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To My Parents

Abstract

Investigations into the High-Temperature Air Drying of Tomato Pieces

The present study investigates the feasibility of using high air temperatures (100 ºC-200 ºC) in the oven for drying tomato pieces and the effects of such high temperatures on the drying kinetics as well as on the quality of the product, especially regarding colour.

First, continuous and intermittent drying methods involving high air temperatures are compared according to their drying kinetics (drying rate, effective moisture diffusivity, drying constants) and visual colour observations. The results indicate that acceptable colour quality of the sample at the required final moisture content (< 15% wet basis) is not achieved using either of these drying methods. However, the drying kinetics and the overall colour change of dried samples under intermittent drying are an improvement on the corresponding continuous drying runs.

Secondly, the intermittent drying process is optimised by designing a time-varying step-down temperature profile in the oven. Tomato samples are dried sequentially at 150 ºC (25 minutes), 130 ºC (15 minutes) and 100 ºC (25 minutes). For every five minutes in the oven, the samples are subjected to 25 ºC in a separate cabinet containing a ventilator for 15-minute tempering intervals. The optimised process results in an acceptable product colour since the time-varying step-down temperature profile in the oven helps maintain the sample temperature below a critical value where colour degradation sets in.

The main contribution of this study is thus to provide comprehensive information on the high-temperature air drying characteristics of tomatoes concerning both kinetics and colour quality. In particular, it is shown how these are affected by controllable factors such as air temperature and sample size.

Kurzreferat

Untersuchungen zur Konvektionstrocknung von Tomaten bei hohen Temperaturen

Im Rahmen der vorliegenden Arbeit wird untersucht, inwiefern hohe Trocknungstemperaturen (100 ºC-200 ºC) zur Konvektionstrocknung von Tomaten geeignet sind und wie sie sich auf die Trocknungskinetik und die Endproduktqualität, insbesondere die Farbqualität auswirken.

Im ersten Schritt werden kontinuierliche und intermittierende Hochtemperatur-Trocknungsverfahren aufgrund ihrer Trocknungskinetik (Trocknungsgeschwindigkeit, Diffusionskoeffizient, Trocknungskonstanten) in Hinblick auf die beobachtete Farbqualität miteinander verglichen. Die Versuchsergebnisse zeigen einerseits, dass sich für den geforderten Restwassergehalt (< 15%) eine akzeptable Farbqualität mit keinem dieser Versuchsverfahren erzielen lässt, und andererseits, dass das intermittierende Verfahren dem kontinuierlichen Verfahren in Bezug auf Trocknungskinetik und die beim Trockenprodukt beobachteten Farbveränderungen überlegen ist.

Im zweiten Schritt wird das intermittierende Verfahren optimiert. Dazu wird ein Trocknungstemperaturprofil mit sinkenden Lufttemperaturstufen unterschiedlicher Dauer entwickelt. Die Trocknung der Tomaten erfolgt am Ende schrittweise nacheinander bei 150 ºC (25 Minuten), 130 ºC (15 Minuten) und abschließend 100 ºC (25 Minuten), wobei die Tomaten nach jeweils 5 Minuten im Ofen für jeweils 15 Minuten zu 25 ºC in einen anderen Schrank mit Ventilator gelegt werden. Im Ergebnis des optimierten Verfahrens ist die Produktfarbe akzeptabel, denn das Trocknungstemperaturprofil mit sinkenden Lufttemperaturen unterschiedlicher Dauer sorgt dafür, dass die Temperatur in den Tomaten den für den Farbabbau kritischen Wert nicht erreicht.

Diese Arbeit liefert im Wesentlichen umfassende Kenndaten zu Trocknungskinetik und Farbqualität von Tomaten für Hochtemperatur-Konvektionstrocknungsverfahren und zeigt dabei, wie sich beeinflussbare Faktoren wie beispielsweise Lufttemperatur und Tomatenstückgröße auf diese Qualitätsmerkmale auswirken.

Nomenclature

Symbol	Definition	Unit
a^*	Redness	-
b^*	Measure of Yellow Colour	-
CI	Colour Intensity	-
D	Moisture Diffusivity	m^2s^{-1}
E^*	Overall Colour Value	-
F_o	Fourier Number	-
g	Acceleration due to Gravity	ms^{-2}
h	Pressure Difference as Height of Water	m
k_{LEWIS}	Drying Constant (Lewis Model)	min^{-1}
k_{PAGE}	Drying Constant (Page Model)	$min^{-n_{PAGE}}$
L^*	Brightness	-
L	Half-Thickness	m
m	Mass	g
n_{PAGE}	Drying Constant (Page Model)	-
p	Water Vapour Pressure	Pa
p^o	Saturated Water Vapour Pressure	Pa
r	Radius	m
R	Drying Rate	g $[H_2O]$ g^{-1} [DM] min^{-1}
R^2	Coefficient of Determination	-
S	Dry Matter	g
t	Time	min
t_{on}	Drying Time in the Oven	min
t_{off}	Tempering Time in the Cabinet	min
T	Temperature	ºC
W	Moisture Content (dry basis)	g g^{-1}
W_R	Ratio of Moisture Content to Initial Moisture Content	-
X	Moisture Content (wet basis)	%
x	Spatial Dimension	m

Greek Letters

Letter	Definition	Unit
Δ	Difference	-
α	Intermittence	-
β	Root of the Bessel Equation of the First Kind of Zero Order	-
γ	Surface Free Energy	-
ρ	Density	kgm^{-3}

Indices

Index	Meaning
0	Initial
c	Cylinder
cap	Capillary
e	Equilibrium
Eff	Effective
n	Index of Summation
s	Sphere

Abbreviations

Abbreviation	Meaning
db	Dry Basis
DM	Dry Matter
eq.	Equation
RH	Relative Humidity
RR	Rehydration Ratio
s.e.	Standard Error
wb	Wet Basis

1 Introduction

Drying represents a highly effective, practical means of reducing post-harvest losses in fruits and vegetables. Such losses are due to the lack of proper processing or to inadequate storage and can reach between 30 and 40% in developing countries in the tropics and subtropics. In addition, the demand for the year-round availability of seasonal food commodities has increased [82]. There is thus a pressing need to match increased production with suitable, simple, inexpensive and effective post-harvest preservation techniques to minimise loss and guarantee the supply and availability of nutrients. Drying offers significant weight and volume savings, minimising packaging and transportation costs and enabling storage of the product at ambient temperature [53, 150, 191]. These goals can be achieved by supplying the necessary latent heat of vaporisation to the water present in the food, removing the resultant vapour from the food. That is, drying is defined as a simultaneous heat and mass-transfer process that yields a dry product [83, 91, 152].

There exist several different methods for drying food, including sun drying, osmotic drying, microwave drying and convectional hot-air drying. Among these techniques, convectional hot-air drying has been the most common method employed for food materials. The major disadvantage of convectional hot-air drying is low energy efficiency, which extends the drying time [83, 110, 149, 150, 201]. This prolonged exposure of food samples to elevated drying temperatures has been reported to be associated with substantial degradation in quality attributes such as colour, flavour, texture, retention of nutrients and reduced rehydration ability [12, 21, 50, 73, 83, 212].

Many studies conducted on convectional hot-air drying have shown that increasing the air temperature increases the rate of moisture removal from the food sample [6, 48, 59, 71, 86, 118, 188, 205, 213]. However, this is often accompanied by degradation in the colour quality (browning) of the food [49, 81, 86, 110, 188]. Maintaining the sample temperature at certain levels at certain moisture contents is a useful strategy for overcoming colour degradation [29, 30, 40, 43, 106, 124]. Further studies have indicated that an improvement in colour quality can be achieved through periodical interruptions of the drying process (intermittent drying) or the employment of step-wise

temperature profiles [30, 43, 136, 137, 138]. However, very few of these studies are based on drying temperatures of above 100 ºC. Of those that are, the intermittence follows 45 minutes of continuous heat application (e.g. 130 °C). There is then just one tempering period of nine hours and a final drying period at 100 °C [137, 138]. In the current study, a new combination process of intermittent drying with a time-varying step-down temperature profile is developed. The difference between this process and the former studies is that here, *higher* temperatures coupled with *multiple*, *short* tempering periods are applied in succession.

Knowledge of the drying kinetics of food materials such as the drying rate, time-temperature-moisture content distributions, as well as theoretical and semi-empirical approaches to moisture movement, is essential for the prevention of quality degradation and for the achievement of fast and effective drying. Such information can be used to optimise production processes [91, 105, 191].

The consumption of dried tomato has recently gained in popularity. Today, dried tomatoes are widely used as ingredients in salads, spicy dishes and pizzas. They are also packed in canola oil with the addition of garlic, herbs and spices and are sold in delicatessens. Other uses for dried tomato include tomato spread, salsa, pesto, soups, sauces and many other manufactured foods [121]. A diet rich in tomatoes and tomato products might also prevent cancer and cardiovascular disease. Lycopene, the natural antioxidant that gives ripe tomato fruits and tomato products their characteristic deep-red colour is considered to be behind these beneficial health effects [37, 63, 93, 144, 176]. Several studies have indicated that lycopene levels remain relatively stable during thermal processing [1, 61, 93, 103, 186]. Moreover, thermal processing (including drying) can even enhance the nutritional value of tomatoes by increasing their bioavailable lycopene content and total antioxidant activity [27, 44, 144, 157, 176]. For these reasons, as well as the fact that most previous research on drying has concentrated on low air temperatures, this study considers the feasibility of using high temperatures for the drying of tomatoes.

2 Theoretical Background

2.1 Fundamentals and Purpose of Drying

Drying is one of the oldest known food preservation techniques. The primary objective of drying is to extend the shelf-life of foods by reducing their water content. This prevents food from microbiological spoilage as well as from the occurrence of chemical reactions such as enzymatic and non-enzymatic browning. In addition to preservation, drying is also used to reduce the cost or difficulty of packaging, handling, storage and transportation, by converting the raw food into a dry product [72, 91, 152, 183].

The terms “drying” and “dehydration” both refer to the simultaneous application of heat and removal of water by evaporation from a wet material[1] [23, 53, 96]. Therefore, they are used interchangeably in the literature: However, BARBOSA-CANAVOS and VEGA-MERCADO point out the difference between drying and dehydration. According to them, dehydrated food products are those with no more than 2.5% water (dry basis, db) while dried food products have more than 2.5% water (db) [18]. Evaporation or concentration is also usually distinguished from drying according to the extent of moisture reduction. In this regard, evaporation refers to the processing of liquids into concentrated forms (i.e. the product retains the liquid conditions) by the application of heat [60, 72, 150, 152]. Furthermore, water may also be removed from solids by means of mechanical processes such as centrifugation, sedimentation or filtration. However, these are not considered as drying operations since dried foods would normally possess a much lower water content than concentrated foods [152, 196]. Additionally, drying is different from frying, baking and roasting although there is significant water reduction by evaporation in all of these. Such processes are intended for purposes of texture and additional flavour development in the products rather than merely to remove the water [152].

The major dried food products include fruits and vegetables, herbs, pasta, dairy products (milk, whey), meat, soluble coffee and tea, breakfast cereals and grains such as rice and wheat [20, 72]. Fig. 2.1 presents a general overview of the fruit and vegetable drying

[1] Notable exceptions are freeze-drying, osmotic drying, and vacuum drying, in which the drying medium is not air [23].

process. Since the variety of these products is extremely large, in individual cases, some of the processing steps may be omitted or others added [67].

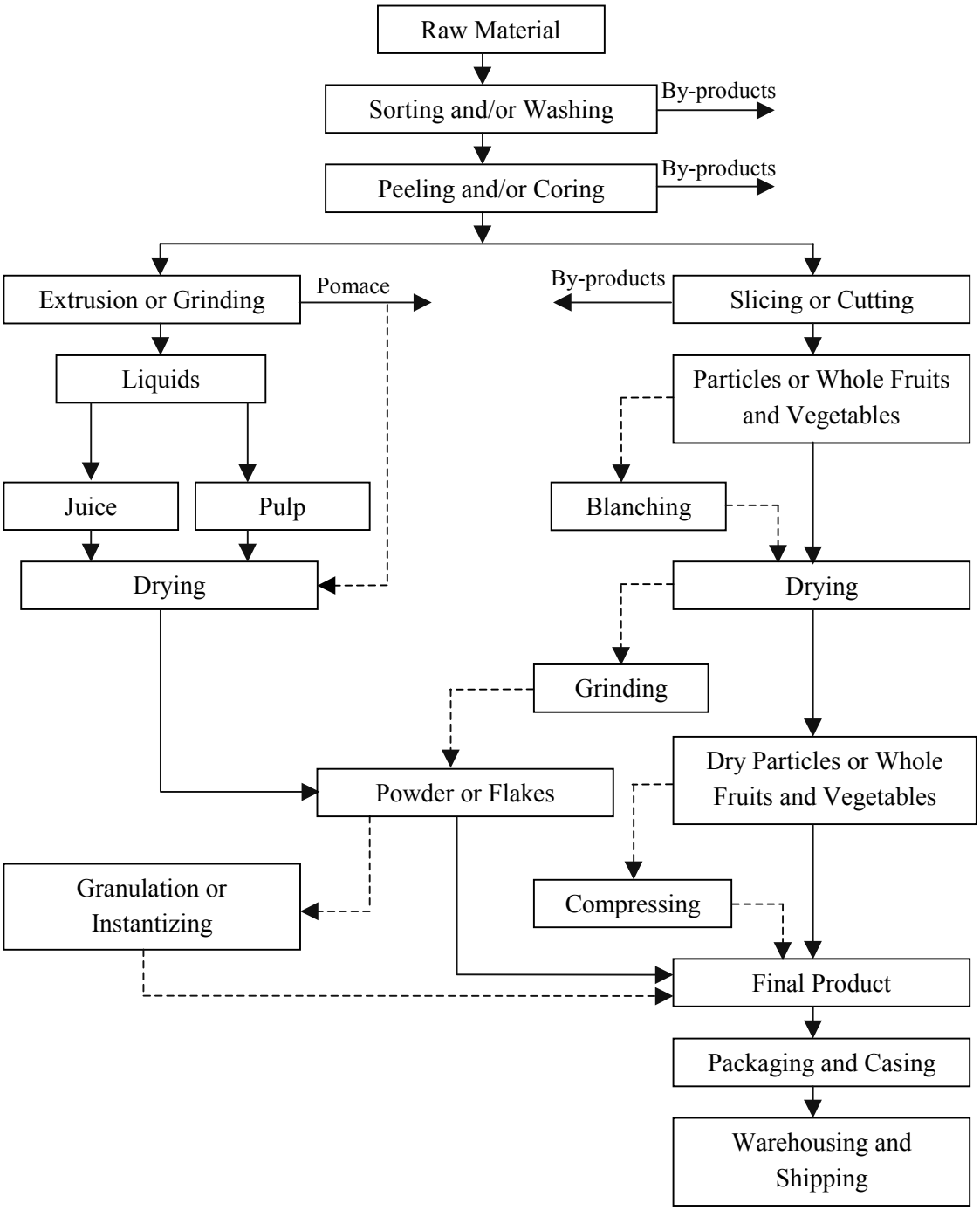

Fig. 2.1: A general scheme for fruit and vegetable drying [67]

2.2 Classification and Structure of Food Materials at the Microcellular Level

Food materials that are subjected to drying can be classified roughly into the following groups: biologically active (cereals, fruits and vegetables, etc.), products with a cell structure that is considered to be biologically inactive (animal products, blanched fruit and vegetables, coffee, tea, etc.), and pure, clearly defined substances (starch) [104]. For food materials of plant origin, different parts are subjected to drying. These include roots (carrot, beet roots), stems (asparagus), bulbs (garlic, onion), leaves (spinach, cabbage), flowers (cauliflower, broccoli), fruits (tomato, pear, apple, plum), and seeds (corn, rice, wheat). Each of these plant parts consists of cellular tissues such as parenchyma and vascular tissues, see Fig. 2.2 [109].

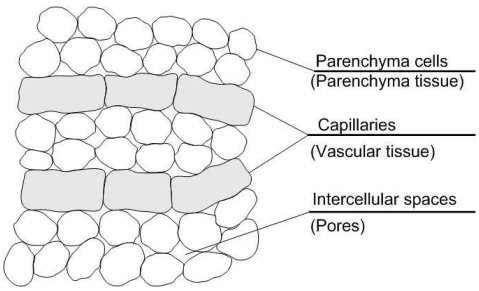

Fig. 2.2: A repeating unit of a capillary-porous plant material showing the parenchyma cells together with the intercellular spaces and the capillaries; adapted from [109]

Parenchyma tissue is the most common cell type, forming the major edible portion of plant materials. Its primary function is to store water and nutrients. The cells in parenchyma tissue are predominantly large, thin-walled and full of vacuoles. The intercellular spaces (pores) on the other hand are interconnected and filled with air and a certain amount of free water. The large vacuoles of the cells as well as the cell walls contain water, referred to as bound water [3, 107, 109, 147]. Such water exerts a vapour pressure less than that of pure water [60, 78, 196]. Therefore during drying, extra energy and time is necessary to remove this water.

In parenchyma tissue, the response of each plant material to processing such as blanching, drying, etc., is governed by the size and shape of the cells, the ratio of the cytoplasm to the vacuoles, the volume of intercellular spaces and, above all, the

thickness and molecular composition of the cell wall [8]. In this regard, AGUILERA AND STANLEY point out the intercellular space differences in apple, potato, peach and carrots. They report that the intercellular spaces occupy 20-25% of the total volume in apple, 15% in peach and 1% in potato and carrot [3].

In addition to parenchyma cells with watery vacuoles, other plant parts may also be edible. These are often composed of storage tissue in which starch granules, proteins and/or oil droplets are packed closely within cells containing no vacuoles and little free water. Examples include the seeds of cereals (e.g. wheat, corn, rice, oat) and legumes (e.g. lentils, beans), and nuts (e.g. almond, hazelnut, walnut) [3].

Capillaries forming the *vascular tissues* are responsible for the transport of water and nutrients, see Fig. 2.2. In fresh fruit and vegetables, some capillaries are filled with free water while others contain air, like the intercellular spaces [109]. However during drying, depending on the extent of the process, water exists in the cells either as liquid in vacuoles or as free or adsorbed water in capillaries. Towards the end of drying, when the vacuoles are virtually emptied, most of the water exists in capillaries [173].

At a fundamental level, fruit and vegetables are considered to be both hygroscopic and capillary-porous materials [39, 160]. The hygroscopic property reflects the fact that there is bound water in the material. On account of this property and when exposed to saturated air, dried fruit and vegetables exert lower vapour pressure at the surface and absorb water vapour from the environment until equilibrium conditions are achieved [39, 125, 196].

2.3 Drying Process

2.3.1 Heat and Mass Transfer

The most important thermodynamic process in food drying is heat and mass transfer. During hot-air drying, there is a simultaneous exchange of heat and mass between the food and the drying air. Heat is transferred from the food's surroundings to its surface by way of radiation, convection or conduction. In the common case of air drying,

convection is the predominant mechanism [3, 23, 67, 72]. This heat transfer to the food surface increases the sample temperature and supplies the required latent heat of vaporisation for both the surface water and the water within the product. At the same time, internal moisture[2] (mass) migrates to the surface of the food and then it evaporates to the surrounding hot air [14, 91, 152, 206]. The transport of moisture from the product surface to the air and the transfer of heat from the air to the product surface are functions of the existing concentration and/or water vapour pressure, and temperature gradients, respectively [3, 7, 104, 181].

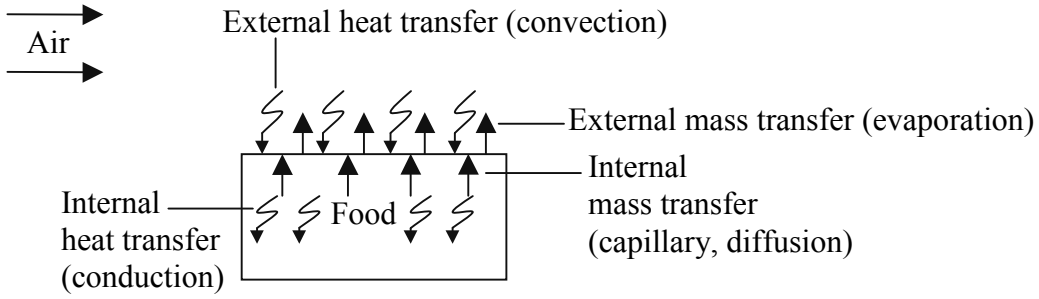

Fig. 2.3: Heat and mass transfer during the drying of a food particle in a hot oven; adapted from [3, 72]

MAROULIS ET AL. describe the transport phenomena during drying shown in Fig. 2.3 as follows [115]:

1) Heat transfer
   - Convective heat (energy) transfer from the air to the food's surface (external heat transfer)
   - Conductive heat transfer within the food (internal heat transfer)

2) Mass transfer
   - Moisture transport within the food toward its external surface (internal mass transfer)

[2] The term moisture refers to the volatile part of a food material. It has been used interchangeably in the literature with "water" to describe the amount of water present in foodstuffs [183, 212].

- Evaporation and convective transfer of the vapour into the air (external mass transfer)

Transport phenomena thus involve both external and internal resistance to heat and/or mass transfer. The factors that slow the rate of these processes determine the drying rate [152, 181]. In other words, the resistance mechanisms control the drying rate. In general, it is accepted that the rate of the drying may be limited either by the rate of internal migration of water molecules to the surface or by the rate of evaporation of water molecules from the surface into the air, depending on the conditions of drying [72, 78, 160]. This indicates that the resistance to mass transfer is considered to be the primary rate-limiting mechanism and the resistance to heat transfer may hence be neglected. The reason for this is that within the food, heat is usually transported more easily than moisture and thus the temperature gradients inside the food can be assumed to be flat (no resistance to internal heat transfer), especially when compared to the steep moisture content gradient [24, 57, 91, 116, 142, 160, 203]. In addition, it is known that heat transfer within the food may be limited by the thermal conductivity of the product as its water evaporates [45, 60, 110, 129]. In conjunction with the external heat transfer, the temperature of the food increases rapidly at the beginning of drying towards the air temperature, indicating a decreasing resistance effect [9]. WANG AND BRENNAN attribute this phenomenon to the decrease in the thickness of the samples during drying, which leads to a faster heat transfer within the food [208]. However, the difference between the food and the air temperature becomes negligible (external heat transfer) only after most of the initial water of the food has evaporated [9, 203]. The air temperature, air humidity and velocity, and exposed surface area all influence the resistance to external heat and mass transfer whereas the internal mass transfer is only affected by the physical nature of the food, its moisture content and temperature. At the beginning of drying, since the internal resistance in the food is low enough to maintain the surface at saturation, evaporation takes place at a constant rate depending mainly on external heat and mass transfer. When the drying rate starts to decrease due to insufficient water at the surface, resistance to internal mass transfer governs the process. Most foods therefore switch from an external drying process during the initial stages to an internal drying process as the product dries out [72, 91, 152]. In addition, the drying rate in the food sample, which decreases from the very beginning of the process (at a

constant temperature), may also indicate that the internal resistance to mass transfer controls the drying [42, 116, 150, 199, 213].

2.3.2 Drying Mechanism

In order to understand the food drying mechanism it is necessary to determine the drying rate, *R*, at specific air temperatures. The mechanism of moisture loss during the drying process may then be described by a series of stages in which the drying rate plays a key role. A typical drying rate curve is illustrated in Fig. 2.4.

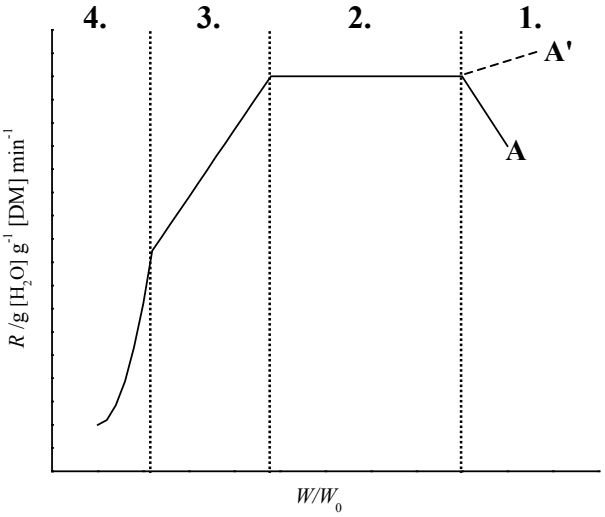

Fig. 2.4: Drying rate as a function of moisture-content ratio; adapted from [60, 196]

In Fig. 2.4, the drying rate is plotted over the moisture-content ratio, which decreases over time. Starting from the right-hand side, the first phase (1) shows the transition period during which the food surface conditions come into equilibrium with the drying air. The points *A* and *A'* represent the initial conditions for a cold and hot material, respectively. The second section of the curve, phase (2), is known as the *constant-rate period*. This is characterised by the removal of free water from the product surface because here, the surface of the food is saturated with free water. The rate of moisture migration from the interior to the surface of the food is at least as high as the evaporation rate at the surface (i.e. there is no internal resistance to mass transfer). This

fast liquid migration to the surface is attributed to the capillary transport of water, which is more rapid than diffusion[3] [166, 194]. The rate of heat transfer from the air to the food surface, on the other hand, is balanced by the rate of energy removal due to the evaporating moisture (i.e. latent heat of vaporisation). Thus, the surface temperature remains at some constant value, which is in fact lower than air temperature due to the cooling effect of the evaporating water on the surface. However, this constant surface temperature does depend on the heat transfer to the food. Finally, water evaporates into the drying air as a result of the water concentration gradient and/or water vapour pressure gradient ($p_{food} - p_{air}$) between the surface of the food and the drying air [72, 152]. Indeed, this water vapour pressure and/or concentration difference remains the same throughout the constant drying period due to the unchanged values of p_{air} and p_{food}. One of the reasons for this is that the drying conditions in the air, T_{air} and relative humidity (RH) do not change, nor does p_{air}. Secondly, the food surface maintains the saturated water vapour pressure, $p_{food} = p^o$, at a specific constant temperature, T_{air}, due to the sufficient supply of water to the food surface. That is, p_{food} remains the same. As a result, the resistance to mass transfer from the surface to the drying air does not change due to the constant temperature and RH in the air. The rate of water evaporating into the air therefore remains constant and is controlled entirely by external heat transfer [91, 104, 196].

As the free and loosely bound moisture contents in the product diminish and mass transfer from the surface to the drying air becomes smaller, the internal resistance to moisture transfer begins to drive the drying process. This is represented in Fig. 2.4 at the end of the second stage where the drying rate is no longer constant but falls progressively throughout the rest of the drying. The drying period beyond this point is termed as the *falling-rate period*, and may be divided into different sub-periods depending on the structure of the dried material (e.g. hygroscopic and non-hygroscopic) [53, 70, 91, 101, 110]. In the case of non-hygroscopic materials there is a single falling rate period, while hygroscopic ones may exhibit two or more falling rate periods. This is explained by the fact that a non-hygroscopic material (e.g. sand, polymer particles and some ceramics) exerts the same partial water vapour pressure, p, at all moisture contents

[3] See subsection 2.3.4

due to the negligible amount of physiochemically bound water and the non-shrinkage property of such material. This partial water vapour pressure is equal to saturated water vapour pressure ($p = p^o$), the same level at which a film of water dries. In the case of a hygroscopic material, however, partial water vapour pressure is dependent on the moisture content due to the large amount of physiochemically bound water and the occurrence of shrinkage during drying [39, 91, 110]. Since the drying rate curve shown in Fig. 2.4 represents an example for hygroscopic materials, the falling rate period is divided into two subsections. The *first falling-rate period*, the third phase (3), follows the end of equilibrium at the surface, which occurs when there is insufficient supply of water from the inner parts of the food. This results in the appearance of increasingly larger proportions of dry spots on the surface, leading to the reduction of surface area for evaporation and an increase in surface temperature [72, 152, 196]. The *second falling-rate period*, the fourth phase (4), begins when the surface is completely dry, but the changeover between the periods is not always clear-cut [60, 78]. For example, in some cases no sharp discontinuity occurs at the end of the first falling-rate period due to the gradual change from partially wetted to completely dry conditions at the surface. During the second falling-rate period, the plane of evaporation slowly recedes from the surface and all evaporation occurs at the interior of the food. Therefore, changes in the external conditions such as air velocity and humidity no longer affect the rate of drying. In addition, the latent heat of vaporisation of water at this stage of the drying process is higher than the latent heat of vaporisation of pure water since water in the food sample is held in multiple layers (i.e. bound water) [194]. As a result, the amount of water removed is relatively small, while the time required is long. This causes the most heat damage to the food and therefore during this period the air temperature should be controlled to balance the rate of drying and extent of heat damage [23, 53, 60, 70, 212].

