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FOOD CONVECTIVE DRYER

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Annotation sheet

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The thesis presents the design of the convective dryer for drying of the banana slices. As a starting point, the theoretical fundamentals related to the drying process and a transport phenomenon during drying were carefully explained. As an initiation step velocity field around the drying samples were analysed by CFD simulations. Drying experiments were performed for thickness of 4 mm banana slices of untreated and citric acid treatment with two different orientations at the temperature 60 °C and velocity 3.3 m/s. Thus, based on drying curves the regression analysis was made to obtain diffusion coefficient. From this experimental results food convective dryer was designed.

Keywords:

Convective dryer, Banana slices, Moisture transfer, CFD simulation, Laboratory experiments, Drying curves, Regression analysis, Diffusivity, Orientation.

Utilization: For Department of Process Engineering, Czech Technical University in Prague.

Declaration

I confirm that the master's thesis work was disposed by myself and independently, under leading of my thesis supervisor. I stated all sources of the documents and literature.

In Prague …………………… ……………………………..

Name and Surname

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Abstract

This master thesis deals with convective drying process and design of food convective dryer. First chapter theoretical part describes principles of drying process and types of dryers and selection process for suitable food material. Second chapter literature search deals with mostly convective drying banana samples, thin layer drying technology and different type of mathematical suitable for to analyse diffusivity of food material. Third chapter CFD describes the velocity field around the drying samples. Later experimental part deals with convective drying of banana samples with different orientation and treatment. Last chapter deals with design of food convective dryer based on experimental results.

1 Theoretical part

1.1 Introduction

Various researchers have classified foods in different ways, generally they are categorized as perishable (which spoils very fast), non-perishable (relatively slower spoilage), harvested food, raw food, fresh food, formulated food, synthetic food and recently popularized functional food. All variety of foods in our day to day life needs some way of preservation mainly to reduce or stop spoilage, to make it available throughout a year, to maintain desired levels of nutritional properties for the longest possible time span and to make value added products. Amongst these, spoilage is the foremost reason for employing food preservation techniques. Spoilage or deterioration of food occurs during handling or due to mechanical, physical, chemical or microbial damage. Out of these, chemical and microbial damages are most frequent causes (Rahman, 1999; Mujumdar, 2004). Commonly employed methods for food preservation are freezing, vacuum packing, canning, preserving in syrup, food irradiation, adding preservatives and drying. One of the biggest advantages of dried foods is that they take much less storage space than canned or frozen foods. [1]

Drying is one of the oldest processes that has been using from ancient times. As per the change of generations drying process adopted various techniques by using basic science principles for various engineering applications. The fundamental concept that involves drying is removing moisture by applying heat energy. Drying has been using as a fundamental process in many industrial branches such as food, chemical, ceramics, pharmaceuticals, agricultural, biotechnology, wood processing industries etc. when it comes to food industries it is a necessary process to prolong the life of food products. Some of drying processes are convenient and economical to preserving foods of all variety. The traditional way of drying food products is sun-drying which is still using by people of India, some countries of Asian and African people.

1.2 Drying process

Drying is a complex operation involving transient transfer of heat and mass along with several rate processes [2]. Drying is the process that removing volatile substances (moisture) thermally to yield a solid product. These volatile substance presents as a bound moisture or unbound moisture in solids. Moisture which extracts a vapour pressure less than that of pure liquid is called as bound moisture. Unbound moisture extracts at equilibrium vapour pressure of pure liquid.

In a thermal drying, two processes occur simultaneously to the wet solid:

1. Energy transfer (in the form of heat mostly) from surrounding environment to evaporate the surface moisture
2. Internal moisture transfer to the surface of the solid and its subsequent evaporation due to process 1

Process 1: The removal of water (moisture) as vapour from the material surface, depends on the external conditions of temperature, air humidity and flow, area of exposed surface and pressure.

Process 2: The movement of moisture internally within the solid, is a function of the physical nature of the solid, the temperature and its moisture content. In a drying operation any one of these processes may be the limiting factor governing the rate of drying, although they both proceed simultaneously throughout the drying cycle.

Transport of moisture within the solid may occur by any one or more of the following mechanisms of mass transfer:

- Liquid diffusion: if the wet solid is at a temperature below the boiling point of the liquid
- Vapor diffusion: if the liquid vaporizes within material
- Knudsen diffusion: if drying takes place at very low temperatures and pressures
- Surface diffusion
- Hydrostatic pressure differences: when internal vaporization rates exceed the rate of vapor transport through the solid to the surroundings
- Combinations of the above mechanism. [2]

1.3 Drying mechanism

As mentioned above, moisture in a solid may be either unbound or bound. There are two methods of removing unbound moisture: evaporation and vaporization. Evaporation occurs when the vapor pressure of the moisture on the solid surface is equal to the atmospheric pressure. This is done by raising the temperature of the moisture to the boiling point. This kind of phenomenon occurs in roller dryers. Second, in vaporization, drying is carried out by convection, that is, by passing warm air over the product. The air is cooled by the product, and moisture is transferred to the air by the product and carried away. In this case the saturation vapor pressure of the moisture over the solid is less than the atmospheric pressure.

The drying behaviour of solids can be characterized by measuring the moisture content loss as a function of time. Products that contain water behave differently on drying according to their moisture content. Figure 1 shows stages of drying at constant drying conditions.

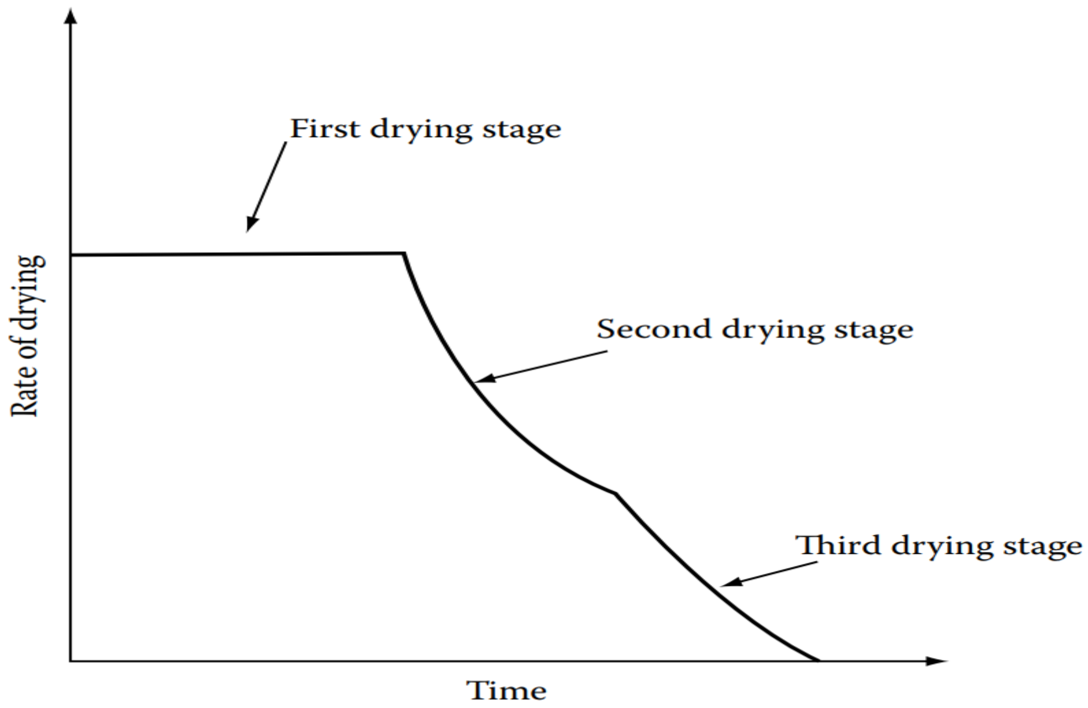

Figure 1. Typical rate of drying curve at constant drying conditions [2]

During the first stage of drying the drying rate is constant. The surface contains free moisture.

Vaporization takes place from there, and some shrinkage might occur as the moisture surface is drawn back toward the solid surface. In this stage of drying the rate-controlling step is the diffusion of the water vapor across the air–moisture interface and the rate at which the surface for diffusion is removed. Towards the end of the constant rate period, moisture must be transported from the inside of the solid to the surface by capillary forces and the drying rate may still be constant. When the average moisture content has reached the critical moisture content (X_{cr}), the surface film of moisture has been so reduced by evaporation that further drying causes dry spots to appear upon the surface. Since, however, the rate is computed with respect to the overall solid surface area, the drying rate falls even though the rate per unit wet solid surface area remains constant. This gives rise to the second drying stage or the first part of the falling rate period, the period of unsaturated surface drying. This stage proceeds until the surface film of liquid is entirely evaporated. This part of the curve may be missing entirely, or it may constitute the whole falling rate period.

