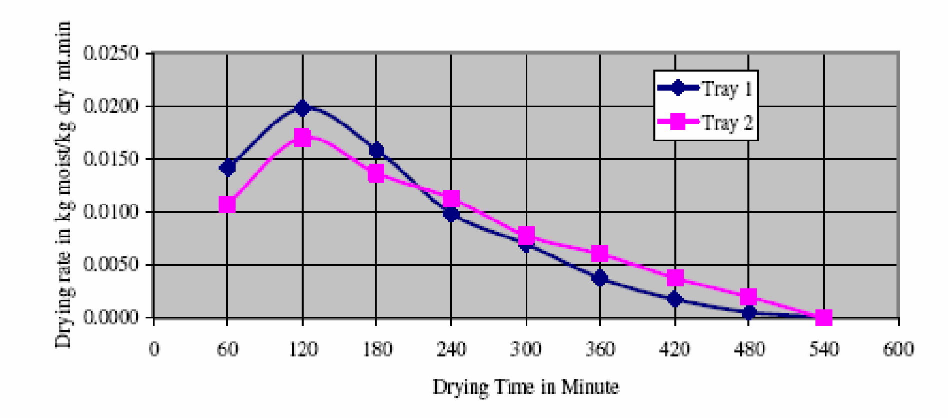


Figure 5. 1 Drying rate profile potato in Tray 1 and Tray 2, at an average inlet temperature = 50.17 °C, relative humidity = 8.08 % and mass velocity flux = 0.19 kg/sm^2. where mt is material

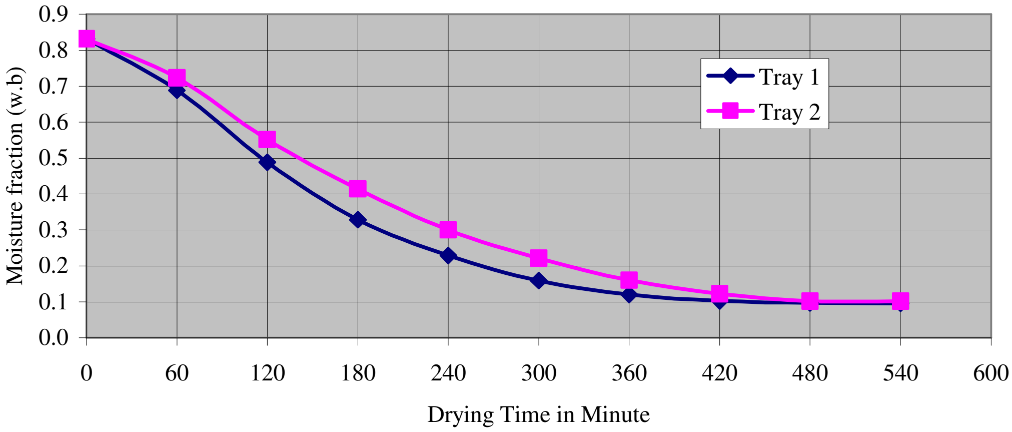


Figure 5. 2 Moisture fraction profile of potato in Tray 1 and Tray 2 at an average inlet temperature = 50.17 °C, relative humidity = 8.08 % and mass velocity flux = 0.19 kg/sm^2

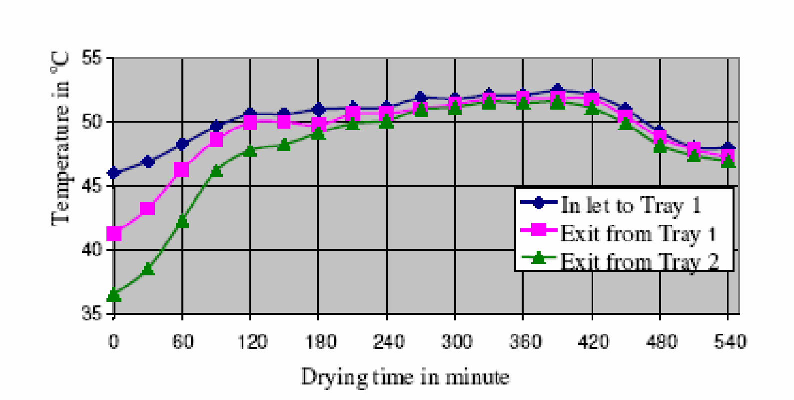


Figure 5. 3 Drying air temperature profile in Tray 1 and Tray 2 at an average relative humidity = 8.08 % and mass velocity flux = 0.19 kg/sm^2

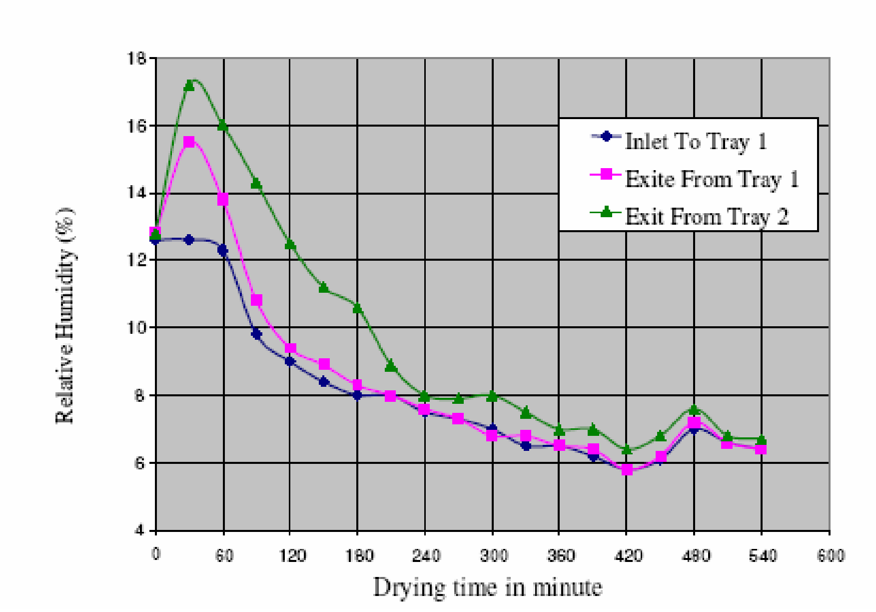


Figure 5. 4 Drying air relative humidity profile Tray 1 and Tray 2 at an average inlet temperature = 50.17 ^{o}C and velocity = 0.19 kg/sm^2

5.5 The Factors Affecting Drying Process of Agricultural Products

5.5.1 Temperature

The effects of the drying air temperature on the drying characteristics of potato are shown in the experimental results of Test 1 (drying air mass velocity flux = 0.19 kg/sm^2, drying air relative humidity =8.08% and average drying air temperature = 50.173 ^{o}C), Test 2 (drying air mass velocity flux = 0.187 kg/sm^2, drying air relative humidity = 12.349% and average drying air temperature = 38.242 ^{o}C) and Test 3 (drying air mass velocity flux = 0.183 kg/sm^2, drying air relative humidity = 18.6% and average drying air temperature = 26.496^{o}C) in Figure 5.5, Figure 5.6, Table B.1 and Table B.2. As shown in Figure 5.5, Figure 5.6, Table B.1 and Table B.2 as drying air temperature increases, the drying rate and the moisture loss increases provided that the other drying parameters and material characteristics remain constant. As drying time goes on the characteristics of the drying material are changed especially, moisture content and at some point the drying material having higher moisture content will have higher drying rate because the inlet temperature for each treatment remains with no major change but the moisture content of the drying material treated with higher temperature have lower value than that of the drying material treated with lower drying air temperature.

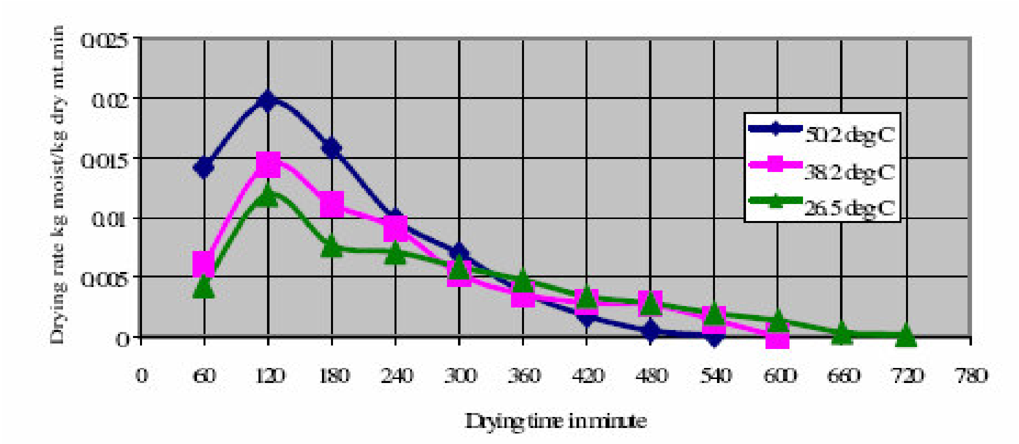


Figure 5. 5 Drying rate curves as function of drying time to show the effect of drying air temperature on the drying rate of potato in the primary rising and the falling drying rate periods in Tray 1

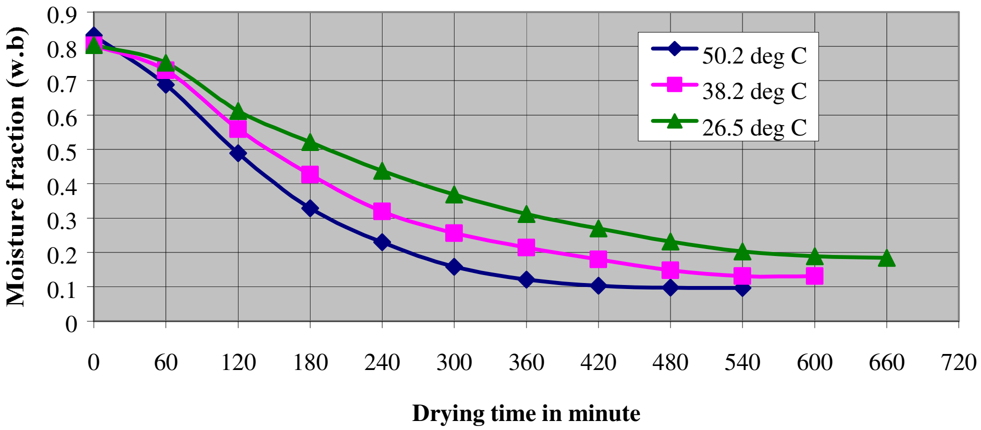


Figure 5. 6 Moisture fraction curves as function of drying time to show the effect of drying air temperature on the moisture loss of potato primary rising and the falling drying rate periods in Tray 1.

5.5.2 Relative Humidity

The effects of the relative humidity of the drying air on the drying characteristics of potato are shown from the experimental results of Test 4 (drying air mass velocity flux = 0.19 kg/sm^2, drying air relative humidity = 14.681 % and average drying air temperature = 50.88 ^{o}C), Test 5 (drying air mass velocity flux = 0.191 kg/sm^2, drying air relative humidity = 23.201 % and average drying air temperature = 51.401 ^{o}C) and Test 6 (drying air mass velocity flux = 0.193 kg/sm^2, drying air relative humidity = 25.85 % and average drying air temperature = 54.06 ^{o}C), in Figure 5.7, Figure 5.8, Table B.3 and Table B.4. As shown in these figures and tables, when the relative humidity of the drying air decreases the drying rate and the moisture loss increase provided that the other drying parameters and material characteristics are constant. As the relative humidity of drying air decreases the capacity of the drying air to absorb moisture will be higher as a result the drying rate will be higher consequently the moisture loss from the material to be dried will be higher. But as time goes on keeping the drying parameters constant there occur a difference in moisture content that is, at the same location and duration of time the material with higher drying rate will have lower moisture fraction than that of the material with lower drying rate. As consequence of this the capacity to loss the moisture content of the material with lower drying rate became high, this is shown in Figure 5.7, Figure 5.8, Table B.3, and Table B.4. As shown from these figures and tables in the first instant the materials with higher drying rate will loss its moisture faster than the material with lower drying rate. From Test 5 and Test 6 drying rate profiles, we didn’t see significant difference in the drying rate as that of the drying rate profiles of Test 4 and Test 5. This is because of the values of the drying parameter temperature in Test 5 and Test 6. Even though the relative humidity of Test 5 is lower than that of Test 6 the drying air temperature of Test 6 is higher and we have seen from Figure 5.5 that as drying air temperature increases the drying rate increases. Therefore, the increase in drying rate due to increase in temperature is compensated by decreased drying air relative humidity. So, as the drying air relative humidity decreases the drying rate and moisture loss increases.

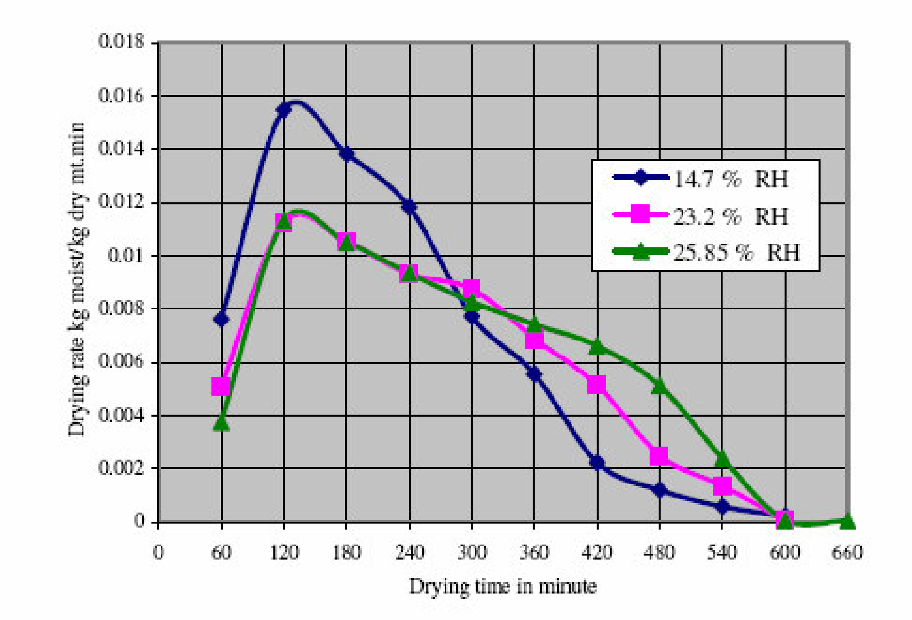


Figure 5. 7 Drying rate curves as function of drying time to show the effect of drying air relative humidity on the drying rate during drying of potato in the primary rising and the falling drying rate periods

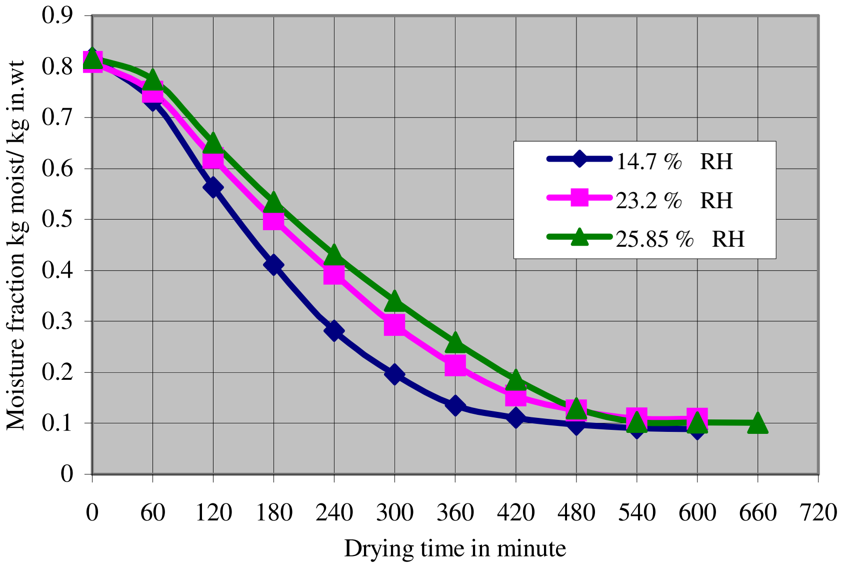


Figure 5. 8 Moisture fraction curves as function of drying time to show the effect of drying air relative humidity on the moisture loss during drying process of potato in the primary rising and the falling drying rate periods

5.5.3 Mass Velocity Flux

The effects of the mass velocity flux of the drying air on the drying characteristics of potato are shown, from the experimental results of Test 1 (at the drying air mass velocity flux = 0.19 kg/sm^2, drying air relative humidity = 8.084 % and an average drying air temperature = 50.173 °C), Test 7 (at drying air mass velocity flux = 0.176 kg/sm^2, drying air relative humidity = 18.681 % and an average drying air temperature = 40.203 °C) and Test 8 (at the drying air mass velocity flux = 0.146 kg/sm^2, drying air relative humidity = 13.776% and average drying air temperature = 48.536 °C) in Figures 5.9, and 5.10, and Tables B.1, B.2, B.5 and B.6. As shown in these figures and tables, when the mass velocity flux of the drying air increases keeping the other drying parameters and material characteristics with no major changes the drying rate and the moisture loss increases. This is because the quantity of lower relative humidity and higher temperature drying air is higher when the drying air mass velocity flux increases. Lower relative humidity and higher temperature drying air has higher capacity of absorbing moisture from the material to be dried section 5.5.1and 5.5.2. But as time goes on keeping the other parameters constant it creates a difference in moisture fraction. That is, at the same location and duration of time the material with higher drying rate will have lower moisture content than that of the material with lower drying rate as consequence of this the drying rate of the low mass velocity flux of the drying air will have higher drying rate. In Test 7 and Test 8 drying rate profiles we didn't see significant difference in the drying rate as that shown by plots from Test 1 and Test 7, and Test 1 and Test 8. This is because the inlet drying air temperature of Test 8 is higher and relative humidity is lower than that of Test 7. It is shown, in Figure 5.5 and Figure 5.7 that as drying air temperature increases and relative humidity decreases the drying rate increases. There fore, the increase in drying rate due to increase in temperature and lowering relative humidity of the drying air has higher effect on the drying rate. So, as the drying air mass velocity flux increase the drying rate and moisture loss increase but it doesn't have the same effect as that of drying air temperature and relative humidity.