Equilibrium between the material and the drying air is reached as the food temperature approaches the drying air temperature. At this point, the partial water vapour pressure of the food and the drying air become equal. The air fails to pick up any moisture from the product and thus drying ceases. The moisture content at this stage is the level to which food can be dried under a given drying condition and is referred to as the equilibrium moisture content [72, 101, 160].

2.3.3 Factors Affecting the Rate of Moisture Removal

There are several factors that influence the drying rate of food. These factors can be grouped into two main categories: factors dependent on process conditions and those dependent on the type of food.

2.3.3.1 Factors Related to Process Conditions

Drying Temperature

One of the key factors affecting the rate of moisture removal is the drying temperature. The greater the temperature difference between the drying air and the food, the greater will be the heat transfer into the food. This results in a higher driving force (water-vapour pressure gradient and/or water concentration gradient between the food surface and the drying air) for moisture removal, which shortens the overall drying time. Increased air temperature improves drying by affecting both external (constant rate period) and internal processes (falling rate periods). However, extremely high temperatures may cause quality loss, especially regarding colour. A practical limit must therefore be found for each food product to maintain maximum product quality [70, 72, 104, 212].

Relative Humidity

The amount of moisture in the air, as measured by the vapour pressure or relative humidity, influences the rate of moisture removal from the sample through its effect on external mass transfer. This suggests that relative humidity exerts more influence on drying in the constant-rate period than in the falling-rate period, where internal mass transfer is the controlling mechanism. The effect of relative humidity on external mass transfer is as follows: an increase in the relative humidity of the air decreases the water vapour pressure or water concentration gradient between the food surface and its surrounding air and thus reduces the rate of external mass transfer. Conversely, a decrease in the relative humidity of the drying air increases this gradient between the food surface and its surrounding air and hence enhances the rate of external mass transfer [72, 212].

Air Velocity

The velocity at which the drying air blows across the food surface affects the rate of moisture removal through its impact on external mass transfer. Increasing the air velocity will take more moisture away from the drying surface of the food, preventing the moisture from creating saturated conditions there. This also shortens the duration of the constant rate period although it does not have a significant effect on the falling rate period [72].

Several researchers have studied the effects of air velocity on the drying rate of different food samples [92, 112, 116, 118]. In these studies, it is revealed that the air velocity, like air humidity, does not influence the drying rate as much as the drying temperature. Furthermore, in some other studies a critical air velocity value above which the drying rate dependence on air velocity becomes negligible has been defined [16, 58, 94, 203]. In addition, IGUAZ ET AL. and WACHIRAPHANSAKUL AND DEVAHASTIN report that the effect of air velocity is more pronounced in the case of low temperature drying [79, 205].

2.3.3.2 Factors Related to the Food Sample

Thickness and Surface Area

The distance that water molecules have to migrate within a food before evaporating from its surface determines how fast that food can dry. In the constant-rate period, smaller pieces have a larger surface area available for evaporation relative to their volume, whereas in the falling-rate period, smaller thickness means a shorter distance for moisture migration to the surface. Thus slicing or dicing into smaller pieces with high surface area will generally facilitate drying [53, 72].

Composition and Structure

The rate of moisture removal from food depends on the composition and structural properties of the particular food material. For example, high concentrations of solutes such as sugars, salts, gums, starches, etc. interact with water molecules in the food and inhibit their mobility. As a result, viscosity in the food increases, water activity

decreases and drying slows down. Moisture migration within a food product may also occur in different directions depending on the orientation of the food microstructure such as fibres and protein strands. Fibres in celery and protein strands in meat, for example, allow more rapid drying along the length than across the cell structure. Similarly, moisture is removed more easily from intercellular spaces than from within the cells since there is an additional resistance to water migration across the cell boundary. Blanching and/or reduction in sample size can increase the rate of moisture removal by weakening this resistance. However, such pre-treatments may also result in severe cell rupture and this kind of damage to the cell may adversely affect the texture of the rehydrated product. In addition, the loss of cellular structure, pore formation and shrinkage of the product, which are microstructural changes that occur during the drying of food materials, strongly affect the rate of drying [53, 72, 104, 128].

2.3.4 Internal Mass-Transfer Mechanisms during Drying

There are different internal mass transfer mechanisms within food during drying. Moisture exists in food materials as bound water within the cell wall and vacuoles, liquid and vapour form in the pores and free water in the capillaries. During drying, water flows from locations of high moisture content to locations of low moisture content due to the differences in capillary attraction and in water vapour pressure and/or concentration. These mechanisms for moisture within the product moving toward its surface may be summarised as follows:

- Liquid movement by capillary forces
- Diffusion of liquids, due to the differences in concentration of solutes at the surface and in the interior of the food
- Diffusion of liquids which are adsorbed in layers at the surfaces of solid components of the food
- Water vapour diffusion in air spaces within the food due to the vapour pressure gradients

One or more of these mechanisms may function simultaneously and their relative importance can change as drying progresses. In addition, the drying conditions

described in section 2.3.3 affect these mechanisms since they alter moisture movement within the food [53, 104, 152, 168].

2.3.4.1 Capillary Movement

Evaporation of water from the surface exerts capillary forces, pulling the unbound water (free water) through the intercellular spaces (pores) and through the surface of the material due to interfacial tension between the water and the food [60, 125]. Thus the capillary forces act in a direction perpendicular to the surface of the solid [150]. As the water reaches the surface through the capillaries, pores and cracks on the surface open and let air enter. Water is then replaced by air entering the food, and wets the surface of the sample. Such redistribution of water lowers capillary force potential (i.e. tension on the surface) slightly. As evaporation at the surface occurs, capillary forces again increase until a further replacement of water by air entering the food through pores and cracks with water again wetting the surface. When the surface moisture first depletes, water can no longer be brought to the surface by capillary forces since no air can enter to replace the water. Hence the moisture recedes into the capillaries, and the drying rate falls [125, 196].

The driving force for capillary flow is considered to be the suction or the pressure difference between the water and the gas at the curved interfaces present in capillaries [91, 96]. For a single capillary, the pressure difference is represented by the height of water given by eq. (2.1) and as shown in Fig. 2.5.

$$h = \frac{2\gamma}{r_{cap} g \rho} \tag{2.1}$$

Capillary radius (r_{cap}) affects the water flow in such a way that small capillaries develop greater tensions than the larger ones. The tension is attributed to the concave curvature of the surface. Liquid water in capillaries of very small diameter will exert a lowered vapour pressure. Thus, the large capillaries tend to empty their water content first [91, 150].

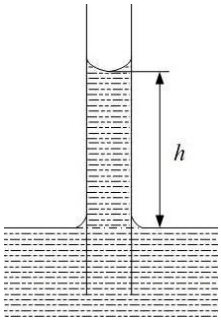

Fig. 2.5: Representation of capillary rise; adapted from [22]

If the moisture movement follows the capillary flow, the drying rate will vary linearly with moisture content as in the case of the constant-rate period. That is, water moves from the interior of the food at the same rate as it evaporates from the surface and the surface remains wet. Therefore, it has been suggested that the internal moisture movement during the constant-rate period is due to the capillary flow [60, 110]. The factors that influence the rate in this period (e.g. air velocity, air temperature and relative humidity of the air) are the same as those for the rate of moisture movement by capillary flow.

2.3.4.2 Diffusion

Diffusion is considered to be the main moisture transport mechanism during the falling-rate period in the drying of food materials. Unlike the free-water flow due to the capillary forces in the constant-rate period, moisture diffusion in food samples occurs randomly, responding to concentration gradients perpendicular to the main flow (drying air). It includes liquid diffusion through pores, diffusion of liquids which are adsorbed in layers at the surfaces of the components of the food, and vapour diffusion in air-filled pores [91, 162, 168]. During the falling-rate period, in addition to diffusion, moisture transport may also take place through other mechanisms such as capillary flow, Knudsen diffusion and hydrodynamic flow, depending on the structure of the food material (i.e. size, shape, and connection of pores in the sample). When there are different transport mechanisms and it is difficult to distinguish between the individual mechanisms, as in the case of falling-rate period, the rate of moisture movement is then described by a lumped value, the

so-called effective diffusivity (D_{eff}), irrespective of which mechanism is really involved in moisture movement. This measure incorporates all possible moisture transport mechanisms in one [114, 162, 170].

The decrease in moisture concentration during drying leads to an unsteady state condition, i.e. the concentration (dc/dx) or the equivalent moisture content gradient (dW/dx) changes over time (falling-rate period). For such conditions FICK's second law of diffusion as given in eq. (2.2) is often applied to analyse moisture transport mechanisms within the sample during the falling-rate period [101, 114, 134, 162, 170, 209].

$$\frac{dW}{dt} = D_{\text{eff}} \frac{d^2W}{dx^2} \tag{2.2}$$

Eq. (2.2) expresses how the concentration changes with time t at different positions in the food [110]. This differential equation is solved analytically for certain sample geometries under the following assumptions:

- The food sample is one-dimensional
- Moisture diffusivity in the sample is constant
- Free-water content at the surface is essentially zero and moisture is initially distributed uniformly throughout the sample
- The shape and size of the sample remains constant during drying (i.e. there is negligible shrinkage)
- Heat transfer proceeds very quickly (negligible internal and external heat-transfer effect)
- Resistance to mass transfer at the surface is negligible compared to the internal resistance of the sample. That is, internal moisture movement is the main resistance to drying (there is no external moisture movement resistance)

Once the shape of the food product has been determined, eq. (2.2) is simplified and solved to obtain the effective moisture diffusivity (D_{eff}). Eqs. (2.3) to (2.5) represent the

reduced analytical equations for the sample geometries of sphere, slab and cylinder, respectively [18, 134, 162].

Sphere:

$$\frac{W - W_e}{W_0 - W_e} = \frac{6}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{n^2} \exp\left(- n^2 \frac{\pi^2 D_{eff} t}{r_s^2} \right) \tag{2.3}$$

Examples of products modelled as spheres include grapes [47], pistachio nuts [92], black tea [139], soybeans [146] and plums [164].

Slab:

$$\frac{W - W_e}{W_0 - W_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left(- (2n-1)^2 \frac{\pi^2 D_{eff} t}{4L^2} \right) \tag{2.4}$$

Food samples assumed to be shaped like a slab geometry include apple and potato cubes [4], dill and parsley [48] and red bell pepper cubes [204].

Cylinder

$$\frac{W - W_e}{W_0 - W_e} = \frac{4}{r_c^2} \sum_{n=1}^{\infty} \frac{1}{\beta_n^2} \exp\left(- \beta_n^2 D_{eff} t \right) \tag{2.5}$$

Pasta [10], raisins [111], rice [153], apple [184] and potato [187] have been modelled as cylinders.

For food samples with more complicated geometries, numerical methods such as finite difference, finite element and control volume have been used for the evaluation of effective moisture diffusivity [161, 162].

Due to long drying times and for purposes of simplification, it is standard procedure to assume that only the first term of the series equations (2.3) to (2.5) is significant; the other terms can be dropped [127, 134, 162, 198]. The effective moisture diffusivity (D_{eff}) is then determined typically by plotting experimental drying data in terms of the natural logarithm (ln) of the moisture-content ratio, $W_{\text{R}} = (W - W_{\text{e}})/(W_0 - W_{\text{e}})$, against time ($t$). The slope of the drying curve is equal to the quantity $\pi^2 D_{\text{eff}} / 4L^2$ in the case of slab geometry in eq. (2.4), from which the value of D_{eff} is then calculated [134, 162, 169].

The effective moisture diffusivities are often expressed as a function of moisture content rather than constant values, especially when plotting $\ln[(W - W_{\text{e}})/(W_0 - W_{\text{e}})]$ against time yields non-linear drying curves. In this case D_{eff} can be determined by the method of slopes. The method calculates experimental values of D_{eff} at each moisture content level essentially by repeated application of the diffusion eqs. (2.3) to (2.5) to the data, starting with the initial moisture content $W = W_0$ and moisture ratio $W_{\text{R}} = (W - W_{\text{e}})/(W_0 - W_{\text{e}}) = 1$ and continuing until the final moisture content is reached [90, 125, 170]. Following this, the experimental drying curve is compared with the theoretical diffusion curve for the given shape of a material, see Fig. 2.6. The slopes of the two curves are estimated at the same moisture-content ratio $W_{\text{R}} = (W - W_{\text{e}})/(W_0 - W_{\text{e}})$ and D_{eff} is calculated from eq. (2.6). Examples of application of this method can be found in the literature for a large variety of food materials such as figs [16], rice [153], paprika [154], apples [184], and corn starch [202].

$$D_{\text{eff}} = \left[\frac{(dW_{\text{R}} / dt)_{\text{experimental}}}{(dW_{\text{R}} / dF_{\text{o}})_{\text{theoretical}}} \right] \cdot L^2 \tag{2.6}$$

$F_{\text{o}} = \dfrac{Dt}{r_{\text{s}}^2}$, Fourier number for diffusion

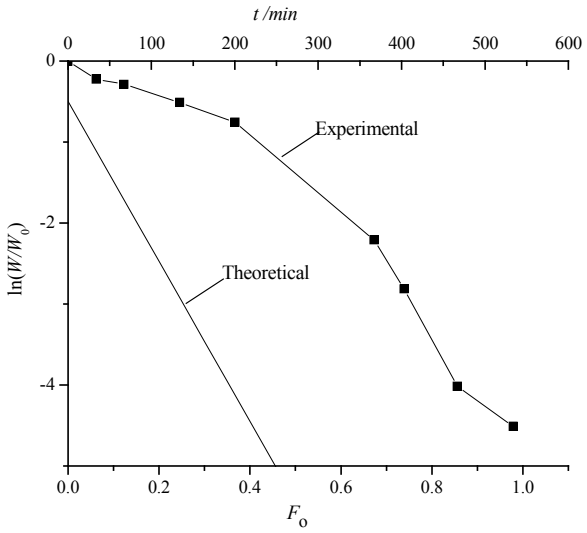

Fig. 2.6: Graphical representation of the method of slopes; adapted from [90, 170]

Effective moisture diffusivity in food ranges between 10^{-13} and 10^{-6} m^2s^{-1}, with most values in the region 10^{-11} to 10^{-8} m^2s^{-1} whereas diffusivity in other materials such as sand, clay, wool, silica gel, wood and glass ranges between 10^{-12} and 10^{-5} m^2s^{-1}, with most values in the region 10^{-9} to 10^{-7} m^2s^{-1}. These lower diffusivity values in food compared to other materials are ascribed to the complicated biopolymer structure of food as well as to the stronger binding of water in it [91, 114]. Tab. 2.1 shows typical effective moisture diffusivity values for various classes of food materials [169].

Tab. 2.1: Typical values of effective moisture diffusivity in food materials [169]

Food Material	$D_{eff} \cdot 10^{-10}$ / m^2s^{-1}
Highly porous	50
Porous	10
Nonporous starch/sugar	1
Nonporous protein/starch	0.1

Moisture diffusivity depends strongly on temperature and moisture content. However, drying itself also causes significant physical changes in the food sample, affecting its moisture diffusivity. For example, during drying, new cracks, pores and channels are

formed in the sample. Moisture can then be transported through these at a faster rate in vapour form. Likewise, the presence of small, water-soluble molecules in the sample such as glucose reduces moisture diffusivity, by decreasing the porosity of the sample over the course of the drying process. These effects combine to form the relationship between moisture content and effective diffusivity, which is presented in Fig. 2.7.

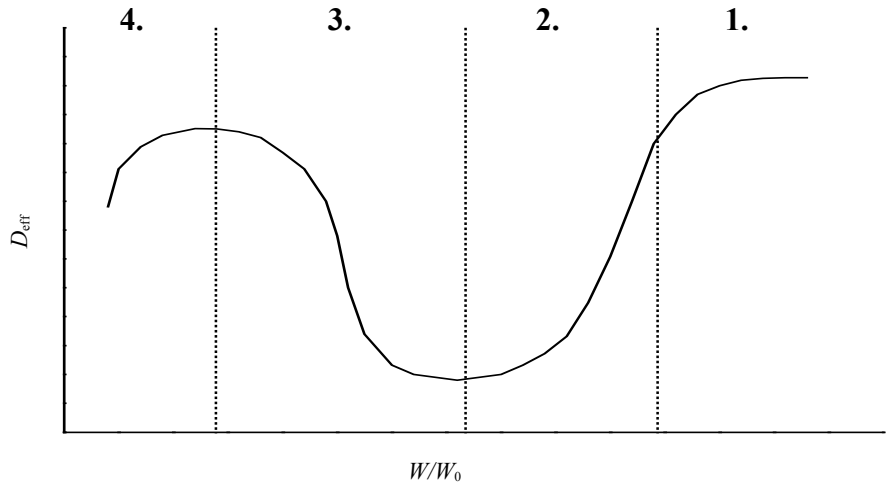

Fig. 2.7: Prevailing mechanisms of moisture transport in food materials; adapted from [18]

In region 1 of Fig. 2.7, moisture exerts its maximum vapour pressure and the migration of moisture is due essentially to capillary flow. This flow also plays an important role in region 2, where moisture easily migrates from water-filled pores to the surface. In region 3, however, the water is bound in multiple layers and moisture begins to diffuse in both liquid and vapour form, resulting in a rise in effective moisture diffusivity. In porous food, effective moisture diffusivity increases gradually as moisture content is reduced to about $W_R = 0.1$. This is due to the further development of porosity in the sample. The water transport mechanism may change from liquid diffusion to much faster vapour diffusion. At very low levels of moisture ($W_R < 0.1$), in region 4, the water is bound very strongly to specific sites by adsorption. This water is referred to as monolayer moisture and leads to a sharp reduction in moisture diffusivity. In this region, the final moisture transport mechanism is vapour diffusion [18, 152, 168, 170].

A key assumption of FICK's second law of diffusion, eq. (2.2), for describing the rate of moisture movement within the food sample, is that there is only internal mass transfer during drying. Other transport mechanisms such as external mass transfer and both internal and external heat transfer are neglected. For the analysis of each of these transport mechanisms, corresponding partial differential equations should be solved numerically. However, this requires considerable computing power and time, and in certain cases, it is not possible to solve them [56, 76, 114, 141, 142, 158, 179, 193]. This has led to the development of numerous semi-theoretical models, which propose simple alternatives to eq. (2.2), while still describing the behaviour of moisture loss over time during drying in a satisfactory manner. Among them, the models by LEWIS eq. (2.7) and PAGE eq. (2.8) are the most commonly applied [24, 141, 148].

$$\frac{W}{W_0} = \exp(-k_{\mathrm{LEWIS}} \cdot t) \tag{2.7}$$

The LEWIS model assumes negligible internal resistance, i.e. no resistance to moisture movement from within the material to the surface of the material. This is in fact inadequate for a complete description of mass transfer during drying, but it is nevertheless widely used due to its simplicity and computational speed. The drawbacks of eq. (2.7) are that it tends to overestimate the early stages and underestimate the later stages of the drying curve [6, 24, 112]. Examples of agricultural products, the drying of which has been modelled by the LEWIS equation, include kiwi [117], and black tea [139].

To overcome the limitations of the LEWIS model, the PAGE model eq. (2.8) offers an empirical modification to the time term by introducing an exponent *n*.

$$\frac{W}{W_0} = \exp(-k_{\mathrm{PAGE}} \cdot t^n) \tag{2.8}$$

Eq. (2.8) has been used by many researchers to describe and predict the rate of moisture loss during drying for several agricultural products such as noodles [28], grapes [47],

rice [79], pistachio nuts [92], onion slices [100], Indian gooseberry [123], and carrots [145].

The parameters k_{LEWIS}, k_{PAGE} and n_{PAGE} have been correlated with different process variables such as air temperature and velocity, and sample conditions (e.g. existence of an external skin). It has been shown that the parameter k increases as drying temperature increases, while n_{PAGE} does not demonstrate a clear trend [123, 172, 179, 188]. However, the dependence of the drying constant n_{PAGE} on air velocity has been reported in other studies [28, 148]. In addition, KARATHANOS AND BELESSIOTIS observed an increase in the parameter n_{PAGE} for the existence of an outer skin on the dried fruit, depending on the thickness and type of product [87].

These models assume a direct relationship between moisture content and drying time. That is, they neglect the fundamentals of the drying process and their parameters have no physical meaning. However, they may be used to describe the drying curve for any particular given conditions (air temperature, sample thickness, etc.) of the experimental process [57, 179]. Furthermore, they require less computation time when compared to the purely analytical models and do not make assumptions regarding sample geometry, moisture diffusivity and conductivity [141].

2.4 Effects of Drying on Product Quality

The quality of dried products is influenced by the particular variety of the raw material as well as its properties (e.g. structure, ripeness), methods of drying and storage conditions. Several physical, chemical, biochemical and/or microbiological changes may occur in food during drying and storage, resulting in significant quality losses. Such changes that reduce the quality of the final dried product as listed in Tab. 2.2 are functions of temperature, moisture content and time. To be able to control these quality changes during drying requires knowledge about the adverse effects of process and product conditions. With this knowledge, it is possible to relate the quality of the dried products to the drying conditions by measuring and comparing the effects of different temperatures and moisture content on the quality degradation reactions [105, 191].

Tab. 2.2: Changes occurring in food products during drying [52, 134, 152, 183]

Physical	Chemical and Biochemical	Nutritional
Shrinkage	Non-enzymatic browning reactions	Microbial survival
Loss in rehydration ability	Enzymatic browning reactions	Vitamin loss
Migration of solids/case hardening	Decrease and loss in flavour and aroma	Protein loss
Loss in colour	Formation of new flavour and aroma	
	Oxidation reactions (vitamins, lipids)	
	Denaturation of proteins	

If dried food is safe in terms of microbial count, which is achieved by lowering the moisture content of the sample to under 15% (wb), then the quality depends mostly on appetising appearance factors such as colour, flavour and aroma, texture or rehydration ability and nutritional value [88, 103, 150]. However, among these sensorial characteristics of food, colour is probably the most important criterion for consumer purchasing decisions since it is the first and most direct visual sign of product quality at the point of sale [20, 99]. Rehydration ability is also important, especially if the product is first going to be consumed upon rehydration [54, 91]. In general, from the consumer's point of view, severe browning and poor rehydration ability indicate reduced quality [49, 119]. One of the key aims of drying technology is to minimise these product changes, while optimising the process and taking into account the cost [72]. In the following subsection, the major product quality changes and their effects on the degradation of food are hence reviewed in more detail.

2.4.1 Changes in Colour Quality

2.4.1.1 Browning Reactions

Browning reactions decrease nutritional value and solubility, create off-flavours, and induce textural alterations in the food. Such reactions are classified into *enzymatic* and

non-enzymatic reactions. The former are enzyme-mediated reactions while examples of the latter include sugar caramelization, sugar-amine reactions (*Maillard reactions*) and ascorbic acid oxidation [99, 134, 150].

Enzymatic Browning

Enzymatic browning occurs in fruits and vegetables such as bananas, pears, mushrooms and potatoes, often upon bruising during handling or when sliced under the presence of air, as well as during the drying process. Protective measures against discoloration by enzymatic browning reactions include the inactivation of enzymes by blanching or heat treatments at temperatures of around 70 to 75 ºC, the use of reductive agents such as sulphur dioxide or ascorbic acid, and the removal of available oxygen [19, 77].

Non-Enzymatic Browning Reactions

In the case of a thermally stabilised product, in which enzymatic activity has been almost completely destroyed by heat, particular attention should be paid to non-enzymatic browning reactions. The most common types of non-enzymatic browning during drying are *Maillard reactions* in which carbonyl groups of reducing sugars, aldehydes and ketones interact with amino compounds such as amino acids, peptides and proteins. These reactions result in brown pigments, known as melanoidins, causing the main discoloration problem in dried products such as white dried soups, tomato soup and other dried fruit and vegetables [19, 83].

The Maillard reaction rate depends on several factors including temperature, the types of the reactant sugars and amines, moisture content and pH. It has been reported in the literature that when a certain intermediate moisture range is reached in the course of the drying process, the Maillard reaction rate starts to increase, and later, at low-moisture ranges, it peaks at a maximum value. That is, the last drying period is associated with high browning. This may be explained by the fact that at this stage, less evaporative cooling takes place, which leads to an increase in sample temperature. Reducing the air temperature during the last drying period is therefore advisable. In this way, the product will not experience unnecessary heat when it is within its critical moisture content range [52, 134, 152, 191].

2.4.2 Rehydration Ability

Rehydration may be described as a process in which dried material is submerged in a fluid (most commonly water) for moistening purposes. However in general, the water that is removed during drying cannot be replaced in exactly the same manner to yield a product identical to the original material. This phenomenon is due to irreversible cellular and structural damage that occurs in plant tissue during drying. Such damage includes loss of turgor pressure in the cell, loss of differential permeability in the protoplasmic membrane, crystallization of polysaccharide gels in the cell wall and coagulation of protoplasmic proteins. These irreversible cellular ruptures lead to loss of integrity and hence, to a dense structure of collapsed or greatly shrunken capillaries with reduced hydrophilic properties. This is reflected in the dried material's inability to imbibe sufficient water to rehydrate fully. That is, the degree to which a dried sample rehydrates is dependent on these cellular and structural disruptions. The rehydration ability of dried materials can thus be considered as a key quality assessment factor since it represents the measure of injury to the material caused by drying [53, 91, 98, 107].

The rehydration of dried plant tissues takes place at three levels: (a) imbibing of water by the dried material, (b) swelling of biopolymers and (c) leaching of solubles into the surrounding water. At the beginning of the rehydration process, absorption of water is rapid due to capillary suction. Then, as the capillaries and pores are filled with water, little moisture movement is expected between the material and its surrounding. Here, moisture movement is restricted to within the material only. That is, polymers (mainly cell walls) start to absorb water and the material swells. The folded, wrinkled cell walls tend to straighten out during swelling. However, because of the high crystallisation of cellulose, especially after prolonged drying, the cell wall takes up considerably less water during swelling compared to its fresh state. Thus rehydrated products hold most of their water in free form (unbound) [107, 147].

During rehydration, the dried material may also lose solubles, but the mechanism of such "leaching" is strongly dependent on the temperature of the rehydrating fluid. At temperatures below 50 ºC, leaching is reported to be very slow since the cell membranes remain intact. However, at high temperatures, the destruction of cell membranes causes

rapid leaching [107]. KROKIDA AND MARINOS-KOURIS studied the effects of water temperature on rehydration capability and rates [98]. They concluded that the rehydration rates of dried materials increase at higher water temperatures.

Investigations correlating the duration and the degree of rehydration indicate faster and more complete reconstitution for lower drying times [81, 163, 182, 207]. The development of higher porosity in the sample enhances the rehydration properties. It has been shown that porosity in fact develops especially during the final stages of drying due to the formation of a glassy state [89, 207]. This glassy state adds substantially to the mechanical strength of the material and thus hinders shrinkage and increases porosity. Similarly, it has been reported that high drying temperatures (i.e. high drying rates) lead to a more porous structure with good rehydration ability whereas low drying temperatures result in a more compact and a denser product with reduced rehydration capacity and rates [13, 81, 120, 131, 155, 163, 205, 207]. This is a result of the fact that in the case of low drying temperatures there is an intensive shrinkage effect on the sample which continues until the end of drying. That is, long drying time due to the low drying rates of moisture removal simply provides more time for the product to shrink. Conversely, at high drying rates the outer layers of the sample become rigid, thus the final volume is fixed early on in the drying. As a result, shrinkage is hindered before the end of drying. This leads to an open (i.e. porous) internal structure of the material due to the tissue splitting and rupturing as drying proceeds [207].