In the second falling rate period or then third drying stage, the rate at which moisture may move through the solid as a result of concentration gradients between the deeper parts and the surface is the controlling step. The heat transmission now consists of heat transfer to the surface and heat conduction in the product. Since the average depth of the moisture level increases progressively and the heat conductivity of the dry external zones is very small, the drying rate is increasingly influenced by the heat conduction. The drying rate is controlled by diffusion of moisture from the inside to the surface and then mass transfer from the surface. During this stage some of the moisture bound by sorption is removed. As the moisture concentration is lowered by drying, the rate of internal movement of moisture decreases. The rate of drying falls even more rapidly than before and continues until the moisture content falls to the equilibrium value (X^*) for the prevailing air humidity and then drying stops. [2]

1.4 Heating methods

Convection, conduction and radiation are fundamental mechanisms used to supply the required heat for the drying.

1.4.1 Convection

Heat is supplied by heated air or gas flowing over the surface of the solid. Heat for evaporation is supplied by convection to the exposed surface of the material and the evaporated moisture carried away by the drying medium. Air (most common), inert gas (such as N_2 for drying solids wet with organic solvent), direct combustion gases, or superheated steam (or solvent vapor) can be used in convective drying systems. Such dryers are also called direct dryers. [2]

1.4.1.1 Drying medium

Drying medium are carriers of heat, in the case of convective drying.

- Air: Most common drying medium (preferred for the lower temperatures <200℃)
- Superheated steam: It also carries a humid air but with prevailing amount of the water vapours. It has greater heat transfer coefficient (preferred for the higher temperatures >200℃)

1.4.2 Conduction

Conduction or indirect dryers are more appropriate for thin products or for very wet solids. Heat for evaporation is supplied through heated surfaces (stationary or moving) placed within the dryer to support, convey, or confine the solids. The evaporated moisture is carried away by vacuum operation or by a stream of gas that is mainly a carrier of moisture. [2]

1.4.3 Radiation

Various sources of electromagnetic radiation with wavelengths ranging from the solar spectrum to microwave (0.2 m to 0.2 μm). Solar radiation barely penetrates beyond the skin of the material, which absorbs only a part of the incident radiation depending on its wavelength. Infrared radiation is often used in drying coatings, thin sheets, and films, for example (4–8 μm band). Radiation can be used to heat the solid volumetrically, thus reducing internal resistance to heat transfer. Energy is absorbed selectively by the water molecules and product gets drier by using less energy. [2]

1.5 Moisture content

Although determination of the moisture content of wet materials appears simple, the results obtained are often not sufficiently accurate. On selecting the techniques of moisture determination, one must consider the desired accuracy, the case of the procedure, the length of the investigation, and the complexity of the required instruments and equipment.

1.5.1 Direct methods

The direct methods consist essentially of determination of the moisture content of a sample by drying carried out in a drying oven with or without blow through of air, or by drying in a vacuum chamber or in a vacuum desiccator. The sample material must be prepared in every case in the following way. The material is disintegrated into pieces of known mass (4 to 5 g) is placed into a previously dried and weighed glass container, which is put into the drying chamber and dried at 105 °C.

1.5.2 Indirect methods

Under industrial conditions the moisture present in material must be determined by faster methods,

- moisture determination based on the change of the ohmic DC resistance, a measurement of the electrostatic capacitance, and a measurement of the loss in an AC field.
- Karl–Fischer analysis: based on the chemical reaction of iodine in the presence of water.
- Distillation method: in which moisture is determined by distillation with toluene.
- Extraction method: which is carried out with absolute ethanol.

These measurements are usually carried out under laboratory conditions. [2]

1.6 Drying of food products

Moisture removal from a material is an important part in food industries. Almost every food product is dried at least once in the stage of preparation.

1.6.1 Microbial damage

During harvesting and subsequent steps involved in processing, food products are prone to different kinds of damage involving mechanical, physical, chemical and microbial damage. Mechanical and physical damage can contribute to enhance the chemical and microbial damages [2]. Each microorganism has an optimum temperature for its growth. Each microorganism needs minimum quantity of water to grow. Microorganisms is one of the main reasons for food losses. There are three types of the microorganisms:

- Bacteria: unicellular micro-organism
- Yeast: kind of fungus
- Fungi: mycelium and sporocarp

It is common knowledge that the factors such temperature, pH, oxygen influence on the growth of the microorganisms in the product. One should accept the fact that most important factors in the controlling spoilage of the product is the water activity. [2]

1.6.2 Water activity

Water activity determines the equilibrium condition at the dried sample surface or at the interface between the moving free and bound water regions. Therefore, a_w determines the rate of diffusion processes inside the samples and the rate of the drying as soon as the free water is removed.

$$a_w = \frac{p^{"}}{p^{"}_{H_2O}} \qquad (1.6.2\text{-}1)$$

Where water activity (a_w) is defined as the ratio of the partial pressure ($p^{"}$) of water over the wet solid system to the equilibrium vapor pressure ($p^{"}_{H_2O}$) of water at the same temperature.

The low level of the water activity suppresses growth of the different kind of the microorganisms and prevents enzymatic reactions with oxidation. Table 1 shows the biochemical process inhibition that depends on the level of activity. [3]

Water activity level	Biochemical processes inhibition
$a_w < 0.60$	Absolute limit for the growth of any microorganism
$a_w < 0.70$	Practical limit for the growth of the mold
$a_w < 0.80$	Suppressed production of the mycotoxins
$a_w < 0.88$	Practical limit for yeast
$a_w < 0.90$	Suppressed growth of the pathogenic bacteria

Table 1. Water activity level [3]

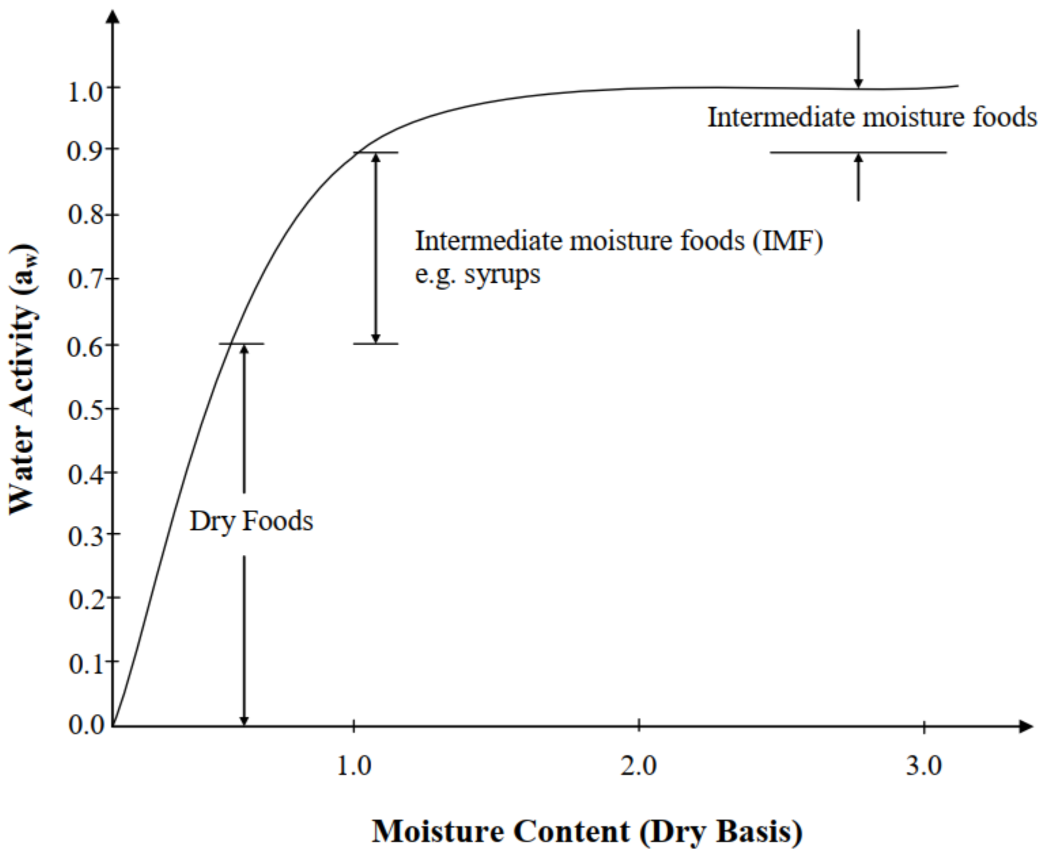

Figure 2. Water activity versus moisture content plot for different types of foods [2]

1.6.1 Product Quality Evolution

The quality attributes of a dried food product can be classified into physical, chemical, biological and nutritional. In general, improper processing conditions results in higher nutritional loss and poorer product quality.

1.6.1.1 Colour

Colour is perhaps the most important attribute, apart from product appearance, that will determine the level of acceptance by consumers. Colour pigments, reactions and enzymatic browning play significant roles in the colour changes of the product during drying. Very often temperature and pH play an important role during processing Evaluation of colour can be carried out by using destructive or by non-destructive methods. Destructive method is carried out by evaluating the extracted colour pigments spectrophotometrically or by using high performance liquid chromatography.