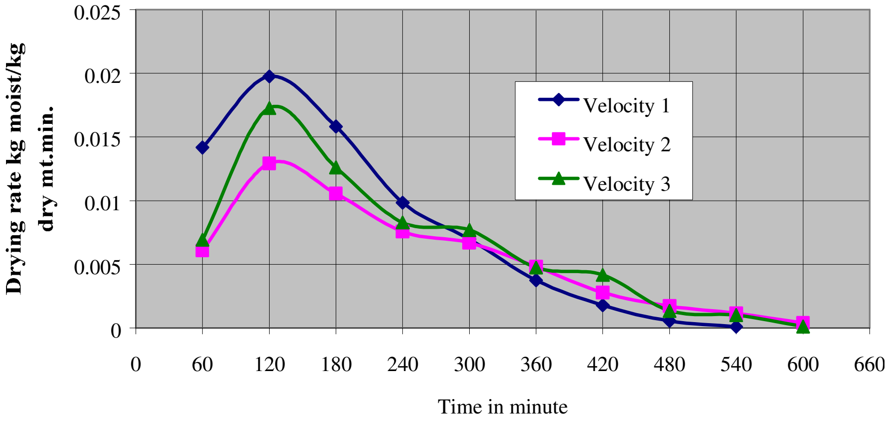


Figure 5. 9 Drying rate curves as function of drying time to show the effect of drying air mass velocity flux on the drying rate during drying of potato in the primary rising and the falling drying rate periods

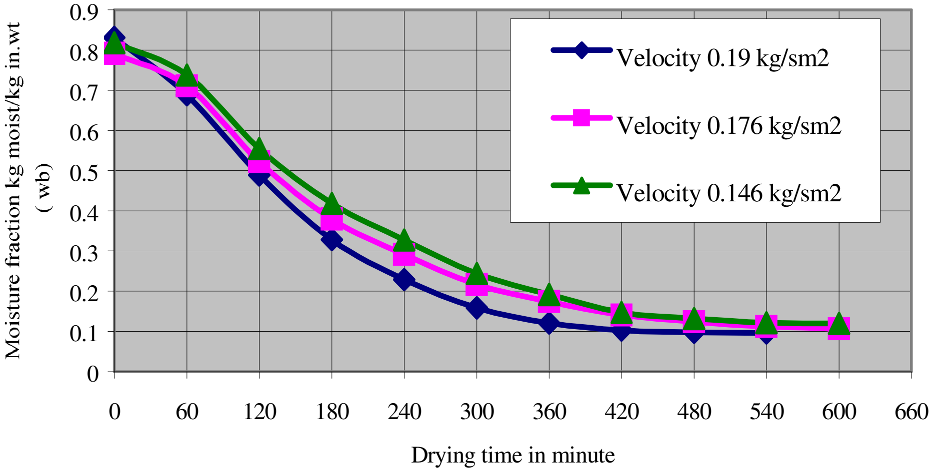


Figure 5. 10 Moisture Fraction Profile of drying Potato to show the effect of drying air mass velocity flux on the moisture loss during drying process of potato in the primary rising and the falling drying rate periods

Table 5. 4 Moisture content and moisture loss percentages

Treatment no	Initial moisture content per kg dry potato	Initial moisture content per kg of fresh potato	Final moisture content per kg of fresh potato	Percent of moisture loss relative to the initial weight of potato	Percent of moisture loss relative to initial weight of moisture
1	4.94	0.8316	0.0965	73.51	88.4
2	4.07	0.8026	0.1306	67.2	83.7
3	4.09	0.8034	0.1916	61.18	76.2
4	4.46	0.817	0.0881	72.89	89.2
5	4.22	0.8086	0.1084	70.02	86.6
6	4.45	0.817	0.1011	71.59	87.6
7	4.45	0.7916	0.1066	68.5	86.5
8	3.798	0.81	0.126	68.4	84.4

5.6 Model for Prediction of Moisture Content on Wet Basis

A feed forward neural network program with a single hidden layer was used to correlate and predict the moisture content of potato in the drying process. It also used in developing correlations which relates the drying parameters that help to show the drying behaviors of potato and determining the moisture content of potato in wet basis as function of the drying parameters: drying air temperature, velocity, relative humidity, initial moisture content of potato and drying time. Experimental data on the drying process of potato reported in Annex A, Annex B, and Annex C have been used to assess the performance of the neural network and the predictive capability of the neural network model. The network has been trained using a subset of available data from the experiments. The developed neural network model is capable of predicting fresh data not belonging to the training subset of the experimental data. Formulation of neural net work relations is found in Matlab software package [14].

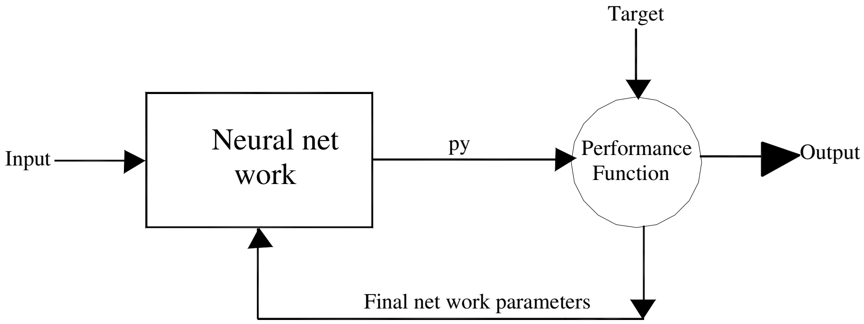


Figure 5. 11 Feed forward flow chart

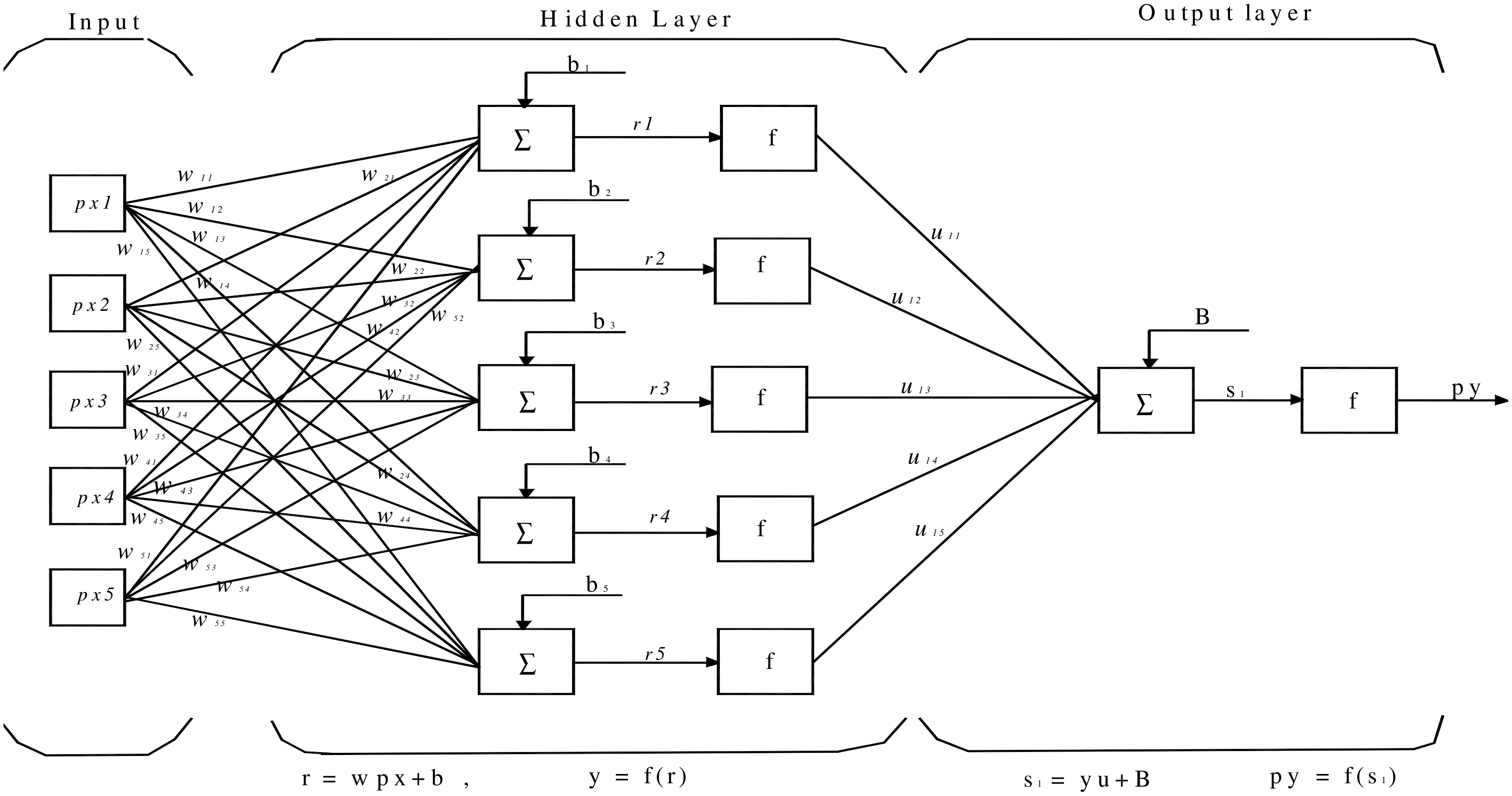


Figure 5. 12 Neural network flowchart

Procedure to use the correlations developed from the experimental data

i. Collect the drying parameter data, temperature, velocity, relative humidity of drying air, the initial moisture content of potato and drying time.

ii. Reject data out of the ranges set in Table 5.5

iii. Normalize all data collected in step i using equation (5.14) through equation (5.18) and normalizing factor ranges from zero to one for this particular study taken as equal to 0.15.

iv. Prepare arguments for the sigmoid transfer function of the hidden layer using Table 5.6, Table 5.7, input data from step iii and (5.19) through equation (5.23).

v. Squash outputs of the hidden layer using arguments from step iv and sigmoid transfer function of equation (5.24) through (5.28).

vi. Prepare the argument of the out put layer using Table 5.7, input data from step v and equation (5.29).

vii. Squash outputs from the output layer using arguments from step vi and linear transfer function of equation (5.30).

viii. Post processing of the outputs from step vii to real data format using equation (5.31).

The model works only with in the drying parameter values ranging from the maximum value to the minimum value as shown in Table 5.5.

Table 5. 5 Maximum and minimum values of drying parameters in all tests

	m_{ow}	t	v	ϕ	T	m_w
max.	0.831618	720	0.193	25.85	54.06	0.831618
min.	0.791599	0	0.146	8.08	26.5	0.088127

Table 5. 6 Synaptic weights of neurons in the hidden layer

Synaptic weights of the first neuron		Synaptic weights of the second neuron		Synaptic weights of the third neuron		Synaptic weights of the forth neuron		Synaptic weights of the fifth neuron	
w_{11}	-4.2761	w_{21}	-4.8078	w_{31}	1.6476	w_{41}	-1.6032	w_{51}	0.4969
w_{12}	-6.0309	w_{22}	-13.7954	w_{32}	-14.824	w_{42}	-6.8275	w_{52}	-13.8375
w_{13}	8.4630	w_{23}	-7.0552	w_{33}	-2.1339	w_{43}	-2.9161	w_{53}	-0.2772
w_{14}	-3.1205	w_{24}	0.7601	w_{34}	5.3802	w_{44}	0.1336	w_{54}	0.4638
w_{15}	-15.3553	w_{25}	-3.1902	w_{35}	-1.3556	w_{45}	-1.1161	w_{55}	- 0.0440

Table 5. 7 Biases for the hidden layer neurons and Synaptic weights for output layer neuron

Biases for the hidden layer neurons		Synaptic weights for output layer neurons, there is only one Output neuron in the network	
b_1	6.36192702744082	u_{11}	0.106371784964606
b_2	11.5480267119463	u_{12}	-0.316950461763409
b_3	4.66478080487753	u_{13}	0.29411313205362
b_4	3.39550824132393	u_{14}	0.65405672193838

The bias for the output layer neuron

$B = 0.15201760276059$

Data preprocessing

The normalization factor eee = 0.15

$$px1 = (1 - 2 * eee) * ((m_{wo} - min\ m_{wo}) \ / \ (max\ m_{wo} - min\ m_{wo})) + eee \qquad (5.14)$$

$$px2 = (1 - 2 * eee) * ((t - min\ t) \ / \ (max\ t - min\ t)) + eee$$

(5.15)

$$px3 = (1 - 2 * eee) * ((v - min\ v) \ / \ (max\ v - min\ v)) + eee$$

(5.16)

$$px4 = (1 - 2 * eee) * ((\phi - min \phi) \ / \ (max \phi - min \phi)) + eee \qquad (5.17)$$

$$px5 = (1 - 2 * eee) * ((T - min\ T) \ / \ (max\ T - min\ T)) + eee \qquad (5.18)$$

Arguments of the sigmoid function of the hidden layer

$$r_1 = w_{11} * px1 + w_{12} * px2 + w_{13} * px3 + w_{14} * px4 + w_{15} * px5 + b_1 \qquad (5.19)$$

$$r_2 = w_{21} * px1 + w_{22} * px2 + w_{23} * px3 + w_{24} * px4 + w_{25} * px5 + b_2 \qquad (5.20)$$

$$r_3 = w_{31} * px1 + w_{32} * px2 + w_{33} * px3 + w_{34} * px4 + w_{35} * px5 + b_3 \qquad (5.21)$$

$$r_4 = w_{41} * px1 + w_{42} * px2 + w_{43} * px3 + w_{44} * px4 + w_{45} * px5 + b_4 \qquad (5.22)$$

$$r_5 = w_{51} * px1 + w_{52} * px2 + w_{53} * px3 + w_{54} * px4 + w_{55} * px5 + b_5 \quad (5.23)$$

Squash outputs from each neuron in the hidden layer and the transfer function (sigmoid) is given as follows:

$$y_1 = 1 \;/\; (1 + Exp(-r_1)) \quad (5.24)$$

$$y_2 = 1 \;/\; (1 + Exp(-r_2)) \quad (5.25)$$

$$y_3 = 1 \;/\; (1 + Exp(-r_3)) \quad (5.26)$$

$$y_4 = 1 \;/\; (1 + Exp(-r_4)) \quad (5.27)$$

$$y_5 = 1 \;/\; (1 + Exp(-r_5)) \quad (5.28)$$

Arguments of the linear transfer function of the output layer

$$s1 = y_1 * u_{11} + y_2 * u_{12} + y_3 * u_{13} + y_4 * u_{14} + y_5 * u_{15} + B \quad (5.29)$$

Squash outputs from each neuron in the output layer and the transfer function (linear) is given as follows:

$$py = s1 \quad (5.30)$$

Post processing of the squash output to real data format

$$m_w = ((py - eee) * (maxm_w - minm_w) / (1 - 2 * eee)) + minm_w \quad (5.31)$$

where

m_{wo}= Initial moisture content on wet basis

t = Drying time [minute]

v = Drying air mass velocity flux [kg/sm^2]

ϕ = Drying air Relative Humidity [%]

T = drying air Temperature [^{o}C]

m_w =moisture fraction wet basis at drying time t

max = maximum

min = minimum and eee = Normalization factor

5.6.1 Results obtained from Correlation Equation verses the Experimental data

Table 5. 6 Comparison of moisture content of potato from the experiments and correlations of Test 1 and Test 2

Drying Time in minute	Test 1			Test 2		
	Moisture fraction on wet basis From:		Error	Moisture fraction on wet basis From:		Error
	Experiment	Correlation formula		Experiment	Correlation formula	
0	0.8316	0.831618	0	0.802643	0.802643	0
60	0.6884	0.688125	0.036382	0.730146	0.702502	3.786049
120	0.4888	0.497206	1.729815	0.55892	0.55766	0.22543
180	0.3289	0.330138	0.39030	0.426707	0.427658	0.222756
240	0.2294	0.2168	5.481498	0.318928	0.323719	1.502117
300	0.1588	0.153201	3.523695	0.256254	0.251676	1.786697
360	0.1209	0.121169	0.228586	0.214122	0.205767	3.901767
420	0.1030	0.105711	2.677076	0.179895	0.176024	2.15175
480	0.0974	0.098266	0.843626	0.147788	0.155253	5.051106
540	0.0964	0.094598	1.834372	0.130921	0.139682	6.692116
600				0.130646	0.127574	2.351576

Table 5. 7 Comparison of moisture content of potato from the experiments and correlations of Test 3 and Test 4.