Attempts to minimise shrinkage and improve the rehydration of dehydrated fruits and vegetables include flash-drying techniques such as explosive puffing and vacuum puffing [53, 84]. In addition, JAYARAMAN ET AL. and SCHULTZ ET AL. have reported that the application of high temperatures for a short time (HTST) as a pre-treatment prior to conventional hot-air drying brings about porosity in the products reduces their drying and rehydration times considerably as well as improving their rehydration characteristics [84, 171].

2.5 Drying Technology

The diversity of food products has led to the development of many different types of methods and equipment in drying technology. The most important factors influencing the choice of method and dryer are as follows [72, 150, 152]:
(1) The state and shape (liquid, solid, particulate, etc.) of the food that is being dried. There exist four basic shapes: a) particulate food either in a bed, in a layer, or dispersed; b) a sheet or a film; c) a block or a slab; and d) a slurry, a solution or a paste. The widest range of dryers is available for particulate food.
(2) The heat transfer mechanism that is used to provide the energy for drying. Heat can be supplied by: a) **convection**, where the heating medium, usually hot-air or combustion gases, is in *direct* contact with the wet material and supplies the thermal energy; b) **conduction**, where heat is transmitted *indirectly* by contact of the wet material with a heated surface; c) **internal heat generation** (dielectric, microwave, radiofrequency); d) **freeze drying**, where moisture is removed by a solid-vapour transition (sublimation) enhanced by low pressure.
(3) Desired physical form and characteristics of the end product.

Convectional Hot-Air Drying

The majority of industrial drying installations rely on convectional hot-air drying at atmospheric pressure since it is the simplest and most economical among the various methods. A wide variety of food materials such as fruit, vegetables, herbs and cereal crops has therefore been dried by convectional hot-air dryers. In addition, it is easy to set and control the optimum drying conditions in these dryers, especially in cabinet dryers. Common atmospheric hot-air dryers include kiln, cabinet (tray), tunnel, and belt or conveyor dryers [83, 127, 152, 201].

The basic configuration of an atmospheric hot-air dryer is an enclosed and heated chamber where food material is placed. It is also equipped with a blower (i.e. fan) and ducts to allow the circulation of hot air around and across the food. When there is no fan the drying takes place under natural convection. The drying process in an atmospheric dryer involves both heating the product and removing water from the product surface [18, 150].

Traditional convective drying methods employ continuous constant air temperature for moisture removal from the food product. The transfer of thermal energy from the heater to the food substance occurs by means of convection. The penetration of this thermal energy is dependent on the thermal conductivity of the material. During drying, as moisture leaves the pores in the outer layers of the food, it is replaced by gas (air). This results in a decrease in the thermal conductivity of the outer layers since the thermal conductivity of air is lower than that of water. Consequently, the product surface behaves like an insulator. The penetration of the delivered heat to the inner section of the food sample is reduced progressively, and water is transferred more slowly to the surface, where evaporation occurs. Thus high heat transfer rates applied at the surface will only result in overheating or over-drying of the surface layer, leading to quality problems without a significant increase in the drying kinetics [57, 110].

Various procedures are applied in order to increase the effectiveness of the drying process. Examples of these include stirring the food samples, drying in a fluidised bed or applying microwave energy. Normally, these procedures require high power supply and/or lead to inhomogeneous heating as in the case of microwave drying, which results in the burning of the food products [55, 75, 150, 152]. Intermittent or discontinuous drying has been reported as an alternative method, especially in the grain industry, because it offers some advantages over the continuous form of drying [25, 32, 69, 106]. In addition, many studies advocate varying the air temperature during drying operations [43, 136, 143, 171, 214]. The latter two methods are presented in more detail in the following subsections.

Intermittent Drying

Intermittent drying is a non-continuous drying process with tempering periods. It involves strict control of the heat input (drying temperature) such that the food material is subjected to particular air conditions at different points over the course of drying. Drying temperature may be pulsated in a number of ways:

(a) Intermittent drying: Heat is supplied intermittently rather than continuously throughout the drying process. That is, the drying cycle, which consists of a drying

and a tempering period, is repeated until the moisture content of the food product is reduced to the desired level;

(b) Dryaeration: Heat is supplied in a continuous manner for a short period of time to the food product in the drying chamber. Following this, the food is transferred to a cool, dark storehouse for a slow cooling process (tempering), which may take up to a few hours. After this, the food is replaced in the drying chamber for a final drying period;

(c) Cyclic drying: Heat is supplied according to a specific cyclic pattern. Variations of these include sinusoidal, square-wave or saw-tooth patterns [32].

Drying causes moisture gradients to develop within the food products, which in turn decrease the drying rate. Tempering periods allow for moisture diffusion from the interior to the external surface of the food sample, thus decreasing such moisture gradients. This happens when the sample surface and the pores close to the surface are saturated with water that has been transferred from the inner sections. The resultant uniform distribution of moisture contributes to a reduction in drying time in the oven, thus reducing the total cost of the drying process. Indeed, after tempering, the surface moisture is easily removed in subsequent drying periods in the oven, which improves the drying rate. This phenomenon is referred to in the literature as the "refreshing effect" [36, 97, 133, 185, 210].

The length of tempering periods used in intermittent drying varies widely. It is important to know the tempering time that is appropriate for a particular set of conditions. The tempering time should be as short as possible to minimise the damage to the food sample caused by chemical changes, respiration and microbial activity [185]. The duration and frequency of tempering depend on the time intervals of both the drying phase and the tempering phase and are greatly affected by the drying temperature. Higher temperatures shorten the required tempering times. Consequently, the total drying time necessary for reaching the desired moisture content (<15% wb) depends on the lengths of both the drying period and the tempering period [35].

Many researchers have studied intermittent drying process for grain drying (especially for rice) by hot air [11, 35, 36, 38, 113, 133, 174, 185, 211]. However there are very few

studies on the intermittent drying of other agricultural products such as fruit and vegetables. PAN ET AL. have studied the intermittent drying of carrot cubes and squash slices in vibrated fluidised beds in a dryaeration process [137, 138]. CHUA ET AL. have conducted intermittent drying experiments with potato, guava and banana pieces under cyclic variations in the air temperature [30]. These studies have all demonstrated a clear advantage of intermittent drying in terms of product quality.

Step-Wise Change in Drying Air Temperature

Step-wise change in drying air temperature is an effective method for reducing drying time and improving product quality. This is because air temperature directly influences sample temperature, which then controls the drying kinetics and quality of the food products. Besides air temperature, air humidity and velocity have also been reported to influence drying characteristics to some extent, depending on the drying conditions. Direct control of these parameters helps to minimise product quality degradation as well as to improve drying kinetics. However, for heat-sensitive materials such as fruit and vegetables, much of the resistance to drying resides within the material, indicating that the air velocity and humidity are not as important as air temperature [16, 58, 92, 112, 116, 118, 143, 203]. Several studies have thus concentrated on the effects of step-wise change in drying air temperature on the drying characteristics. The interesting outcomes of these studies include shorter effective drying time, higher moisture-removal rates, lower product-surface temperature and higher product quality including reduced shrinkage, cracking and brittleness, and improved colour and nutrient retention [17, 29, 43, 136]. For instance, DEVAHASTIN AND MUJUMDAR have applied a mathematical model to demonstrate that the drying time of grains can be reduced by up to 30% by employing step-wise changes in the drying temperature [43]. In another study, ÖZILGEN ET AL. have recommended starting drying at high temperatures and then decreasing the temperature continuously in order to achieve better colour retention in apples [136]. Additionally, CHUA ET AL. have shown that with the appropriate choice of temperature-time variation, it is possible to decrease the change in product colour for fruits and vegetables [30].

2.6 Tomato and Tomato Drying

The tomato (*Lycopersicum esculentum*), usually regarded and consumed as a vegetable with savory dishes, is one of the world's most widely grown fruit. Global tomato production in 2004 was estimated at almost 124 million metric tons, representing an increase of 31% over the course of the previous decade [46, 121].

The tomato fruit consists of skin (epidermis), pericarp, seeds, and locular contents (Fig. 2.8). Jelly-like parenchyma cells that surround the seeds fill the locular cavities and resemble a non-porous material while the inner wall structure resembles fibrous material. Tomato represents a large range of highly moist, hygroscopic, and capillary-porous shrinking materials. It normally contains 5 to 7.5% dry matter. Nearly half of the dry matter is in the form of reducing sugars, with slightly more fructose than glucose [41, 71].

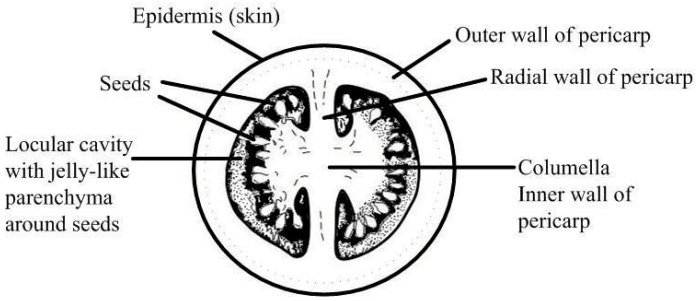

Fig. 2.8: Transverse sections of mature tomato fruit showing the main anatomical features; adapted from [41]

Tomatoes are commonly consumed in fresh form. However due to their high moisture content they are very perishable and thus have limited shelf-life. There is a consequent imbalance in the supply and demand of tomato, especially during the non-harvesting season. In order to overcome these difficulties fresh tomatoes are processed and preserved in the form of sauces, juices, ketchup and dried fruit and powders. GOULD reported that processed products such as tomato juice, paste, puree, ketchup and sauce and make up over 80% of total tomato consumption [66].

Drying has been practised for many years as a means of preserving tomatoes. Although the drying process offers an alternative way of providing tomato for commerce, it is not as popular when compared to tomato paste production, on account of its adverse effect on final product quality. Nevertheless, interest in the production of dried tomato is on the increase thanks to the possibility of using it in pizza toppings, snacks, instant soups, salads, pasta and other savoury dishes [121]. Different techniques, including sun or solar-drying [68, 165], convectional hot-air drying [5, 46, 62, 71, 135, 214], heat pump drying [148], osmotic drying [195] and combined drying techniques [50, 73, 175] have been applied to dry tomatoes.

Sun drying is frequently used to preserve tomatoes, however it is extremely weather-dependent and brings with it the problems of long drying time and contamination through dust, soil and insects. Moreover, sun-dried tomatoes or other fruits and vegetables generally have a higher moisture content above 15%, which is too high for storage stability [26, 135, 152].

Osmotic drying is another common method, however it alone does not stabilise the product sufficiently to allow for long-term storage [126, 150, 199]. Indeed, after immersing the tomatoes in osmotic solutions (salt or sugar solutions), they are air-dried to reduce the water activity to such a level that spoilage is prevented or at least retarded. However, case hardening is reported to be more problematic with osmosed air-dried products due to the salt or sugar in the osmotic solution forming a crust on the surface [42, 126, 180].

Convectional hot-air drying is by far the most economical common method utilised in the food industry [26, 83, 127, 152, 201]. An illustration of the process of drying tomatoes by the convectional method is presented in the flow diagram in Fig. 2.9.

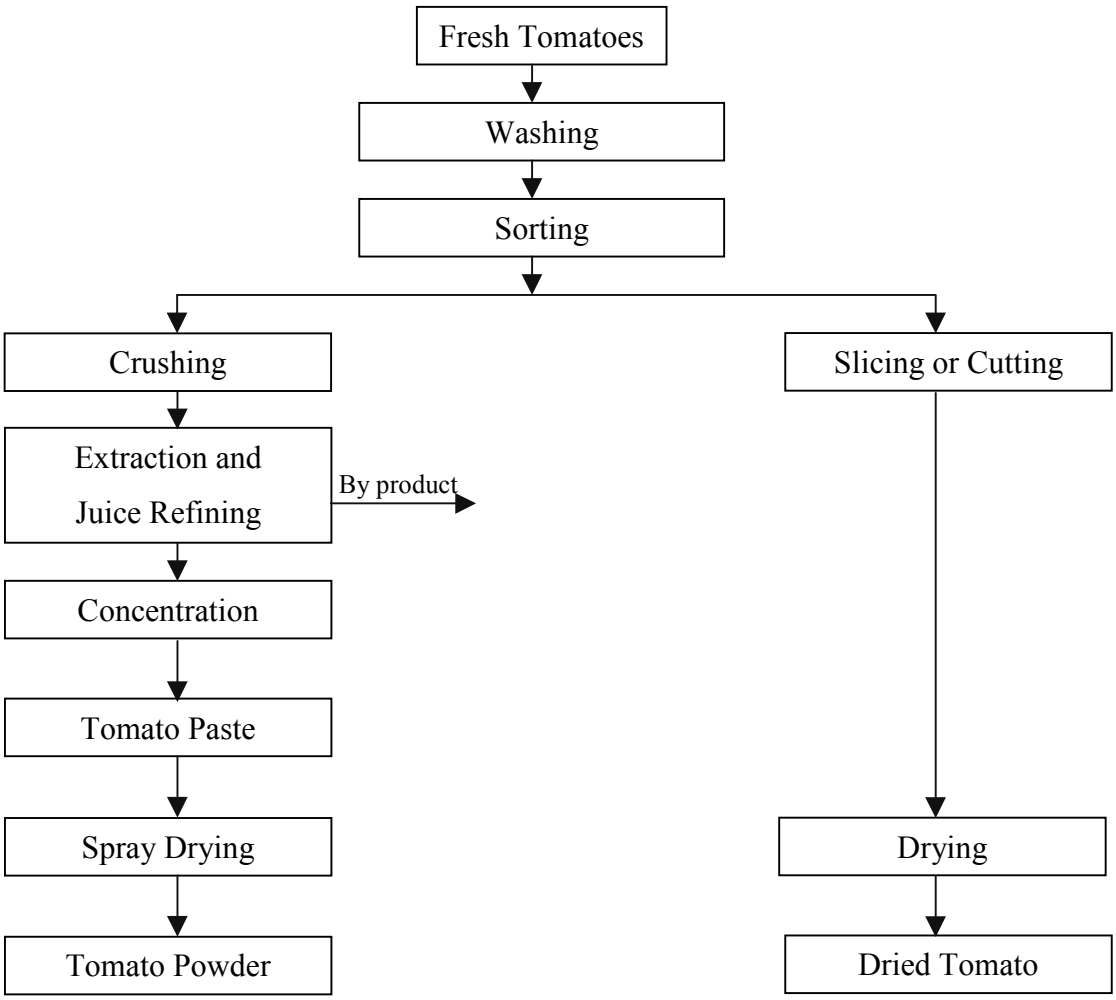

Fig. 2.9: Flow diagram of the tomato-drying process; adapted from [121]

There are also some new techniques used for drying food such as microwave and infrared drying. These can be very useful methods for reducing the drying time when compared to low-temperature hot-air oven drying. However the quality of the dried products is low. The main problem with these methods is non-uniform heating, which causes loss in colour quality due to various levels of burning. Moreover, it is difficult to use these methods for thick and highly moist food types such as fruits and vegetables due to the puffing effect that occurs during such drying processes. Nevertheless, they may offer acceptable end products for food which is low in initial moisture and thin in shape and size, such as for instance herbs. Another drawback associated with these drying methods is their high initial cost [132, 152, 150].

Fresh tomatoes used in the drying process should be consistent in size, free from blemishes, red in colour, firm with thick-walled flesh, and most importantly, free from mould and bacteria [121]. Tab. 2.3 summarises the operating conditions and sample properties from previous studies on tomato drying by the convectional hot-air method.

Tab. 2.3: Overview of previous studies on tomato drying

Tomato Shape and Thickness / cm		Initial Moisture Content / % wb	Drying Temperature / ºC	Drying Time / h	Moisture Transfer Description	Reference
slices	1.0	96	80	5	-	[68]
slices	0.7	94	60	18	-	[135]
slices	0.5	95	80	3.16	FICK's second law	[71]
halves	-	95	110	4	-	[214]
halves	1.6	95	80	7	FICK's second law	[62]
halves	1.6	94	110	4	FICK's second law	
pulp in slabs	1.5	89	70	3	FICK's second law	
pulp in slabs	2.0	91	70	3	FICK's second law	
quarters	-	-	40	16	LEWIS and PAGE	[148]
slices	1.5	95	75	6	FICK's second law	[5]
halves	6.5	-	110	5.5	-	[65]
halves	-	95	70	24	FICK's second law	[46]

As can be seen in Tab. 2.3, the air temperature typically ranges from 40 ºC to 110 ºC. Tomatoes are cut into different shapes such as halves, slices, slabs or quarters. The thickness of the tomato samples is generally lower than 5 cm. Drying times are usually very long and change from a few to over 15 hours, depending upon the drying

temperature and tomato size. Such long treatments allow sufficient time for the occurrence of chemical reactions (e.g. non-enzymatic browning) that may alter the colour and flavour of the sample and damage nutrients such as vitamin C [12, 50, 73, 85, 135]. The limitations of hot-air drying in tomato processing thus include overheating of the surface which results in inferior product quality (particularly in colour) and lower drying rates. In addition, structural changes in the dried tomato samples inhibit the rehydration characteristics [73, 121]. Damage caused through the drying process can be avoided by optimising the operating conditions for tomato products. Therefore, an understanding of the characteristics of tomato in terms of hygroscopicity, drying kinetics and moisture diffusivity is essential for any optimisation study. In the literature, FICK's second law of diffusion has been used to explain the drying mechanism in tomato samples [5, 46, 62, 71, 165]. Several researchers have fitted the moisture content data from tomato samples to semi-theoretical and empirical models based on this law of diffusion [46, 148, 165].

Studies concerning the effects of drying on tomato antioxidant components has demonstrated that the lycopene in tomatoes is substantially stable during industrial drying [61, 93, 103, 214]. From this point of view, ZANONI ET AL. reported that the lycopene content of tomato halves at 10% final moisture content decreased by a maximum of 10% after drying at 110 ºC for four hours and did not change during drying at 80 ºC for seven hours [214]. SHI ET AL. found that the lycopene content of tomatoes at 3-4% final moisture content decreased by about 4% after drying at 95 ºC for 6-10 hours [178]. Lycopene loss of about 2.35% was stated by LAVELLI ET AL. for tomato halves dried to 20% final moisture content at 80 °C for 6.6 hours [103]. In addition, SHI ET AL. pointed out the importance of the duration of heat treatment at 100 °C on lycopene loss in tomato puree, reporting a 0.15% loss after a cooking period of five minutes compared to a 3.47% loss after 60 minutes of cooking [177]. Other studies have indicated that food processing is in fact a value-added step to lycopene due to higher lycopene bioavailability following thermal treatment [27, 144, 157, 176].

3 Aim

Most dried fruits and vegetables are produced by means of convectional hot-air drying on account of its simple application. However it is a very energy-intensive process, often leading to a serious reduction in food quality with colour degradation and lower rehydration ability. The quality degradation occurs as samples are exposed to heat for long periods of time due to the low heat and mass transfer during hot-air drying [31, 50, 83, 110, 149, 152, 201].

Until now, most of the research on the hot-air drying of fruit and vegetables has concentrated on relatively low drying temperatures in the range of 40-90 ºC [14, 99, 201]. Yet a few studies have been conducted on the drying kinetics and quality of agricultural materials at drying temperatures above 100 ºC [137, 138]. In fact, high-temperature air drying (>100 ºC) may overcome the problem of low heat and mass transfer associated with low-temperature air drying (<100 ºC) as there is high potential for savings in drying time. Many of the properties of the dried product such as colour and rehydration ability can then be superior due to shorter exposure of the food to the drying conditions [83, 212]. However, in the absence of a better understanding of the drying characteristics concerning both kinetics and quality (in particular, colour) and of how these are affected by controllable factors (air temperature and sample size), high-temperature air drying may also result in improperly dried material with substantial degradation particularly in colour quality, i.e. browning and locally burned areas on the samples [29, 49, 86, 191]. The focus of this study is on tackling and resolving these issues.

Drying kinetics should be analysed in terms of drying rate, effective diffusivity and the drying constants of selected semi-empirical models in order to compare the effects of different drying conditions and select the optimal process and sample parameters. Regarding the dried product colour quality, drying time and temperature are the most important operating parameters since colour degradation (i.e. non-enzymatic browning) is directly influenced by sample temperature, moisture content and exposure time [31, 49, 95]. Knowledge of moisture and temperature data for the sample at the point of

browning is therefore required to be able to control the process temperature and minimise its adverse effects on colour quality.

It has been reported in the literature that intermittent drying, which involves interruption of the drying process for a period of time known as tempering, provides increased drying rates in the subsequent drying periods, leading to thermal-energy savings [36, 137, 138, 185]. Furthermore, by tempering, the sensible heat of the material accumulated during the drying period can be used to evaporate some moisture from the sample without applying extra heat energy. Meanwhile, due to evaporative cooling, the sample temperature decreases. This drying technique also minimises the adverse effects of air temperature on the product quality because long exposure time to continuous drying conditions is prevented [106]. Examples of such quality benefits from intermittent drying include the retention of beta-carotene in carrots [137] and less fissure in rice [11, 133]. An alternative approach to the intermittent process for the reduction of quality degradation in food products is to employ a time-varying step-down temperature profile during drying. Both of these drying methods have been applied to grain, which has a very low initial moisture content (e.g. 20-30%), size and a low drying temperature (30-50 ºC) [35, 43, 133, 174]. However there is a large gap in the literature regarding the use of these methods at higher drying temperatures and for agricultural products with high initial moisture content such as tomatoes.

A number of studies have been published on the hot-air drying of tomato [5, 46, 62, 71, 135, 214]. In these studies, drying air temperatures tend to be lower than 100 ºC. No work on high-temperature intermittent drying, kinetics and quality for tomatoes has been reported to date. There is a particular lack of information concerning the behaviour of tomato samples when exposed to high drying temperatures.

The aim of this study is hence to investigate the feasibility of using high air temperatures (100 ºC-200 ºC) in the oven for drying fruit and vegetable pieces. In order to achieve this aim, the drying kinetics as well as the dried-product quality of tomato are analysed in detail. The main process and product parameters investigated in the experiments are drying air temperature, sample geometry and exposure time.

4 Material and Methods

4.1 Material

4.1.1 Tomato

For each experimental test, fresh tomatoes (*Lycopersicum esculentum*) were purchased from the supermarket under the same brand name to ensure the consistency of results. The tomato samples were cut into different shapes and thickness manually and dried at relatively high air temperatures > 100 ºC, see Fig. 4.1.

Among the studies related to the drying of tomatoes, see Tab. 2.3, tomato halves and slices seem to be the most popular sample shapes at low drying air temperatures (< 110 ºC). However pre-experiments demonstrated that slices and thick samples are not suitable from the quality point of view for drying at temperatures higher than 100 ºC due to their uneven structure and small surface area per volume. Therefore in this study tomato cubes and rings were chosen in order to compare the drying characteristics of differently shaped samples of varying thickness at high air temperatures (> 100 ºC).

4.1.2 Equipment

The following equipment was used in this study.

Colour Instrument
Minolta Europe GmbH, Langenhagen
Chroma-Meter CR-310

Digital Thermometer
Voltcraft-304 4 channel
Thermo couples, 0600 1301
NiCr-Ni Typ K

Drying Oven
Heraeus, Hanau
KT 50D

Laboratory Balance
Ohaus, Scout
SC 2020

Precison Balance
Sartorius-Werke GmbH, Göttingen
2842

4.2 Methods

4.2.1 Experimental Process

A series of experiments was conducted to study the high temperature drying of tomato samples. As illustrated in Fig. 4.1, tomatoes were processed using three different drying methods. All of the drying experiments were carried out in an electrically heated conventional laboratory oven under natural convection. Once the desired temperatures (steady-state conditions) in the oven were achieved, a thin layer of tomato cubes/rings weighing about 25 g was distributed uniformly on a sheet of baking paper and the sample was then placed onto the oven shelf. Moisture loss was recorded periodically using a digital balance (accuracy of 0.01 g) as a function of drying time. For this purpose, the drying samples were withdrawn from the oven at five-minute intervals throughout the drying process, rapidly weighed and replaced in the oven. The weighing of the product was performed in approximately 30 seconds and did not significantly change the steady-state drying conditions. In the intermittent drying experiments, for every five minutes in the oven, samples were withdrawn, weighed and then subjected to 25 ºC in a separate cabinet containing a ventilator for 15-minute intervals and then placed back into the oven. During these 15-minute periods (tempering) the sample weight was recorded at five-minute intervals in order to monitor the moisture loss in the absence of heat application.

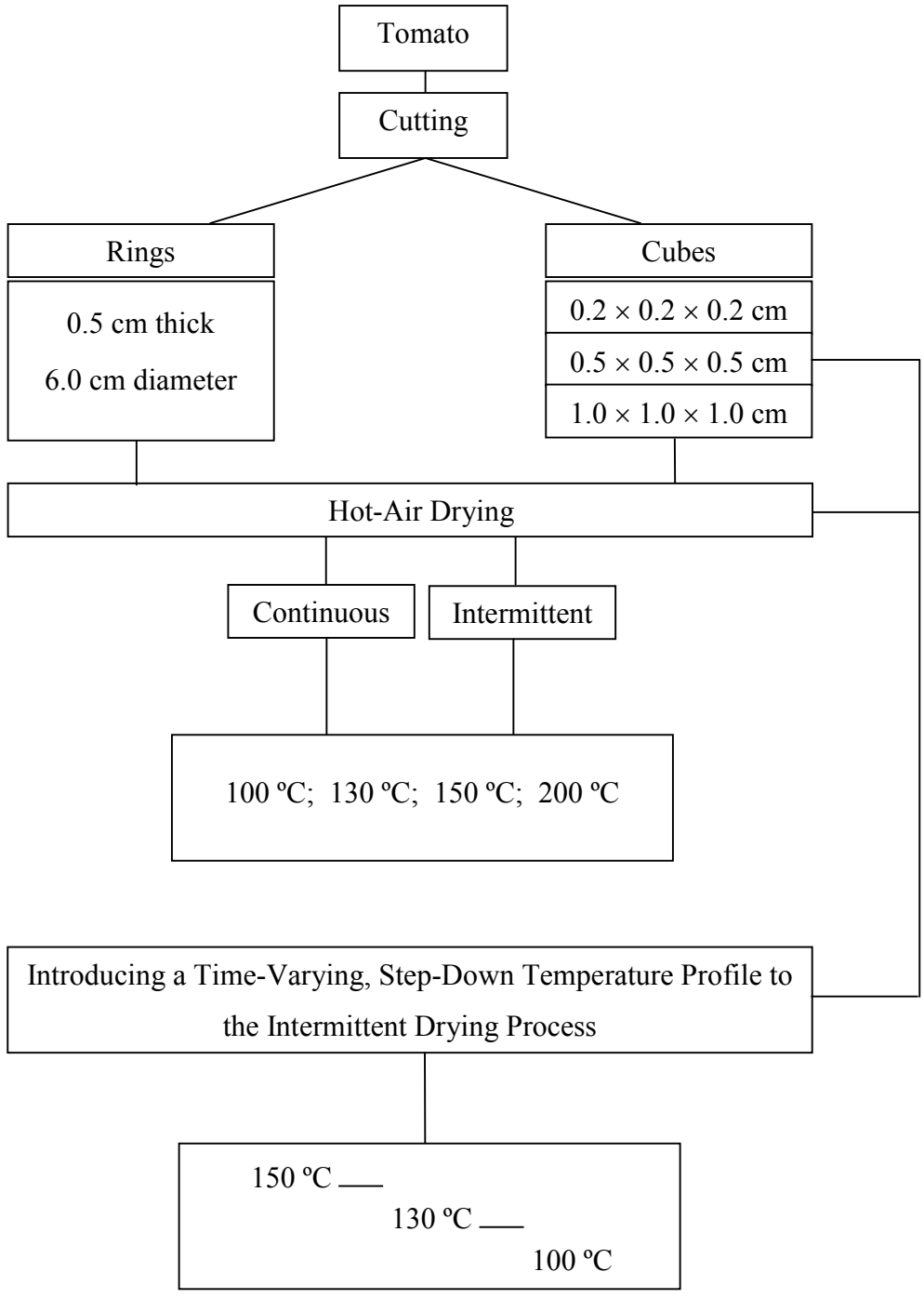

Fig. 4.1: Experimental Design and Process

4.2.1.1 Continuous Air Drying

The drying tests were carried out at different thicknesses: 0.2, 0.5, and 1.0 cm for cubes and 0.5 cm for rings. Tomato cubes and rings were dried at relatively high air temperatures ranging from 100 to 200 ºC in order to determine the drying kinetics and onset of browning at these temperatures. Browning development at different drying temperatures, thickness and shapes was determined visually and recorded as a function of time, sample temperature and moisture content.