1.6.1.2 Texture

Structural collapse in food due to moisture removal from the food product results in significant changes in texture. This causes shrinkage and change in porosity of the dried product. Texture attributes such as hardness, springiness, chewiness, gumminess, cohesiveness and resilience can be determined by texture profile analyses.

1.6.1.3 Shrinkage

The measurement of shrinkage is carried out based on the displacement methods to determine its apparent volume. The greater difference between the density of the solvent and sample enables n-heptane to distinguish the finer difference of sample's weight between in the air and solvent.

1.6.1.4 Porosity

Porosity is a measurement of pore or empty spaces of a material to that of the total volume or simply it can be defined as the volume fraction of air in the food product.

1.6.1.5 Flavour

Flavour is the primary concern to consumers irrespective of the texture, shape and colour of a dried product. Flavour of food consists of various food aroma compounds that constitute the taste and odour of the food. Some flavour compounds are volatile, and these are carried away during moisture removal process. The change in shape and texture influence the microstructure of the food product and controls the release of flavour during processing and consumption. Flavour properties of a food product can be analyses via chemical analyses or sensory evaluation.

1.6.1.6 Shelf life

Storage and packaging play an important role in affecting the shelf life of a dried product. Typically, the optimum relative humidity for dried product storage is 55 – 70% at moisture content ranging from 2 to 20%. Packaging should be moisture proof and able to prevent the transfer of oxygen into the product and cause off flavour formation.

1.6.1.7 Antioxidants

Most fruits and vegetables contain various antioxidants which are beneficial to human health such as in lowering incidence of degenerative diseases i.e. cancer, arthritis, arteriosclerosis, heart diseases, inflammation, brain dysfunction. [1]

1.7 Classification of dryers

There are numerous schemes used to classify dryers [1]. Table 2 lists the criteria and typical dryer types,

Criterion	Types
Mode of operation	➢ Batch ➢ Continuous
Heat input	➢ Convection, conduction, radiation ➢ Adiabatic or nonadiabatic
State of material in dryer	➢ Stationary ➢ Moving, agitated, dispersed
Operating pressure	➢ Vacuum ➢ Atmospheric
Drying medium(convection)	➢ Air ➢ Superheated steam
Drying temperature	➢ Below boiling point ➢ Above boiling point ➢ Below freezing point
Relative motion between drying medium and drying solids	➢ Co current ➢ Counter current ➢ Mixed flow
Number of stages	➢ Single ➢ Multi stage
Residence time	➢ Short (< 1 minute) ➢ medium (1-60 minutes) ➢ long (>60 minutes)

Table 2. Basic classification on criteria [1]

Classification of dryers based on the mode of thermal energy input is perhaps the most useful since it allows one to identify some key features of each class of dryers.

1.7.1 Direct dryers

These are also known as convective dryers. About 85 percent of industrial dryers are estimated to be of this type despite their relatively low thermal efficiency caused by the difficulty in recovering the latent heat of vaporization contained in the dryer exhaust in a cost-effective manner. Hot air produced by indirect heating or direct firing is the most common drying medium. Drying gas temperatures may range from 50 ℃ to 400 ℃ depends on the material (of course this is general information and the temperature does not go so high for food products). Dehumidified air may be needed when drying highly heat-sensitive materials. [1]

1.7.2 Indirect dryers

This type of dryers involves supplying of heat to the drying material without direct contact with the heat transfer medium. heat is transferred from the heat transfer medium to the wet solid by conduction. Since no gas flow is presented on the wet solid side it is necessary to either apply vacuum or use gentle gas flow to remove the evaporated moisture so that the dryer chamber is not saturated with vapor. Heat transfer surfaces may range in temperature from – 40 ℃to about 300 ℃ (of course not for food products). Heat may also be supplied by radiation (using electric or natural gas-fired radiators) or volumetrically by placing the wet solid in dielectric fields in the microwave or radio frequency range. Since radiant heat flux can be adjusted locally over a wide range it is possible to obtain high drying rates for surface-wet materials. [1]

Figure 3 showing that classification of dryers based on the mode of operation and Figure 4 showing various feedstock for different dryers.

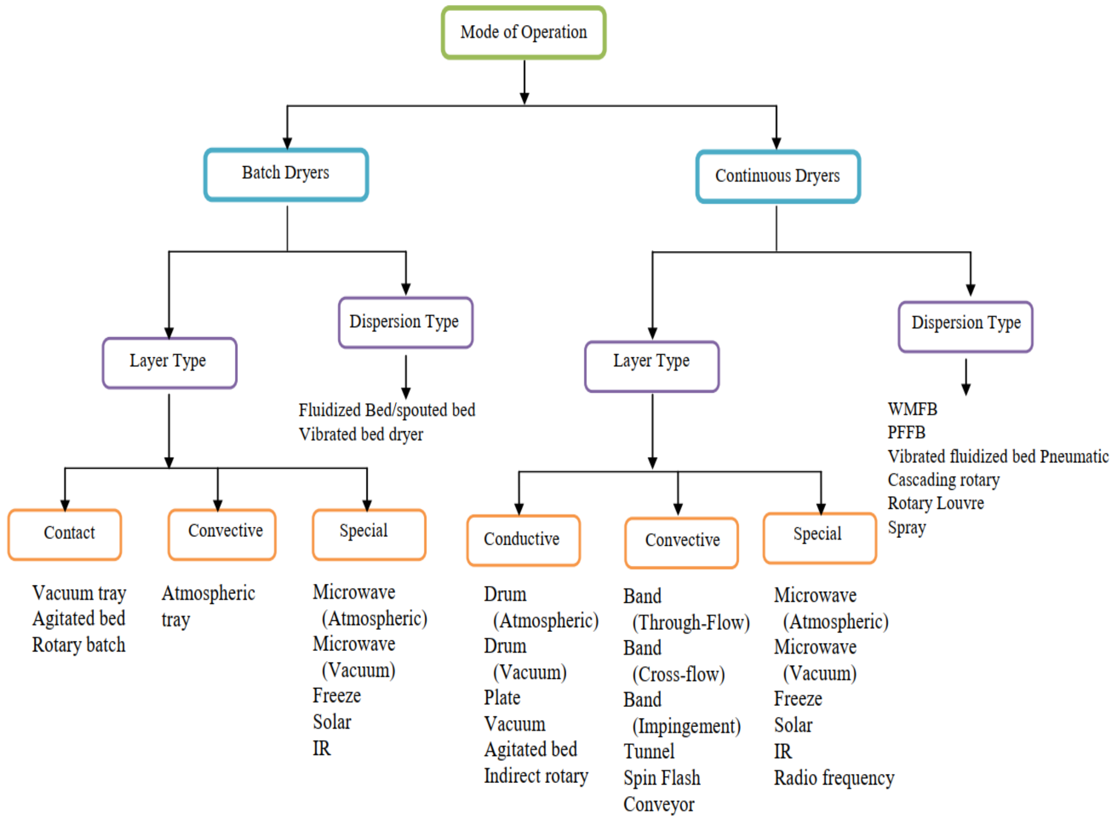

Figure 3. Classification of dryers [1]

Nature of Feed	Liquids			Cakes		Free-Flowing Solids					Formed
	Solution	Slurry	Paste	Centrifuge	Filter	Powder	Granule	Fragile crystals	Pellet	Fiber	Solids
Convective dryers											
Belt conveyor dryer							√	√	√	√	√
Flash dryer				√	√	√	√			√	
Fluid bed dryer	√	√		√	√	√	√		√		
Rotary dryer				√	√	√	√		√	√	
Spray dryer	√	√	√								
Tray dryer (batch)				√	√	√	√	√	√	√	√
Tray dryer (continuous)				√	√	√	√	√	√	√	
Conduction dryers											
Drum dryer	√	√	√								
Steam jacket rotary dryer				√	√	√	√		√	√	
Steam tube rotary dryer				√	√	√	√		√	√	
Tray dryer (batch)				√	√	√	√	√	√	√	√
Tray dryer (continuous)				√	√	√	√	√	√	√	√
Cone (batch)				√	√	√	√		√		
Thin-film contact		√	√	√	√	√	√		√	√	

Figure 4. Classification of dryers [1]

1.8 Convective drying kinetics

1.8.1 Drying experiments (Lumped approach)

To determine the drying rate, the mass of a sample placed in the airflow (constant temperature, humidity, and velocity) must be measured as a function of time. In order to obtain results that can be applied for scale-up, the following aspects must be considered. The sample must not be too small, and the conditions of drying must if possible be identical to the conditions anticipated in the industrial unit.