Drying Time in minute	Test 3			Test 4		
	Moisture fraction on wet basis from:		Error [%]	Moisture fraction on wet basis from:		Error [%]
	Experimental	Correlation formula		Experimental	Correlation formula	
0	0.803380653	0.803381	0	0.816952	0.816952	0
60	0.752423993	0.761352	1.186556	0.733225	0.72571	1.024977
120	0.612082037	0.612583	0.081844	0.563053	0.56497	0.340374
180	0.521351931	0.507432	2.669899	0.411124	0.406954	1.014245
240	0.437391115	0.437202	0.043261	0.28125	0.277807	1.224265
300	0.368082368	0.37396	1.596748	0.196159	0.190431	2.920183
360	0.311706303	0.312385	0.217709	0.135068	0.140747	4.204661
420	0.271623672	0.264622	2.577647	0.110469	0.115448	4.507278
480	0.238216099	0.234374	1.612763	0.097065	0.103117	6.23541
540	0.214640523	0.216417	0.827555	0.090616	0.097098	7.153437
600	0.198532585	0.204976	3.245565	0.088127	0.094075	6.749093
660	0.193943764	0.196386	1.259169			
720	0.191619	0.188643	1.55332			

Table 5. 8 Comparison of moisture content of potato from the experiments and correlations of Test 5 and Test 6.

Drying Time in minute	Test 5			Test 6		
	Moisture fraction on wet basis from:		Error [%]	Moisture fraction on wet basis from		Error [%]
	Experimental	Correlation formula		Experimental	Correlation formula	
0	0.808616404	0.808616	0	0.81656	0.81656	0
60	0.750160483	0.742464	1.025913	0.775052	0.781068	0.776234
120	0.620876554	0.620977	0.016256	0.650335	0.650596	0.040098
180	0.5	0.501963	0.392596	0.534709	0.530306	0.823512
240	0.393073762	0.394721	0.41909	0.431654	0.431406	0.057443
300	0.292422933	0.295565	1.074638	0.340563	0.342184	0.476089
360	0.213256056	0.211601	0.775888	0.258694	0.256141	0.987114
420	0.153995108	0.154093	0.063857	0.18577	0.184577	0.642022
480	0.125041268	0.121791	2.599649	0.129278	0.13793	6.692574
540	0.109320773	0.105653	3.355057	0.102792	0.112901	9.834749
600	0.108441558	0.097946	9.678231	0.1019	0.100847	1.032849
660				0.101125	0.095286	5.773812

Table 5. 9 Comparison of moisture content of potato from the experiments and correlations of Test 7 and Test 8.

Drying Time in minute	Test 7			Test 8		
	Moisture fraction on wet basis from:		Error [%]	Moisture fraction on wet basis from:		Error [%]
	Experimental	Correlation formula		Experimental	Correlation formula	
0	0.791599208	0.791599	0	0.818519	0.818519	0
60	0.710886076	0.709308	0.222028	0.743084	0.741253	0.24635
120	0.521847975	0.525397	0.680088	0.555095	0.563331	1.483707
180	0.379445882	0.381172	0.455033	0.417885	0.417846	0.00931
240	0.291126529	0.281574	3.281243	0.327718	0.316582	3.398189
300	0.216443784	0.214587	0.857724	0.243881	0.244762	0.36111
360	0.174772401	0.170537	2.423185	0.192241	0.190685	0.809207
420	0.140979983	0.142797	1.289061	0.146917	0.153059	4.180416
480	0.124261132	0.125401	0.917582	0.132316	0.129476	2.146388
540	0.111717365	0.114145	2.172955	0.121331	0.115222	5.034474
600	0.106597563	0.106625	0.025462	0.120032	0.10648	11.29079

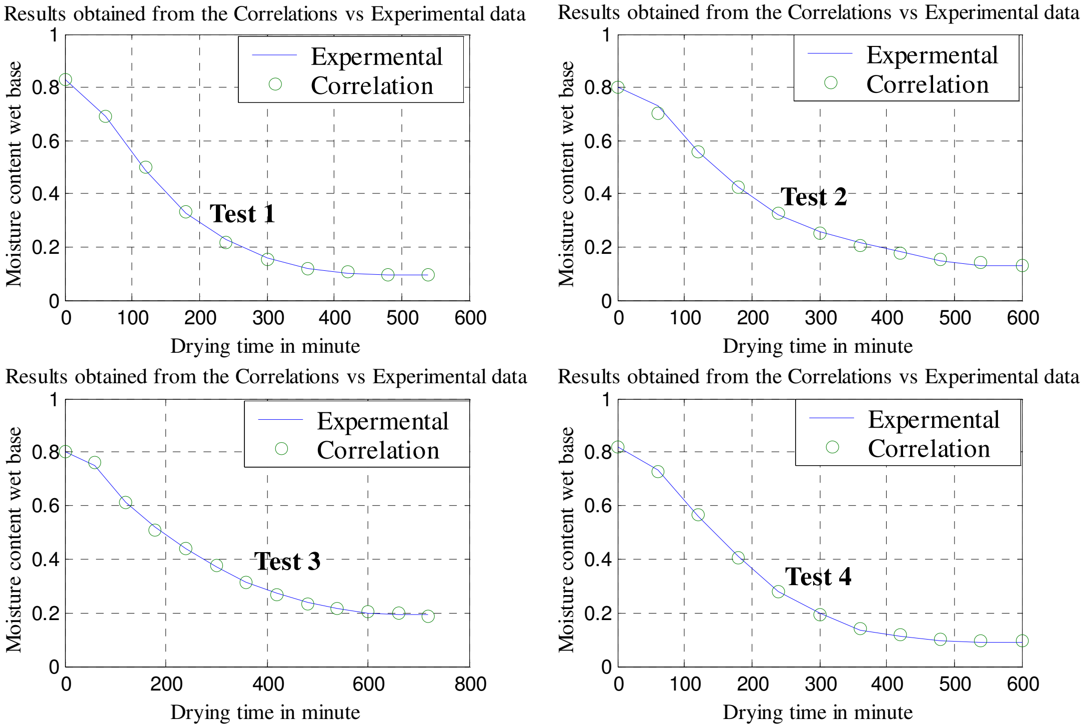


Figure 5. 13a Testing of Results from Empirical Equation by Experimental Data of Test 1, Test 2, Test 3 and Test 4

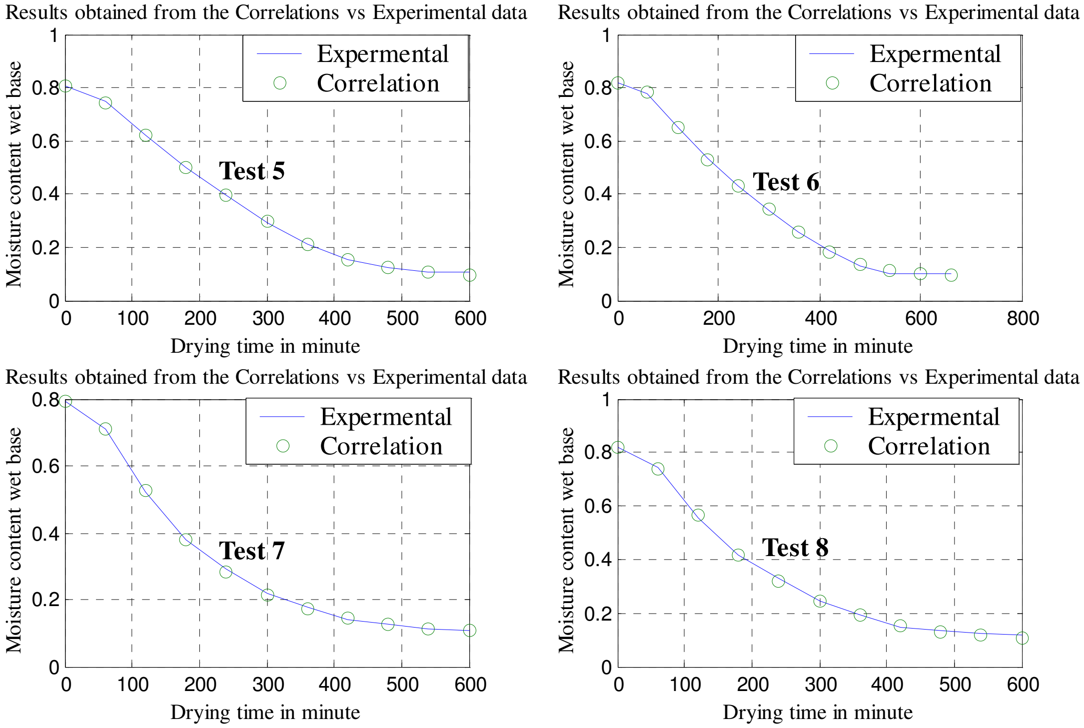


Figure 5. 13b Testing of Results from Empirical Equation by Experimental Data of Test 5, Test 6 Test 7 and Test 8

Visual Basic Program is used to develop a relation between moisture content wet basis and the drying parameters on excel spread sheet that predict the drying characteristics of potato. The correlation constants are obtained from a feed forward neural network using a drying data in a separate Matlab program. As shown in Tables 5.8 through Table 5.11 and Figure 5.13a and Figure 5.13b, the deviation of the results from the correlations with that of the experimental data are minimal. The maximum error is 11.3 %. About 96% of the total results are within 6% error, but the correlation formulas are limited to the data ranges stated in Table 5.5 that is, the extrapolating capacity of the correlation formula is poor because of the nature of the neural network.

Chapter Six

Conclusion and Recommendation

6.1 Conclusion

In this study the experimental set up has been developed to investigate the drying rate of the selected material. The drying air temperature and relative humidity and moisture content profiles have been developed with the food materials during forced convective air drying.

All profiles describe the drying phenomena inside each trays of the drying chamber. Finally correlation have been developed from the experimental data to relate the drying parameters; drying air temperature, relative humidity, velocity, initial moisture content of material to be dried and drying time that predict the moisture content on wet basis.

Based on the experimental analysis result obtained, the following conclusions are derived

1. Potato can be dried with an air temperature ranging from 26 to 54 ^{o}C, relative humidity ranged from 8 to 26% under air mass flux velocity of ranged 0.146 to 0.193 kg/sm^{2}.

2. The initial moisture content of the local fresh potato ranges from 79 to 83%(w.b) and from 380 to 450 % (d.b) and the final or the equilibrium moisture content of the dried potato ranges from 8.8 to 19.2%(w.b) and from 48.1 to 97.5% (d.b).

3. Total moisture loss percentage for all the tests ranged from 61.2 to 73.5% of the original total weight of the fresh fruit. Total moisture loss percentage for all the tests ranged from 83.7 to 89.2% of the original water weight in the fresh potato.

4. The results showed that the drying rate of potato is consisting of two distinct periods which are the increasing drying rate period called the primary drying rate period and the drying rate period called the falling drying rate period.

5. The drying time of potato for the total drying treatment range from 9 to 12hours. The increasing drying rate period for drying fresh potato extends only 2 hours. This drying rate period is very short that is ranging from 16.7 to 22.2% of the total time of the drying process. The total falling drying rate period for drying potato extended from 7 to 10 hours that is between 77.8 to 83.3 % of the total drying time of the drying process.

6. As drying air temperature and mass velocity flux increases moisture loss increases but as drying air relative humidity decreases moisture loss increases.

7. The drying air temperature has the greatest effect on the whole drying process and on the drying time of potato within the falling drying rate period but it doesn't show an effect on the drying time of the primary drying period. The relative humidity of the drying air had the next remarkable effect followed by the air velocity.

8. As we go up from the bottom tray to upward, the drying rate decreases. This is because the inlet drying air temperature to the upper tray is lower than that of the lower tray and also the drying air is relatively wet.

9. From the experimental data the following correlation is developed. But before use

of this correlation one has to follow the procedures in section 5.6 and through equations (5.15) to (5.30)

$$m_w = ((py - eee) * (maxm_w - minm_w) / (1 - 2 * eee)) + minm_w$$

10. 96 percent of the total results from the correlation is within 6 percent error compared to the experimental data. Hence, we can use the correlation comfortably.

11. From the correlations developed it is possible to see the drying behavior of potato and the moisture content of potato wet basis with in the limits of the drying parameters set.

6.2 Recommendation

As it has been discussed in chapter three and five the input drying parameters such as the drying air temperature and relative humidity are with certain deviation to the set point. This is because the drying air has been taken directly from the environment as an input to the drying chamber and there is no way to take an action to adjust the values of the deviations. Therefore, one can study on how to control and adjust at specific value of air temperature, relative humidity to overcome the problem. Considering all the above explanations the following points are recommended as future work.

1. One can do the experimental analysis of grains with the help of the present experimental setup

2. As the drying air is exhausted to the surrounding so, one can study the recirculation of the drying air to improve the thermal efficiency of the drying chamber.

References

1. Adam equipment Co. Ltd. "*AMB moisture balance AMB 50, AMB 110, and AMB 310 "Operating manual."* Bond Avenue, Denbigh East Estate Milton Keynes, MK1 1SW,UK (2000).

2. Delta-T device Ltd., *"User manual for DL2e Data logger Hard Ware Reference''*, version 3,128, low Road, Burwell, Cambridge CBS OEI, UK(200).

3. Delta-T Device Ltd., "*User manual for DL2e Data logger, getting started",* version 5.0, 128 Low road, Burwell, Cambridge CBS OEJ, UK (2000).

4. Delta-T Device Ltd., "*User manual Relative Humidity and Air Temperature sensors."* 128 Low road, Burwell, Cambridge CBS OEJ, UK (2000).

5. Delta-T Device Ltd., *"User manual Temperature probes"*, 128 Low road, Burwell, Cambridge CBS OEJ, UK (2000).

6. Kilk-Othimer, *"Encyclopedia of Chemical Technology",* third edition, volume 8, A Wilkey-Interscience publication, USA.

7. Abraham Seboka, "*Experiment on Re-circulating Air Conditioning",* Unit, AAU,2000.

8. W.C Chiang and J.N. Petersen, "*Experimental Measurement of temperature and moisture profiles during Apple drying",* Washington State University. Pullman, A 99164-2710 USA.

9. Raghavan and Z.Alikhani, *"Molecular Sieves and sand for particulate medium drying of corn"* G.V.S Macdonald Collage of McGill University, Ste Anne de Bellevue, P.Q., H9x ICϕ, Canada.

10. P.l. Ballaney, Refrigeration and Air Conditioning, 13th Edition, 2002.

11. L.R Verma and A. Noomhorm, "*Rice Drying Simulation"*, Louisiana State University Agricultural Center. Baton Rouge, Louisiana 70803-4505 USA.