4.2.1.2 Intermittent Drying

The drying conditions (drying temperature and relative humidity) used throughout each experiment were the same as those for continuous drying. However, intermittence (tempering periods) was varied during the process in order to study the effect of tempering time on the drying kinetics and colour quality. Intermittence is defined in the following eq. (4.1):

$$\alpha = \frac{t_{on}}{t_{on} + t_{off}} \tag{4.1}$$

Tab. 4.1 shows the α-values used in the intermittent drying process. Sample temperature measurements were taken, and the sample colour was checked visually to compare intermittent drying to continuous drying.

Tab. 4.1: Intermittence employed in the drying experiments

Drying Time in the Oven (t_{on}) / min	Tempering Time in the Cabinet (t_{off}) / min	Cycle Time ($t_{on} + t_{off}$) / min	Intermittence $\alpha = \frac{t_{on}}{t_{on} + t_{off}}$
5	15	20	1/4
5	5	10	1/2
15	15	30	1/2

4.2.1.3 Optimisation of the Drying Process and Application of a Time-Varying Step-Down Temperature Profile

Tomato cubes were heated sequentially at 150 ºC (25 minutes), 130 ºC (15 minutes) and 100 ºC (25 minutes) in the dryer. For every five minutes in the oven, the cubes were subjected to 25 ºC in a separate cabinet containing a ventilator for 15 minutes of tempering (α=1/4). The duration of each period of drying at the various temperatures was set according to the browning, sample temperature and moisture content information obtained from continuous and intermittent drying runs.

4.2.2 Analysis of the Drying Data

4.2.2.1 Moisture Content

There are two ways of expressing the moisture content of food. The moisture content can be reported as a percentage or fraction either on a *wet basis* (% wb), based on the weight of wet material or on a *dry basis* (db) in g [H_2O] g^{-1} [DM], based on the weight of the dry material. Accordingly, the wet-basis moisture content of samples was calculated using eq (4.2):

$$Moisture\ Content\ (\%wb)\ or\ X_{(t)} = \left(\frac{m_{(t)} - S}{m_{(t)}} \right) \cdot 100 \tag{4.2}$$

and the dry-basis moisture content was calculated as follows,

$$Moisture\ Content\ (db)\ or\ W_{(t)} = \frac{m_{(t)} - S}{S} \tag{4.3}$$

In drying processes it is more advantageous to express the water content of a material in dry basis form. This is due the fact that the dry matter remains constant during drying, therefore it (DM) can be used as a reference point [72, 152].

Initial moisture content was determined by the standard oven method, based on change in mass after drying for 24 h at 105 ºC [71]. Average initial moisture content was found to be 19.3 g $[H_2O]$ g^{-1} [DM] (db) or 95.07% (wb). Each drying experiment was continued until the moisture content of the sample was less than 0.18 g $[H_2O]$ g^{-1} [DM] (< 15% wb). Final moisture content of 15 to 25% corresponds to a water activity value of 0.65-0.75, at 25 ºC [88, 103]. The dried product can therefore be considered as shelf-stable at room temperature.

Drying experiments at 200 ºC led to severely burnt samples, resulting in negative values in moisture content. Therefore an exception was made here and the penultimate moisture content values and drying times were considered as the final ones.

4.2.2.2 Drying Rate

The drying rate is computed as the decrease in water concentration between two subsequent measurements divided by the elapsed time between the measurements as shown in the following equation.

$$\frac{dW}{dt} = \frac{W_{(t)} - W_{(t+\Delta t)}}{\Delta t} \tag{4.4}$$

The drying rate data from different drying tests were analysed relative to moisture content. In addition, the drying rate is expressed as g $[H_2O]$ g^{-1} [DM] min^{-1}, which is independent of the surface area because shrinkage complicates the measurement of the outside surface area of the sample [88].

4.2.2.3 Determination of Effective Moisture Diffusivity

The effective moisture diffusivity was determined experimentally using FICK's second law of diffusion for slab geometry as shown in eq. (2.4) for different temperatures and thickness. Eq. (2.4) may further be simplified to eq. (4.5) by considering only the first term of the series solution:

$$\frac{W}{W_0} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{\text{eff}} t}{4L^2}\right) \tag{4.5}$$

Here, the moisture-content ratio was also reduced to W/W_0 instead of $(W - W_e)/(W_0 - W_e)$ because during high-temperature (> 100 ºC) air drying, samples may be dried up to the point where only the dry matter remains [146, 170]. Taking the natural logarithm (ln) of both sides of the eq. (4.5) yields a linear function:

$$\ln\frac{W}{W_0} = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{\text{eff}}}{4L^2} t \tag{4.6}$$

Thus, D_{eff} can be obtained from the slope of the graph of $\ln(W/W_0)$ versus time

$$\text{Slope} = \frac{\pi^2 D_{\text{eff}}}{4L^2} \tag{4.7}$$

4.2.2.4 Application of Semi-Empirical Moisture Diffusion Models

Two semi-empirical diffusion models, LEWIS eq. (2.7) and PAGE eq. (2.8) were fitted to the experimental data in order to predict the moisture content and describe the drying characteristics of the samples. For this reason the drying data from different drying tests were analysed as moisture-content ratio W/W_0 versus drying time (t). The values of the parameters k_{LEWIS}, k_{PAGE} and n_{PAGE} were determined by performing non-linear regression analysis on the experimental data using the software package *Origin 7G*. The correlation coefficient (R^2) and standard errors (s.e.) were used as primary criteria for selecting the best model to define the drying curves of the tomato samples.

4.2.2.5 Measurement of Temperature Profiles

Air and sample temperatures were measured by fine-wire type-K thermocouples connected to a data acquisition and recording system (*Voltcraft 304* 4-channel). For monitoring the temperature profiles, a thermocouple was inserted at the bottom, centre and half-centre of the samples. Due to difficulties in placing the thermocouple at the surface, it was inserted to half-centre depth. A fourth thermocouple was placed just above the samples in order to measure the temperature of the air inside the oven.

4.2.2.6 Colour Analysis

Quantitative colour measurements of the samples were carried out by the Commission Internationale de L'Eclairage (CIE) method and recorded in the "L*a*b*-Colour measurement system". This method describes colours in a three-dimensional co-ordinate system. L* indicates the brightness, a* redness and b* is a measure of yellow colour. The colour co-ordinates (L*a*b*) of fresh and dried samples were measured using a Minolta Chroma Meter CR-310. The apparatus was calibrated using a standard white tile (standard white No. 21133006). The dried or fresh samples were then transferred into a 10 cm-diameter glass dish. A piece of black paper was placed on top of this in order to achieve standard measurement conditions. The chroma meter was positioned below the glass dish and measurements were performed from underneath the samples. Each sample was measured four times and the mean was calculated.

The L*a*b*-system quantifies the colour differences between samples. The overall colour difference between the two samples (ΔE^*) and the colour intensity (CI) values are calculated as follows:

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{4.8}$$

$$CI = \sqrt{a^{*2} + b^{*2}} \tag{4.9}$$

4.2.2.7 Rehydration Analysis

Rehydration capacity or ratio was determined by immersing 0.25 g dried samples in 10 mL distilled water at 25 ºC for various lengths of time, see Tab. 4.2. At the end of the rehydration period, the samples were removed from the water and then drained over a mesh for one minute and gently blotted on paper towels in order to eliminate the excess surface water.

Tab. 4.2: Rehydration times of dried tomato cubes

Water Temperature / ºC	**Rehydration Time / min**									
25	5	10	15	20	25	30	35	40	65	90

Rehydration ratio is expressed as the drained weight of the rehydrated sample divided by the weight of dried sample [156].

$$RR = \frac{m_{rehydrated\ sample}}{m_{sample}} \tag{4.10}$$

5 Results

The focus of this chapter is on the experimental results. First, data are presented from high-temperature continuous drying under natural convection, followed by those from intermittent drying and finally the results from the optimisation of the drying process and application of a time-varying step-down temperature profile.

The effects of using high temperatures on the drying behaviour of differently shaped tomato samples of varying thickness are shown graphically and in tables. Furthermore, sample-temperature development data for different drying conditions (air temperature and thickness) are used to determine the relationship between the sample temperature, moisture content and the start of browning. It is clear from the figures that using an air temperature of above 100 ºC continuously does not produce acceptable dried products. Under the drying conditions (drying equipment, thickness) in the experiments, the samples had an unacceptable colour by the time they reached their final moisture content of lower than 0.18 g [H_2O] g^{-1} [DM] (< 15% wb). In order to overcome these difficulties experienced during high-temperature continuous drying an alternative method, intermittent drying, was applied. The intermittent drying process itself improved the results. Although acceptable colour quality of the sample at the required final moisture content was not achieved, both the drying kinetics and the overall colour change of dried samples under intermittent drying were an improvement on the corresponding continuous drying runs. An optimised intermittent drying process with a time-varying step-down profile was hence designed for 0.5 cm-thick cubes, based on the results gained from both of the former drying processes (continuous and intermittent drying). This time, the final colour was acceptable. In addition, a rehydration ability test was carried out on the dried samples.

For continuous and intermittent drying the arithmetic mean is taken from three experiments, whereas for the optimised intermittent drying process, a further seven replications were carried out to increase the precision (arithmetic mean from 10 experiments). These results are discussed in more detail in section 6.

5.1 Continuous Drying

The experimental results were analysed to determine the drying rates and maximum exposure time values (changes in sample colour and temperature) for high-temperature drying. Moisture transfer within the tomato samples was described by FICK's second law of diffusion eq. (2.2), assuming constant effective moisture diffusivity. In addition, two semi-empirical diffusion models, eq. (2.7) and eq. (2.8), were selected from the literature and applied to the data to estimate the moisture content values at different times of drying.

5.1.1 Analysis of Drying Rates

In this subsection, the effects of different air temperatures, sample shape and sample thickness on the drying rate are investigated.

5.1.1.1 Drying Rate at Different Air Temperatures

For each experiment, tomato samples with an initial weight of 25 g were placed into the oven. These were weighed again at five-minute intervals to monitor the weight loss during drying. Drying curves (moisture-content ratio vs drying time) were then plotted using the recorded weights. A typical drying curve for different air temperatures is shown in Fig. 5.1.

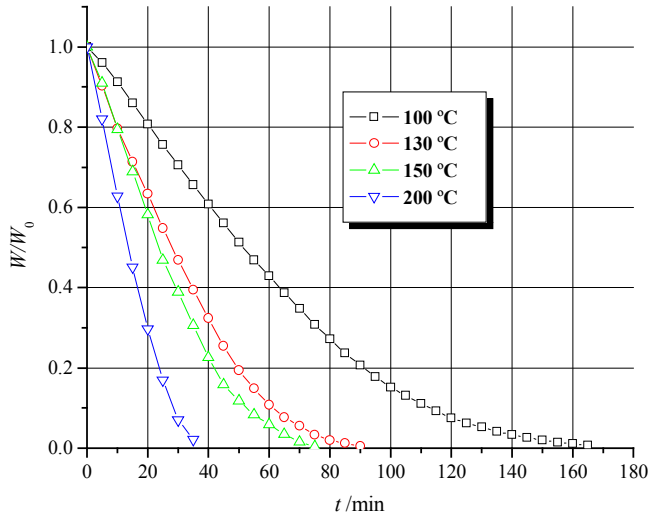

Fig. 5.1: Drying curves of 0.5 cm-thick tomato cubes at different drying temperatures

Fig. 5.1 indicates that the drying time shortens as the drying temperature increases. For example, drying 0.5 cm-thick tomato cubes at a temperature of 150 ºC compared to those dried at 100 ºC resulted in a 54.5% reduction in drying time. Similar trends were observed for 0.2 cm, 1.0 cm-thick tomato cubes and 0.5 cm-thick rings, see Tab. 5.1. However, the colour quality of the samples dried at 100 ºC was found to be superior when compared with those dried at 150 ºC and 200 °C. Sample colour will be discussed in more detail in subsection 5.1.4.

In order to check for the existence of different drying periods, drying rates were calculated from the slopes of the drying curves, at each measurement point, see eq. (4.4) and expressed as the quantity of moisture removed per unit of time relative to dry matter, g [H_2O] g^{-1} [DM] min^{-1}. The variation in the drying rates as a function of the moisture-content ratio (W/W_0) for 0.5 cm-thick tomato cubes is shown in Fig. 5.2. As can be seen in this graph, at the very beginning of the drying, the drying rate increases to a maximum value and then decreases continuously with decreasing moisture content. The highest drying rate was obtained during the experiments at 200 ºC. The drying kinetics of other tomato samples with different thickness and shape were found to be similar to the results presented here.

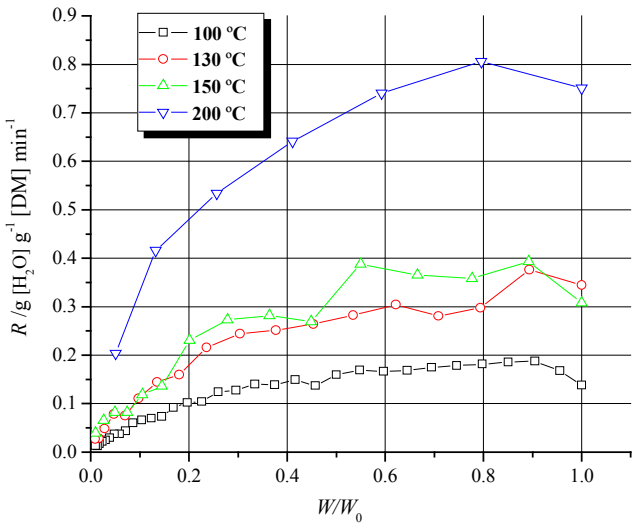

Fig. 5.2: Effects of drying temperature on the drying rates of 0.5 cm-thick tomato cubes

5.1.1.2 Drying Rate at Different Sample Thickness and Shape

In order to investigate the influence of thickness and shape on the drying rate, further experiments were carried out on cubes of various thickness (0.2 cm, 0.5 cm, 1.0 cm) and on rings (0.5 cm thick). The differences are illustrated in Fig. 5.3 for drying at 100 ºC.

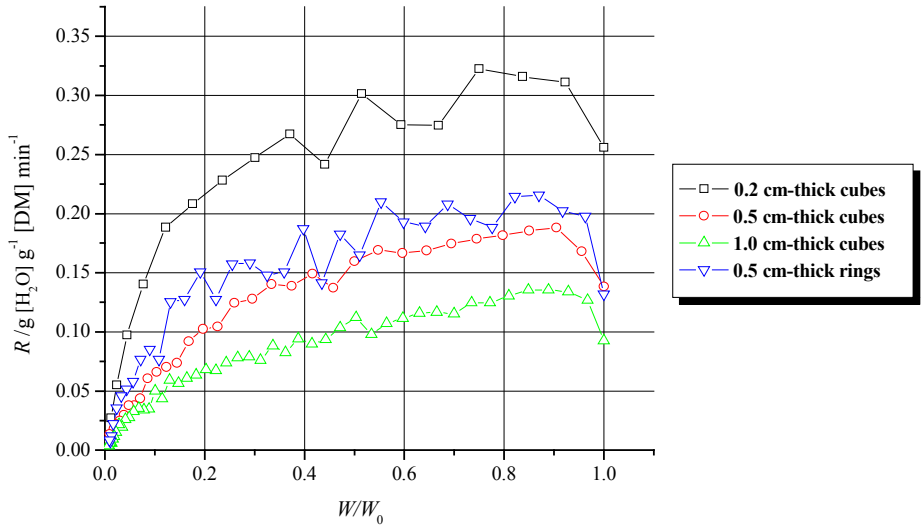

Fig. 5.3: Effects of thickness and shape on the drying rates of tomato samples dried at 100 ºC

The drying time that elapsed between the initial moisture content of the tomato samples and their required moisture content (< 15%) is shown in Tab. 5.1 for various drying temperatures. However it should be noted that drying at 200 ºC caused negative values of moisture content in the later drying periods as the dry matter was burnt. In this case the penultimate moisture content values and drying times were recorded in place of the final ones.

Tab. 5.1: Drying times and final moisture-content values of tomato samples for continuous drying

Tomato Samples	Drying Temperature / ºC	Final Moisture Content / % wb	Drying Time / min
0.2 cm-thick tomato cubes	100	10.46	90
	130	15.60	60
	150	1.06	40
	200	57.47	20
0.5 cm-thick tomato cubes	100	11.47	165
	130	7.13	90
	150	5.83	75
	200	30.91	35
1.0 cm-thick tomato cubes	100	10.36	245
	130	12.62	140
	150	4.96	110
	200	33.05	55
0.5 cm-thick tomato rings	100	15.61	170
	130	11.40	110
	150	10.05	75
	200	38.29	40

5.1.2 Modelling Moisture Diffusion during the Continuous Drying Process

In this subsection, two alternative approaches are applied for the mathematical modelling of the drying of tomato samples. The first one is a theoretical model, namely FICK's second law of diffusion. Here, the effect of air temperature and sample thickness on moisture diffusion are investigated. The second approach is the application of semi-empirical moisture diffusion models, namely LEWIS eq. (2.7) and PAGE eq. (2.8) to the experimental data. These equations represent a simple alternative to FICK's second law of diffusion eq. (2.2).

5.1.2.1 Calculation of Effective Moisture Diffusivity

FICK's second law of diffusion is used to describe the moisture transfer during the drying process. In order to apply this law, the effective moisture diffusivity (D_{eff}) is determined from the slope of the drying curves plotted from the natural logarithm of the moisture-content ratio. This is illustrated in Fig. 5.4 for 0.5 cm-thick tomato cubes at different air temperatures and in Fig. 5.5 for different samples at constant air temperature (100 ºC). As can be seen in Tab. 5.2, the effective moisture diffusivity values for all samples are calculated to be in the range of $0.37 \cdot 10^{-9}$ to $10.63 \cdot 10^{-9}$ $m^2 s^{-1}$.

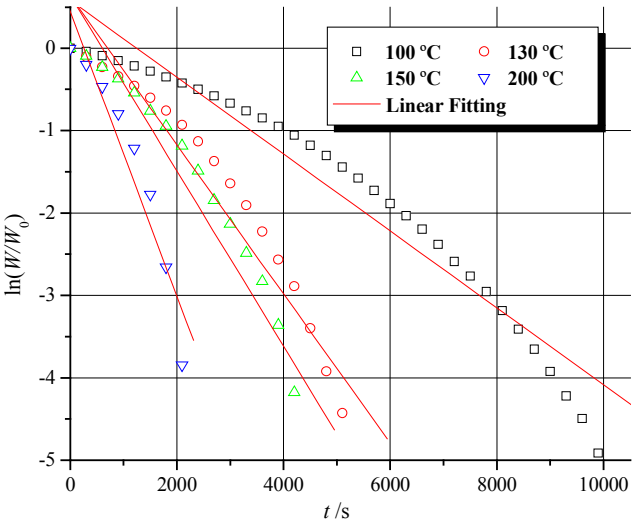

Fig. 5.4: Drying curves plotted from the natural logarithm (ln) of the moisture-content ratio of 0.5 cm-thick tomato cubes *at different air temperatures* for the determination of effective diffusivity values

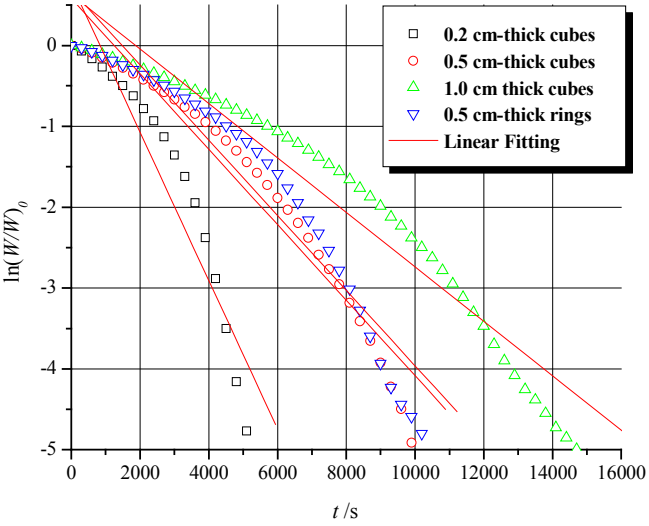

Fig. 5.5: Drying curves plotted from the natural logarithm (ln) of the moisture-content ratio of samples with *different thickness and shape* dried at 100 °C for the determination of effective diffusivity values

Tab. 5.2: Effective moisture diffusivity values for all tomato samples at different drying temperatures; continuous drying process

Tomato Samples	Drying Temperature / °C	$D_{eff} \cdot 10^{-9}$ / m^2s^{-1}	R^2
0.2 cm-thick tomato cubes	100	0.3718	0.8938
	130	0.4701	0.8812
	150	1.0577	0.7878
	200	-	-
0.5 cm-thick tomato cubes	100	1.1824	0.9444
	130	2.2916	0.9192
	150	2.7103	0.8957
	200	4.3821	0.9128
1.0 cm-thick tomato cubes	100	3.7300	0.9426
	130	5.3941	0.9325
	150	7.3808	0.8748
	200	10.6387	0.9446
0.5 cm-thick tomato rings	100	1.1775	0.9149
	130	1.7662	0.8884
	150	2.5136	0.8661
	200	3.3689	0.8955

5.1.2.2 Application of the Semi-Empirical Moisture Diffusion Models

The second approach for describing the relationship between the moisture content and the drying time under different drying conditions (i.e. drying temperature and sample thickness) involves using the moisture-content ratio W/W_0 drying curves to estimate the parameters in the semi-empirical diffusion models. By doing so, the moisture content of tomato samples at any time during drying may also be predicted. Therefore in this subsection two well known semi-empirical diffusion models, LEWIS and PAGE, are fitted to the experimental moisture-content ratio data. Subsequently, non-linear regression analyses are run on the moisture-content ratio data to calculate the model parameters, represented by eq. (2.7) and eq. (2.8). Figs. 5.6 and 5.7 show the variations in the experimental and predicted moisture-content ratio according to the LEWIS and PAGE models, respectively, as a function of drying time.

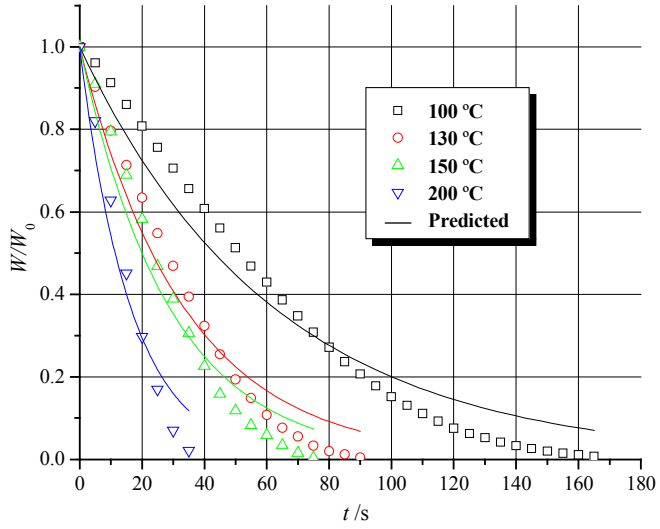

Fig. 5.6: Variation in experimental and predicted moisture-content ratio over drying time according to the LEWIS model, for 0.5 cm-thick cubes at different drying temperatures

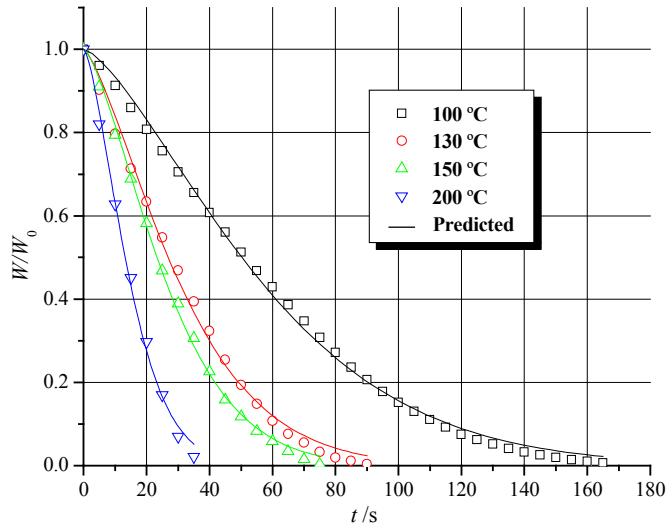

Fig. 5.7: Variation in experimental and predicted moisture-content ratio over drying time according to the PAGE model, for 0.5 cm-thick cubes at different drying temperatures

The fitted curve parameters (drying constants k_{LEWIS}, k_{PAGE}, and n_{PAGE}) are presented in Tab. 5.3 along with the standard errors and coefficient of determination (R^2) for the various experimental conditions.

Tab. 5.3: Fitted parameters for the LEWIS eq. (2.7) and PAGE eq. (2.8) models for continuous drying

Tomato Samples	Drying Temperature	LEWIS model			PAGE model				
		$k_{LEWIS} \cdot 10^{-2}$	s.e.	R^2	$k_{PAGE} \cdot 10^{-3}$	s.e.	n_{PAGE}	s.e.	R^2
	/ °C	/ min^{-1}			/ min$^{-n_{PAGE}}$				
0.2 cm-thick cubes	100	2.64	0.0016	0.9457	3.44	0.0008	1.5437	0.0626	0.9939
	130	3.62	0.0026	0.9469	5.62	0.0014	1.5472	0.0742	0.9942
	150	6.31	0.0054	0.9603	15.66	0.0041	1.4775	0.0904	0.9947
	200	8.80	0.0090	0.9671	30.31	0.0095	1.4335	0.1270	0.9946
0.5 cm-thick cubes	100	1.60	0.0006	0.9622	2.52	0.0002	1.4337	0.0242	0.9979
	130	2.98	0.0014	0.9672	7.07	0.0011	1.3926	0.0453	0.9958
	150	3.47	0.0019	0.9636	7.17	0.0008	1.4506	0.0333	0.9983
	200	6.10	0.0053	0.9594	14.97	0.0033	1.4867	0.0762	0.9964
1.0 cm-thick cubes	100	1.14	0.0003	0.9681	2.06	0.0022	1.3693	0.0228	0.9969
	130	1.86	0.0006	0.9692	4.22	0.0005	1.3606	0.0307	0.9966
	150	2.36	0.0009	0.9708	6.15	0.0009	1.3454	0.0381	0.9957
	200	4.05	0.0024	0.9661	10.12	0.0011	1.4218	0.0347	0.9985
0.5 cm-thick rings	100	1.44	0.0006	0.9496	1.59	0.0002	1.5062	0.0371	0.9956
	130	2.10	0.0011	0.9484	2.75	0.0005	1.5132	0.0503	0.9947
	150	2.97	0.0019	0.9473	4.30	0.0010	1.5354	0.0646	0.9943
	200	4.58	0.0045	0.9356	6.11	0.0014	1.6513	0.0735	0.9968

5.1.3 Temperature Development in the Samples

Monitoring the temperature distribution is important for understanding the reasons behind quality changes (e.g. change in colour) that occur during drying. Therefore the internal temperature at three locations in the tomato samples during drying was recorded as well as the air temperature using fine-wire type-K thermocouples. Fig. 5.8 shows a typical graph of the temperatures measured halfway to the centre, at the centre and at the bottom of the sample for drying at 100 ºC.