- The sample must be placed in a similar way in the laboratory unit
- The ratios of the drying surface to the non-drying surface must be identical
- The conditions of heat transfer by radiation must be similar
- The temperature and the moisture content of air and its velocity and direction must be identical with respect to the sample. [2]

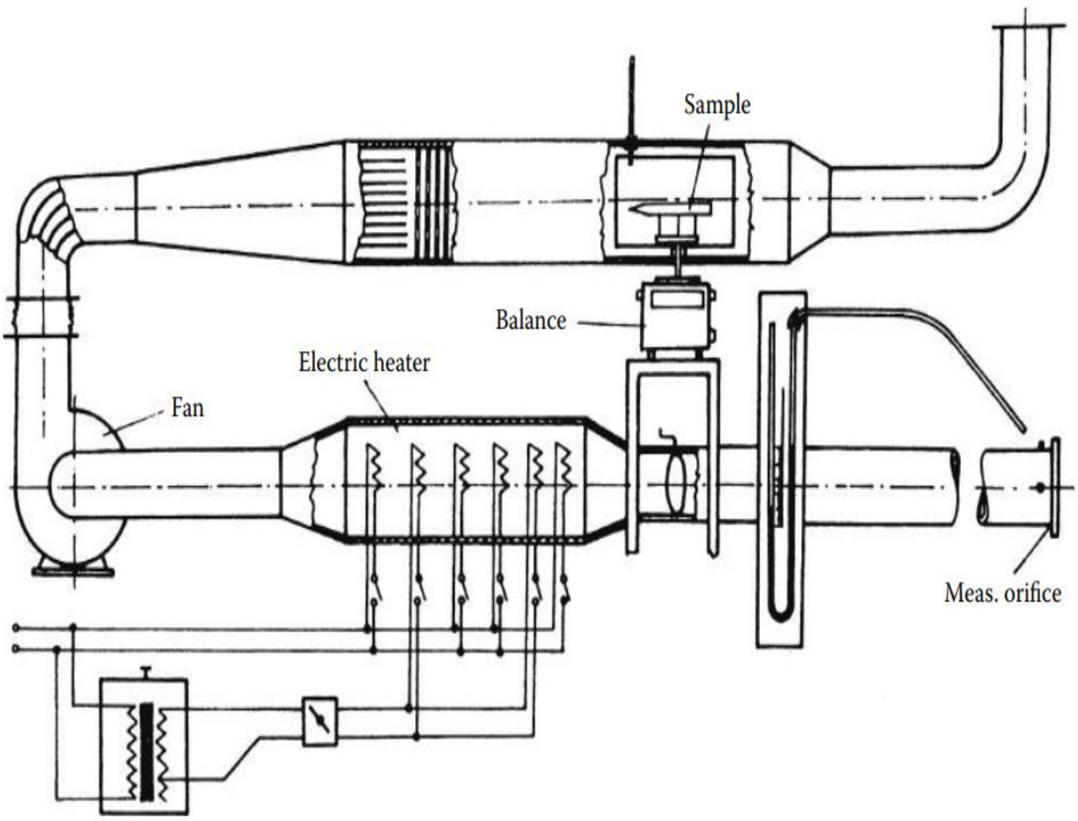

Figure 5. Convective drying apparatus [2]

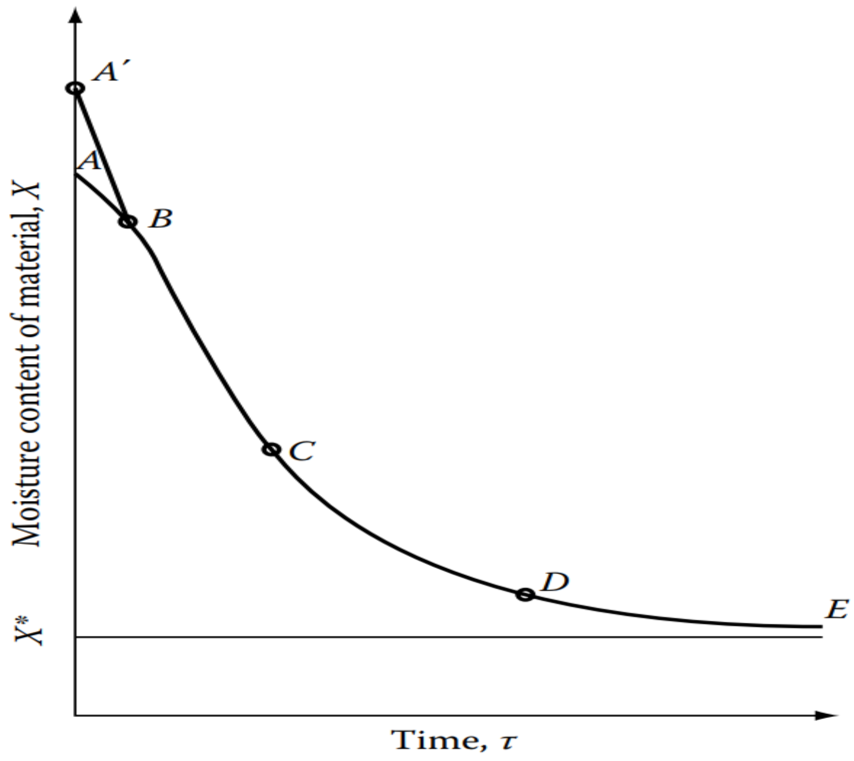

Figure 6. Batch, convection drying curve [2]

Moisture content (X),

$$M_{ws} = M_w + M_s \quad (1.8.1\text{-}1)$$

$$X = \frac{M_w}{M_s} = \frac{M_{ws} - M_s}{M_s} \quad (1.8.1\text{-}2)$$

Where M_{ws} is mass of wet solid, M_w is mass of water content, M_s is mass content of dry solid.

1.8.2 Moisture diffusivity

Diffusion in solids during drying is a complex process that may involve molecular diffusion, capillary flow, Knudsen flow, hydrodynamic flow, or surface diffusion. If we combine all these phenomena into one, the effective diffusivity can be defined from Fick's second law.

$$\frac{\partial X}{\partial t} = D_{eff} \nabla^2 X \quad (1.8.2\text{-}1)$$

Where,

D_{eff}: The effective moisture diffusivity ($m^2/2$)

X: The material moisture content (kg/kg db)

t: Time (s)

1.8.2.1 Simplified methods

Fick's equation is solved analytically for certain sample geometries under the following assumptions:

- Surface mass transfer coefficient is high enough so that the material moisture content at the surface is in equilibrium with the air-drying conditions.
- Air drying conditions are constant.
- Moisture diffusivity is constant, independent of material moisture content and temperature.

The analytical solution for slab, spherical, or cylindrical samples is used in the analysis. Several alternatives exist concerning the methodology of estimation of diffusivity using the above equations.

1.8.2.2 Regular Regime Method

The regular regime method is based on the experimental measurement of the regular regime curve, which is the drying curve when it becomes independent of the initial concentration profile. Using this method, the concentration-dependent diffusivity can be calculated from one experiment.

1.8.2.3 Numerical Solution (Regression Analysis Method)

If X_i and T_i are the experimental values of material moisture content and temperature, X_{ic} and T_{ic} are the corresponding calculated values using the mathematical model, then the relative deviations between experimental and calculated values.

The moisture diffusivity in solids is a function of both temperature and moisture content. The temperature dependence of diffusivity is adequately described by the Arrhenius equation,

$$D = D_0 \exp(-E/RT) \qquad (1.8.2.3\text{-}1)$$

Where,

D_0: Arrhenius factor (m2/s)

E: Activation energy for diffusion (kJ/kmol)

R is the gas constant (kJ/(kmol K))

T is the temperature (K). [2]

2 Literature searches

In this chapter, it is mostly discussed about convective drying processes of banana from different resources. Based on these data and laboratory equipment, which is in the department of process engineering, faculty of mechanical engineering, CTU in Prague basic experimental parameters for this thesis were selected.

2.1 Thin layer drying characteristics of kachkal banana

The present study [4] investigated the thin-layer drying characteristics of kachkal banana (Musa ABB) in a convective tray dryer with four different drying temperatures of 40, 50, 60 and 70 °C which exhibited falling rate period. The peel of banana represents 40% of the total weight of fresh banana. The bananas were cut into 4 mm thickness and placed in stainless steel trays Before starting the drying experiment, the initial moisture content of the peel was determined by hot air oven method which was found to be 85.47 % wet basis.

2.1.1 Drying kinetics

Mathematical modelling of the convective drying process employing diffusion theory can adequately described the profile of water distribution within the agricultural products to a solid of perfect geometry. Establishment of functional relationship between the diffusion coefficient and the moisture content is also required.

Equations were used for to express moisture ratio (MR) in dimensionless form

$$MR = (M_t - M_e) / (M_i - M_e) \quad (2.1.1\text{-}1)$$

The M_e values were neglected because the values were very small comparing to those values of M_i and M_t, therefore moisture ratio can be reduced to the following Equation.

$$MR = M_t / M_i \quad (2.1.1\text{-}2)$$

The drying data of MR versus drying time was analysed for nine thin-layer drying models given in figure 7 to select the best model to describe the thin layer drying curve of kachkal banana.