12. Robert E. Treybal " *Mass transfer Operations*" McGraw Hill Book company, 1981.

13. Robert H. Perry, Done Green, *"Perry's Chemical Engineering Hand book",* Sixth Edition.

14. Matlab software package

15. Alemayehu Ambaw, *"Modeling Chemical Engineering Process Using Artificial Nueral Newtoks"*, 2004

Annex A

Tables of Relative Humidity and Temperature of Drying Air at each Tray Inlet and Exit as Function of drying Period of potato drying

Table A.1 Relative humidity and temperature of drying air at each tray inlet and exit as function of drying period of Test 1

Drying Time in minute	Relative humidity at the exit of the trays			Temperature at each tray		
	At the inlet of Tray 1	Tray 1	Tray 2	At the Inlet of Tray 1	Tray 1	Tray 2
0	12.6	12.8	12.8	46	41.28	36.56
30	12.6	15.5	17.2	46.88	43.2	38.53
60	12.3	13.8	16	48.24	46.24	42.32
90	9.8	10.8	14.3	49.6	48.56	46.16
120	9	9.4	12.5	50.56	49.92	47.76
150	8.4	8.9	11.2	50.56	49.96	48.24
180	8	8.3	10.6	50.96	49.7	49.12
210	8	8	8.9	51.04	50.6	49.84
240	7.5	7.6	8	51.12	50.65	50.08
270	7.3	7.3	7.9	51.84	51.02	50.96
300	7	6.8	8	51.76	51.34	51.12
330	6.5	6.8	7.5	52.08	51.76	51.52
360	6.5	6.5	7	52.08	51.78	51.44
390	6.2	6.4	7	52.4	51.81	51.52
420	5.8	5.8	6.4	52.08	51.75	51.04
450	6.1	6.2	6.8	50.96	50.42	49.84
480	7	7.2	7.6	49.2	48.78	48.16
510	6.6	6.6	6.8	48	47.81	47.36
540	6.4	6.4	6.7	47.92	47.24	46.96

Table A.2. Relative humidity and temperature of drying air at each tray inlet and exit as function of drying period of Test 2

Drying Time in minute	Relative humidity at the exit of the trays			Temperature at each tray		
	At the inlet of Tray 1	Tray 1	Tray 2	At the Inlet of Tray 1	Tray 1	Tray 2
0	16.5	16.5	16.6	33.33	31.78	29.55
30	16.2	17.6	20.5	34.51	31.3	30.08
60	15.5	17	20	35.35	33.18	31.96
90	14	15	17.2	36.04	35.1	33.56
120	13.5	14.5	16.3	36.61	36.01	34.88
150	13.4	14.8	16.4	36.62	36.32	35.4
180	13	13.8	15.5	37.55	37.39	36.76
210	13	13.7	14.8	38.16	38.01	37.53
240	13.2	13.6	15	38.55	38.43	38.02
270	12.8	13.5	14.5	37.29	36.95	35.91
300	12.5	12.8	13.8	30.67	29.51	29.45
330	11.4	12.3	13.4	28.82	27.69	28.56
360	11	12.1	13.1	37.72	37.37	36.61
390	11.2	11.7	12.3	39.54	39.46	39.14
420	10.8	11.1	11.9	40.7	40.76	40.62
450	10.5	10.6	11.2	40.89	40.96	40.96
480	10	10.2	10.7	40.47	40.5	40.47
510	10.2	10.6	11	40.56	40.46	40.34
540	10.2	10.5	10.6	40.22	40.06	39.84
570	10.2	10.2	10.6	39.4	39.24	39
600	10.1	10.2	10.6	38.41	38.23	38

Table A.3. Relative humidity and temperature of drying air at each tray inlet and exit as function of drying period of Test 3

Drying Time in minute	Relative humidity at the exit of the trays			Temperature at each tray		
	At the inlet of Tray 1	Tray 1	Tray 2	At the Inlet of Tray 1	Tray 1	Tray 2
0	22	22	22	22.61	21.01	20.37
30	22.2	30	35.3	22.73	20.69	18.98
60	22	27.1	31.8	23.03	21.47	19.46
90	21	24.4	28.8	23.68	22.47	20.75
120	20.5	24.3	28.5	24.24	23.3	21.98
150	20.5	24.4	27.8	24.7	24.01	22.86
180	20.4	24	26.7	25.09	24.55	23.56
210	20.1	23.5	24	25.49	25.16	24.29
240	20.2	22.7	23.3	25.88	25.67	24.93
270	20.2	21	21.6	26.13	25.99	25.39
300	20.1	21	21.3	26.36	26.3	25.83
330	19	20	20.3	26.79	26.77	26.39
360	18.6	19.3	19.6	27.19	27.24	26.95
390	18.4	19	19.3	27.48	27.57	27.38
420	17.8	18.5	18.8	27.79	27.9	27.8
450	17.4	18.2	18.7	28.29	28.47	28.43
480	17	17.6	18.2	28.85	29.08	29.11
510	17.1	17.8	18.2	29.12	29.38	29.54
540	16.4	16.1	16.4	29.19	29.45	29.64
570	16.2	16.8	17.1	29.29	29.51	29.68
600	16.8	17.5	17.8	28.58	28.72	28.82
630	17	17.3	17.4	28.12	28.19	28.2
660	17	17.3	17.4	27.65	27.65	27.62
690	17.2	17.5	17.5	27.12	27.12	26.89
720	17.3	17.5	17.6	27	26.89	26.78

Table A.4 Relative humidity and temperature of drying air at each tray inlet and exit as function of drying period of Test 4

Drying Time in minute	Relative humidity at the exit of the trays			Temperature at each tray		
	At the inlet of Tray 1	Tray 1	Tray 2	At the Inlet of Tray 1	Tray 1	Tray 2
0	19.2	19.6	19.8	47.68	40.19	35.49
30	18.2	22.4	33.5	48.24	43.2	38.92
60	18	21.5	28.6	48.64	45.84	43.04
90	17.8	19	24.5	48.72	47.04	45.04
120	17.2	18.3	22.5	49.2	48.08	46.56
150	16.4	17.1	19.1	49.52	48.56	46.88
180	15.5	16.7	18.1	49.2	48.48	47.21
210	15.2	16.3	16.8	49.56	48.76	47.84
240	14.8	15.5	16	50	49.36	48.24
270	13.8	14.3	14.8	51.36	51.04	50.24
300	13.2	13.4	14.1	52.24	51.92	51.2
330	13	13.2	13.8	52.64	52.4	51.76
360	12.8	12.6	13.1	52.8	52.24	51.92
390	12.4	12.6	13.1	52.72	52.24	51.68
420	12.2	12.4	13.1	52.72	52.24	51.68
450	12.6	13	14.4	52.32	51.84	51.28
480	12.8	13	13.6	52.16	51.76	51.12
510	13	13.1	13.7	52	51.6	51.04
540	13.4	13.2	13.5	52.16	51.84	51.28
570	13.5	13.3	13.8	52.32	52	51.28
600	13.3	13.3	13.8	52.32	52	51.28
630	13.2	13.3	13.7	52.24	51.12	51.01

Table A.5. Relative humidity and temperature of drying air at each tray inlet and exit as function of drying period of Test 5

Drying Time in minute	Relative humidity at the exit of the trays			Temperature at each tray		
	At the inlet of Tray 1	Tray 1	Tray 2	At the Inlet of Tray 1	Tray 1	Tray 2
0	24.5	24.5	24.5	47.76	42.08	38.48
30	24.2	33.5	35.5	49.92	44.56	42.64
60	25.5	33.5	35.5	49.92	46.16	44.96
90	26	31.1	33.5	50.48	48.24	46.24
120	25.2	30.2	32.4	50.32	48.88	47.2
150	25	29.4	31.5	49.92	48.72	47.44
180	25	28.4	30.3	50	49.12	48.24
210	24.8	26.4	29.1	49.92	49.28	48.4
240	24.4	25.4	27.2	50.08	49.6	49.04
270	23.6	24	26	50.56	50.24	49.6
300	23	23	24.6	51.12	50.8	50.24
330	21.8	21.6	22.8	51.92	51.68	51.12
360	21.2	20.9	22.1	52.96	52.72	52.24
390	21.3	21	22.3	53.28	52.8	52.4
420	21.3	21.1	22.6	53.12	52.64	52.24
450	21.5	21.4	22.6	53.44	52.96	52.56
480	21.6	21.4	22.7	53.6	53.2	52.8
510	21.6	21.4	22.7	53.28	52.88	52.4
540	21.9	21.6	22.8	53.12	52.72	52.16
570	22	21.8	23	53	52.5	52
600	22	22.8	23	52.8	52.2	51.9

Table A.6. Relative humidity and temperature of drying air at each tray inlet and exit as function of drying period of Test 6.

Drying Time in minute	Relative humidity at the exit of the trays			Temperature at each tray		
	At the inlet of Tray 1	Tray 1	Tray 2	At the Inlet of Tray 1	Tray 1	Tray 2
0	31.1	31.4	31.8	48.08	38.55	33.67
30	29.4	42.6	46	51.2	44.08	40.46
60	28.5	38.6	42	51.68	46.64	43.52
90	27.8	38.4	39.8	51.12	47.04	44.4
120	27.7	36.8	38.6	51.44	47.92	45.68
150	27.6	34.6	35.8	52.08	49.36	47.28
180	27.3	32.7	34.4	52.08	50.08	48.16
210	27.2	31.8	34.6	52.64	51.12	49.2
240	26.9	31.4	32.1	53.12	51.92	50
270	26.5	30.2	31.2	53.36	52.8	50.16
300	25.5	27.6	29.2	53.84	53.2	50.96
330	24.8	25.5	26.8	54.56	54.16	51.84
360	24.4	24.9	25.9	55.2	54.88	52.72
390	24.2	24.6	25.35	55.04	54.72	52.56
420	24.2	24.4	25.3	55.28	54.96	52.96
450	24.2	24.7	25	56	55.76	53.68
480	24	24.6	24.8	56.24	56	54.08
510	24	24.2	24.4	56.88	56.72	54.72
540	23.9	24	24.1	57.36	57.12	55.2
570	23.9	24	24	57.68	57.36	55.6
600	23.9	24	24	56.4	56.24	54.96
630	23.8	23.8	23.9	56	55.9	54.4
660	23.8	23.8	23.9	56.1	56	54

Table A.7. Relative humidity and temperature of drying air at each tray inlet and exit as function of drying period of Test 7

Drying Time in minute	Relative humidity at the exit of the trays			Temperature at each tray		
	At the inlet of Tray 1	Tray 1	Tray 2	At the Inlet of Tray 1	Tray 1	Tray 2
0	20.2	20.4	20.6	36.88	32.32	29.7
30	19.6	30	41.6	38.13	33.14	30.62
60	19.8	29.2	41	38.61	35.51	32.39
90	21.1	28.6	36.5	38.27	36.63	33.15
120	20.4	26.7	33	38.71	37.62	34.92
150	20.3	24	27.5	38.83	37.99	36.61
180	20.5	23.5	25.4	38.84	38.24	37.12
210	20.3	22.2	23.4	38.67	38.23	37.26
240	20	21	22.3	38.94	38.64	37.75
270	19.1	20.8	22.3	39.52	39.33	38.38
300	18.1	18.8	20.2	40.71	40.6	39.71
330	18	18.8	20	41.36	41.28	40.46
360	18.4	18.9	19.4	41.76	41.68	40.93
390	19	19.4	19.8	41.12	41.04	40.27
420	18.2	18.4	18.8	40.96	40.88	40.18
450	17.5	17.6	17.8	41.36	41.28	40.73
480	16.4	16.5	16.7	41.04	41.12	40.67
510	16.6	16.4	16.6	41.68	41.76	41.28
540	16.5	16.4	16.6	42.48	42.48	42.08
570	16.4	16.4	16.4	43.04	43.04	42.64
600	15.9	15.6	16	43.36	43.36	42.72

Table A.8. Relative humidity and temperature of drying air at each tray inlet and exit as function of drying period of Test 8.

Drying Time in minute	Relative humidity at the exit of the trays			Temperature at each tray		
	At the inlet of Tray 1	Tray 1	Tray 2	At the Inlet of Tray 1	Tray 1	Tray 2
0	16.2	16.4	16.5	44.24	39.22	34.5
30	15.1	29.5	39	44.66	41.2	36.54
60	15.5	27	36.4	46.12	44.24	40.33
90	15.8	26.3	33.3	47.4	46.56	44.16
120	15.7	24.4	30.3	48.44	47.67	45.76
150	15.4	22.5	29	48.6	47.44	45.24
180	15.2	22.2	26.5	49.01	48.12	47.87
210	15.1	20.8	23.6	50.02	49.6	48.94
240	14.5	18.7	21.3	50.12	49.48	49.01
270	14.1	17.9	21	50.78	49.06	48.9
300	13.7	16.5	20.1	50.89	50.02	49.96
330	13.3	15.4	18.6	51.02	50.82	50.42
360	13	14.4	17	51.1	50.86	50.36
390	12.6	13.9	15.2	51.26	50.81	50.46
420	12.5	14.4	15.2	51.16	50.67	50.04
450	12.5	14.3	14.5	49.88	49.4	48.84
480	12.1	14	14	48.02	47.88	47.1
510	11.9	13.8	13.8	47	46.8	46.24
540	11.7	13.7	13.8	46.88	46.18	45.9
570	11.6	12.9	13	46.64	46.08	45.24
600	11.8	13.6	13.6	46.02	45.46	44.68

Table A.9. Relative humidity and temperature of drying air at each tray inlet and exit as function of drying period of Test 9

Drying Time in minute	Relative humidity at the exit of the trays			Temperature at each tray		
	At the inlet of Tray 1	Tray 1	Tray 2	At the Inlet of Tray 1	Tray 1	Tray 2
0	15.7	15.8	15.9	41.84	31.51	28.22
30	14.2	28.7	47.1	44.88	34.52	27.97
60	14	23	36.5	45.68	39.49	33.68
90	14	21.2	31	45.76	42.96	37.43
120	13.8	18.5	23.2	45.92	44.96	41.6
150	13.8	16.3	20.9	46	45.52	42.88
180	13.6	14.5	17.8	46.4	46.16	44.56
210	13.4	13.5	14.3	46.64	46.48	45.12
240	13.3	13.3	14.1	46.96	46.8	45.68
270	12.9	12.9	13.1	47.44	47.12	45.84
300	12.6	12.6	12.9	48.32	48.08	46.88

Annex B

Moisture Content on Wet and Dry Basis and Drying Rate as Function of Drying Time During Drying of Potato.

Table B.1. Moisture content on wet and dry basis and drying rate as function of drying time on Tray1 of Test 1, 2 and Test 3

Time in min	Test 1			Test 2			Test 3		
	m(w.b)	m(d.b)	N	m(w.b)	m(d.b)	N	m(w.b)	m(d.b)	N
0	0.8316	4.9389		0.8026	4.0670		0.8034	4.0860	
60	0.6884	4.0882	0.0142	0.7301	3.6996	0.0061	0.7524	3.8268	0.0043
120	0.4888	2.9026	0.0198	0.5589	2.8320	0.0145	0.6121	3.1130	0.0119
180	0.3289	1.9530	0.0158	0.4267	2.1621	0.0112	0.5214	2.6516	0.0077
240	0.2294	1.3622	0.0098	0.3189	1.6160	0.0091	0.4374	2.2246	0.0071
300	0.1588	0.9431	0.0070	0.2563	1.2984	0.0053	0.3681	1.8721	0.0059
360	0.1209	0.7180	0.0038	0.2141	1.0849	0.0036	0.3117	1.5853	0.0048
420	0.1030	0.6114	0.0018	0.1799	0.9115	0.0029	0.2716	1.3815	0.0034
480	0.0974	0.5787	0.0005	0.1478	0.7488	0.0027	0.2382	1.2116	0.0028
540	0.0964	0.5723	0.0001	0.1309	0.6634	0.0014	0.2146	1.0917	0.0020
600				0.1306	0.6620	0.00002	0.1985	1.0097	0.0014
660							0.1939	0.9864	0.0004
720							0.1916	0.9746	0.0002

Table B.2. Moisture content on wet and dry basis and drying rate as function of drying time . on Tray 2 of Test 1, 2 and Test 3.