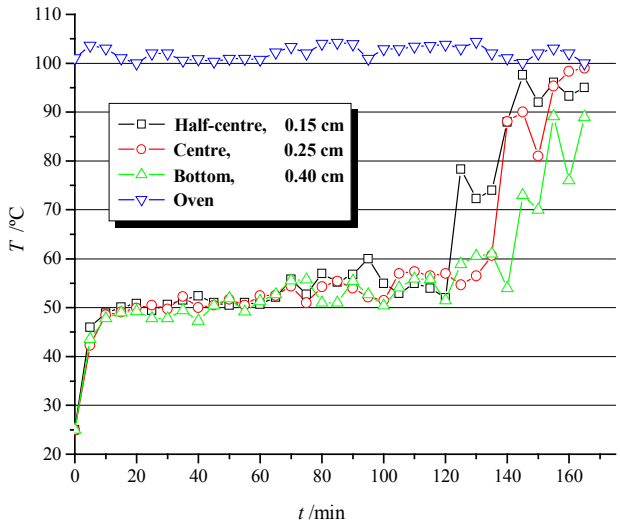

Fig. 5.8: Temperature development at different locations of 0.5 cm-thick tomato cubes; drying temperature 100 ºC

In Fig. 5.8, the variations in sample temperature observed at different depths are very small. Furthermore, it was impractical to place and maintain the thermocouples in the samples due to shrinkage. Therefore, in subsequent experiments, the sample temperature was only recorded at the centre. The measurements of the centre temperature of 0.5 cm-thick tomato cubes at four different drying air temperatures are displayed in Fig. 5.9. It is clear from this graph that the higher the drying air temperature, the faster the increase in temperature at the centre of the tomato.

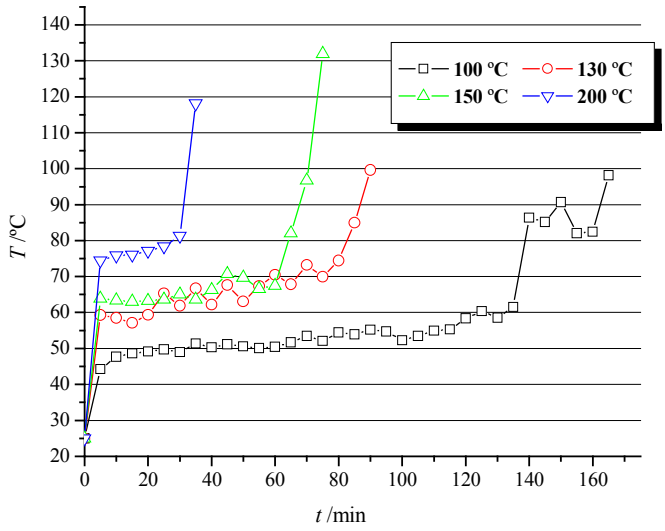

Fig. 5.9: Temperature development at the centre of 0.5 cm-thick tomato cubes; different drying temperatures

5.1.4 Colour Measurements

At air temperatures above 100 ºC, extremely rapid drying caused the tomato samples to turn brown and burn after a certain exposure period. Therefore during drying, the samples were examined visually and the moisture content and temperature values at the point of browning were determined. Tab. 5.4 lists the data on maximum and minimum exposure time, sample temperature and moisture content at the point of browning for the different drying temperatures.

Tab. 5.4: Temperature-moisture profile at the onset of browning during continuous drying

Tomato Samples	Drying Temperature	Sample Temperature / °C		Moisture Content / % wb		Browning Time / min	
	/ °C	min	max	min	max	min	max
0.2 cm-thick cubes	130	64	78	57	71	40	50
	150	67	71	61	77	25	30
	200	78	80	77	86	15	15
0.5 cm-thick cubes	130	68	82	32	64	60	80
	150	69	70	68	79	40	50
	200	75	78	90	91	15	15
1.0 cm-thick cubes	130	70	90	39	50	105	130
	150	68	73	71	79	70	75
	200	78	79	82	93	15	30
0.5 cm-thick rings	130	76	78	57	71	70	90
	150	66	72	63	64	55	60
	200	81	92	79	85	15	30

5.2 Intermittent Drying

In this section, the effects of tempering during the high-temperature intermittent drying process on drying kinetics, product temperature and colour are investigated. For this, an optimal tempering period was determined at the beginning of the intermittent drying runs. Having selected the optimal intermittent drying scheme, the drying experiments were carried out and the results are examined analogously to section 5.1. It is important to note that in certain areas of the presentation of the intermittent drying results, the drying time generally excludes the tempering periods and only takes into account the drying time in the oven. The reason for this is that during tempering, the evaporation of moisture occurs without heat treatment. This weight loss is then combined with the weight lost during the drying time in the oven. As a result, unless otherwise stated or indicated in the graphs and tables, the drying time should be interpreted as drying time in the oven only.

5.2.1 Varying Intermittence

Three different tempering periods were compared in order to determine the optimal period for reducing the drying time in the oven while maintaining the overall drying time within an acceptable range and avoiding possible quality changes (e.g. colour). The selected tempering periods can be seen in Tab. 4.1 as five minutes ($\alpha=1/2$) and 15 minutes ($\alpha=1/4$, $\alpha=1/2$). The reason for applying the five-minute ($\alpha=1/2$) and 15-minute ($\alpha=1/2$) intermittent drying schemes was to see how the frequency and the duration of tempering affect the drying process. Fig. 5.10 shows that the $\alpha=1/4$ scheme leads to the highest reduction in the drying time required for the tomato samples to reach the desired moisture content of lower than 15% (wb). The other intermittent schemes and the constant drying process have higher drying times. Therefore, in the subsequent experiments, only the $\alpha=1/4$ mode was applied during the intermittent drying runs.

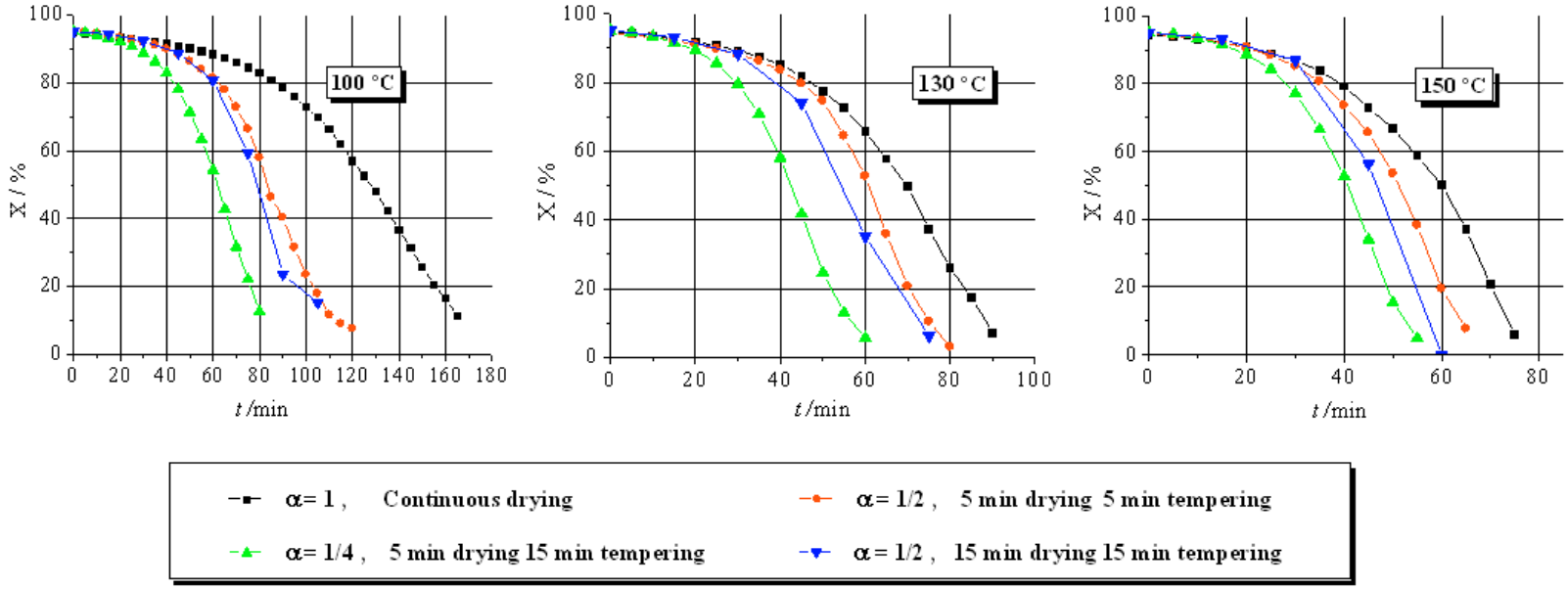

Fig. 5.10: Comparison of the intermittent drying schemes and constant drying at different temperatures for 0.5 cm-thick tomato cubes; *x*-axis *exchudes* the tempering periods

5.2.2 Analysis of Drying Rates

In this subsection, the drying rates in the intermittent drying process for 0.2 cm, 0.5 cm, 1.0 cm-thick tomato cubes and 0.5 cm-thick rings at different drying air temperatures (100 ºC, 130 ºC, 150 ºC and 200 ºC) are presented.

5.2.2.1 Drying Rate at Different Air Temperatures

In order to investigate the effect of tempering on the drying rate at different air temperatures, the drying rate data are plotted against the moisture content ratio in Fig. 5.11 and Fig. 5.12.

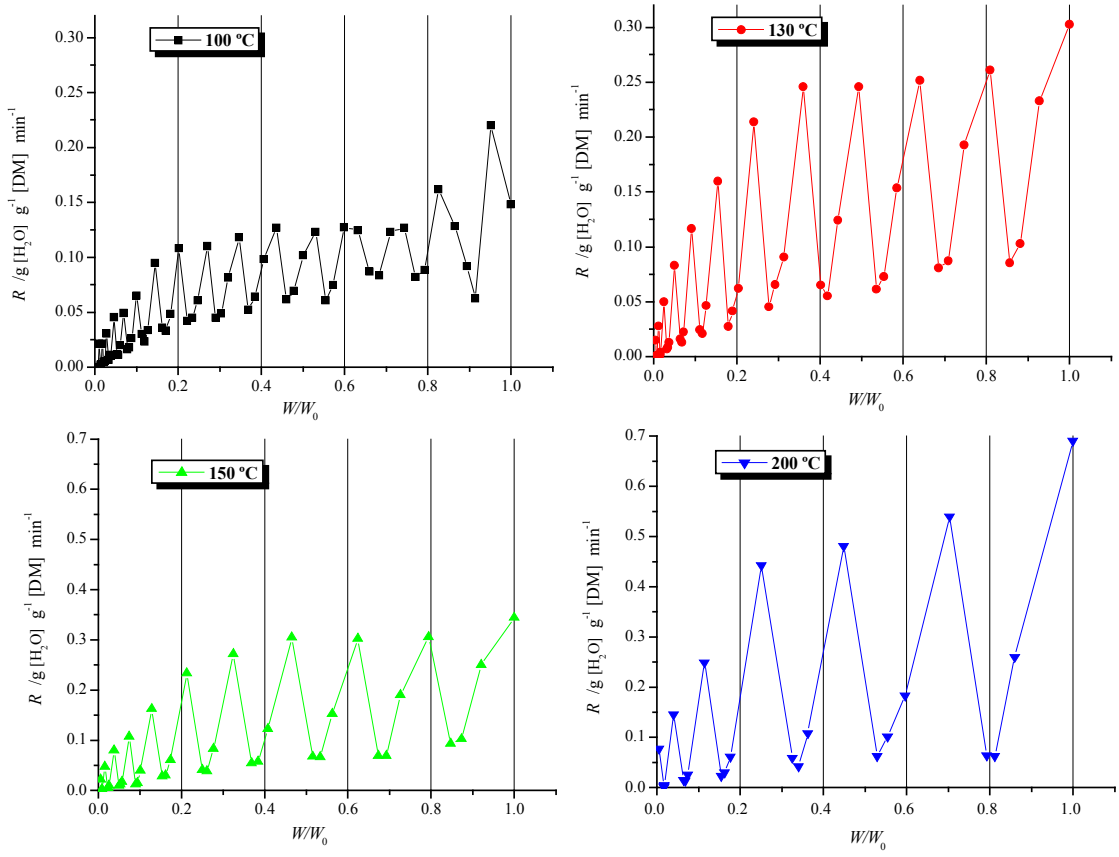

Fig. 5.11: Effects of drying temperature on the drying rates of 0.5 cm-thick tomato cubes; intermittence α=1/4, i.e., five minutes of drying followed by 15 minutes of tempering in each cycle; graph *includes* the tempering periods

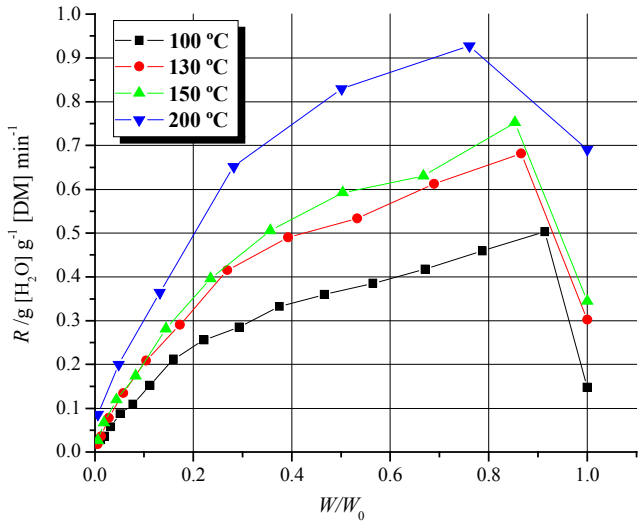

Fig. 5.12: Effects of drying temperature on the drying rate of 0.5 cm-thick tomato cubes; intermittence α=1/4, i.e., five minutes of drying followed by 15 minutes of tempering in each cycle; graph *excludes* the tempering periods

The difference between these graphs is that in Fig. 5.11 the tempering periods throughout the drying process are included, whereas in Fig. 5.12 they are excluded. Fig. 5.11 is thus characterised by a "zig-zag" shape. In Fig. 5.12 the weight loss is shown as though it occurs only during the drying time in the oven. In fact, some of the weight loss occurs outside the oven, where no extra energy is applied.

5.2.2.2 Drying Rate for Different Sample Thickness and Shapes

The effect of tempering on the drying rates of tomato samples cut to different thickness and shapes can be seen in Fig. 5.13. In this graph the drying rates are calculated for the drying time in the oven. In addition, the drying time necessary to reach the required moisture content (< 15% wb) from the initial moisture content is shown in Tab. 5.5 for various temperatures of the tomato samples.

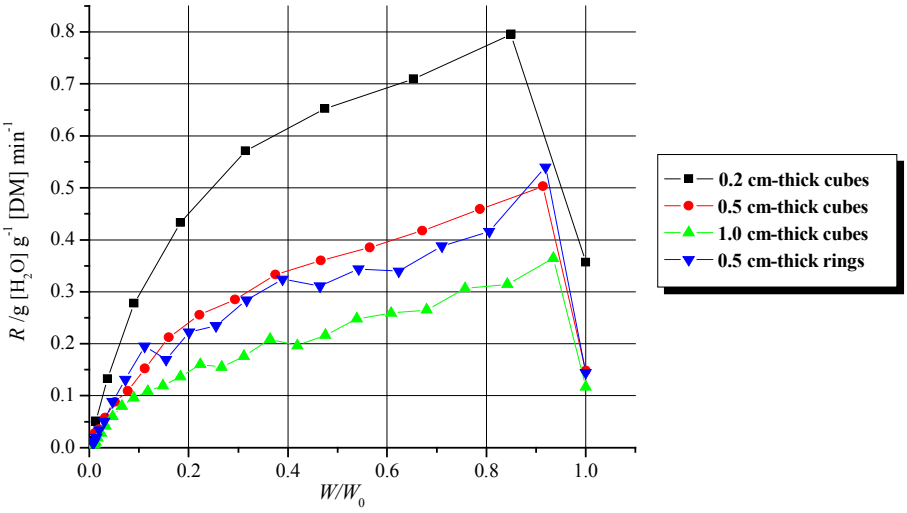

Fig. 5.13: Effects of thickness and shape on the drying rates of tomato samples dried at 100 ºC; intermittence α=1/4, i.e., five minutes of drying followed by 15 minutes of tempering in each cycle; graph *excludes* the tempering periods

Tab. 5.5: Drying times and final moisture content values of tomato samples for intermittent drying

Tomato Samples	Drying Temperature / °C	Final Moisture Content / % wb	Drying Time in the Oven / min	Overall Drying Time / min
0.2 cm-thick tomato cubes	100	5.00	50	185
	130	4.46	40	145
	150	1.66	35	125
	200	50.28	15	65
0.5 cm-thick tomato cubes	100	12.72	80	305
	130	5.65	60	225
	150	4.9	55	205
	200	24.19	30	120
1.0 cm-thick tomato cubes	100	13.33	125	485
	130	10.64	85	325
	150	10.06	75	285
	200	28.19	40	145
0.5 cm-thick tomato rings	100	12.52	100	385
	130	11.98	65	245
	150	0.68	60	225
	200	33.23	30	120

5.2.3 Modelling Moisture Diffusion during the Intermittent Drying Process

In subsection 5.1.2 mathematical modelling was applied to describe the moisture transfer as well as to predict the moisture content at different times of the continuous drying process. However the models can also be useful in highlighting the effect of tempering on moisture diffusion during intermittent drying. This can be achieved by comparing the corresponding parameters, such as effective moisture diffusivity (D_{eff}) and drying constants (k_{LEWIS}, k_{PAGE}, n_{PAGE}), of the different drying processes (continuous vs intermittent drying). Therefore, in the following subsections, first D_{eff} and then k_{LEWIS}, k_{PAGE}, and n_{PAGE} are determined from the experimental data for different drying conditions.

5.2.3.1 Calculation of Effective Moisture Diffusivity

D_{eff} values were calculated from the slopes of Fig. 5.14 and Fig. 5.15 at various drying air temperatures and for tomato samples with different thickness and shape dried, respectively. In these graphs, the abscissa represents the drying time in the oven only (i.e. *excluding* tempering time).

The calculated effective moisture diffusivity values for different experimental conditions (drying air temperature and product thickness) are presented in Tab. 5.6. According to this table, the effective diffusivity values for all samples are within the range of $0.81 \cdot 10^{-9}$ to $16.31 \cdot 10^{-9}$ $m^2 s^{-1}$.

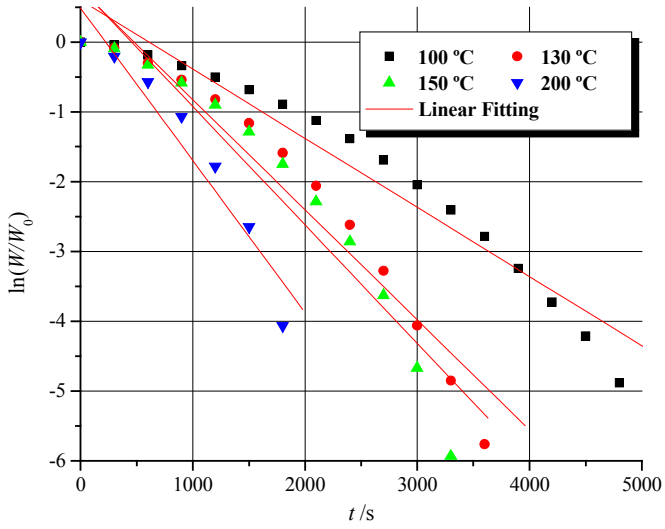

Fig. 5.14: Drying curves plotted from the natural logarithm (ln) of the moisture-content ratio of 0.5 cm-thick tomato cubes *at different air temperatures* for the determination of effective diffusivity values; intermittence α=1/4, i.e., five minutes of drying followed by 15 minutes of tempering in each cycle, *x*-axis *excludes* the tempering periods

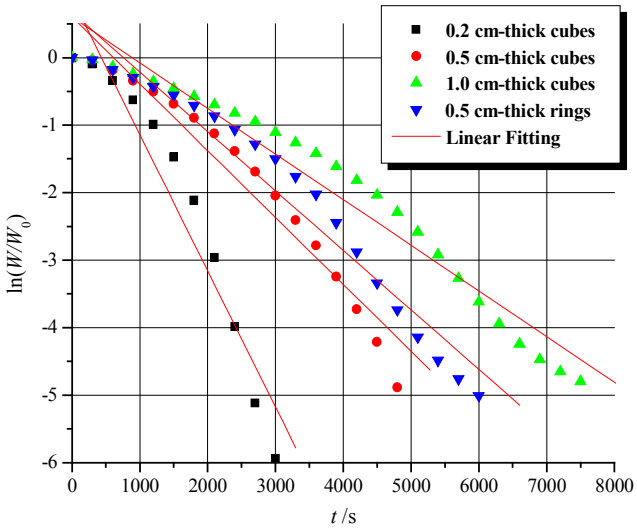

Fig. 5.15: Drying curves plotted from the natural logarithm (ln) of the moisture-content ratio of samples with *different thickness and shape* dried at 100 °C for the determination of effective diffusivity values; intermittence α=1/4, i.e., five minutes of drying followed by 15 minutes of tempering in each cycle; *x*-axis *excludes* the tempering periods

Tab. 5.6: Effective moisture diffusivity values for all tomato samples at different drying temperatures; intermittent drying process

Tomato Samples	Drying Temperature / ºC	$D_{eff} \cdot 10^{-9}$ / m^2s^{-1}	R^2
0.2 cm-thick tomato cubes	100	0.8186	0.9258
	130	0.9970	0.8990
	150	1.2523	0.8776
	200	1.3455	0.8966
0.5 cm-thick tomato cubes	100	2.5100	0.9481
	130	4.0021	0.9397
	150	4.3061	0.9195
	200	5.5220	0.9224
1.0 cm-thick tomato cubes	100	6.8484	0.9571
	130	9.8700	0.9400
	150	11.9559	0.9549
	200	16.3127	0.9528
0.5 cm-thick tomato rings	100	2.2326	0.9526
	130	2.8876	0.8936
	150	4.5581	0.7971
	200	4.7621	0.8714

5.2.3.2 Application of the Semi-Empirical Moisture Diffusion Models

The tempering effect on intermittent drying as well as the prediction of moisture content at different times of drying are studied by applying the same semi-empirical moisture diffusion models as used in subsection 5.1.2.2. The variations in the predicted moisture-content ratio according to the LEWIS eq. (2.7) and PAGE eq. (2.8) models along with the experimental moisture-content ratio for intermittent drying of tomato samples are illustrated in Fig. 5.16 and Fig. 5.17, respectively. In these graphs the *x*-axis represents the drying time in the oven, excluding the tempering time in the cabinet.

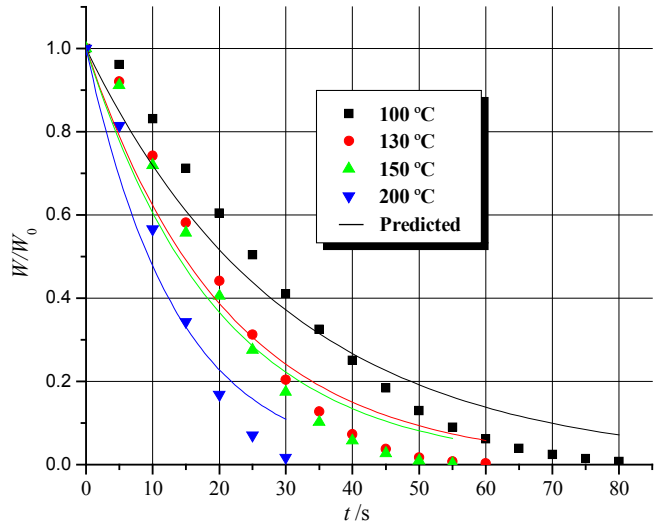

Fig. 5.16: Variation in experimental and predicted moisture-content ratio over drying time according to the LEWIS model, for 0.5 cm-thick cubes at different drying temperatures; intermittence α=1/4, i.e., five minutes of drying followed by 15 minutes of tempering in each cycle; *x*-axis *excludes* the tempering periods

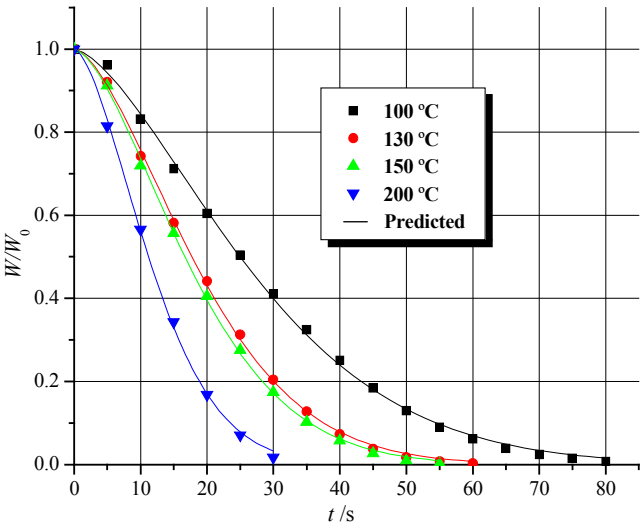

Fig. 5.17: Variation in experimental and predicted moisture-content ratio over drying time according to the PAGE model, for 0.5 cm-thick cubes at different drying temperatures; intermittence α=1/4, i.e., five minutes of drying followed by 15 minutes of tempering in each cycle; *x*-axis *excludes* the tempering periods

The fitted parameters (drying constants k_{LEWIS}, k_{PAGE}, and n_{PAGE}) calculated using non-linear regression analysis for different tomato samples and drying temperatures are presented in Tab. 5.7.

Tab. 5.7: Fitted parameters for the LEWIS eq. (2.7) and PAGE eq. (2.8) models for intermittent drying

Tomato Samples	Drying Temperature	LEWIS model			PAGE model				
		$k_{LEWIS} \cdot 10^{-2}$	s.e.	R^2	$k_{PAGE} \cdot 10^{-3}$	s.e.	n_{PAGE}	s.e.	R^2
	/ °C	/ min^{-1}			/ min^{-nPAGE}				
0.2 cm-thick cubes	100	5.40	0.0054	0.9398	5.92	0.0007	1.7234	0.0436	0.9991
	130	6.33	0.0076	0.9320	6.07	0.0007	1.8136	0.0438	0.9993
	150	7.72	0.0090	0.9460	11.06	0.0013	1.7174	0.0471	0.9993
	200	11.52	0.0218	0.9329	17.25	0.0047	1.8608	0.1250	0.9983
0.5 cm-thick cubes	100	3.30	0.0020	0.9544	4.95	0.0004	1.5367	0.0270	0.9990
	130	4.73	0.0037	0.9526	7.03	0.0006	1.5969	0.0274	0.9994
	150	5.01	0.0041	0.9529	7.83	0.0006	1.5925	0.0273	0.9994
	200	7.38	0.0082	0.9507	13.8	0.0017	1.6203	0.0480	0.9991
1.0 cm-thick cubes	100	2.32	0.0009	0.9686	5.00	0.0005	1.3918	0.0269	0.9980
	130	3.24	0.0017	0.9645	6.58	0.0006	1.4454	0.0271	0.9988
	150	3.86	0.0024	0.9614	7.35	0.0007	1.4872	0.0317	0.9988
	200	6.07	0.0046	0.9673	16.31	0.0014	1.4500	0.0279	0.9994
0.5 cm-thick rings	100	2.84	0.0015	0.9596	4.78	0.0006	1.4789	0.0371	0.9976
	130	3.51	0.0025	0.9475	5.06	0.0009	1.5620	0.0519	0.9971
	150	4.09	0.0033	0.9435	5.39	0.0011	1.6092	0.0627	0.9967
	200	6.03	0.0077	0.9258	6.92	0.0017	1.7663	0.0883	0.9973

5.2.4 Temperature Development in the Samples

The temperature development of 0.5 cm-thick tomato cubes at the four different drying air temperatures is presented in Fig. 5.18.