Model	Mathematical Equation	References
Lewis	MR = exp (-kt)	Doymaz (2005)
Page	MR = exp (-kt^n)	Page (1949)
Modified Page	MR = exp (-kt)^n	Yaldiz *et al.* (2001)
Henderson and Pabis	MR = a exp (-kt)	Doymaz (2004c)
Logarithmic	MR = a exp (-kt) + c	Togrul and Pehlivan (2002)
Two-Term Model	MR = a exp (-k_0t) + b exp (-k_1t)	Rahman *et al.* (1997)
Approximation of Diffusion	MR = a exp (-kt) + (1-a) exp (-kat)	Lahsasni *et al.* (2004)
Wang and Singh	MR = 1 + at + bt^2	Wang and Singh (1978)
Modified Page Equation II	MR = exp [-c (t/L_c^2)^n]	Doymaz (2005)

Figure 7. Mathematical models used for thin-layer drying of kachkal banana

2.1.2 Effective moisture diffusivity

Fick's second law for unsteady state diffusion Equation was used to model the moisture diffusivity of Kachkal banana.

$$\mathrm{MR} = \frac{\mathrm{Mt-Me}}{\mathrm{Mi-Me}} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2} exp\left(\frac{(2n+1)^2\pi^2 D_{eff}\, t}{4h_c^2}\right) \quad (2.1.2\text{-}1)$$

Neglecting the higher order terms, it can be written as

$$\mathrm{MR} = \frac{8}{\pi^2} exp\left(\frac{-\pi^2 D_{eff}\, t}{4h_c^2}\right) \quad (2.1.2\text{-}2)$$

Where h_c is characteristic dimension (volume/area), D_{eff} is effective moisture diffusivity ($m^2/2$) and t is time(s).

2.1.3 Results and discussion

- The effect of drying air temperature on drying time showed that increase in drying air temperature resulted in decrease in drying time. At 40 °C it took approximately 15 hours to reach the safe final moisture content and the same sample required only 3 hours at 70 °C to and 5 hours 30 min at 60 °C reach the same moisture value.
- The models were evaluated based on coefficient of determination (R^2) and the reduced chi-square (χ^2). The selection of best model to describe the drying behaviour of kachkal peel paste was based on the highest R^2 and lowest χ^2 values.
- The average value of χ^2 varied from 2.236 x 10^{-4} to 8.44 x 10^{-2} and value of R^2 varied between 0.806 to 0.998. For all mentioned thin-layer drying models, R^2 values were

greater than 0.924 except Page model, which showed the minimum R^2 value of 0.806. It can be concluded that modified Page model was found to be the best fit model with least χ^2 value of 2.236 x 10^{-4} and highest R^2 value of 0.998, thus modified Page model was selected as suitable model to represent the thin-layer drying behaviour of kachkal peel.

- The highest diffusivity value of 7.80 x10^{-9} m^2/s was observed at 70 °C and the lowest D_{eff} value of 2.05 x10^{-9} m^2/s was observed at 40 °C. D_{eff} found in this study were in the range of 10^{-9} to 10^{-8} m^2/s.

2.2 Thin layer drying of mango slices

The drying experiments [5] were performed in a convective air oven at temperature of 60, 70 and 80 °C with constant sample thickness (3 mm). The oven is consisted of heating unit, temperature control unit, drying chamber and centrifugal fan that has a fixed air velocity of 0.5 m/s.

- Henderson and Pabis model is the first term of a general series solution of Fick's second law. The model was used to predict the drying characteristics of corn (Henderson and Pabis, 1961) and it is

$$MR = A \exp(-kt) \tag{2.2-1}$$

- Newton (Lewis) model is a special case of the Henderson and Pabis Model where the intercept is unity and is used to describe the drying of barely (Bruce, 1985) and grape seed (Roberts et al., 2008) and it is

$$MR = \exp(-kt) \tag{2.2-2}$$

- Page model is an empirical modification of Newton (Lewis) model to overcome its shortcoming it was successfully used to describe the drying characteristics of some agricultural products (Singh et al., 2006; Hassan-Beygi et al., 2009; Doymaz and Ismail, 2011) and it is

$$MR = \exp(-kt^n) \tag{2.2-3}$$

- Non-linear regression analysis was used to evaluate the parameters of the selected models.

2.2.1 Effective moisture diffusivity

Fick's second law for unsteady state diffusion Equation was used to model the moisture diffusivity of Kachkal banana.

$$\mathrm{MR} = \frac{\mathrm{Mt - Me}}{\mathrm{Mi - Me}} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\,exp\left(\frac{(2n+1)^2\pi^2 D_{eff}\, t}{4h_c^2}\right) \qquad (2.2.1\text{-}1)$$

Neglecting the higher order terms, it can be written as

$$In\ \mathrm{MR} = In\frac{8}{\pi^2} - \left(\frac{\pi^2 D_{eff}\, t}{4\boldsymbol{h_c^2}}\right) \qquad (2.2.1\text{-}2)$$

Where h_c is characteristic dimension (volume/area), D_{eff} is effective moisture diffusivity ($m^2/2$) and t is time(s).

2.2.2 Results and discussion

- The time required to reduce the moisture content of mango slices from 82.5% (wb) to a final 9 % (wb) were 3, 5 and 7 hours at 80 °C,70 °C and 60° C respectively.
- It was observed that the main factor influencing drying kinetics was the drying temperature.
- The diffusivity values were found to be 4.97 x 10^{-10}, 6.79 x 10^{-10} and 10.83 x 10^{-10} m^2/s at 60, 70 and 80 ℃ respectively. Effective diffusivity values for mango slices increases greatly with increasing drying air temperature.
- Page model was found to be the most suitable model for describing the thin-layer drying characteristics of mango slices.
- Temperature and time influence, falling rate period and diffusion phenomenon similar in drying of banana slices.

2.3 Air-drying behavior of Dwarf Cavendish and Gros Michel banana slices

This journal [6] describes air-drying behaviour of untreated, Sodium bisulfite ($NaHCO_3$) and ascorbic/citric acid treated Dwarf Cavendish and Gros Michel banana slices by varying temperatures from 40 ℃ to 70 ℃. The bananas were hand peeled and sliced into 2 mm thickness with a knife on a polyethylene cut board.

- Banana slices from each variety were divided into three groups. The first group comprised of intact banana slices (untreated slices). The second group slices were kept in 0.1 % ascorbic acid/citric acid (1:1) mixture for 1 min (acid treated slices). The third group samples were dipped into 1% sodium bisulphite solution for 2 min, slices were rinsed in distilled water for 30 s, wiped with tissue paper, and brought to the experiment.
- The initial moisture content of the banana slices was determined by drying 5 g of pureed sample at 105 °C until a constant mass was reached. The initial moisture content, which was between 4.0 and 4.5 kg/kg db for both Cavendish and Michel varieties.
- The average velocity of the air approaching to the slice was 3.3 m/s, and it varied between 3.1 and 3.6 m/s as measured by an anemometer.

2.3.1 Equations used

$$R = -\frac{M_S}{A}\frac{dX}{dt} \quad (2.3.1\text{-}1)$$

$$\frac{\partial X}{\partial t} = D\frac{\partial^2 X}{\partial x^2} \quad (2.3.1\text{-}2)$$

$$X = X_0\text{, } t = 0\text{, } x = x \quad (2.3.1\text{-}3)$$

$$X = X_e\text{, } t = 0\text{, } x = h/2 \quad (2.3.1\text{-}4)$$

$$\frac{dX}{dt} = 0, t = t, x = 0 \quad (2.3.1\text{-}5)$$

$$X^*(t) = \frac{\bar{X}(t) - X_{eq}}{X_0 - X_{eq}} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}exp\left(-\frac{(2n+1)^2\pi^2}{4}F_0\right) \quad (2.3.1\text{-}6)$$

Fourier number is Dt/h_c^2 , For long drying times, e.g. $F_o > 0.1$, the first term of Eq. (2.3.1-6) is good enough for estimating the average moisture content in the infinite slab (Geankoplis, 1993).

$$X^* = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 Dt}{h^2}\right) \quad (2.3.1\text{-}7)$$

The relative magnitudes of D and k determine the relative effectiveness of the internal and surface moisture transfers on the process that can be checked using the Biot number(kh_c/D)

If Bi > 10, the internal transfer is dominant, If Bi < 0:1, the surface moisture transfer is dominant, the process is controlled by the air at the material surface. Throughout the drying, temperature assessed by a linearized Arrhenius equation.

2.3.2 Results and discussion

- Banana slices were white-yellowish at the beginning and developed a yellow-brownish colour in the course of the drying.
- The discoloration decreased with increasing temperature implying an enzymatic character of the browning. Under the same conditions, the pre-treated slices exhibited less discoloration than the untreated slices, and the sulphite treatment caused less browning than the acid treatment.
- The variety, temperature, and pre-treatment did not affect the shape of the banana slices during the drying.
- Effect of the heat transfer on the drying compared to the mass transfer was assumed negligible due to modified Lewis number estimated greater than 60.
- Diffusion equation for an infinite slab for a Fourier number greater than 0.1. In all conditions the equation fitted the process well. The effective moisture diffusivity (D) increased with increasing temperature between 40 °C and 70 °C in untreated samples. It increased between 40 °C and 60 °C, and decreased at 70 °C in the pretreated samples probably due to case hardening and starch gelatinization above 60 °C. It was estimated to be of the order of 10^{-11} and 10^{-10} m^2/s.