Time in min	Test 1			Test 2			Test 3		
	m(w.b)	m(d.b)	N	m(w.b)	m(d.b)	N	m(w.b)	m(d.b)	N
0	0.8316	4.9389		0.8026	4.0670		0.8034	4.0860	
60	0.7230	4.2937	0.0108	0.7664	3.8835	0.0031	0.7720	3.9263	0.0027
120	0.5515	3.2755	0.0170	0.6103	3.0923	0.0132	0.6521	3.3168	0.0102
180	0.4139	2.4582	0.0136	0.5024	2.5456	0.0091	0.5460	2.7768	0.0090
240	0.3001	1.7823	0.0113	0.3989	2.0214	0.0087	0.4581	2.3300	0.0074
300	0.2214	1.3149	0.0078	0.3104	1.5729	0.0075	0.3853	1.9597	0.0062
360	0.1604	0.9528	0.0060	0.2577	1.3059	0.0045	0.3230	1.6428	0.0053
420	0.1223	0.7263	0.0038	0.2068	1.0479	0.0043	0.2734	1.3906	0.0042
480	0.1021	0.6064	0.0020	0.1649	0.8355	0.0035	0.2373	1.2071	0.0031
540	0.1021	0.6061	0.000004	0.1327	0.6722	0.0027	0.2143	1.0900	0.0020
600				0.1321	0.6694	0.00005	0.1976	1.0048	0.0014
660							0.1931	0.9823	0.0004
720							0.1931	0.9821	0.0000

Table B.3. Moisture content on wet and dry basis and drying rate as function of drying time on Tray 1 of Test 4, 5 and Test 6

Time in min	Test 4			Test 5			Test 6		
	m(w.b)	m(d.b)	N	m(w.b)	m(d.b)	N	m(w.b)	m(d.b)	N
0	0.8170	4.4630		0.8086	4.2251		0.8166	4.4514	
60	0.7332	4.0056	0.0076	0.7502	3.9197	0.0051	0.7751	4.2251	0.0038
120	0.5631	3.0760	0.0155	0.6209	3.2441	0.0113	0.6503	3.5452	0.0113
180	0.4111	2.2460	0.0138	0.5000	2.6125	0.0105	0.5347	2.9149	0.0105
240	0.2813	1.5365	0.0118	0.3931	2.0538	0.0093	0.4317	2.3531	0.0094
300	0.1962	1.0716	0.0077	0.2924	1.5279	0.0088	0.3406	1.8565	0.0083
360	0.1351	0.7379	0.0056	0.2133	1.1143	0.0069	0.2587	1.4102	0.0074
420	0.1105	0.6035	0.0022	0.1540	0.8046	0.0052	0.1858	1.0127	0.0066
480	0.0971	0.5303	0.0012	0.1250	0.6534	0.0025	0.1293	0.7047	0.0051
540	0.0906	0.4950	0.0006	0.1093	0.5712	0.0014	0.1028	0.5604	0.0024
600	0.0881	0.4814	0.0002	0.1084	0.5666	0.0001	0.1019	0.5555	0.0001
660							0.1011	0.5513	0.0001

Table B.4. Moisture content on wet and dry basis and drying rate as function of drying time on Tray 2 of Test 4, 5 and Test 6.

Time in min	Test 4			Test 5			Test 6		
	m(w.b)	m(d.b)	N	m(w.b)	m(d.b)	N	m(w.b)	m(d.b)	N
0	0.8170	4.4630		0.8086	4.2251		0.8166	4.4514	
60	0.7437	4.0630	0.0067	0.7649	3.9965	0.0038	0.7809	4.2570	0.0032
120	0.5925	3.2369	0.0138	0.6453	3.3719	0.0104	0.6631	3.6147	0.0107
180	0.4613	2.5201	0.0119	0.5333	2.7867	0.0098	0.5537	3.0183	0.0099
240	0.3555	1.9422	0.0096	0.4317	2.2554	0.0089	0.4528	2.4682	0.0092
300	0.2700	1.4749	0.0078	0.3383	1.7675	0.0081	0.3621	1.9742	0.0082
360	0.1964	1.0727	0.0067	0.2539	1.3264	0.0074	0.2802	1.5274	0.0074
420	0.1435	0.7841	0.0048	0.1773	0.9264	0.0067	0.2088	1.1380	0.0065
480	0.1125	0.6147	0.0028	0.1436	0.7503	0.0029	0.1489	0.8119	0.0054
540	0.0895	0.4888	0.0021	0.1276	0.6666	0.0014	0.1132	0.6169	0.0032
600	0.0842	0.4597	0.0005	0.1242	0.6488	0.0003	0.1054	0.5747	0.0007
							0.1032	0.5627	0.0002

Table B.5. Moisture content on wet and dry basis and drying rate as function of drying time on Tray 1 of Test 7, 8 and Test 9.

Time in min	Test 7			Test 8			Test 9		
	m(w.b)	m(d.b)	N	m(w.b)	m(d.b)	N	m(w.b)	m(d.b)	N
0	0.7916	3.7984		0.8185	4.5102		0.8169	4.4627	
60	0.7109	3.4111	0.0065	0.7383	4.0682	0.0074	0.6640	3.6275	0.0139
120	0.5218	2.5041	0.0151	0.5551	3.0587	0.0168	0.2755	1.5048	0.0354
180	0.3794	1.8207	0.0114	0.4179	2.3026	0.0126	0.1040	0.5679	0.0156
240	0.2911	1.3970	0.0071	0.3277	1.8058	0.0083	0.0877	0.4793	0.0015
300	0.2164	1.0386	0.0060	0.2439	1.3438	0.0077	0.0825	0.4509	0.0005
360	0.1748	0.8386	0.0033	0.1922	1.0593	0.0047			
420	0.1410	0.6765	0.0027	0.1469	0.8095	0.0042			
480	0.1243	0.5963	0.0013	0.1323	0.7291	0.0013			
540	0.1117	0.5361	0.0010	0.1213	0.6686	0.0010			
600	0.1066	0.5115	0.0004	0.1200	0.6614	0.0001			

Table B.6. Moisture content on wet and dry basis and drying rate as function of drying time on Tray 2 of Test 7, 8 and Test 9.

Time in min	Test 7			Test 8			Test 9		
	m(w.b)	m(d.b)	N	m(w.b)	m(d.b)	N	m(w.b)	m(d.b)	N
0	0.7916	3.7984		0.8185	4.5102		0.8169	4.4627	
60	0.7155	3.4334	0.0061	0.7431	4.0946	0.0069	0.7711	4.2124	0.0042
120	0.5539	2.6580	0.0129	0.5829	3.2122	0.0147	0.4881	2.6661	0.0258
180	0.4219	2.0246	0.0106	0.4547	2.5054	0.0118	0.2335	1.2757	0.0232
240	0.3274	1.5710	0.0076	0.3591	1.9785	0.0088	0.0998	0.5454	0.0122
300	0.2437	1.1693	0.0067	0.2708	1.4922	0.0081	0.0950	0.5189	0.0004
360	0.1836	0.8809	0.0048	0.2000	1.1020	0.0065			
420	0.1489	0.7143	0.0028	0.1519	0.8372	0.0044			
480	0.1274	0.6115	0.0017	0.1358	0.7481	0.0015			
540	0.1131	0.5427	0.0011	0.1237	0.6815	0.0011			
600	0.1081	0.5186	0.0004	0.1227	0.6759	0.0001			

Annex C

Drying Rate, Moisture Content, Temperature and Relative Humidity Profiles on Potato Drying

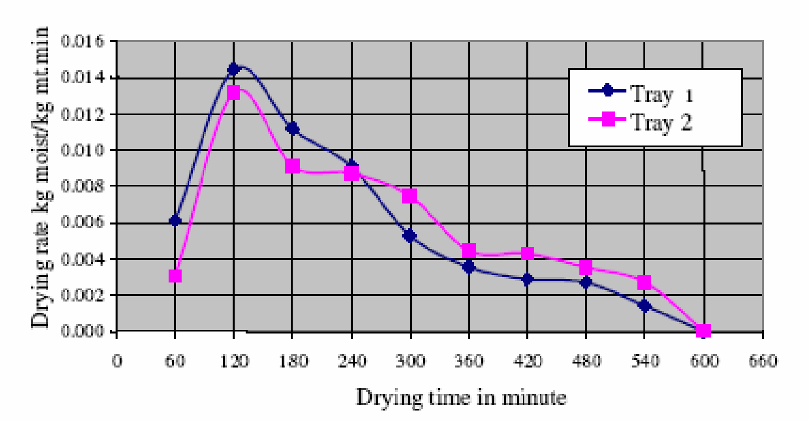


Figure C. 1 Drying Rate Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 38.242 °C, Relative humidity = 12.35 % and mass velocity flux = 0.187 kg/sm^2

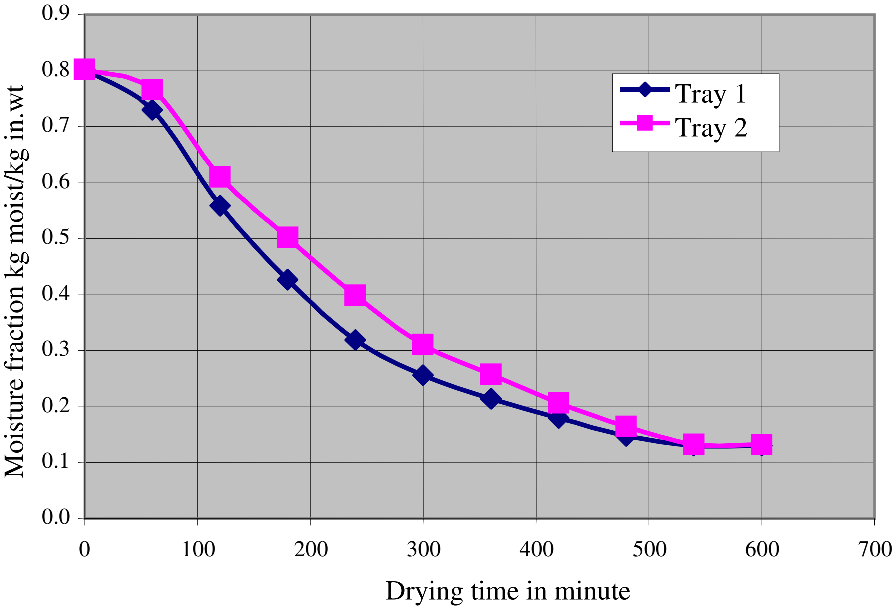


Figure C. 2 Moisture Content Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 38.24 °C, Relative humidity = 12.35 % and mass velocity flux = 0.187 kg/sm^2

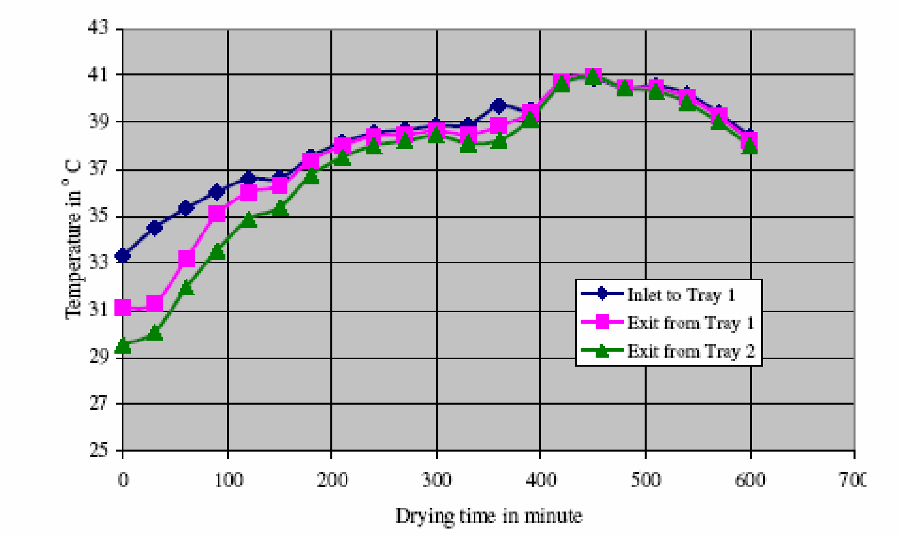


Figure C. 3 Drying Air Temperature Profile of Potato Drying in Tray 1 and Tray 2 at an average Relative humidity = 12.35 % and mass velocity flux = 0.187 kg/sm^2

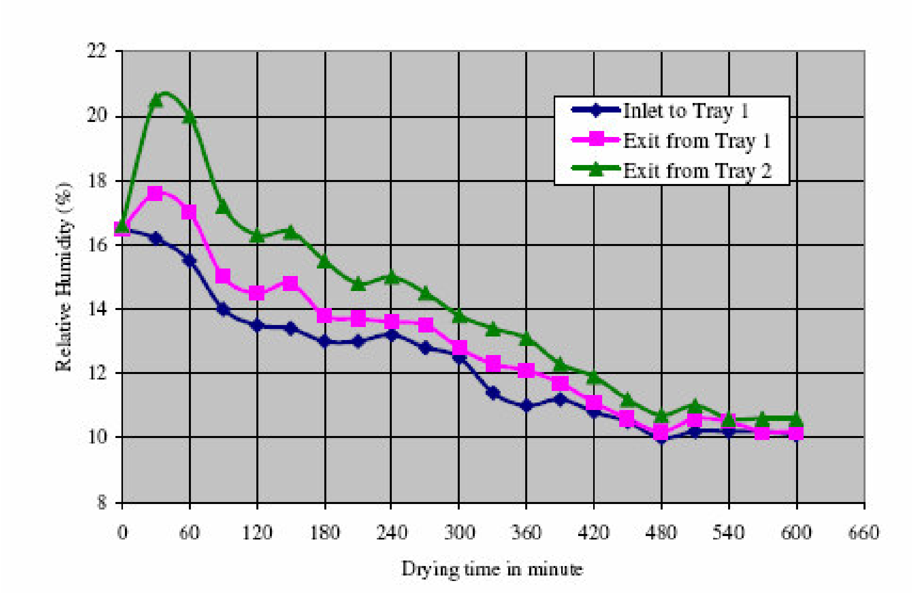


Figure C. 4 Drying Air Relative Humidity Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 38.24 ^{o}C and mass velocity flux = 0.187 kg/sm^2

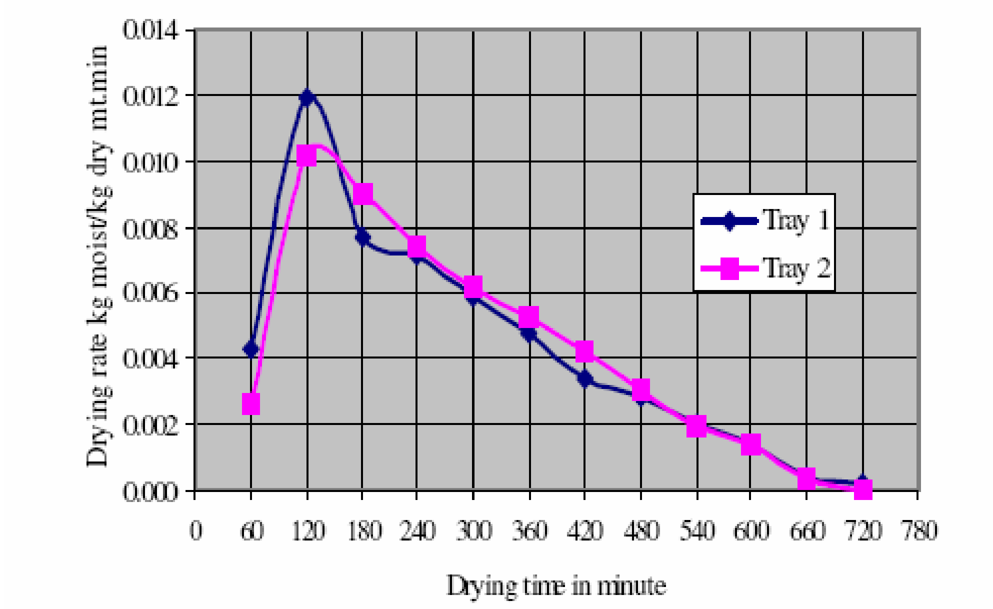


Figure C. 5 Drying Rate Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 26.5 °C, Relative humidity = 18.6 % and mass velocity flux = 0.183 kg/sm^2