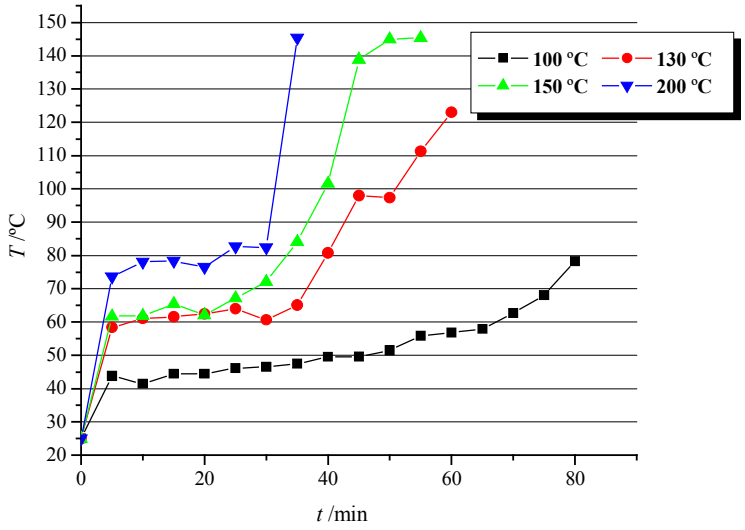

Fig. 5.18: Development of temperature at the centre of 0.5 cm-thick tomato cubes dried at different drying temperatures; *x*-axis *excludes* the tempering periods

The increases in sample temperature were also recorded every minute during five-minute drying periods in the oven (α=1/4) in order to obtain a more detailed picture of the effect of tempering on the temperature development in the sample. This is reflected in Fig. 5.19 (a), (b), (c), (d) for the drying temperatures 100 ºC, 130 ºC, 150 ºC and 200 ºC, respectively. In these graphs, the vertical lines starting at the end of each five-minute drying period represent the decrease in sample temperature to 25 ºC during the tempering periods.

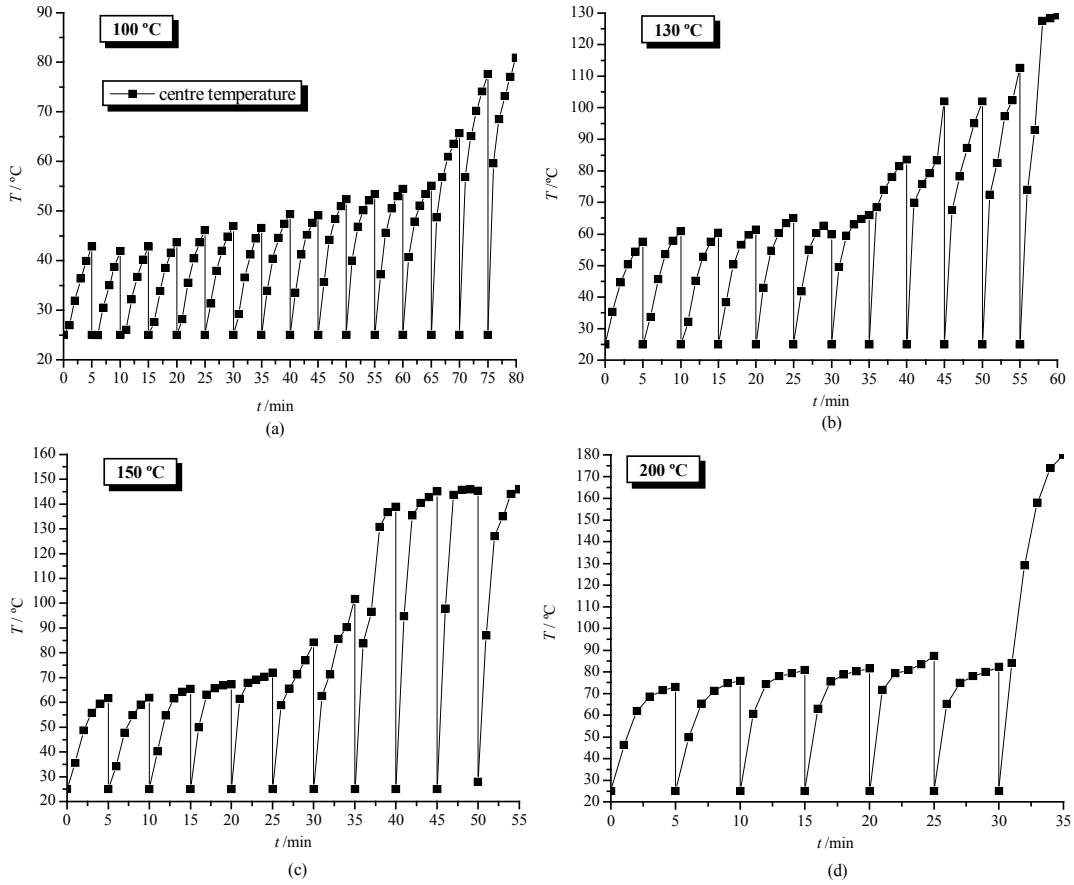

Fig. 5.19: Development of temperature at the centre of 0.5 cm-thick tomato cubes before and after the tempering periods during the intermittent drying (α=1/4) at 100 °C (a), 130 °C (b), 150 °C (c) and 200 °C (d); *x*-axis *excludes* the tempering periods

5.2.5 Colour Measurements

In order to study the effect of tempering on the colour quality of tomato samples, the product colour was examined visually during the intermittent drying process. At the point where it started to turn into an unacceptable brown colour (onset of browning), the temperature and moisture content of the sample were noted. Tab. 5.8 shows the maximum and the minimum exposure time at the onset of browning along with the sample moisture content and temperature at these points.

Tab. 5.8: Temperature-moisture profile at the onset of browning during intermittent drying

Tomato Samples	Drying Temperature	Sample Temperature		Moisture Content		Browning Time	
		/ ºC		/ % wb		/ min	
	/ ºC	min	max	min	max	min	max
0.2 cm-thick cubes	130	64	85	65	75	25	25
	150	66	83	68	77	20	20
	200	83	84	86	87	10	10
0.5 cm-thick cubes	130	94	102	29	36	45	45
	150	66	73	60	77	25	30
	200	76	81	85	87	15	15
1.0 cm-thick cubes	130	72	99	29	47	60	70
	150	78	94	58	61	45	50
	200	72	74	79	81	25	25
0.5 cm-thick rings	130	82	106	33	69	50	55
	150	68	78	35	41	45	50
	200	78	83	83	85	20	20

5.3 Optimisation of the Drying Process and Application of a Time-Varying Step-Down Temperature Profile

The experimental results of the continuous and intermittent drying processes indicate that using extremely high air temperatures (> 100 ºC) causes browning on the surface of the samples before they reach the acceptable moisture content level (< 15% wb). In order to overcome this problem a series of experiments was carried out involving a time-varying step-down temperature profile in the oven during the intermittent drying process. With this in mind, 0.5 cm-thick tomato cubes were heated at 150 ºC (25 minutes), 130 ºC (15 minutes) and 100 ºC (25 minutes) intermittently. This means that for every five minutes in the oven, the samples were subjected to 25 ºC in a separate cabinet containing a ventilator for 15-minute intervals. The moisture content of the samples was reduced from initially 95% to lower than 15% (wb) without any browning effect. The colour quality of the dried tomatoes was then compared to the quality of those dried at 55 ºC and 70 ºC. Following this, the dried samples from the optimised process were rehydrated in water (25 ºC) to measure the water uptake capacity. The results of the intermittent drying with a time-varying step-down temperature profile are presented graphically and in tables in the following subsections.

5.3.1 Analysis of Drying Rates

The drying behaviour was analysed using the moisture content, drying rate and sample temperature data in the same way as in sections 5.1 and 5.2.

5.3.1.1 Drying Curve

The curve of moisture content over drying time in the oven during the optimised intermittent drying process is plotted in Fig. 5.20 which also includes standard-deviation bars.

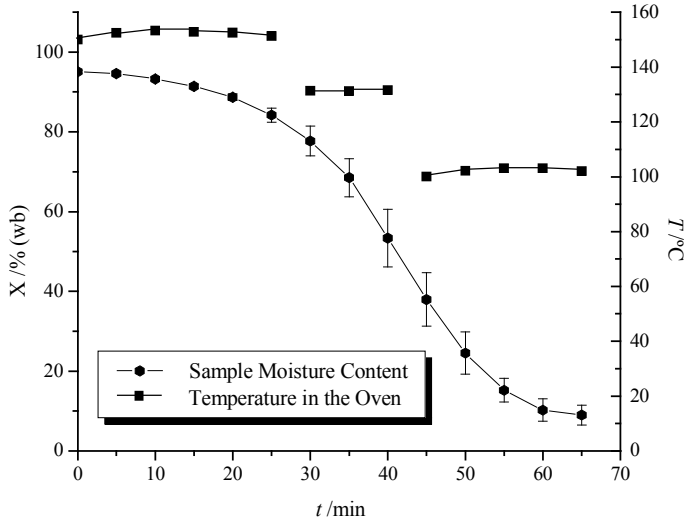

Fig. 5.20: Variation in the moisture content (wb) of 0.5 cm-thick tomato cubes versus drying time in the oven during intermittent drying with a time-varying step-down temperature profile; *x*-axis *excludes* the tempering periods; *n*=10

5.3.1.2 Drying Rate Curve

The drying rate curve for 0.5 cm-thick tomato cubes along with the drying temperature in the oven is shown in Fig. 5.21.

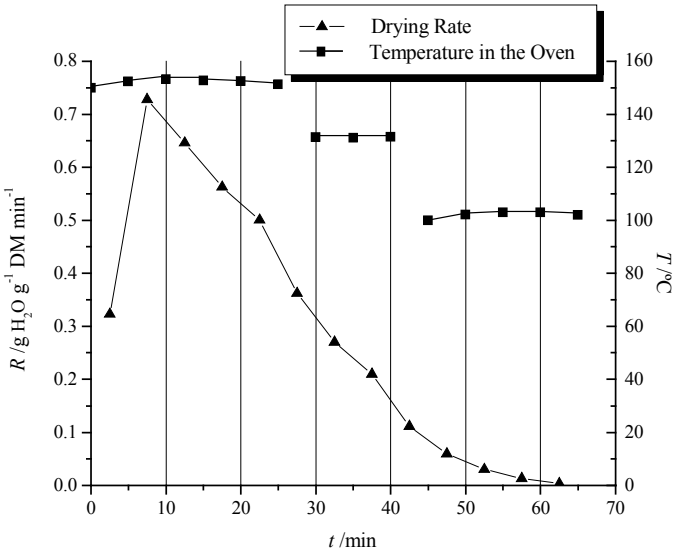

Fig. 5.21: Drying rate of 0.5 cm-thick tomato cubes versus drying time in the oven during intermittent drying with a time-varying step-down temperature profile; *x*-axis *excludes* the tempering periods

5.3.2 Temperature Development in the Sample

The effect of the time-varying step-down temperature profile of the drying air on the sample temperature development during the intermittent drying process is presented in Fig. 5.22, including standard deviations, for 0.5 cm-thick tomato cubes.

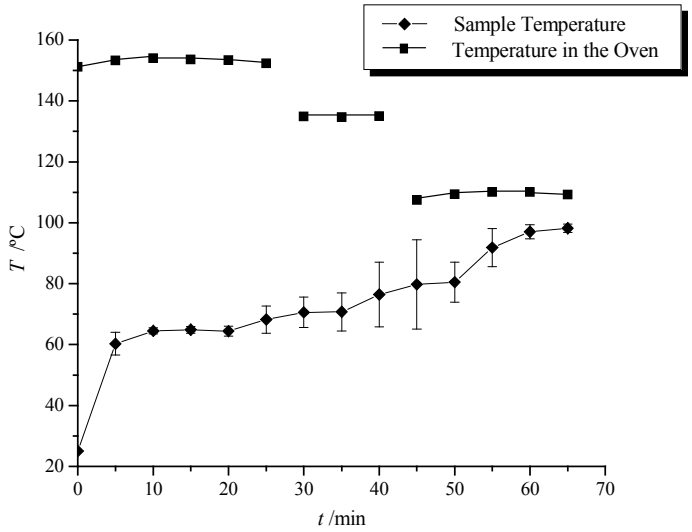

Fig. 5.22: Centre-temperature development in 0.5 cm-thick tomato cubes during intermittent drying with a time-varying step-down temperature profile; *x*-axis *excludes* the tempering periods; *n*=4

5.3.3 Colour Measurements

No browning was observed during the visual inspection of the surface of the dried tomato samples. However since quantitative evaluation of the final colour quality is necessary, further continuous drying experiments with 0.5 cm-thick tomato cubes were performed at the more common drying temperatures of 55 ºC and 70 ºC. The colour quality of these dried samples and those dried using the optimised process were analysed by L*a*b* method and compared. The overall colour difference (ΔE^*) and the colour intensity (*CI*) of tomato samples dried using a time-varying step-down temperature profile process as well as continuous drying at 55 ºC and 70 ºC are presented in Tab. 5.9.

Tab. 5.9: Colour results for the optimised process and the low-temperature drying experiments

Sample	Drying Method	*ΔE**	*CI*
0.5 cm-thick tomato cubes	Intermittent drying with a time-varying step-down temperature profile	15.38	18.83
0.5 cm-thick tomato cubes	Continuous drying at 70 ºC	16.84	16.63
0.5 cm-thick tomato cubes	Continuous drying at 55 ºC	15.53	18.66

5.3.4 Rehydration Analysis

The rehydration ratios calculated according to eq. (4.10) at various lengths of time for the tomato samples dried using the optimised process are shown in Fig. 5.23.

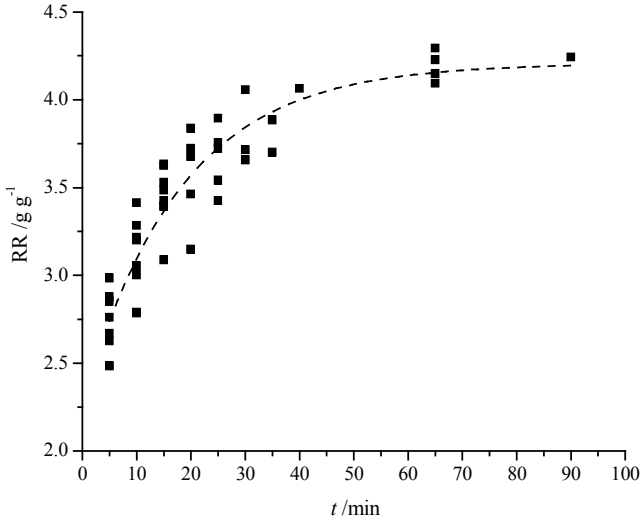

Fig. 5.23: Rehydration ratios for tomatoes dried using the optimised process at a water temperature of 25 ºC

6 Discussion

The main drawback of air drying is low heat and mass transfer. In order to increase the heat and mass transfer between the sample and the drying air, high temperatures are necessary. In general, air temperatures of between 40 and 90 ºC are used for drying fruit and vegetables [14, 99, 201]. The current study presents comprehensive research on the feasibility of using air temperatures higher than 100 ºC during drying, without compromising colour and rehydration quality, and seeks to optimise the process for achieving it. This section provides detailed discussion and offers explanations for the experimental results. It starts off with the effects that increasing air temperature has on the drying kinetics and on the visual colour quality (6.1.1) and is followed by the influence of sample geometry on such drying behaviour (6.1.2). Intermittent drying and the application of a time-varying step-down temperature profile reduce the drying time in the oven and improve drying rates and product quality, providing an alternative to the continuous drying process. Hence, in 6.2 the effects of tempering on the drying characteristics are discussed, in 6.3 a comparison is drawn between intermittent and continuous drying and finally, in 6.4, there is discussion of the optimisation process, which introduces a gradual temperature reduction in the oven during intermittent drying. The effects of these combined processes are also examined in terms of colour quality (6.4.1) and rehydration ability (6.4.2).

6.1 Effects of Process and Product Characteristics on the Drying Kinetics

The process and product characteristics investigated in this study are drying air temperature and the thickness and shape of the samples, respectively. The experimental data for the moisture-content ratio were plotted against drying time for different temperatures and sample geometry in order to see the effects of these variables on the drying characteristics of tomato. The drying curves indicate clearly that drying temperature and sample thickness are key variables affecting the time required to reach final moisture content (< 15% wb). Furthermore, the sample shape was found to be less important than the drying temperature and sample thickness. These results are consistent with the findings reported in the literature where air temperature and sample thickness are considered to be the most important factors affecting the drying characteristics [58,

112, 163, 203]. In the following subsections, the effects of drying air temperature, sample thickness and shape on the drying time, drying rate, effective moisture diffusivity and the drying constant will therefore be discussed individually in more detail.

6.1.1 Drying Air Temperature Effects

Drying Time

Increasing the drying air temperature resulted in a notable decrease in drying time. Figs. 6.1 and 6.2 show clearly how an increase in air temperature can decrease the drying time of 0.5 cm-thick tomato cubes very efficiently for continuous and intermittent drying, respectively. This efficiency may be attributed to a greater rate of heat transfer into the tomato samples from the drying air, i.e. the larger the temperature *differences* between the product and the air, the greater the heat transfer [70, 212].

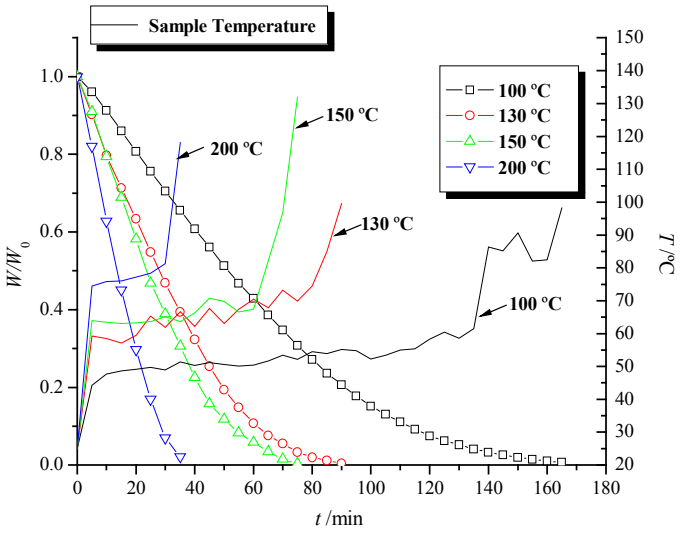

Fig. 6.1: Drying curves and sample-temperature profiles of 0.5 cm-thick tomato cubes at different drying temperatures; continuous process

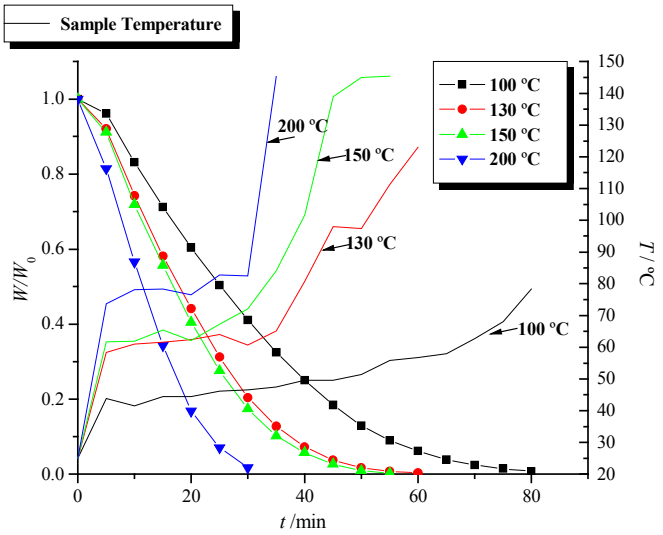

Fig. 6.2: Drying curves and sample-temperature profiles of 0.5 cm-thick tomato cubes at different drying temperatures; intermittent process; α=1/4, i.e., five minutes of drying followed by 15 minutes of tempering in each cycle; *x*-axis *excludes* the tempering periods

As can be seen in Figs. 6.1 and 6.2, the sample temperatures have their highest values as the drying air temperature increases because the *changes* in the air temperature affect the inner temperatures of the tomatoes considerably. The advantage of this behaviour is that higher inner temperature results in increased water vapour pressure generation within the sample pores [2, 7, 69, 145, 180, 181]. This occurs because the pores of the samples become saturated as water and/or water vapour diffuses towards the tomato surface by molecular diffusion (e.g. liquid diffusion), vapour diffusion and capillary forces or a combination of these moisture transport mechanisms. In the oven, however, where the temperature was higher, the partial water vapour pressure was far from saturation. This resulted in a water vapour pressure gradient between the tomato surface and drying air, which provided the driving force for moisture removal since water/water vapour migrates from locations of high to low water vapour pressure/concentration. Consequently, water and/or water vapour diffuses from the surface of the tomatoes to the air and the surface starts to dry out. A drying zone is developed, which slowly increases in size. Therefore it is reasonable to say that as air temperature increases, other drying conditions remaining the same, moisture removal increases and drying time decreases substantially. Similar findings have been reported by JUMAH ET AL. for the

convectional drying of tomato paste [85], MASKAN ET AL. for the hot-air drying of grapes [118] and ZANONI ET AL. for tomato halves in the cabinet dryer [214]. However, it is also important to point out that increasing the drying temperature indefinitely will not be efficient; there will be some limits. First, it is necessary to consider the effects of higher temperature on the quality characteristics (e.g. colour). Second, the marginal reduction in drying time achieved by increasing the temperature becomes smaller as higher temperatures are applied. For example, from Fig. 6.3 it is clear that increasing the air temperature from 100 to 150 ºC resulted in a larger reduction in drying time than increasing it from 150 to 200 ºC. The colour quality of the samples was also severely degraded at 200 ºC.

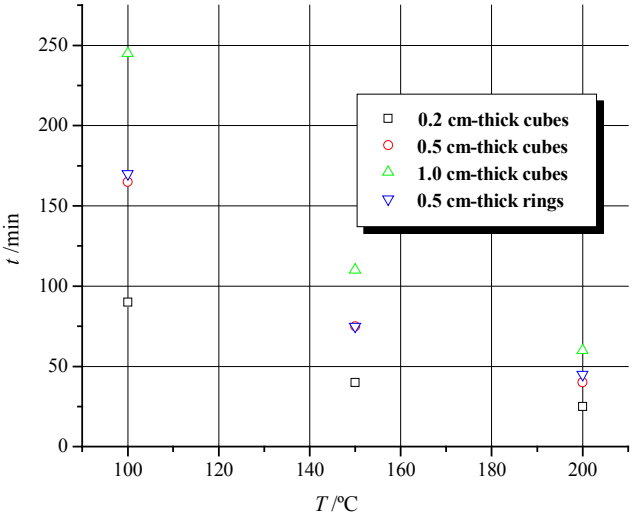

Fig. 6.3: Effects of drying temperature on the drying time of tomato samples; continuous process

Drying Rate

The drying air temperature affected the rate of change in moisture content of tomato samples. In order to see this effect, drying-rate curves were plotted by calculating the difference in moisture content, g [H_2O] g^{-1} [DM], between consecutive sampling times and dividing this value by the time interval in minutes (i.e. slopes of the drying curves). By doing so it was also possible to check for the existence of different drying periods, providing the necessary information to analyse the controlling mechanism of the drying process.

Figs. 5.2 and 5.12 show the effect of air temperature on the drying rates of tomato cubes. It is seen that the drying rate of tomato samples increases significantly as air temperature increases from 100 to 200 ºC since drying at high temperatures provided higher heat transfer and therefore a higher driving force for moisture transport to the tomato surface. A typical pattern in these graphs is that the drying rate of tomato samples reached a maximum value after an initial warm-up period and then decreased gradually in two steps, namely the "first falling rate" and the "second falling rate" periods. Although the initial moisture content was as high as 95% (wb) no constant rate period was observed and drying moved quickly to the falling rate period. Several other researchers have reported similar observations during the drying of tomatoes and other various fruits and vegetables [5, 46, 62, 64, 65, 204, 214]. MAZZA AND LE MAGUER attribute the absence of a constant-rate period to the colloidal and hydrophilic nature of food samples that causes the water molecules to be held tightly by the material [122]. Another reason for the absence of a constant-rate period may be explained by the thin (single) layer arrangement and excessively rapid heating, which leads the surface of the tomato samples to dry out very quickly. This means that the rate of moisture evaporation from the sample surface to the drying air is faster than the rate at which that moisture is replenished at the surface. In other words, water could not be supplied from the interior to the surface at a sufficient rate to moisturise the surface of the tomato samples. However, a constant-rate period requires a film of water at the surface to be replenished continuously from inside the material. On the other hand TURHAN ET AL. have suggested that foods with a damaged cell structure might show a constant drying rate at the beginning of the process [197]. In their experiments the unblanched pepper samples dried at 50 ºC only exhibited a falling rate period while the blanched samples had both constant-rate and falling-rate periods. The authors ascribed this to the damaged cell wall membrane caused by the heat treatment during blanching, which increased the amount of free moisture to be removed. VACCAREZZA ET AL. have indicated that drying at elevated temperatures modifies the permeability characteristics of cells and masks the effect of blanching [203]. Overall, these findings suggest that the constant-rate period might vanish, particularly at higher drying air temperatures, whether the sample is blanched or not [160]. Additionally, a pseudo constant-rate period may exist between the falling-rate periods [202]. This is the result of the transportation by water of low molecular weight components such as sugars and salts to the surface of the sample,

which then form a crust on the surface (case hardening). This crust may cause a short constant drying-rate period by creating additional resistance to the moisture movement [85]. The drying rate thus remains constant during this stage until this crust cracks at points on the surface where water vapour finds its way to evaporate to the drying air. In the present study, such pseudo constant-rate periods were determined between two falling-rate periods with moisture-content ratios from 0.45 to 0.33 while drying at 100 ºC and 0.44 to 0.27 while drying at 150 ºC, see Fig. 5.2. Visual observation of the samples confirmed this behaviour because after 20 minutes of continuous drying at 150 ºC, the surface of the tomato cubes started to dry out. Such pseudo constant-rate periods between two falling-rate drying stages have also been reported by LABUZA AND SIMON for the air drying of apples pretreated with different surfactants [102], by LEWICKI ET AL. for the foam-mat drying of maltodextrin [108] and by MASKAN AND IBANOGLU for the air drying of tarhana dough [120].

On further drying, at the second falling-rate stage, the difference in the temperature and the vapour pressure/moisture content became smaller between the drying air and the tomato surface due to the increase in sample temperature and decrease in water content [104, 196]. As a result, the driving force for drying lessened and the reduction in the drying rate of the samples was larger than during the earlier stages of drying. The shape of the drying-rate curves at this stage, which is actually typical for colloidal or capillary-porous food products, reflects this phenomenon as shown in Figs. 5.2 and 5.12. Such patterns as in Figs. 5.2 and 5.12 are similar to those reported for other hot-air drying of tomato samples [62, 71, 214].

In summary, higher air-temperature values create larger temperature differences between the sample and the drying air in the oven and hence increase the drying rate.

Effective Moisture Diffusivity

The effects of air temperature on moisture transport within the sample may be described by analysing the mechanisms which resist drying. The drying rate of the samples at the very beginning of the process decreases (i.e. no constant-rate period exists), see

Figs. 5.2 and 5.12, the internal temperature gradients within the tomato samples are very small, see Fig. 5.8, and thus the heat transfer effects (external resistance) are negligible. Taken together, these imply that internal resistance to moisture movement as a result of water vapour pressure/or water concentration gradient existing between the deeper parts and the surface is the controlling mechanism during the falling-rate period of tomato [104, 150, 192, 199]. Hence, tomato drying can be treated as a diffusion-controlled moisture transport phenomenon. FICK's second law of diffusion eq. (2.2) was therefore applied for describing the transport mechanisms of the falling-rate period using the effective diffusivity approach, which was calculated assuming a uniform initial moisture distribution, an infinite slab geometry and a constant moisture diffusivity. In addition, the moisture diffusivity is assumed to be a lumped value since it includes the moisture inside the tomato samples transported both in the form of liquid by capillary and/or diffusional flow and vapour by diffusional flow [162, 170, 187]. Linear regression analysis was applied to obtain the effective diffusivity values, due to the assumption of their being constant, as shown in Figs. 5.4, 5.5, 5.14 and 5.15. Here, $\ln(W/W_0)$ is plotted against the drying time. The slopes of these curves represent the effective diffusivity coefficients of tomato samples for various drying conditions. The D_{eff} values and the corresponding R^2 values can be seen in Tabs. 5.2 and 5.6 for different drying conditions. The effective moisture diffusivity values, D_{eff}, of tomato samples during drying varied within a range of $0.37 \cdot 10^{-9}$ to $10.63 \cdot 10^{-9}$ m^2s^{-1} for continuous and $0.81 \cdot 10^{-9}$ to $16.31 \cdot 10^{-9}$ m^2s^{-1} for intermittent drying. These ranges are higher than those of $1.52 \cdot 10^{-10}$ to $9.12 \cdot 10^{-10}$ m^2s^{-1} determined by HAWLADER ET AL. for 0.5 cm-thick tomato slices dried at 40 to 80 ºC [71], $1.31 \cdot 10^{-9}$ recorded by SACILIK ET AL. for tomato halves dried in a solar tunnel dryer [165], $0.32 \cdot 10^{-10}$ to $4.01 \cdot 10^{-10}$ m^2s^{-1} reported by UDDIN ET AL. for the drying of 0.5 cm and 1.0 cm-thick pineapple slabs at air temperatures from 50 to 80 ºC [199] and $1.596 \cdot 10^{-10}$ to $8.487 \cdot 10^{-10}$ m^2s^{-1} found by YUSHENG AND POULSEN for 0.45 cm-thick potato slabs air-dried at 40 to 70ºC [213]. The higher D_{eff} values reported in the current study compared with the literature are due to the differences in drying air temperature and product structure. This is reflected in Tabs. 5.2 and 5.6, where the effective diffusivity increased greatly with increasing air temperature. Several researchers reported the same observation for the drying of various fruit and vegetables [71, 118, 164, 180, 199, 192]. Among them, GIOVANELLI ET AL. obtained higher D_{eff} values for 1.6 cm-thick tomato halves dried at 110 ºC than for those dried at 80 ºC [62].