2.4 Drying description of cylindrical pieces of bananas

This article [7] describes about drying of cylindrical pieces of bananas by using analytical solutions of the diffusion equation with boundary conditions of the first and third kind.

2.4.1 Diffusion equation

Two-dimensional diffusion equation with symmetry in relation to the y-axis

$$\frac{\partial X}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(rD\frac{\partial X}{\partial r}\right) + \frac{\partial}{\partial y}\left(\frac{\partial X}{\partial y}\right) \qquad (2.4.1\text{-}1)$$

Where X is the moisture content in dry basis, D is the effective mass diffusivity, t is the time, r and y are coordinates of position.

2.4.1.1 Model 1: Boundary condition of the third kind

Liquid diffusion with convective boundary condition was one of the three models used to describe the drying process (model 1). The boundary condition of the third kind, also called Cauchy boundary condition, is defined by (Silva et al., 2012b).

$$-D\frac{\partial X(r,y,t)}{\partial r}|_{r=R} = h\left[X(r,y,t)|_{r=R} - X_{eq}\right] \quad (2.4.1.1\text{-}1)$$

$$-D\frac{\partial X(r,y,t)}{\partial r}||_{r=\pm L/2} = h\left[X(r,y,t)|_{r=\pm L/2} - X_{eq}\right] \quad (2.4.1.1\text{-}2)$$

Where h is the convective mass transfer coefficient and X_{eq} is the equilibrium moisture content in dry basis. Eq. (2.4.1.1_1) refers to an infinite cylinder with radius R while Eq. (2.4.1.1_2) refers to an infinite slab with thickness L. The composition of these two simple geometries generates the finite cylinder. In these two equations it was imposed the same value h, which means same resistance to the moisture transport in every surface.

2.4.1.1.1 Analytical solution

To solve above equations analytically, few assumptions were followed

- the dimensions of the finite cylinder do not vary during drying
- the initial distribution of X is uniform
- diffusion is the only transport mechanism inside the cylinder
- the solid is considered homogeneous and isotropic
- the effective mass diffusivity does not vary during drying
- the convective mass transfer coefficient is constant during drying
- drying is considered under isothermal conditions.

$$X_{(r,y,t)} = X_{eq} - \left(X_{eq} - X_0\right)\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} A_{n,1}\, A_{m,2}\, J_0\,\left(\mu_{n,1}\frac{r}{R}\right)\cos\left(\mu_{n,2}\frac{y}{L/2}\right) \times exp\left[\left(-\frac{\mu_{n,1}^2}{R^2}\frac{\mu_{m,2}^2}{(L/2)^2}\right)Dt\right] \quad (2.4.1.1.1\text{-}1)$$

$$A_{n,1} = \frac{2Bi_1}{J_0(\mu_{n,1})(Bi_1^2+\mu_{n,1}^2)} \quad (2.4.1.1.1\text{-}2)$$

$$A_{m,2} = (-1)^{m+1} \frac{2Bi_2\left(Bi_1^2+\mu_{n,2}^2\right)^{1/2}}{(\mu_{n,2})(Bi_2+Bi_2^2+\mu_{n,1}^2)} \quad (2.4.1.1.1\text{-}3)$$

Bi_1 and Bi_2 are the mass transfer Biot numbers for the infinite cylinder and infinite slab,

$$Bi_1 = \frac{hR}{D} \quad (2.4.1.1.1\text{-}4)$$

$$Bi_2 = \frac{h(L/2)}{D} \quad (2.4.1.1.1\text{-}5)$$

$$Bi_2 = \frac{Bi(L/2)}{R} \quad (2.4.1.1.1\text{-}6)$$

$$\frac{J_0(\mu_{n,1})}{J_1(\mu_{n,1})} = \frac{\mu_{n,1}}{Bi_1} \quad (2.4.1.1.1\text{-}7)$$

$$cot\, \mu_{m.2} = \frac{\mu_{m,2}}{Bi_2} \quad (2.4.1.1.1\text{-}8)$$

$$\bar{X}(t) = \frac{1}{V}\int X\,(r,y,t)\,dV \quad (2.4.1.1.1\text{-}9)$$

$$\bar{X}(t) = X_{eq} - \left(X_{eq} - X_0\right)\sum_{n=1}^{\infty}\sum_{m=1}^{\infty} B_{n,1}\, B_{m,2} \times exp\left[\left(-\frac{\mu_{n,1}^2}{R^2}\frac{\mu_{m,2}^2}{(L/2)^2}\right)Dt\right] \quad (2.4.1.1.1\text{-}10)$$

$$B_{n,1} = \frac{4Bi_1^2}{(\mu_{n,1}^2)(Bi_1^2+\mu_{n,1}^2)} \quad (2.4.1.1.1\text{-}11)$$

$$B_{m,2} = \frac{2{Bi_2}^2}{(\mu_{n,2}^2)(Bi_2+Bi_2^2+\mu_{n,1}^2)} \quad (2.4.1.1.1\text{-}12)$$

$$X^*(t) = \frac{\bar{X}(t)-X_{eq}}{X_0-X_{eq}} = \sum_{n=1}^{\infty}\sum_{m=1}^{\infty} B_{n,1}\, B_{m,2} \times exp\left[\left(-\frac{\mu_{n,1}^2}{R^2}\frac{\mu_{m,2}^2}{(L/2)^2}\right)Dt\right] \quad (2.4.1.1.1\text{-}13)$$

2.4.1.1.2 Determination of the process parameters

In order to determine D and h for an experimental dataset, the algorithm developed by Da Silva et al. (2010) will be adapted for a finite cylinder. The objective function to be minimized is given by (Bevington and Robinson, 1992; Taylor, 1997).

$$\chi^2 = \sum_{i=1}^{N_p}\left[\bar{X}_i^{exp} - \bar{X}_i^{ana}(D, Bi_1)\right]^2 \frac{1}{\sigma_i^2} \quad (2.4.1.1.2\text{-}1)$$

2.4.1.1.3 Arrhenius-type equations

In order to relate the effective mass diffusivities D and the drying temperatures T, an Arrhenius-type function can be used (Hii et al., 2009; Nastaj and Witkiewicz, 2009; Da Silva et al., 2012).

$$D = D_0\, exp\left[-\frac{E_a}{R(T+273.15)}\right] \qquad (2.4.1.1.3\text{-}1)$$

$$h = A\, exp\left[-\frac{B}{(T+273.15)}\right] \qquad (2.4.1.1.3\text{-}2)$$

Where A and B are fitting parameter

2.4.1.2 Model 2: Boundary condition of the first kind

Model 2 is two-dimensional, but the external resistance to the moisture transport is neglected. Consequently, the boundary condition is of the first kind. In this case, supposing that Bi_1 and Bi_2 are considered infinite. According to Da Silva et al. (2012), for small mass transfer Biot numbers, a few terms of the series are enough for obtaining results with negligible truncation errors.

2.4.1.3 Model 3: Series represented by the first term

Model 3 is one-dimensional, with no external resistance and the finite cylinder is considered an infinite slab. In this case, Eq. (2.4.1.1.1_13) is written as follows (Nguyen and Price, 2007; Fernando et al, 2011)

$$X^* = \frac{8}{\pi^2}\exp[-\frac{\pi^2 Dt}{L^2}] \qquad (2.4.1.3\text{-}1)$$

2.4.2 Results and discussion

Models 2 and 3 present statistical indicators which can be considered very poor in the simulation of the drying kinetics of banana pieces. Therefore, such models should be discarded in the description of the process. Model 1 presents results in the determination of the process parameters, which are compatible with values found in the literature for similar products.

2.5 Mathematical models to describe thin-layer drying

- In this article [8], several empirical models were selected to simulate experiments of thin layer drying accomplished with whole bananas at temperatures of 40 ^{0}C, 50 ^{0}C, 60 ^{0}C and 70 ^{0}C.
- Two main groups of models are used in this journal. The first group corresponds to the empirical models and second one corresponds to the diffusion models.

- Among the six empirical models investigated in this study, the worst results were obtained with Wang and Singh, Lewis and Henderson, Pabis and the Peleg model reasonably described the processes.

2.6 Determination of effective moisture diffusivity and assessment of quality

2.6.1 Material preparation

In this article [9] bananas were peeled and sliced into 3 mm thickness with a slicing machine. The sliced bananas were pre-treated by dipping them in 0.1 g per 100 ml ascorbic acid solution for 1 min to prevent enzymatic browning reaction.

2.6.2 Drying procedure

Drying was performed in duplicate at the drying air temperatures of 70 ^{0}C, 80 ^{0}C, 90 ^{0}C and 100 ^{0}C and at the superficial air velocity of 1.3 m/s. As observed from the experiments, the deviation of moisture content from the two experiments was very small. The samples were dried to about 0.04 kg/kg db. In order to follow moisture evolution, moisture loss from the samples was determined throughout the drying period by weighing them every 5 min using an electronic balance.