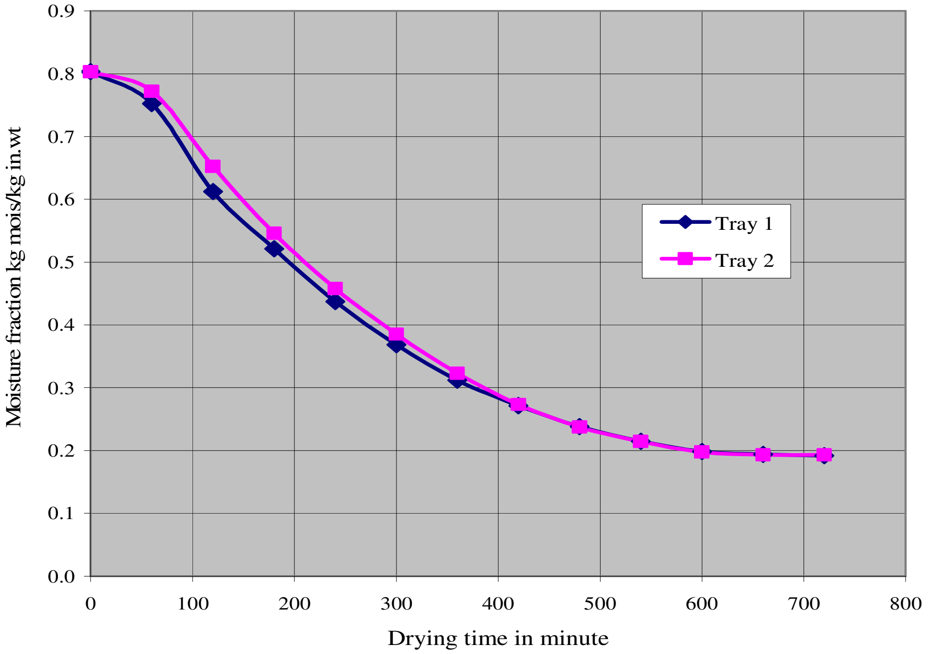


Figure C. 6 Moisture Content Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 26.5 °C, Relative humidity = 18.6 % and mass velocity flux = 0.183 kg/sm^2

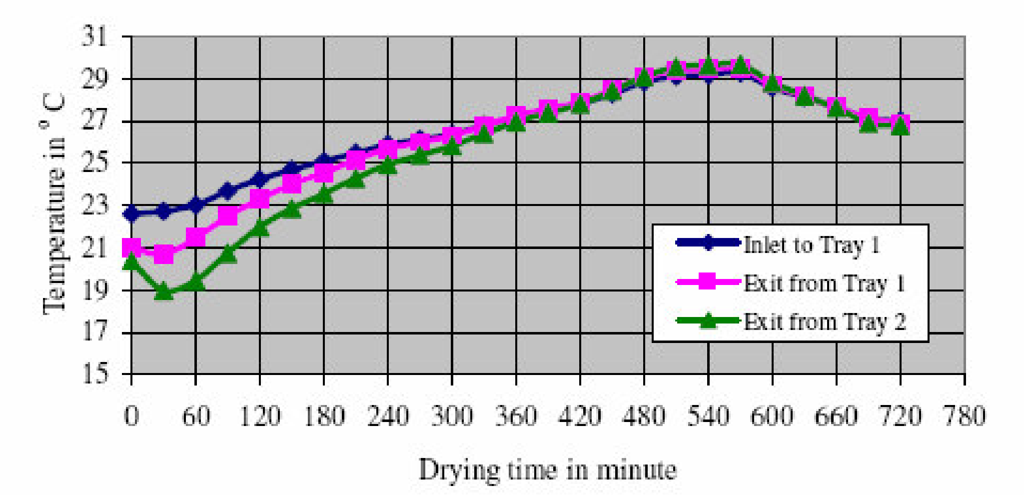


Figure C. 7 Drying Air Temperature Profile of Potato Drying in Tray 1 and Tray 2 at an average Relative humidity =18.6 % and mass velocity flux = 0.183 kg/sm^2

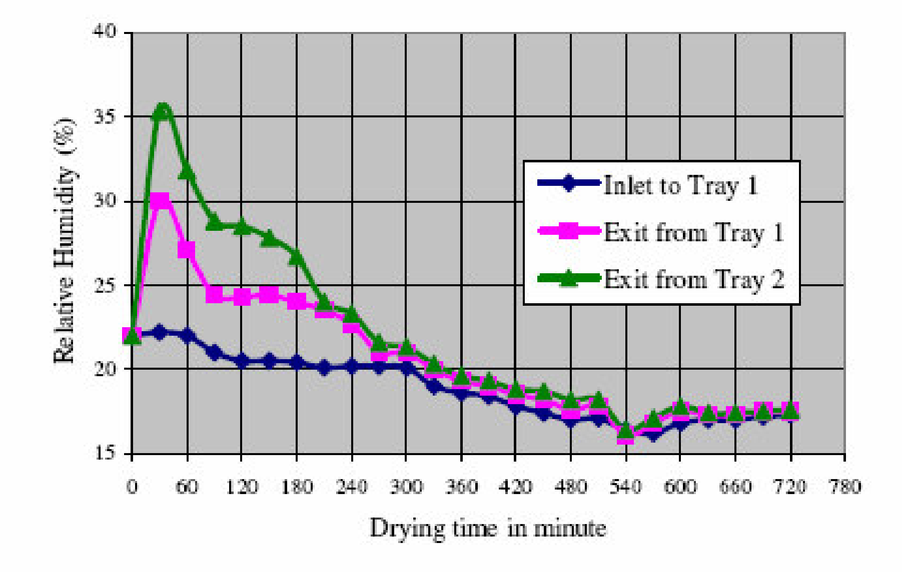


Figure C. 8 Drying Air Relative Humidity Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 26.5 ^{o}C and mass velocity flux = 0.183 kg/sm^2

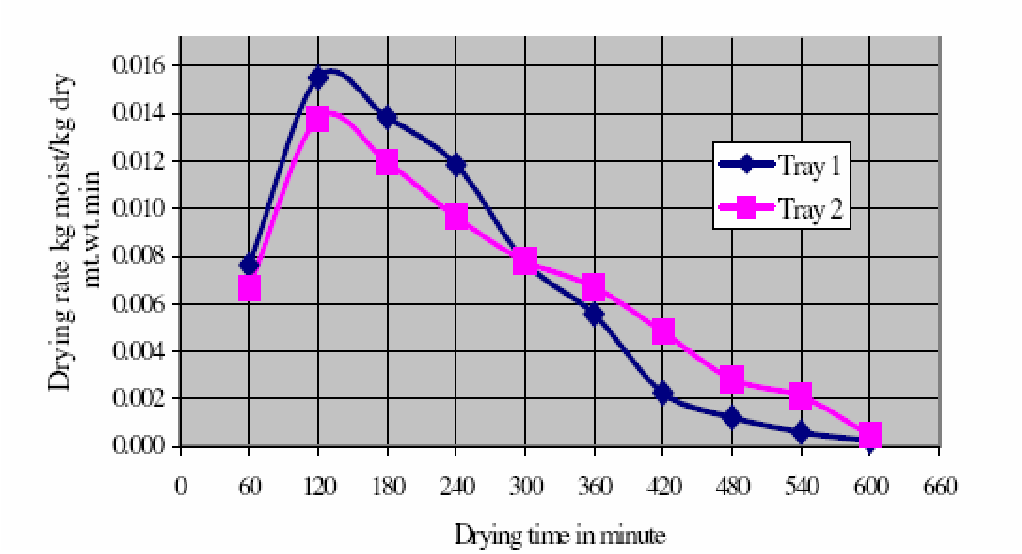


Figure C. 9 Drying Rate Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature of 50.9 °C, Relative humidity = 14.7 % and mass velocity flux = 0.19 kg/sm^2

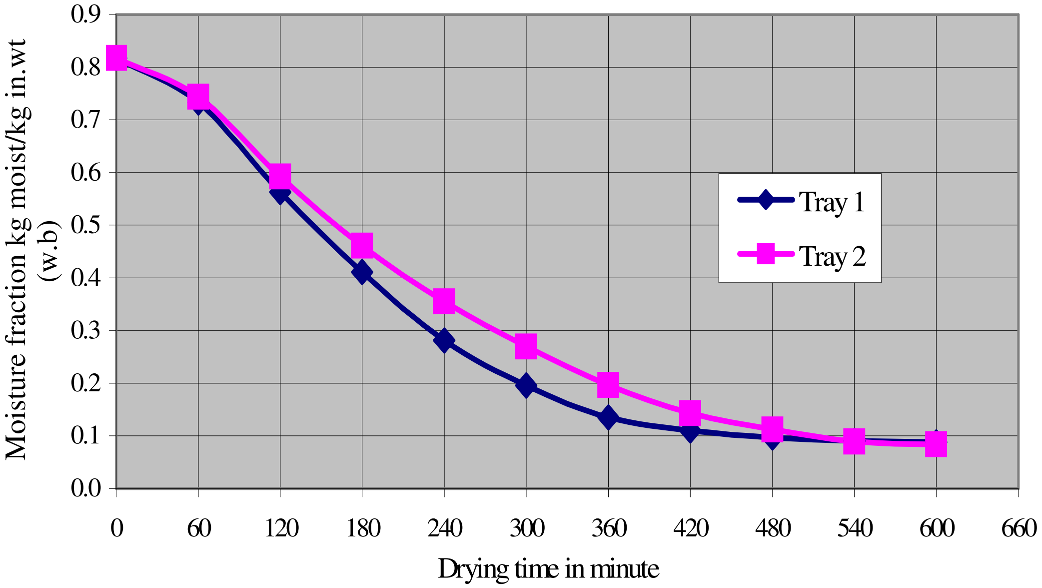


Figure C. 10 Moisture Content Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 50.9 °C, Relative humidity = 14.681 % and mass velocity flux = 0.19 kg/sm^2

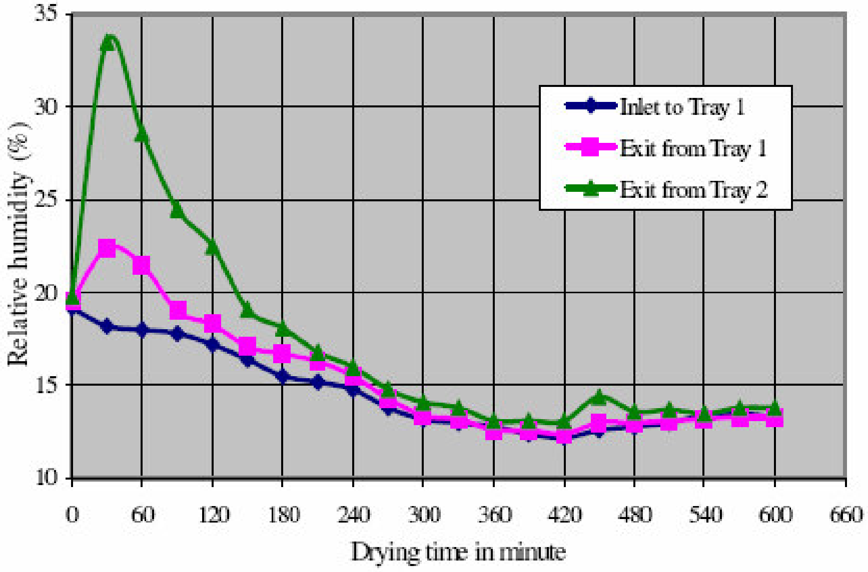


Figure C. 11 Drying Air Relative Humidity Profile of Potato Drying Tray 1 and Tray 2 at an average inlet temperature = 50.9 °C and mass velocity flux = 0.19 kg/sm^2

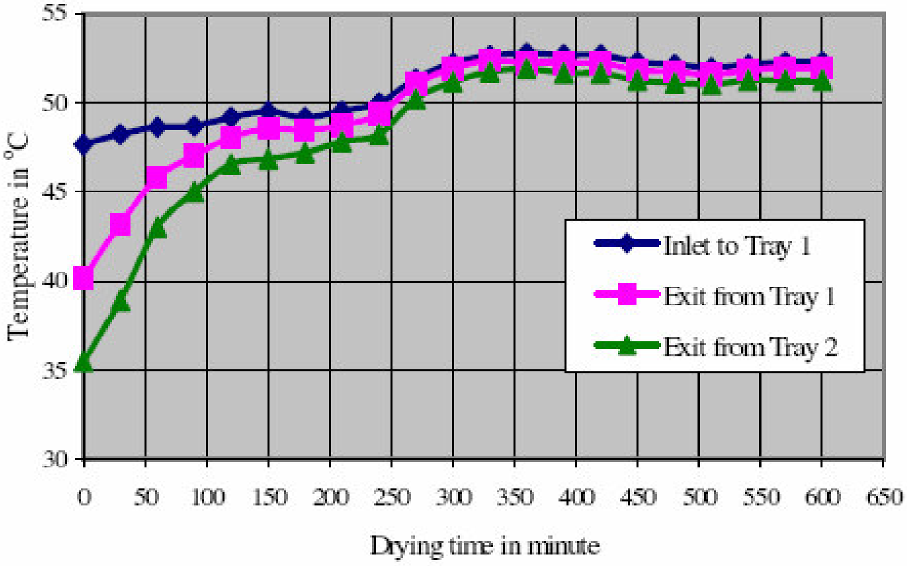


Figure C. 12 Drying Air Temperature Profile of Potato Drying in Tray 1 and Tray 2 at an average Relative humidity = 18.6 % and mass velocity flux = 0.19 kg/sm^2

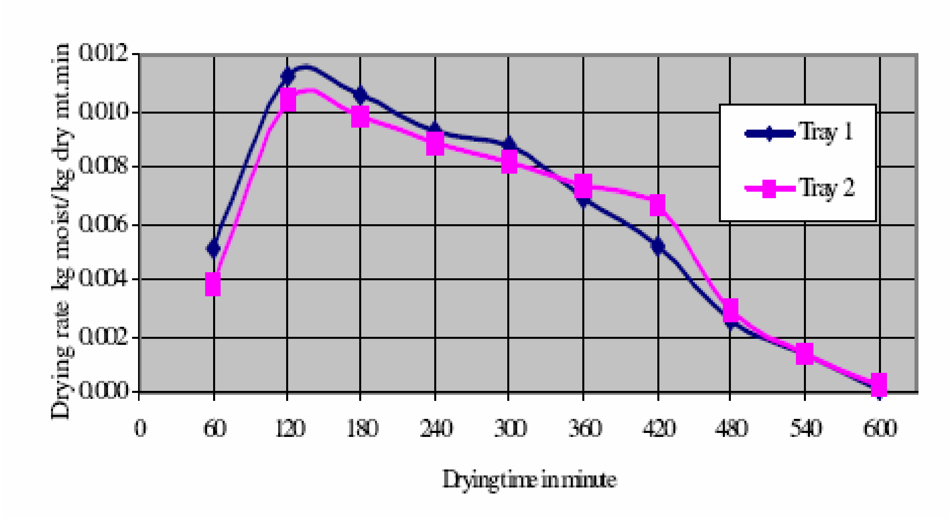


Figure C. 13 Drying Rate Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 51.45 °C, Relative humidity = 23.2 % and mass velocity flux = 0.191 kg/sm^2.