Such patterns can be attributed to the higher vapour pressure inside the tomato samples. Since increasing the air temperature caused more immediate heating within the tomatoes (increased heat transfer), the resulting higher sample temperatures led to higher vapour pressure in the pores.

Regarding the assumption of a constant value for effective moisture diffusivity, it may be seen in Figs. 5.4, 5.5, 5.14 and 5.15 that the plots of $\ln(W/W_0)$ versus time are not linear. This suggests that the moisture diffusivity is not constant throughout the drying process. The deviations from the straight lines may be due to a concentration-dependent diffusivity (changes in the mechanisms of liquid and vapour flow), structural alterations (such as collapse/shrinkage) in the tomato samples during drying, and changes in the sample temperature [71, 102, 168, 170, 180]. TOLEDO suggested that diffusivity may be constant if cells do not collapse and pack together as in the case of firm solid food such as grains [194]. The assumption of constant diffusivity and thickness is therefore not realistic, as also reported by HUSAIN ET AL. [76]. Similar non-linear drying curves were obtained for apples [4], tomato [71], mango and cassava fruits [74], cake batter [167], cereal [198] and pineapple [199]. On the other hand, linear curves were reported for potatoes [4], figs [16], pistachio nuts [92] and banana [130]. KEEY suggested that the period of linearity is longer when the variation in moisture concentration is lower [96]. Because of the higher variations in diffusivity, this kind of data is sometimes represented in two or even three separate linear portions (first falling-rate, second falling-rate and third falling-rate periods) with two or three respective effective diffusivity values for liquid and vapour diffusivity [5, 42, 94]. However, it is difficult to determine where the end points for the first and the second falling-rate periods are because generally there is no clear-cut transition between the falling-rate periods. Consequently, the distinction is made subjectively, as also indicated by TÜTÜNCÜ AND LABUZA and ÜRETIR ET AL. [198, 200]. Depending on the selection of the end point, the slope of the line and thus the effective diffusivity both change. As in the general case of non-linear drying curves, the method of slopes was applied to estimate the effective moisture diffusivity of tomato samples at various moisture contents for each drying temperature [90, 125]. The application of this method is illustrated in Fig. 6.4 for the continuous drying of 0.5 cm-thick tomato cubes at 100 ºC.

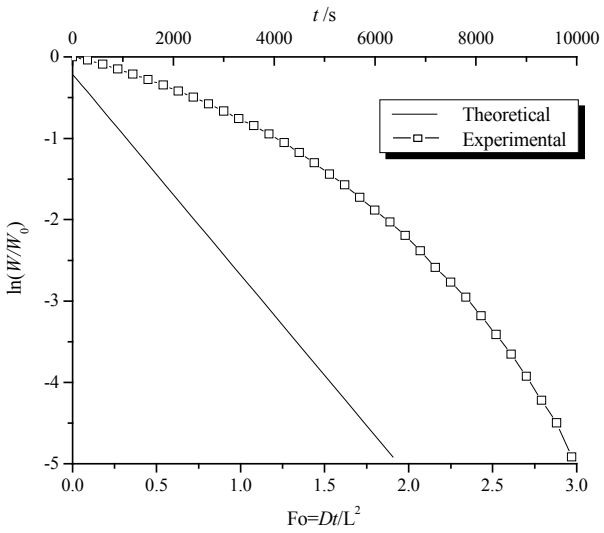

Fig. 6.4: Experimental drying curve and theoretical plot of the natural logarithm (ln) of moisture-content ratio versus drying time and the corresponding Fourier number; application of the method of slopes for the continuous drying of 0.5 cm-thick tomato cubes at 100 ºC

D_{eff} values were calculated by taking the ratio of the slopes of the curves, as indicated in eq. (2.6). In the case of intermittent drying, calculations exclude the tempering time. The effective diffusivity values for different air temperature and sample size ranged from $9.45 \cdot 10^{-11}$ m^2s^{-1} to $26.50 \cdot 10^{-9}$ m^2s^{-1} and $12.60 \cdot 10^{-11}$ m^2s^{-1} to $31.25 \cdot 10^{-9}$ m^2s^{-1} for continuous and intermittent drying, respectively, at all temperatures, and for all sample shapes and thickness (see Tab. 6.1). These values are comparable to those calculated for constant diffusivity in the present study. Interestingly, there appear to be no results reported in the literature about tomato effective diffusity changing with moisture content during drying. However, SAHBAZ ET AL. determined D_{eff} values for 1 cm-thick mushroom cubes dried in the temperature range of 60 to 80 ºC that were lower than the ones in the present study [166]. The differences can be attributed to the higher drying temperatures and the particular structure of the samples used in the current study.

Tab. 6.1: Effective moisture diffusivity of tomato samples determined by the application of the method of slopes for various drying conditions

Tomato Samples	Drying Temperature	Continuous Drying	Intermittent Drying
		$D_{eff} \cdot 10^{-9}$	$D_{eff} \cdot 10^{-9}$
	/ °C	/ m^2s^{-1}	/ m^2s^{-1}
0.2 cm-thick tomato cubes	100	0.0945-0.8742	0.1260-1.5289
	130	0.1286-1.3485	0.1530-2.2737
	150	0.2910-4.8631	0.2600-3.5276
	200	0.4491-1.7858	0.4344-2.5002
0.5 cm-thick tomato cubes	100	0.3372-3.5268	0.3042-5.6822
	130	0.8624-8.5600	0.6975-7.7031
	150	0.8002-12.1536	0.7806-10.6060
	200	1.6707-10.0036	1.7310-11.9883
1.0 cm-thick tomato cubes	100	0.9267-7.7132	1.0765-11.8847
	130	2.0899-17.2579	2.0446-20.3859
	150	2.5695-40.3999	1.8499-21.0257
	200	3.9481-26.5050	6.0447-31.2545
0.5 cm-thick tomato rings	100	0.2523-2.8796	0.2892-3.8758
	130	0.4662-2.7786	0.51849-7.8628
	150	0.6389-9.9873	0.7087-2.4730
	200	0.8898-9.1297	1.1113-13.1860

The influence of air temperature on the variation of effective diffusivity with moisture-content ratio during the continuous drying of 0.5 cm-thick tomato is shown in Fig. 6.5. As can be seen in this graph, the diffusivity increased with the increase in drying air temperature. This effect has already been discussed for the approach assuming constant effective diffusivity. Similar trends were also observed for the other sample shape and size in the present study.

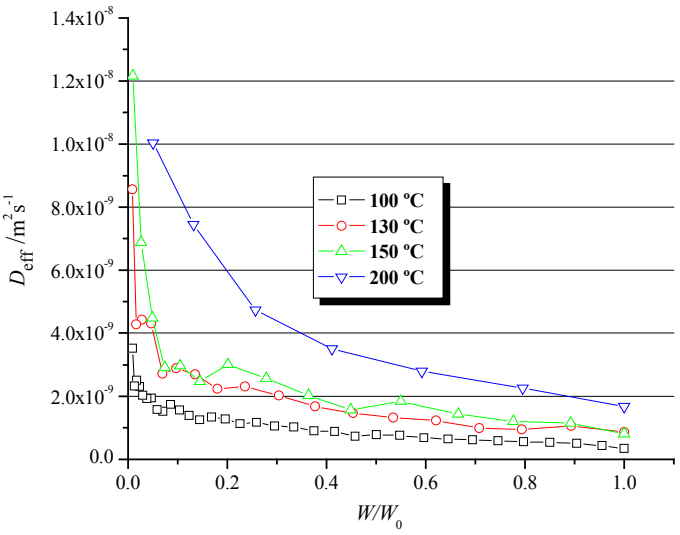

Fig. 6.5: Variation of effective diffusivity in 0.5 cm-thick tomato cubes at different moisture-content ratios during continuous drying

It is also evident from Fig. 6.5 that the effective moisture diffusivity increases with a decrease in moisture content. However this increase in D_{eff} had different patterns at different stages of the process. At the beginning of the drying, when the moisture content was high and initial sample temperature was far less than air temperature, D_{eff} values first increased at a low rate. In contrast, as the moisture-content ratio W/W_0 approached 0.2 (3.95 g [H_2O] g^{-1} [DM]) and the sample temperature its maximum value, D_{eff} increased at a faster rate. This behaviour might be due to a change in the transfer mechanism of moisture during drying and the continuous increase in the tomato temperature throughout the process. In the initial stages of drying, at high moisture contents, water diffusion along with capillary movement was the main moisture transport mechanism, whereas as drying progressed, vapour diffusion became the predominant mechanism, resulting in higher values of D_{eff} [154, 168]. This change in

the moisture transport mechanism may be attributed to the porosity difference during the early (low porosity) and latter (high porosity) stages of drying. In a study by SRIKIATDEN AND ROBERTS it is reported that the formation of higher porosity in the dried layer of apples at a moisture content below 4.5 g [H_2O] g^{-1} [DM] facilitated the transfer of water vapour and increased the effective moisture diffusivity relative to the early stages of drying [184]. Furthermore, in some of the continuous and intermittent drying experiments (when only the drying time in the oven is considered) the effective diffusivity dropped after reaching a maximum value at moisture contents between 0.2 and 0.38 g [H_2O] g^{-1} [DM] (25% wb). This fall in effective diffusivity might be explained by the influence of strongly bound water on the sorption sides of the tomato samples at very low moisture contents, reducing the availability of water molecules for diffusion [90, 168, 170]. Another possible reason might be the shrinkage and wrapping of the samples resulting in differential drying [102, 154]. SING AND GUPTA also observed a fall in D_{eff} values during the convective drying of carrot cubes at moisture content levels of 0.2 to 0.3 g [H_2O] g^{-1} [DM] [180]. They attributed the decrease in D_{eff} at lower moisture contents (towards the end of drying) both to the constant product temperature as the sample and surrounding air temperatures converged and to the non-availability of free water for diffusion. It may thus be inferred that the effective diffusivity of the tomato samples in the current study is also a strong function of moisture content rather than temperature, particularly at lower moisture contents. Indeed, the sample temperature was found to be nearly equal to the drying air temperature towards the end of drying. However, a drop in D_{eff} was not determined at drying temperatures above 100 ºC. The browning effect and the higher temperature levels within the sample might explain this behaviour.

On the basis of the above discussion, it may be suggested that effective diffusivity becomes larger as the air temperature increases and moisture content decreases during tomato drying. This is in accordance with the results reported by RAMESH for the drying of cooked rice [153], RAMESH ET AL. for the air drying of paprika [154], SAHBAZ ET AL. for mushroom drying [166], TANG AND CENKOWSKI for air-dried potato [187]. However, it is also important to note that shortly before the final drying stage, the increased resistance to moisture diffusion can cause a decrease in effective diffusivity when further moisture is removed. Such behaviour is also reported by SAKIN ET AL. for

the baking of cake batter [167], SING AND GUPTA for the osmotic and convectional air drying of carrot cubes [180], and UZMAN AND SAHBAZ for the drying of corn starch [202].

Drying Constants

The effect of air temperature on the tomato-sample drying constants k_{LEWIS}, k_{PAGE} and n_{PAGE} was investigated by fitting the experimental moisture-content ratio data to the chosen models, LEWIS eq. (2.7) and PAGE eq. (2.8), using non-linear regression analysis and comparing the estimates for the k_{LEWIS}, k_{PAGE}, and n_{PAGE} values (see Tabs. 5.3 and 5.7). The k values for the LEWIS and PAGE models show the same trend as D_{eff} (i.e. at the same sample thickness the k values increase with increased drying air temperature under all experimental conditions, $k_{200\,°C} > k_{150\,°C} > k_{130\,°C} > k_{100\,°C}$) due to the more intense heat and mass transfer at higher drying air temperatures. An example of this relationship is shown in Fig. 6.6. Here, the PAGE-model k values for the continuous drying process are plotted against drying air temperature at different thicknesses. As can be seen in this graph, the parameter k increases linearly with air temperature. These observations are consistent with the drying characteristics of parsley and dill within the range of 40 to 70 ºC reported by DOYMAZ ET AL. [48], the study on hot-air drying of cauliflower temperatures ranging from 50 to 70 ºC by THAKUR AND JAIN [190], and with the modelling of the hot-air drying kinetics of red bell pepper from 50 to 80 ºC by VEGA ET AL. [204].

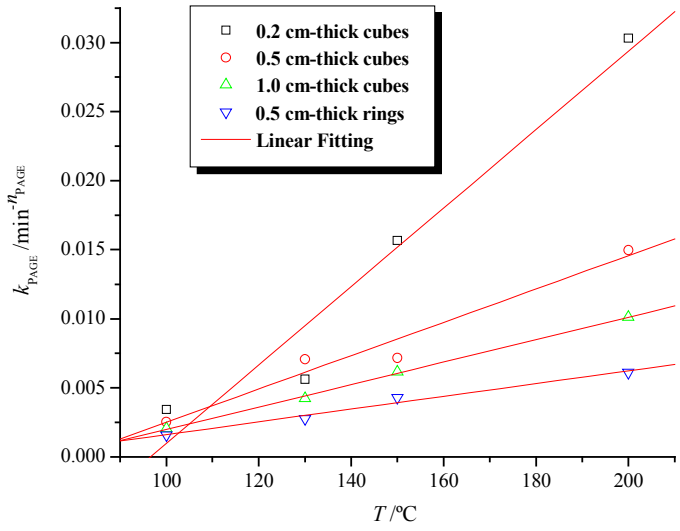

Fig. 6.6: Effects of drying temperature on the drying constant, k_{PAGE}, for different sample geometry during the continuous process

Similarly to the PAGE model case, the variation of k_{LEWIS} with the drying temperature follows a linear trend for all other tested drying conditions. However, the constant n_{PAGE} in the PAGE model eq. (2.8) does not exhibit any clear pattern with regard to air temperature, indicating that there is no direct dependence on temperature, see Fig. 6.7.

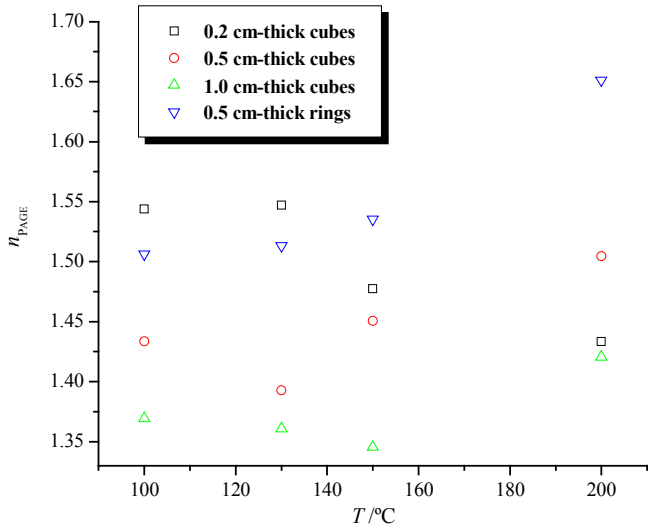

Fig. 6.7: Effects of drying temperature on the drying constant n_{PAGE} for different sample geometry during the continuous process

The influence of air temperature on the drying constant n_{PAGE} for various food products has also been discussed in other studies. These include CHEN ET AL. for Udon noodles dried at 65 ºC [28], GIRI AND PRASAD for the microwave-vacuum and convective hot-air drying of mushrooms [64], METHAKHUP ET AL. for air-dried Indian gooseberries [123], SENADEERA ET AL. for various vegetables dried in a fluidised bed [172] and SIMAL ET AL. for the drying of kiwi fruits at temperatures of 40 to 90 ºC [179]. All of these found the parameter n_{PAGE} not to depend on air temperature.

The best model for describing the drying characteristics and predicting the moisture content of tomato samples at different drying temperatures is the one with the highest coefficient of determination, R^2, and the lowest standard errors, s.e. In all cases R^2 values for the PAGE and LEWIS models are greater than the acceptable R^2 value of 0.90, indicating a good fit (see Tabs. 5.3 and Tabs. 5.7). The experimental and predicted moisture-content ratios obtained using LEWIS and PAGE models are shown in Figs. 5.6 and 5.7 for continuous drying, and in Figs. 5.16 and 5.17 for intermittent drying, respectively. As may be seen in Figs. 5.6 and 5.16, the LEWIS model does not adequately fit the drying curves. In particular, there are deviations at intermediate moisture levels where the model underestimates the experimental data and at low moisture levels where the model overestimates the experimental data. The PAGE model, on the other hand, provides an excellent fit for the data under all conditions tested with consistently higher R^2 values and lower standard errors. This result is in accordance with the earlier observations of air-dried tomato samples by DOYMAZ ET AL. [46], fluidised bed-dried vegetables by SENADEERA ET AL. [172], air-dried candle nuts by TARIGAN ET AL. [188] and cauliflower hot-air drying by THAKUR AND JAIN [190].

Colour quality

Visual observations of tomato samples during drying revealed a gradual discoloration from the typical red colour of fresh tomato to brick-red, and then brown and even black as the air temperature increased. This behaviour implies a non-enzymatic character. Browning is dependent on the duration at the specific air and sample temperature as well as on the moisture content of the tomatoes [31, 49, 91, 95]. Therefore in this study

a temperature-moisture profile for the onset of browning during drying was established. In Tabs. 5.4 and 5.8 a strong influence of air temperature on browning is apparent. According to these tables, as the air temperature increases from 130 to 200 ºC the sample temperature and moisture content at the time of browning also increase. This emphasizes the importance of controlling temperature and time schedules, particularly when products such as fruits and vegetables are dried at high air temperatures.

ZANONI ET AL. reported that the onset of browning started when tomato temperature was above 80 ºC and moisture content was between 47.6 and 26.7 at a drying time of between 170 and 190 minutes at 110 ºC [214]. However in the current study an air temperature of 100 ºC did not lead to any change in colour quality, whereas the acceptable colour limit was exceeded (browning occurred) when air temperatures were higher than 100 ºC. The difference between the browning observations at 100 ºC obtained in this study and those cited in the literature may be attributed to the use of different tomato sizes, varieties, and the drying equipment. EICHNER AND WOLF confirmed the dependence of the intensity of browning on their using different carrot varieties during a heating process at 90 ºC and 110 ºC [51]. They suggest that the tolerable limits of browning must be determined separately for each carrot type due to the possibility of change in amino acid and reducing sugar content of different carrot varieties. Similarly, RAJ ET AL. also emphasised the importance of the variety of onion for the browning of the dried product [151]. They suggest that lower reducing to non-reducing sugars ratios of particular varieties resulted in less discoloration (browning) of the dried onions.

6.1.2 Sample Thickness and Shape Effects

The distance that water must travel within tomatoes greatly affects the drying time required to reach the recommended final moisture content (< 15% wb). This phenomenon is reflected in Fig. 6.8 showing the drying curves for tomato samples of varying thickness and shape dried at 100 ºC. It is immediately apparent from this graph that the drying time increases with increasing sample thickness when all other process variables remain constant.

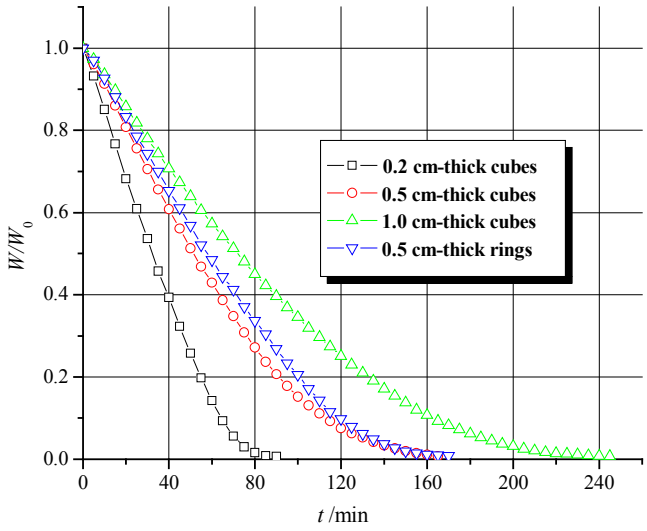

Fig. 6.8: Effects of sample thickness and shape on the drying behaviour of tomato at an air temperature of 100 °C during the continuous process

Regarding the sample shape factor, the drying times of 0.5 cm-thick rings may be compared to those of 0.5 and 1.0 cm-thick cubes at each air temperature. It was found that cutting the tomatoes into 0.5 cm-thick rings rather than cubes of the same thickness did not result in extreme lengthening of the drying time for the air temperatures investigated. They were only a little higher than the drying times of 0.5 cm-thick cubes but lower than those for 1.0 cm-thick cubes (see Tabs. 5.1 and 5.5).

The effect of thickness and shape on the drying behaviour of tomatoes is even clearer in the drying rate curves (Figs. 5.3 and 5.13). For example, the drying rate curves for thinner samples (e.g. 0.2 cm-thick cubes) are steeper than those for thicker ones under the same drying conditions. This indicates that higher thickness causes a slower rate of moisture removal due to the increased distance that the moisture has to travel. In the present study, the effect of sample thickness on the drying rate was found to be similar to the studies on air-dried and sun-dried grape leather by MASKAN ET AL. [118], hot-air drying of organic apple slices by SACILIK AND ELICIN [163], fluidised bed-drying of bean, potato and peas of different shapes by SENADEERA ET AL. [172] and air-dried semolina pasta by TEMMERMAN ET AL. [189].

In the theory (FICK's second law of diffusion), effective diffusivity is assumed to be independent of sample thickness [170, 198]. It would therefore generally be expected that when sample thickness increases, the slope of the $\ln(W/W_0)$ vs time curve should decrease. However, in the current study, D_{eff} values calculated according to FICK's second law of diffusion were found to *increase* with increasing thickness. This might be due to the presence of air pockets in the thicker samples, allowing moisture to travel more rapidly. Indeed, LABUZA AND TÜTÜNCÜ, in their study of the influence of sample geometry on effective moisture diffusivity, also report an increase in D_{eff} values with increasing thickness [198]. They attribute this phenomenon to a possible increase in the captured air between the drying materials, allowing for an increase in moisture flow. Similarly, UDDIN AND RAHMAN observed that the effective diffusivity increased with increasing thickness of pineapples [199]. They have suggested that for thicker samples different internal structures are developed during drying, possibly due to less shrinkage which allows faster moisture transport than for thinner samples. On the other hand, GIOVANELLI ET AL. report a decrease in effective diffusivity with an increase in thickness of tomato pulp slabs having 1.5 cm and 2.0 cm thickness dried at 70 ºC [62]. One possible reason for this disparity might be the different structure of their samples (pulp has a damaged cell structure) as well as the absence of skin.

It has been suggested that the drying constant, k_{LEWIS}, represents the effect of mass-transfer area (surface area) on the drying rates [59, 126, 152]. It is assumed that the larger the surface area per unit volume, the higher the drying rate and thus the larger the drying constant, k_{LEWIS}. As can be seen in Tab. 6.2, this assumption is confirmed for all samples under the continuous and intermittent drying processes. Accordingly, the faster drying rate of 0.2 cm-thick cubes relative to 0.5 and 1.0 cm-thick cubes and to 0.5 cm-thick rings is due both to the lower thickness and to the higher surface area per unit volume. Furthermore, the k_{LEWIS} values for 0.5 cm-thick rings at each drying temperature were found to be higher than those for 1.0 cm-thick cubes, indicating that it took less time for the rings to reach the acceptable water content level (< 15 % wb) for storage compared to the 1.0 cm-thick cubes. This is also confirmed by looking at the drying rate curves in Figs. 5.3 and 5.13. All of these findings are consistent with the study of ISLAM AND FLINK who compared the drying rates of 5.0 cm and 1.0 cm-thick potato slices to French cut potatoes with a thickness of 7.8 cm [80]. The authors also attribute the faster

drying rate both to the lower thickness and to the higher surface area per unit volume effects. Moreover from the results of the current study it is possible to determine which one of these parameters (i.e. thickness or shape) has more influence on the drying rate. By comparing 0.5 cm-thick rings to 0.5 cm-thick cubes (same thickness but different shape), it can be seen that the surface area-to-volume ratios are higher for the cubes than for the rings. This difference is due to the shape. Since the tomato rings are less exposed to drying than the tomato cubes of same thickness the k values for the rings are lower than for the 0.5 cm-thick cubes. However when the k_{LEWIS} values of 0.5 cm-thick cubes are compared to 1.0 cm-thick cubes (different thickness but similar shape), one can easily notice that the fall in the k_{LEWIS} values for 1.0 cm-thick cubes are much higher than those for rings. This indicates that the thickness has a greater effect on the drying rate than a change in shape for a sample of the same thickness. Therefore in order to lessen the drying time and minimise energy consumption, it may be advisable to reduce the thickness of the samples rather than to change their shape.

Tab. 6.2: Comparison of the drying constant k_{LEWIS} by sample geometry and drying temperature; continuous process

Tomato Samples	Surface Area	Volume	Surface Area per Volume	$k_{LEWIS}\cdot10^{-2}$ / min^{-1}			
				100	130	150	200
	/ cm^2	/ cm^3	/ cm^{-1}	/ ºC	/ ºC	/ ºC	/ ºC
0.2x0.2x0.2 cubes	0.24	0.008	30.00	2.64	3.62	6.31	8.80
0.5x0.5x0.5 cubes	1.50	0.125	12.00	1.60	2.98	3.47	6.10
1.0x1.0x1.0 cubes	6.00	1.000	6.00	1.14	1.86	2.36	4.05
0.5 cm-thick rings	46.23	7.270	6.35	1.44	2.10	2.97	4.58

6.2 Effects of Tempering on the Drying Process

The introduction of tempering periods (breaks) between the drying cycles reduced the required drying time in the oven substantially. In the present study three different tempering schemes were first applied in order to see the most efficient schedule for the tested drying conditions (see Tab. 4.1). The experimental drying curves for the intermittent drying of tomato samples with different tempering schedules for each drying temperature are presented in Fig. 5.10. It is evident from these graphs that samples dried under the α=1/4 scheme have steeper drying curves at each drying temperature than those dried under the other schemes (α=1/2 and α=1). Thus a drying-time interval of five minutes in the oven accompanied by a tempering-time interval of 15 minutes in each drying cycle minimised the accumulated drying time. This indicates that the drying time in the oven can be reduced considerably by applying longer and more frequent tempering periods. In the experiments, a tempering period of more than 15 minutes was not tested since the moisture loss did not change after 15 minutes. Besides, it was also considered important to maintain an acceptable total drying time (drying time in the oven plus tempering time). Similar experiments have been conducted by PAN ET AL. on the intermittent drying of carrots [137]. However, in their study the samples were only tempered once, for 9.5 hours, after a period of continuous drying at 130 °C. Due to the still high moisture content, the samples were placed back in the dryer for a final drying period at 100 °C.