2.6.2.1 Shrinkage measurement

$$\text{Diameter Shrinkage} = D/D_0$$

$$\text{Thickness Shrinkage} = L/L_0$$

D is the sample diameter of dried sample (mm), D_0 is the sample diameter before drying (mm), L is the dried sample thickness (mm), L_0 is the sample thickness before drying (mm).

2.6.3 Results and discussion

- It was found that the changes of moisture content with time were not different amongst two diameter sizes.
- The shrinkage mainly occurred in the axial direction of banana slices.

- high-temperature drying produced high porous structure of dried banana slices and the value of hardness decreased so it is better to use low temperatures.

2.7 Diffusion coefficient estimation difficulties

The research [10] object is carrot slices. Before the experiment execution carrots were washed under running water, wiped and cut into slices with 15 mm thickness. The carrots were not peeled and blanched. To obtain the experimental data the carrot samples were dried at three constant temperatures: 60, 80 and 90 ^{0}C. Each sample contains carrot slices that were imposed in a single layer on an individual tray with a perforated base.

The diffusion coefficient values that were calculated by the simplified formula and formula with 10 terms of series. It can be concluded that the diffusion coefficient values differ slightly and exhibit the same low changes of values.

- The first term of series in calculation of the diffusion coefficient it does not depend on the drying time, but on the drying product moisture.
- For approximate calculation of the diffusion coefficient value a simplified formula can be used. If the study requires highest precision, a series formula with a larger number of terms should be used at small experiment times.

2.8 Experimental setup of an air source heat pump for drying banana chips

- In this article [11] Drying with a heat pump (HP) is recommended as an energy efficient technology because it can reduce energy consumption with ensuring the product quality. the major advantages of a heat pump dryer (HPD) for fruits drying.
- Higher energy efficiency due to the refrigeration system and the recovery of the exhausted hot air to recycle and reduce wasted energy.
- Drying at low temperature can improve quality.
- With the applications of sensors and advanced controllers, it is possible to control the drying temperature, relative humidity and air flow rate.
- There are some other significant works can be done in the future work to make the system can be used successfully: varying the air velocity, testing the closed drying system, electrical consumption, full load of the drying chamber, changing the

refrigerant amount in the HP system and optimizing the parameters. It is better to use closed heat pump system instead of open system for better efficiency.

Figure 8. Experimental set up [11]

Figure 9. Drying chamber [11]

From above literatures, with recommendation of thesis supervisor suitable parameters were selected for convective drying experiments. As a basis step thickness of banana 4 mm was selected, which is convenient to cut and place on drying chamber. When it comes to journal [6], they found best results at the temperature 60 °C and approaching velocity 3.3 m/s for different treatments with plane orientation. This thesis was highly influenced by journal [6].

Temperature 60 °C, working velocity 3.3 m/s, thickness of banana samples 4 mm, type of treatments (untreated and citric acid treatment) were selected as suitable parameters for laboratory experiments. In this present thesis part orientation was main factor, which was deeply discussed in fourth chapter experimental part.

For analysis of drying kinetics, it is necessary to apply the proper equations for mass transfer. Literature search provided me suitable one for mass transfer.

From literature [6], it was notable that effective moisture transfer (D_{eff}) of banana at 60 °C estimated to be of the order of 10^{-11} and 10^{-10} m^2/s for different treatments. From book [1], it was 3.0 x 10^{-13} to 2.1 x 10^{-10} for different types of banana at temperature range 20-40 °C and moisture content in the range of 0.01 to 3.5 kg/kg db.

It is necessary to analyse velocity field around the samples, which is difficult to know during experiments. CFD simulations makes easy of this process. Next chapter describes velocity field analysation around samples.

3 CFD simulation

This chapter will provide the analysis of air flow around banana slices in the drying chamber. It includes consideration both plane and vertical orientation of the banana slices in drying chamber. In order to simulate the behaviour of the velocity field of drying air simulations ware performed in turbulent flow region. The simulation was done iteratively until an acceptable convergence of the results is reached.

3.1 Introduction

CFD is a branch of fluid mechanics and by uses of the applied mathematical modelling, numerical method and software tools provides the prediction of fluid flow, heat, mass and momentum transfer, phase change, chemical reactions, mechanical movement, stress or deformation of solid structures. [3]

CFD, as a tool of research for enhancing the design process and understanding of the basic physical nature of fluid dynamics can provide benefits to the food processing industry in many areas, such as drying, sterilisation, mixing, refrigeration and other application areas. In the past, few years' great development has taken place in these areas. [3]

Drying is a common food manufacturing process. The drying rate is a strong function of air flow or air velocity. Therefore, it is of great importance to know the air flow and velocity in the drying chamber, thus leading to know the areas of adequate air velocities for proper drying. However, airflow and air velocity are difficult to measure during operation because several sensors are needed to be placed at various directions of airflow and locations. Since there are some difficulties in modelling the complex phenomena, especially the gas turbulence, CFD is a powerful tool to aid the prediction of drying process. [3]

3.2 Modelling

The actual geometry model was designed in CATIA V5, according to the parameters (shown in following figures of the chamber dryer that used in experimental part. The CFD simulation of drying process was analysed in using ANSYS FLUENT.