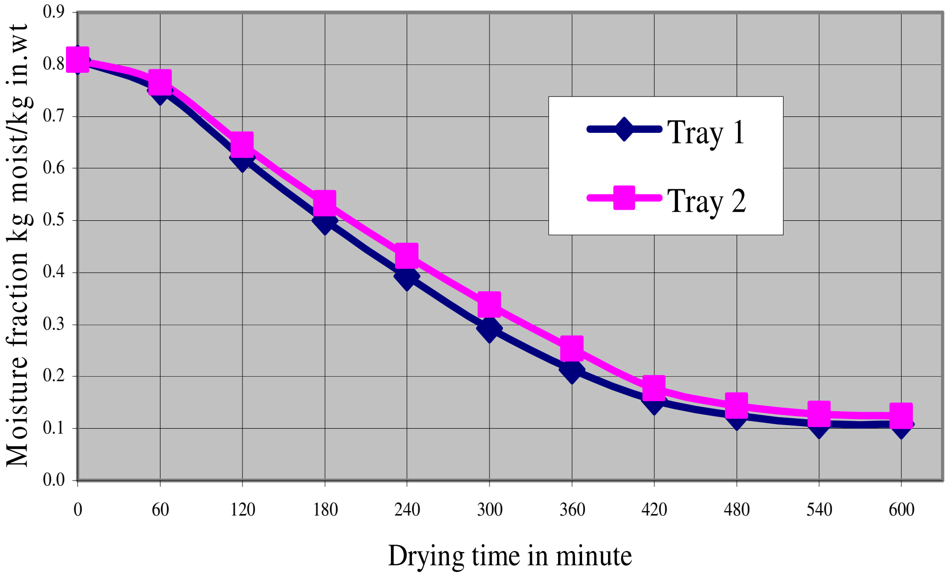


Figure C. 14 Moisture Content Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 51.45 °C, Relative humidity = 23.2 % and mass velocity flux = 0.191 kg/sm^2

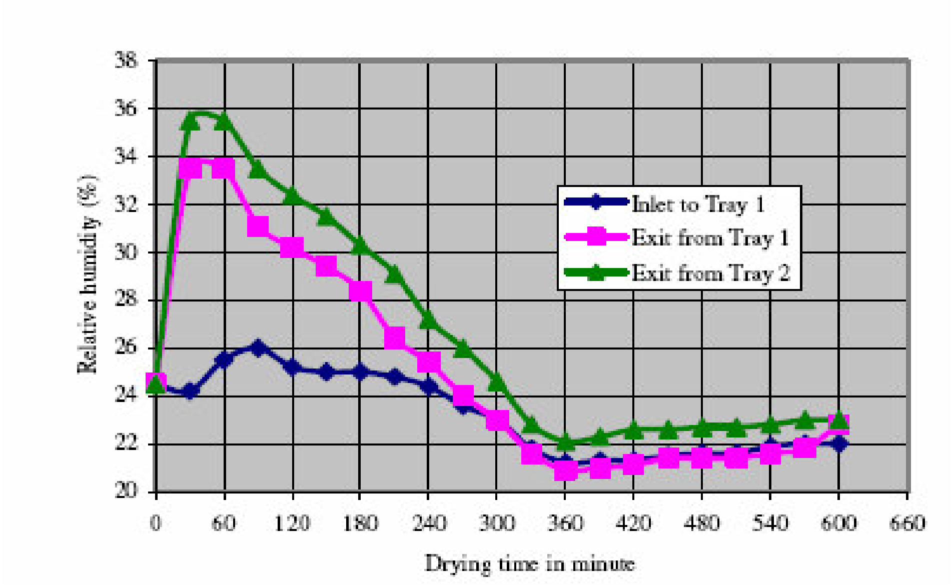


Figure C. 15 Drying Air Relative Humidity Profile of Potato Drying Tray 1 and Tray 2 at an average inlet temperature = f 51.45 °C and mass velocity flux = 0.191 kg/sm^2

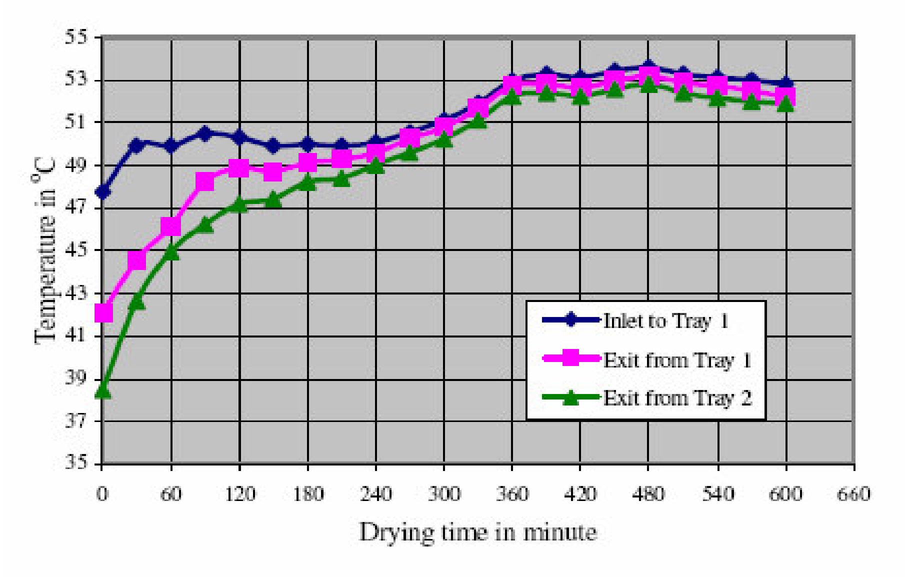


Figure C. 16 Drying Air Temperature Profile of Potato Drying in Tray 1 and Tray 2 at an average relative humidity = 23.2 % and mass velocity flux = 0.191 kg/sm^2

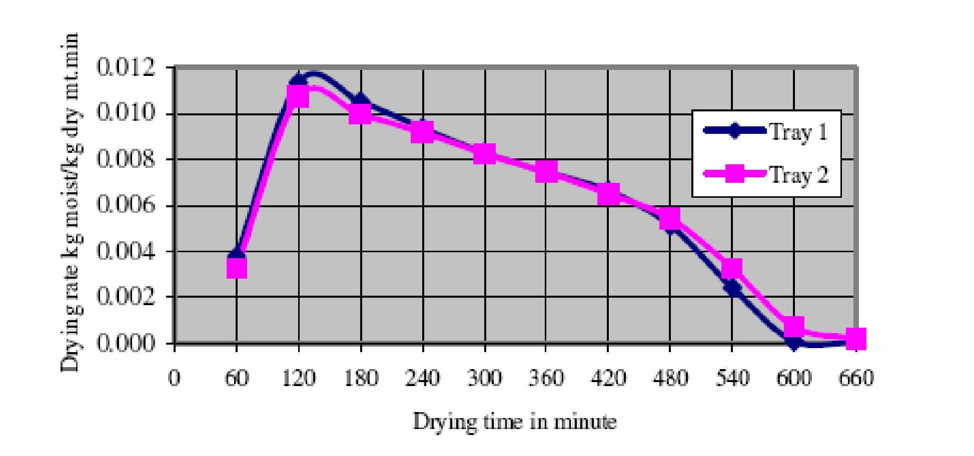


Figure C. 17 Drying Rate Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 54 °C, Relative humidity = 25.85 % and mass velocity flux = 0.193 kg/sm^2

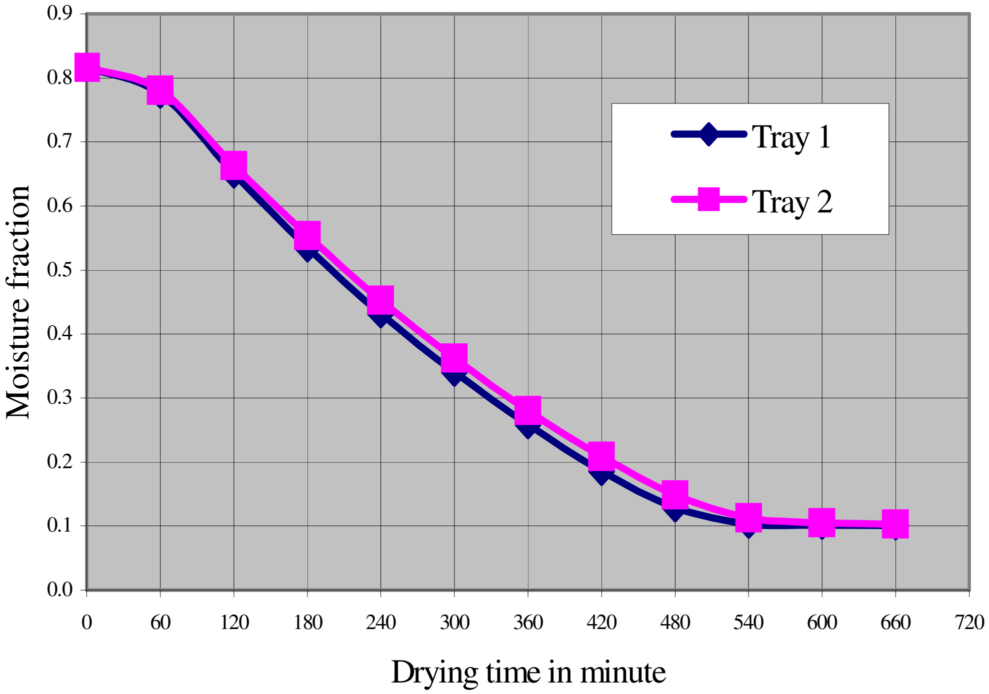


Figure C. 18 Moisture Content Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 54 °C, Relative humidity = 25.85 % and mass velocity flux = 0.193 kg/sm^2

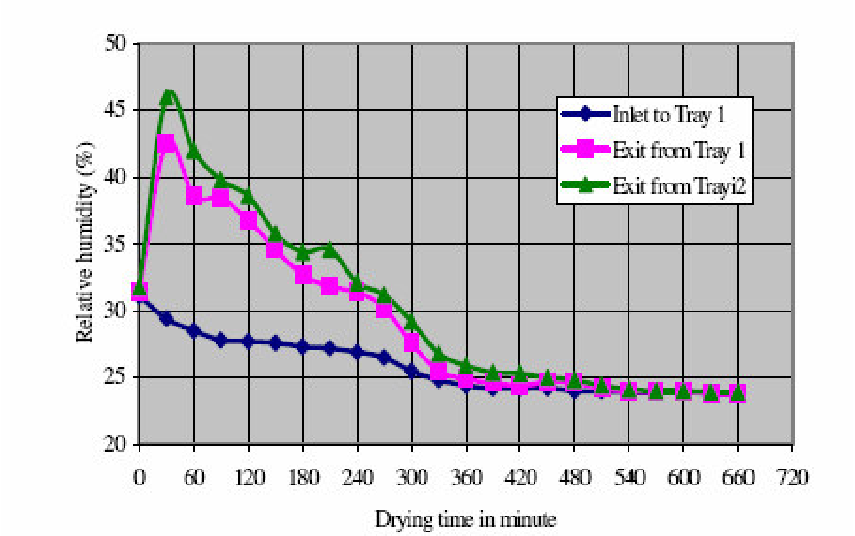


Figure C. 19 Drying Air Relative Humidity Profile of Potato Drying Tray 1 and Tray 2 at an average inlet temperature = 54 °C and mass velocity flux = 0.193 kg/sm^2

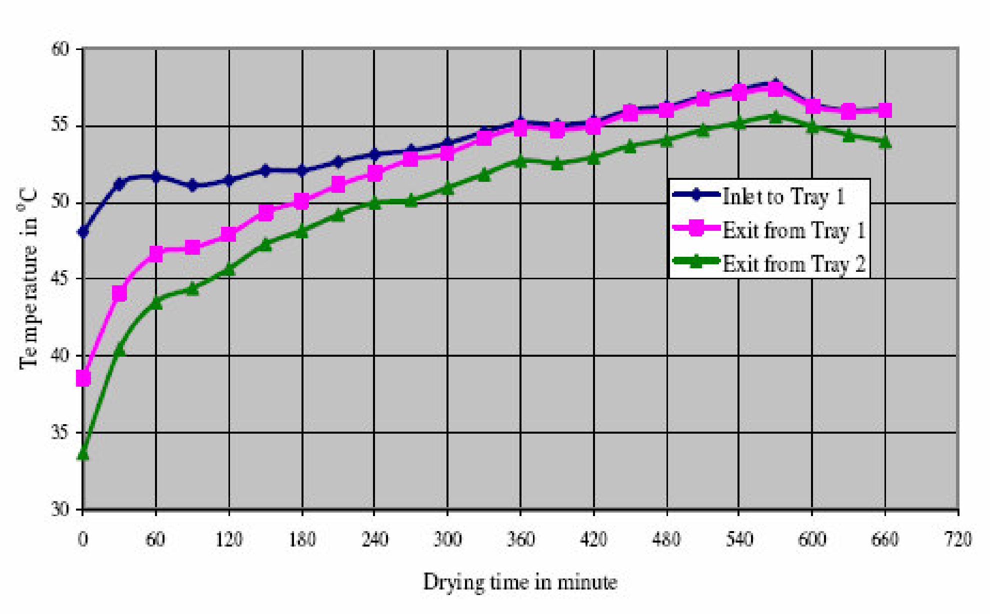


Figure C. 20 Drying Air Temperature Profile of Potato Drying in Tray 1 and Tray 2 at an average Relative humidity = 25.85 % and mass velocity flux = 0.193 kg/sm^2

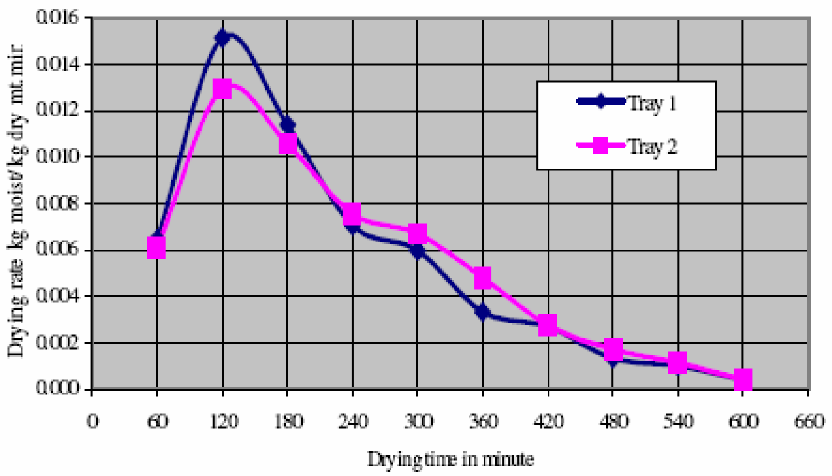


Figure C. 21 Drying Rate Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 40.2 °C, Relative humidity = 18.7 % and mass velocity flux= 0.176 kg/sm^2

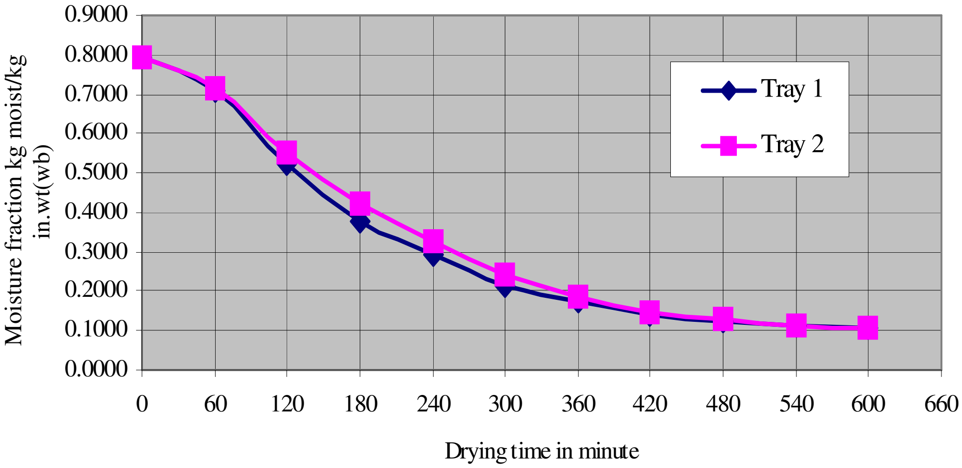


Figure C. 22 Moisture Content Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 40.2 °C, Relative humidity = 18.7 % and mass velocity flux = 0.176 kg/sm^2

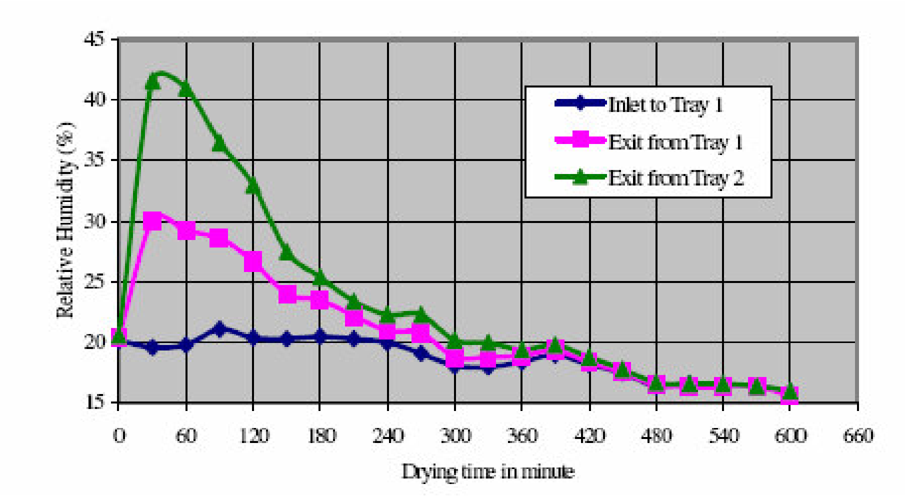


Figure C. 23 Drying Air Relative Humidity Profile of Potato Drying Tray 1 and Tray 2 at an average inlet temperature = 40.2 °C and mass velocity flux = 0.176 kg/sm^2