It is also worth noting that in the current study, the intermittent drying curves were plotted using elapsed or accumulated drying time in the oven, *excluding* the tempering periods. These curves may thus be interpreted as equivalent to the continuous drying curves and the effect of tempering on the drying characteristics of tomato samples can be examined clearly. In a study on the intermittent drying of rough rice, CIHAN AND ECE used a similar concept for showing the effect of tempering on the drying rate [35]. The authors also calculated the D_{eff} values excluding the tempering time.

The drying times in the oven for the continuous and intermittent processes of 0.5 cm-thick tomato samples indicate that drying at 100 ºC with intermittency of α=1/4 provides the highest efficiency. This is because the difference between the drying times

of the continuous and intermittent processes is 85 minutes at 100 ºC whereas it decreases to 30, 20 and 5 minutes at drying temperatures of 130 ºC, 150 ºC and 200 ºC, respectively. Similar findings were also obtained for other thicknesses and shapes. Therefore it may be argued that increasing the drying temperature above 100 ºC decreases the tempering efficiency (drying time in the oven saved when comparing intermittent to continuous drying). On the other hand, this is perhaps not surprising since tomatoes drying at 100 ºC in the oven already take longer than those drying at higher temperatures and thus allow for more tempering periods anyway (there is more oven time to be saved). Applying tempering periods during drying at temperatures of lower than 100 ºC will also increase the overall drying time substantially.

During drying in the oven, the temperature in the tomato increases quite rapidly and, as a result, the water on the surface of the samples evaporates much faster than moisture diffuses from the inner parts. As such, this can lead to the development of a "moisture gradient" between the surface and the inner parts of the tomato samples. The moisture that evaporates from the pores close to the surface is then replaced by air, preventing heat transfer to the inner sections (i.e. the thermal conductivity is lowered) [57, 110, 181]. The outer layer may then behave like an insulator wall, causing a continuous fall in the drying rate. This problem may be overcome by tempering. In the experiments, a 15-minute break at room temperature (25 ºC) allowed the internal moisture to migrate to the tomato surface. By wetting the surface area and the pores with water from the inner parts, the moisture gradient within the tomato decreased. Such a decrease in moisture gradient was also ascertained by XING ET AL. who investigated the moisture distribution during the intermittent drying of pasta using nuclear magnetic resonance. The authors observed a wet layer near the surface of pasta samples after five minutes of tempering at 22 ºC [210]. In the present study, tempering also had a positive influence on heat transfer due to the increased temperature gradient between the tomato and the oven. In addition, in each subsequent stage back in the oven, heat was transferred more efficiently from the surface through the water-filled pores to the inner parts of the tomato samples (i.e. thermal conductivity of water is higher than the air). Following such a tempering period, the drying rate increased (so-called "refreshing effect") by a considerable amount. This is reflected in Fig. 6.9 by the continuing zig-zag shape ending with a flat plateau on the drying rate curves. Accordingly, during the first five

minutes of tempering, the moisture content continued to decrease but more slowly than when the sample was in the oven; letting the drying temperature fall to room temperature reduced the drying potential. Further tempering (after 10 minutes) levelled the moisture content. This pattern is more noticeable during the initial stages of drying and is progressively less profound during the later stages of drying. It may be ascribed to the more rapid moisture redistribution and migration toward the tomato surface during the initial stage due to the higher initial moisture content.

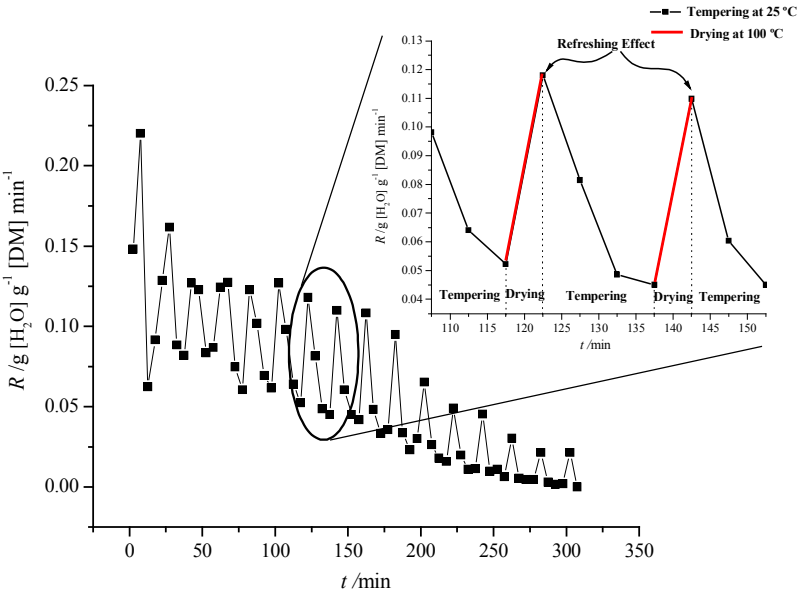

Fig 6.9: Effects of tempering on the drying rate; drying temperature of 100 °C; graph *includes* the tempering periods

The periodic interruption of the drying process also controlled the tomato's temperature by cooling its surface. Overheating of the samples was thus delayed. This may be attributed to the fact that any change in the external air temperature first affects the tomato surface. By tempering, very high sample temperature and long exposure times to the conditions of the continuous drying experiments were avoided. Consequently, change in the product colour was minimised, although non-enzymatic browning reactions could not be prevented completely. These results are presented in Tab. 5.8. RIEBLINGER reports that the continuous drying of parsley leaves at 90 ºC gave better product colour quality than those dried at 105 ºC and 120 ºC [159]. This underlines the direct effect of drying temperature and exposure time on the colour quality.

Interestingly, in the same study it is also reported that decreasing the drying temperature to 50 ºC and 75 ºC did not provide a better colour quality of parsley leaves than those at 90 ºC. The author attributed this colour change at 50 ºC and 75 ºC mainly to enzymatic rather than non-enzymatic browning reactions, although the latter were not negligible. This indicates that at low drying temperatures, enzymatic-browning may occur due to the functioning of the enzymes at low temperatures. Therefore, during tempering, since the temperature is periodically lowered to the room temperature, enzymatic reactions might also cause damage to the product colour. In order to prevent this from happening, blanching before drying as a pre-treatment is known to help inactivate these enzymes [83, 150]. However, since fresh tomato did not display any browning at room temperature, it is concluded that enzymatic reactions are not an issue for the present study. Lower temperature during the intermittent periods outside the oven did not have any negative influence on the colour observable to the naked eye.

In summary, tempering reduces the drying time required in the oven, decreases the moisture gradients within the sample, helps to improve the heat transfer, provides a means to control the sample temperature and minimises the colour changes in the samples. However the overall drying process (time both inside and outside the oven) takes longer.

6.3 Comparison between Continuous Drying and Intermittent Drying

The drying time in the oven required to reach the target moisture content (< 15% wb) at various temperatures was highly dependent on the drying method applied. This is clear when comparing the drying times in the oven for continuous and intermittent process in Tabs. 5.1 and 5.5. The drying time in the oven was shorter for intermittent than for continuous drying. These data indicate that considerable oven drying time and hence energy may be saved through the application of the intermittent process. PAN ET AL. reported similar findings for the intermittent drying of carrots and squash [137, 138].

In a study on the drying of rice, CIHAN AND ECE assumed constant effective diffusivity and excluded the tempering time during the calculations [35]. They found higher D_{eff}

values associated with the intermittent drying than those for the continuous process at the same drying temperature. Comparison of Tabs. 5.2 and 5.6 shows that the effective moisture diffusivity values for intermittent drying of tomato samples were also higher than those for continuous drying. However in the present study, differently from CIHAN ET AL. [35], D_{eff} values for intermittent drying including the tempering periods were also calculated using the method of slopes. These values, along with the continuous drying data, were then plotted against the moisture-content ratio, see Fig. 6.10. Here, D_{eff} values for the intermittent drying exhibit a different pattern than the equivalent in the continuous drying. This is mainly because of the decrease in sample temperature during tempering, which slowed down the transport of moisture. However, as the samples were returned to the oven, the D_{eff} values increased again due to the increase in sample temperature. It may therefore be useful to consider the peak values (data corresponding to the time in the oven) of the intermittent drying curve for comparisons with continuous drying. It may be inferred from this graph that the D_{eff} values for both processes increase with decreasing moisture content. However, the transport of moisture mechanisms during continuous drying are slightly higher than those during intermittent drying, until reaching a moisture-content ratio of 0.2 (80% water wb). After reaching this point, the D_{eff} values for intermittent and continuous drying converge. Once a moisture-content ratio of 0.04 (50% wb) has reached, the D_{eff} values for intermittent drying overtake those for continuous drying.

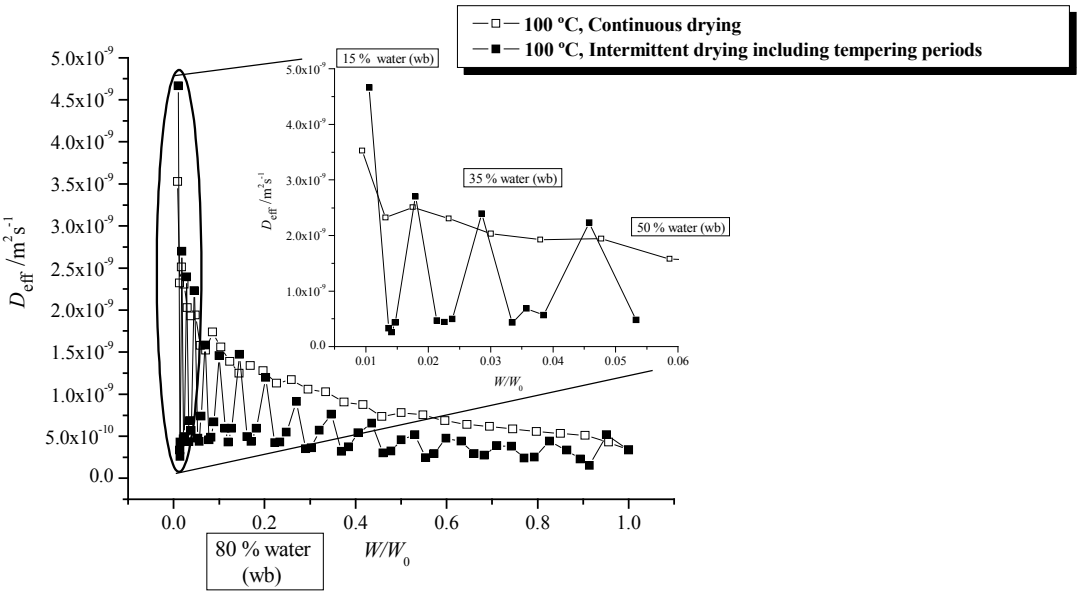

Fig. 6.10: Comparison of moisture transport during the intermittent and continuous processes; drying temperature of 100 °C; tempering periods are *included* in the calculations

During the intermittent process, as opposed to continuous drying, the sample temperature was reduced to room temperature (25 ºC) after each five-minute drying period in the oven. Therefore during each subsequent drying period in the oven the sample temperature had to increase from 25 ºC. The duration of the maximum sample temperature was thus shortened as compared to the constant drying sample temperature profiles. The change in tomato sample colour, which is highly dependent on moisture content and temperature, was therefore expected to improve by intermittent drying. This expectation was met according to the visual observations since the severity of browning is higher for continuous than for intermittent drying, see Fig. 6.11.

(a) (b)

Fig. 6.11: Visual comparison of tomato samples dried intermittently (a) and continuously (b) at 150 °C

The onset of browning for continuous and intermittent processes at different drying conditions is shown in Tabs. 5.4 and 5.8. For each experimental condition during the intermittent process, browning appeared on the surface of the tomatoes earlier than for the continuous drying. However, although the browning occurred at similar sample temperatures, the range of moisture-content values for the intermittent process was slightly lower (except for 0.2 cm-thick cubes). This indicates that the application of intermittent drying, where the period of heating of tomato samples was followed by cooling, delays browning. It is interesting to note that at the point of browning, the moisture-content range of 0.2 cm-thick tomato cubes was quite similar to the range for the continuous drying data, suggesting that intermittent drying may not delay browning for very thinly cut samples. This may be ascribed to the immediate response of thin tomato samples to the ambient air changes, i.e. the temperature increment occurs faster in 0.2 cm-thick cubes compared to the thicker tomato samples when they are placed back into the oven.

6.4 Optimisation of the Drying Process and Application of a Time-Varying Step-Down Temperature Profile

The intermittent process accelerates the drying compared to the continuous process, requiring less drying time for the tomato samples in the oven. However, both processes are accompanied by an increased potential for quality degradation especially with regard to colour at drying temperatures higher than 100 ºC. Therefore it is still necessary to determine the optimal conditions to avoid browning. In this conjunction, several authors have recommended step-wise changes in the drying air temperature in order to enhance the colour quality of different foods [17, 30, 31, 33, 34, 43, 136, 214]. Starting the process at a high temperature and gradually reducing it (step-down scheme) is known to produce favourable results in terms of shortening the drying time to reach the required moisture content due to the significant effect of evaporative cooling at the beginning of the drying. Since tomato has a very high initial moisture content (95% wb), one way to alleviate the browning problem is to introduce a time-varying step-down profile to the drying temperature in the oven during the intermittent drying process. For doing this, precise adjustments of the duration of the drying in the oven at

specific temperatures are required. These adjustments may be designed according to the critical range of sample temperature and moisture content at the onset of browning for that specific drying temperature (Tab. 5.8). In other words, before the tomato temperature and moisture content reach these critical ranges illustrated in Tab. 5.8, the temperature should be reduced for the next drying stage in the oven to prevent the browning. Similarly, other quality degradation reactions that occur during the drying of tomatoes, such as oxidation of ascorbic acid and lycopene, are also a function of moisture content, sample temperature and drying time. According to GOULA AND ADAMOPOULOS, the decrease in ascorbic acid in tomato halves occurred rapidly during the early stages of drying (within the first two hours) at a sample temperature in the range of 75 to 85 ºC. It then levelled off by the time a moisture content of 60% and a sample temperature of about 85 ºC had been reached [65]. SHI AND LE MAGUER report that most of the loss in lycopene occurred within the first hour of heat treatment of tomato puree [175]. All of this information indicates that it is advantageous to maintain the sample temperature as low as possible (< 80 ºC) from an initial (95% wb) to intermediate moisture content level (50 to 60% wb) in order to avoid browning as well as the chemical reactions mentioned above. Therefore in the experiments a critical maximum sample temperature range of 65-70 ºC for the very early stages of drying (from 95 to 80% wb moisture content) and 70 to 90 ºC (from 80 to 50% wb moisture content) for the intermediate moisture content levels were considered.

In the present study, four different process temperatures and tomato samples (cubes at different thickness and, rings) were investigated altogether. However the optimisation process was limited to 150 ºC, 130 ºC and 100 ºC as process temperatures and 0.5 cm-thick tomato cubes as a drying material. The reason for this was that the drying of 0.5 cm-thick tomato cubes provided the highest efficiency after 0.2 cm-thick cubes due to the larger surface area per unit volume, see Tab. 6.2. In addition, the temperature values of 0.2 cm-thick tomato cubes were already found to be around 70 ºC in the first five minutes of drying at temperatures of 130 ºC, 150 ºC and 200 ºC. This temperature value is too close to the critical sample temperature of 65-70 ºC for starting the drying. Furthermore, as mentioned before, the intermittent drying of 0.2 cm-thick tomato cubes was found to have a lower effect on delaying the browning than the other samples due to the quicker response of thin tomato samples to the high air temperatures. 200 ºC was

excluded from the potential drying temperatures for the optimisation process since the temperature values of tomato cubes and rings rise above 70 ºC during the first five-minute of drying, see Fig. 6.12.

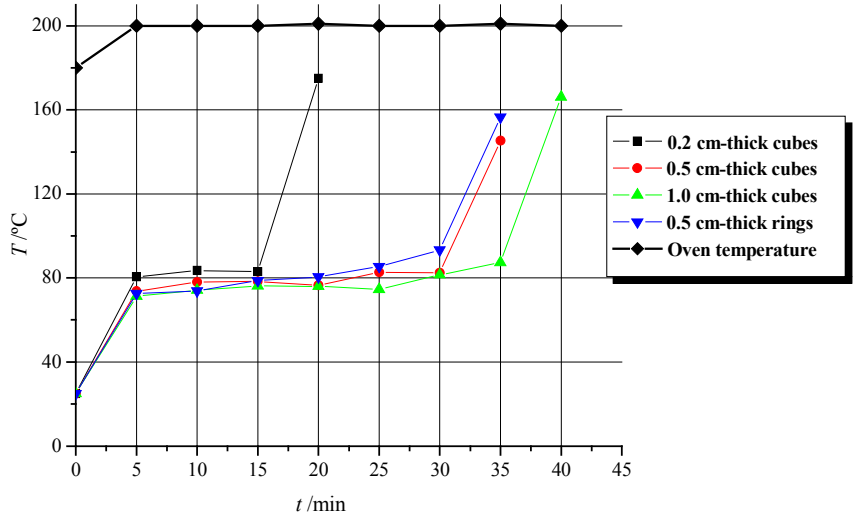

Fig. 6.12: Temperature profiles for different sample geometry at 200 ºC during intermittent drying; *x*-axis *excludes* the tempering periods

This temperature value is also above the critical sample value of 65-70 ºC, for browning and for other chemical reactions that cause quality loss. The process optimisation procedure was designed with knowledge of this as well as of the product's time-temperature-moisture content distribution during drying, see Tab. 6.3. Accordingly, intermittent drying was started at a temperature of 150 ºC. The drying in the oven at 150 ºC is stopped after 25 minutes since further drying at 150 ºC decreases the moisture content to below 84% and increases the sample temperature to above 70 ºC as well as the duration of this high sample temperature. As shown in Tab. 5.8, browning starts at a moisture content range of 60 to 77% (wb) when the drying temperature is 150 ºC. Therefore in order to prevent browning the temperature was decreased to 130 ºC and drying performed for another 15 minutes in the oven intermittently until the moisture content reached 54%. According to LENIGER AND BRUIN, the rate of non-enzymatic browning reactions reaches a maximum in the intermediate moisture range [105]. This is consistent with the present study's result since the moisture content of the tomato samples approaches the browning range of 29 to 36% (wb) at 130 ºC, see Tab. 5.8. Within this range, a small absolute decrease in water has a very large impact on the

moisture content percentage and hence the sample is more prone to browning. Because of this the rest of the drying was performed at 100 ºC for which no browning had been observed during the former experiments.

Tab. 6.3: Drying parameters at different stages of the optimised process

Drying Temperature / ºC	Drying Time in the Oven / min	Overall Drying Time / min	Moisture Reduction to / % wb	Sample Temperature Increase to / ºC
150	25	100	84	68
130	15	60	54	86
100	25	100	9	98

The amount of water that evaporated in the oven and at different stages of tempering, including standard deviations, is illustrated in Fig. 6.13. According to this graph, nearly 48% of the water was removed during tempering at room temperature. Most of this water evaporated during the first five minutes of tempering since the latent heat required for the evaporation was supplied by the tomato sample itself, i.e. the tomato temperature was higher than 25 ºC during the first few minutes of tempering. This occurred in the absence of an external heat source. The sample temperature also decreased because of the evaporative cooling effect [137, 152].

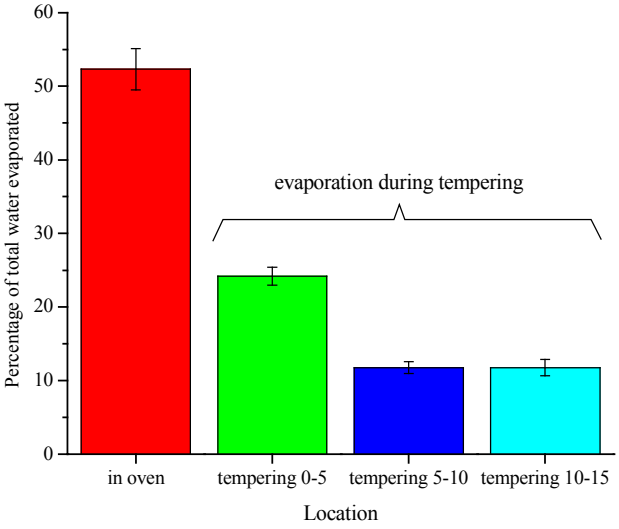

Fig. 6.13: Water evaporation by location (oven/tempering cabinet) during the optimised process, *n*=10

6.5 Final Product Quality

In the next two sub-sections, the final product quality at the end of the optimised process is assessed both quantitatively and qualitatively in terms of colour quality and rehydration ability.

6.5.1 Colour Quality

Knowing the temperature-water content profiles for colour degradation at different drying temperatures helped to avoid the occurrence of browning in the dried samples during the optimised process. By introducing breaks between the drying cycles and gradually decreasing the drying temperature throughout the process, it was possible to maintain the temperature in the sample at certain levels, and overheating, especially at low moisture contents, was avoided.

The comparison of the quantitative colour results from the optimised process with those from experiments at temperatures of 55º C and 70º C shows no clear difference, see Tab. 5.9. This suggests that intermittent drying with a time-varying step-down

temperature profile offers an alternative to continuous drying for reducing colour degradation.

6.5.2 Rehydration Ability

Following the intermittent drying with time-varying step-down temperature experiments, the dried tomato samples were rehydrated in water at 25º C. The samples demonstrated rapid and relatively complete rehydration behaviour, see Fig. 5.23. This indicates that the physical and chemical changes during such drying due to process conditions did not cause significant injury to the tomato samples. Indeed, it is generally accepted that samples dried at high temperatures possess higher rehydration capacity than those dried at low temperatures [81, 163, 182, 207]. This can be ascribed to the formation of a more porous structure in the products at high drying temperatures, which facilitates rehydration.

The shape of the curve in Fig. 5.23 is similar for the rehydration of various fruit and vegetable samples reported in the literature [50, 64, 94, 98, 117, 122, 140]. It reflects the high increase in the rate of water uptake (corresponding to higher rehydration ratio) during the initial stages of reconstitution, which then decreases as the process approaches the equilibrium state. This can be attributed to the fact that during the rehydration of dried plants, first the cell walls absorb water rapidly into the dried material, increasing the water content, and then the cells swell gradually due to the natural elasticity of the cellular structure [107].

7 Summary and Outlook

The major challenge during the drying of food is to reduce the moisture content of the samples to an acceptable level (< 15% wb) without sacrificing their quality, particularly regarding colour. Prolonged exposure of food to constant process conditions during convectional air drying causes quality degradation and inefficiency. This is due to low heat transfer and the resistance to moisture transfer within the food product. Increasing the temperature gradient between the sample surface and the air produces a higher rate of moisture removal and thus lowers the drying time required. However, it may also lead to surface browning on the drying product. To overcome this problem, intermittent drying can be employed, avoiding the adverse effects of high temperature drying by decreasing the moisture gradients between the outer sample layers and the core. That is, the outer layers are covered with water in each drying pass in the oven, accelerating moisture removal, reducing the drying time in the oven and thus hindering quality degradation.

In this study, the feasibility of using drying temperatures between 100 ºC and 200 ºC for tomato samples and the effects of such high temperatures on the drying kinetics as well as on the product quality are investigated. In order to evaluate the effects of drying temperature and sample geometry on the drying process and colour quality, tomato samples with different shapes and size (tomato cubes with varying thickness and 0.5 cm-thick rings) were dried at four air temperatures. Two different drying methods were applied: continuous hot-air drying and intermittent drying, during which the period of heating the tomato samples is followed by periods of cooling at room temperature.

The first stage of this investigation involves a comparative study conducted on the continuous and intermittent drying of tomato samples. Comparison of drying time, kinetics (drying rate, effective moisture diffusivity, drying constants), and quality parameters such as colour is necessary in order to decide which process conditions and sample geometry produce the best quality dried products. The results show that the samples undergo greater moisture loss during the initial phases of drying compared to the final ones. With other drying conditions remaining the same, increasing the drying air temperature results in an increase in the drying rate and thus a notable decrease in

overall drying time. The drying time required for reaching an acceptable final moisture content (< 15% wb) is influenced by drying temperature and sample thickness. Sample shape, however, is of less effect than the drying temperature and sample thickness. No constant-rate period is observed and all the drying occurs in the falling-rate period, suggesting a diffusion-controlled process.

The effective moisture diffusivity of tomato samples is calculated using two data-processing methods. The first is based on the linearised analytical solutions of FICK's diffusion equation, assuming constant diffusivity. The main advantage of this method is its simplicity. The second is based on the ratio of the theoretical to the experimental diffusivity values, applying the method of slopes. While the former method provides only one diffusivity value for a given drying curve (particular drying temperature and sample geometry), the latter approach presents diffusivity as a function of moisture content over the entire duration of drying. Both methods are qualitatively similar, demonstrating the general trend that effective moisture diffusivity increases with increasing air temperature.

The removal of moisture is also simulated using semi-empirical models. The results of non-linear regression analysis suggest that the PAGE model describes the drying behaviour of tomato samples more accurately than the LEWIS model.

The comparison between the continuous and intermittent drying data indicates a substantial reduction in drying time in the oven for the intermittent process, suggesting that it can also be applied to achieve energy savings. In order to provide the best efficiency in reducing the drying time, more frequent and longer tempering periods are recommended. In the current study, five minutes drying in the oven followed by a 15-minute tempering period is ascertained to be the most efficient scheme. Cooling the tomato samples for 15 minutes during tempering minimises surface overheating by decreasing the sample temperature to room temperature. At the same time, this potential heat (sensible heat of product accumulated during the drying period) is in fact utilised to evaporate some moisture from the sample without applying extra heat energy. In addition, with further tempering, the surface of the tomato samples is coated with water

supplied from the inner parts. As a result, moisture gradients within the sample decrease, and a long exposure time to continuous drying conditions is prevented.

Regarding the changes in product colour, the tomato samples were visually observed during the continuous and intermittent drying processes. The critical sample temperature, the sample moisture content and the duration of drying at the onset of browning were noted. From these observations it is concluded that browning appears on the surface of the tomatoes at drying temperatures higher than 100 ºC and an increase in the air temperature from 130 to 200 ºC increases the sample temperature and leads to the occurrence of browning at higher moisture contents. Moreover, intermittent drying minimises the changes in product colour although non-enzymatic browning reactions could not be prevented completely.

The second stage of the study therefore focuses on the design of an optimised process involving the combination of intermittent drying with a time-varying step-down temperature profile in the oven. This is then analysed in terms of drying rate, colour and rehydration ability. The time-varying step-down temperature profile in the oven helps to maintain the sample temperature below a critical value where colour degradation sets in.

For optimising the process, the drying kinetics of different tomato samples were evaluated and the most efficient sample geometry was chosen. Based on these evaluations, it was decided that 0.5 cm-thick tomato cubes should be used as a sample for the process optimisation. Moreover, browning values as a function of drying temperature and moisture content were utilised to select the optimal drying temperatures and determine the duration of drying at these temperatures. Tomato cubes were then heated sequentially at 150 ºC (25 minutes), 130 ºC (15 minutes) and 100 ºC (25 minutes) using a conventional oven. For every five minutes in the oven, the cubes were subjected to 25 ºC in a separate cabinet containing a ventilator for 15-minute tempering intervals.

Finally, the colour quality of the tomato samples dried applying the optimised process were evaluated both visually and by the L*a*b* method. Since there was no visible browning of dried tomatoes the quantitative colour values obtained from L*a*b*

method were then compared with those of tomatoes dried using a continuous process at 55 ºC and 70 ºC. The colour values achieved by the optimised process were found to be quite similar to those samples dried at 55 ºC and 70 ºC. However, the intermittent process with a time-varying step-down temperature profile shortened the drying time in the oven. Furthermore, after the colour analysis, the tomato samples dried using the optimised process were rehydrated in water. The samples exhibited rapid and relatively complete rehydration behaviour, indicating no significant injury to the tomato samples on account of the physical and chemical changes during such drying.

Intermittent drying with a time-varying step-down temperature profile process is thus found to be suitable for the drying of tomatoes. It might also be applied to other fruit and vegetables to obtain good quality dried products. Future research on time-varying step-down temperature profile processes may additionally include experimental studies for the prediction of product quality in terms of nutritional loss such as vitamin C. Moreover, this process may even be combined with osmotic drying at the beginning to reduce the initial water content of fruit and vegetables, which may lead to further energy savings.

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