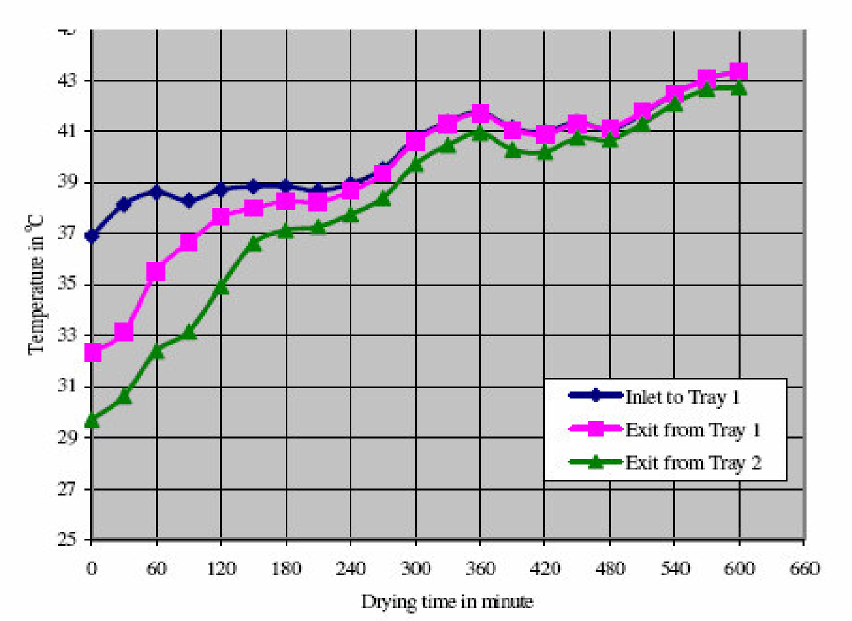


Figure C. 24 Drying Air Temperature Profile of Potato Drying in Tray 1 and Tray 2 at an average Relative humidity = 18.7 % and mass velocity flux = 0.176 kg/sm^2

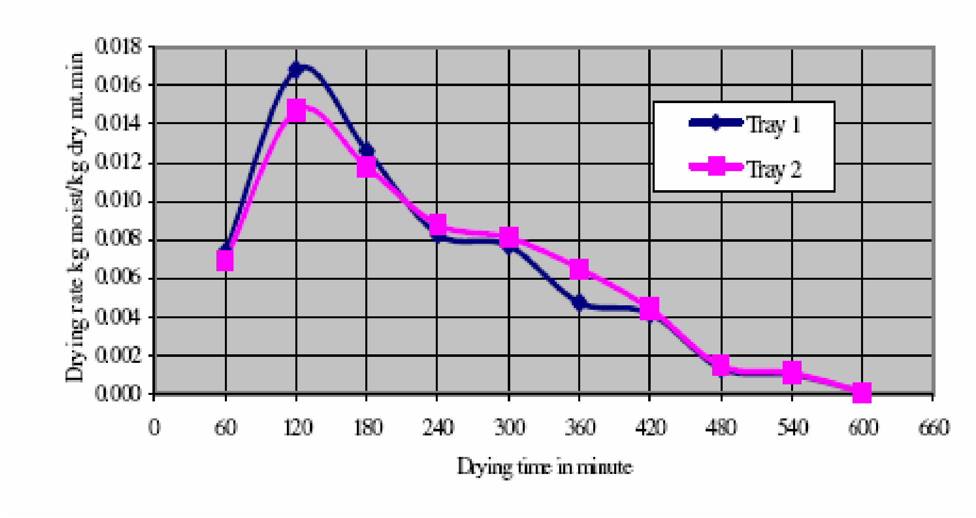


Figure C. 25 Drying Rate Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 48.5 °C, Relative humidity = 13.8% and mass velocity flux = 0.146 kg/sm^2

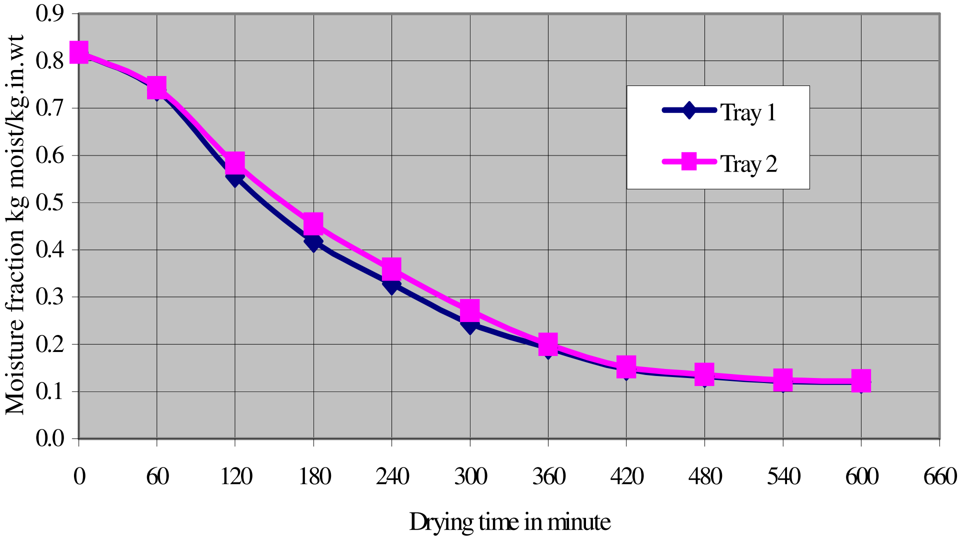


Figure C. 26 Moisture Content Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 48.5 °C, Relative humidity of 13.8 % and mass velocity flux 0.146 kg/sm^2

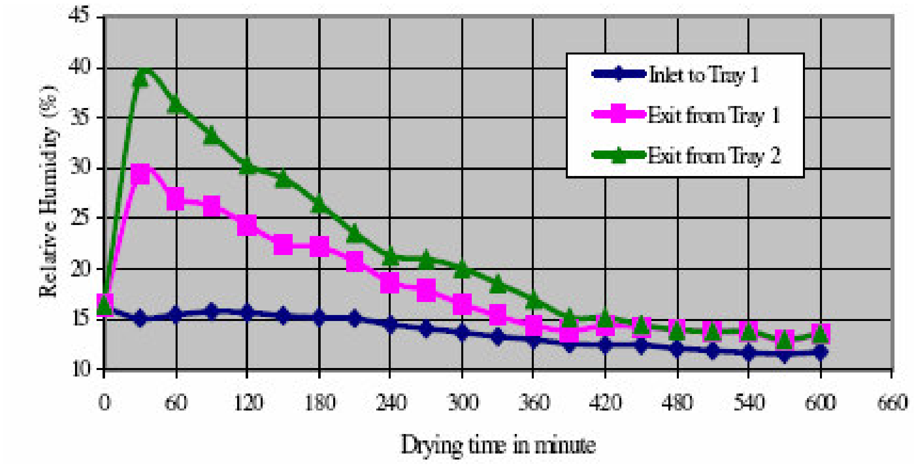


Figure C. 27 Drying Air Relative Humidity Profile of Potato Drying Tray 1 and Tray 2 at an average inlet temperature = 48.5°C and mass velocity flux = 0.146 kg/sm^2

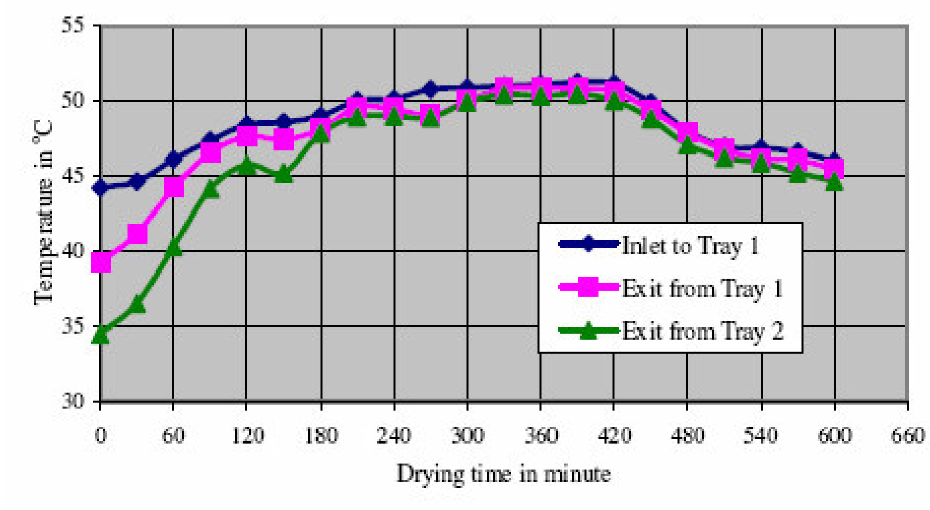


Figure C. 28 Drying Air Temperature Profile of Potato Drying in Tray 1 and Tray 2 at an average Relative humidity =13.8% and mass velocity flux = 0.146 kg/sm^2

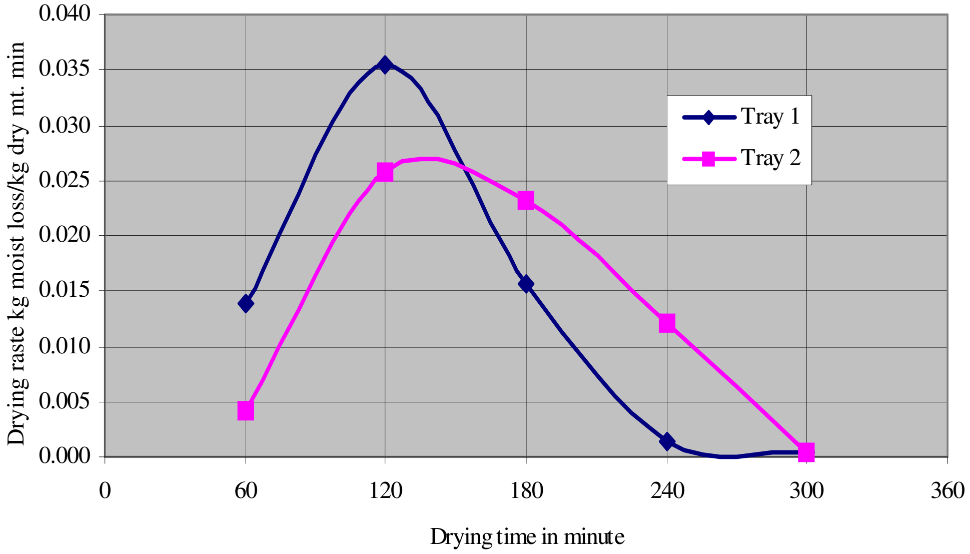


Figure C. 29 Drying Rate Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 50.6 °C, Relative humidity = 15.13% and mass velocity flux = 0.191kg/sm^2

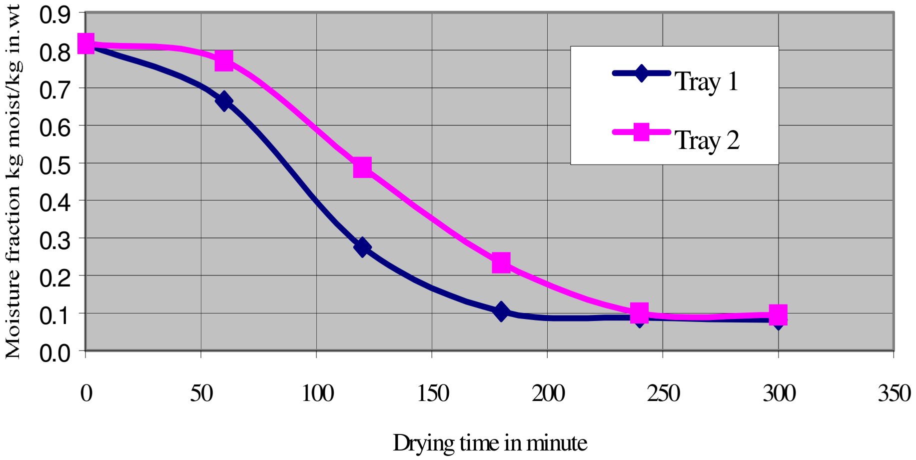


Figure C. 30 Moisture Content Profile of Potato Drying in Tray 1 and Tray 2 at an average inlet temperature = 50.6 °C, Relative humidity =15.13 % and mass velocity flux = 0.191 kg/sm^2

Annex D

Terminologies in Drying

Un-bound mixture: In hygroscopic material, it is the moisture in excess of equilibrium moisture content corresponding to saturation humidity in the surrounding atmosphere. All water in non-hygroscopic materials is unbound moisture.

Capillary flow: It is flow of liquid though the interstices and over the surface of a solid, caused by liquid-solid molecular attraction.

Constant rate period: It is the drying period during which the rate of liquid removal per unit of drying surface is constant.

Critical moisture content: It is that obtained when the constant rate period ends and the falling rate period begins.

Direct heat drier: It is one of a class of drying equipment in which heat is transferred to the material being dried by direct contact with the heating medium. The latter is usually a hot gas and the heat transfer mechanism is convection.

Equilibrium moisture content: It is moisture content which a given material can be dried under specific conditions of gas temperature and humidity.

Dryer efficiency: It is the fraction of total energy supplied used to heat and evaporate the liquid.

Dry basis: It indicates the moisture content of a wet material as the weight of moisture per unit weight of dry material.

Falling rate period: It is a drying period during which the instantaneous drying rate per unit surface or weight of dry material continual decreases.

Fiber saturation point: it is the bound moisture content of cellular materials at which the wall cells are completely saturated, where as the cavities are liquid-free. It is the equilibrium moisture content occurring when the humidity of surrounding atmosphere approaches saturation.

Free moisture content: It is the liquid content that is removable at a given temperature and humidity. Free moisture may include both bound and unbound moisture, and is equal to the average moisture content minus the equilibrium moisture content for the prevailing conditions of drying.

Humidity: It denotes the amount of vapor actually present in a gas and is generally expressed as weight of vapor per unit weight of dry gas.

Indirect heat dryer: It is one of class of drying equipment in which heat is transferred primarily by conduction and the heating medium is physically separated from the material by the wall.

Internal Diffusion: It occurs in a material during drying where liquid or vapor flow obeys the fundamental laws of diffusion.

Moisture gradient: It refers to the moisture profile in a material at a given moment in a drying process. The nature of the moisture gradient depends on the mechanism of moisture flow inside the material.

Percent saturation: It is the ratio of partial pressure of condensable vapour in a gas phase to the vapor pressure of the liquid at the same temperature expressed as a percentage. For water vapor in air, this is percent relative humidity.

Unaccomplished moisture change: it refers to the ratio of free moisture percent at any time to that initially present.

Unbound moisture: In hygroscopic materials the moisture in excess of the equilibrium moisture content corresponding to saturation humidity in the surrounding atmosphere. All water in non-hygroscopic material is unbound moisture.

Wet basis: It expresses the moisture in material as percentage of the weight of wet material. This base is less satisfactory for drying calculation than the dry basis for which the percentage change of moisture per unit weight of dry material is constant for all moisture contents.

Liquid diffusivity is solids usually decrease with moisture concentration on; liquid and vapor diffusivity also change as material shrinks during drying.

Annex E

Dimension of the sliced potato and the tray used in the drying chamber

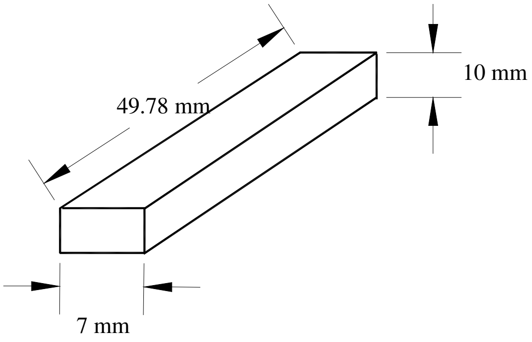


Figure E.1 Sample of sliced potato

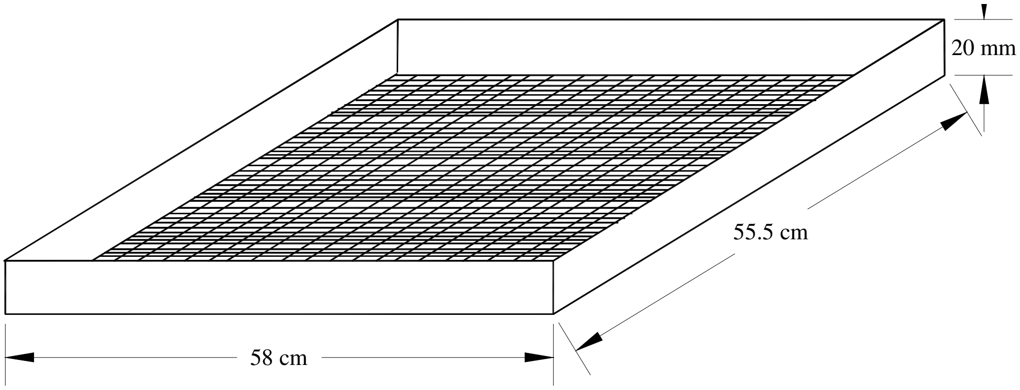


Figure E.2 *D*imension of tray used in the drying chamber