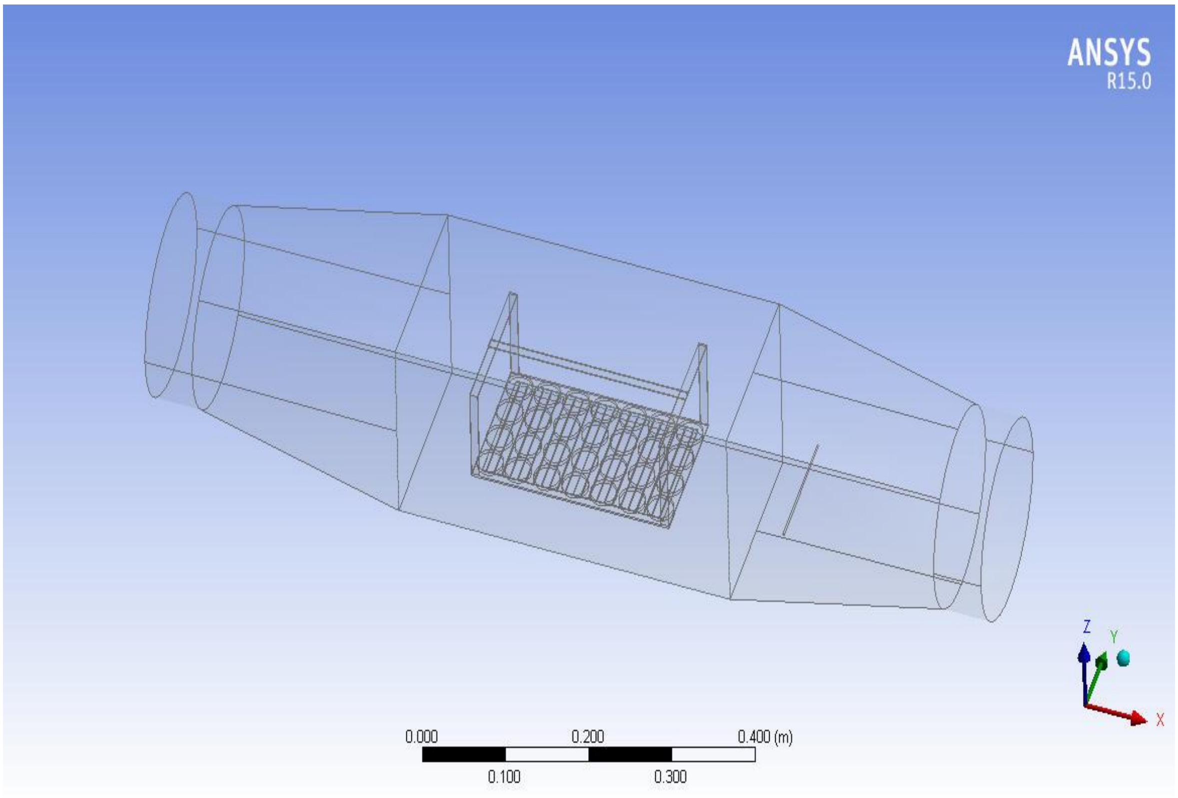

Figure 10. Model of drying chamber with single layer plane arrangement

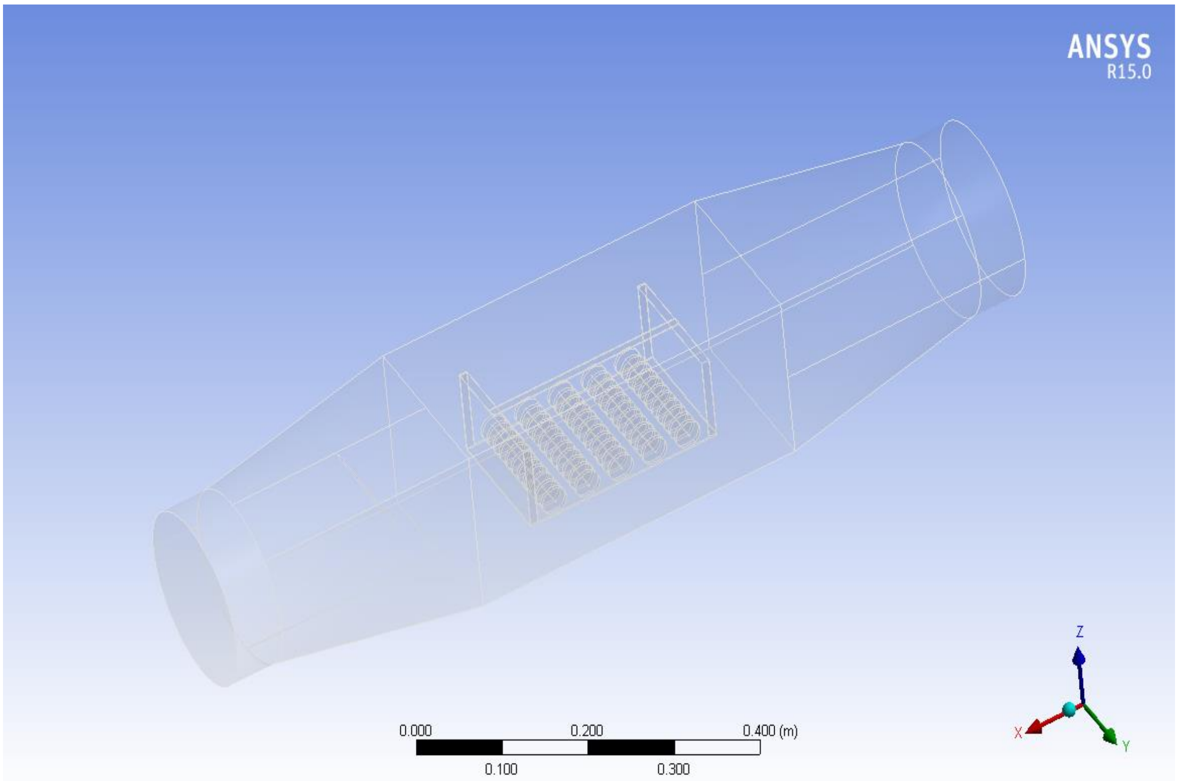

Figure 11 Model of drying chamber with single layer vertical arrangement

3.3 Meshing

A hexahedral mesh was created in all the models. Hex (or quad) meshes generally work better (i.e., more accurate) for wall-bounded flows since we can maintain orthogonal grids in the wall normal direction. This is a consequence of the better accuracy of the hex elements since the angle between faces can be kept close to 90-degrees. Aside from "numerical" efficiency, there is also a "computational" efficiency factor. Structured grids with hex or quad mesh (curvilinear) can be implemented a bit easier and usually execute quite a bit faster than algorithms that support unstructured [12].

Name	Plane arrangement	Vertical arrangement
No of Elements	873670	952094
Total nodes	170706	175959

Table 3. Mesh statistics

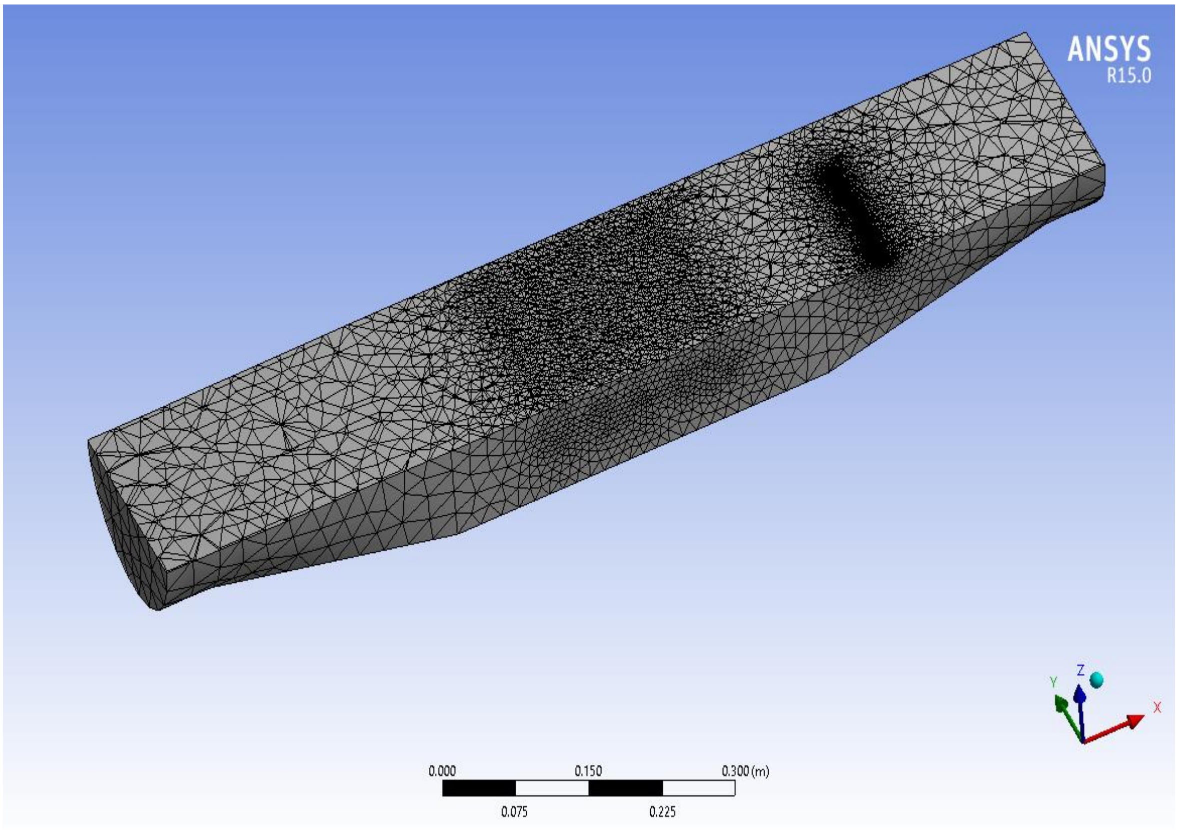

Figure 12. Sectional view of vertical arrangement meshed model

3.4 Flow Model

To identify which flow model fits to the here presented air flow it is necessary to estimate the Reynolds number *Re* which is an indicator whether the flow inside the chamber is laminar or turbulent. The Reynold number in a pipe is defined as

$$Re_h = \frac{D_h u}{v} \quad (3.4\text{-}1)$$

where D_h is the hydraulic diameter in [m] = 0.032 m

u is mean velocity of the fluid in [m/s] = 3.3 m/s

v the kinematic viscosity of the fluid in [m^2/s] = 18.86 x10^{-6} m^2/s at 60°C

$Re_h = \frac{0.032*3.3}{18.86*10^{-6}} = 5599$ > 4000

laminar flow occurs when Re_h < 2300 and turbulent flow occurs if Re_h > 4000. Therefore, we can conclude that the flow in the channel is turbulent.

3.4.1 Turbulent Model

For the modelling of the turbulent flow of the air through the drying chamber the standard $k - \mathcal{E}$ model was used. It is the most widely used engineering turbulence model for industrial applications. The model is robust and has a good compromise between accuracy and computational costs. This model is based on the assumptions that the flow is “fully turbulent and the effects of molecular viscosity are negligible". The transport equations are based on the equation (3.4.1-1) for the turbulent kinetic energy *k* and the equation (3.4.1-2) for the rate of its dissipation Ɛ,

$$\frac{\partial}{\partial t}(pk) + \frac{\partial}{\partial x_i}(pku_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon - Y_m + S_k \quad (3.4.1\text{-}1)$$

$$\frac{\partial}{\partial t}(p\varepsilon) + \frac{\partial}{\partial x_i}(p\varepsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}(G_k + C_{3\varepsilon}G_b) - C_{3\varepsilon}\rho\frac{\varepsilon^2}{k} + S_\varepsilon \quad (3.4.1\text{-}2)$$

where G_k is the generation of turbulence kinetic energy due to the mean velocity gradients, G_b is the generation of turbulence kinetic energy by buoyancy, Y_m represents the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate. The turbulent viscosity μ_t is computed by

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon} \tag{3.4.1-3}$$

The variables S_k and S_ε are user-defined sources or sinks and the in ANSYS Fluent pre-defined constants are

$C1_\varepsilon$ = 1.44, $C2_\varepsilon$= 1.92, C_μ = 0.09, σ_k = 1.0, σ_ε = 1.3

which are empirically obtained constants from experiments. [13]

3.5 Boundary conditions

The boundary conditions for the calculations were determined considering the measurements directly from the laboratory dryer.

Physical parameters	Notes
Fluid	Air
Density of air	1.125 kg/m^3
Velocity of air at inlet	3.3 m/s
Temperature in drying chamber	333.15 K
Laboratory temperature	193.15 K

Table 4. Boundary conditions

Inlet, outlet of the drying chamber was shown in figure 13. Air was entering through inlet (closest one to thermometer) at the velocity of 3.3 m/s which was indicated left side in figure and leaving through outlet (from right side).

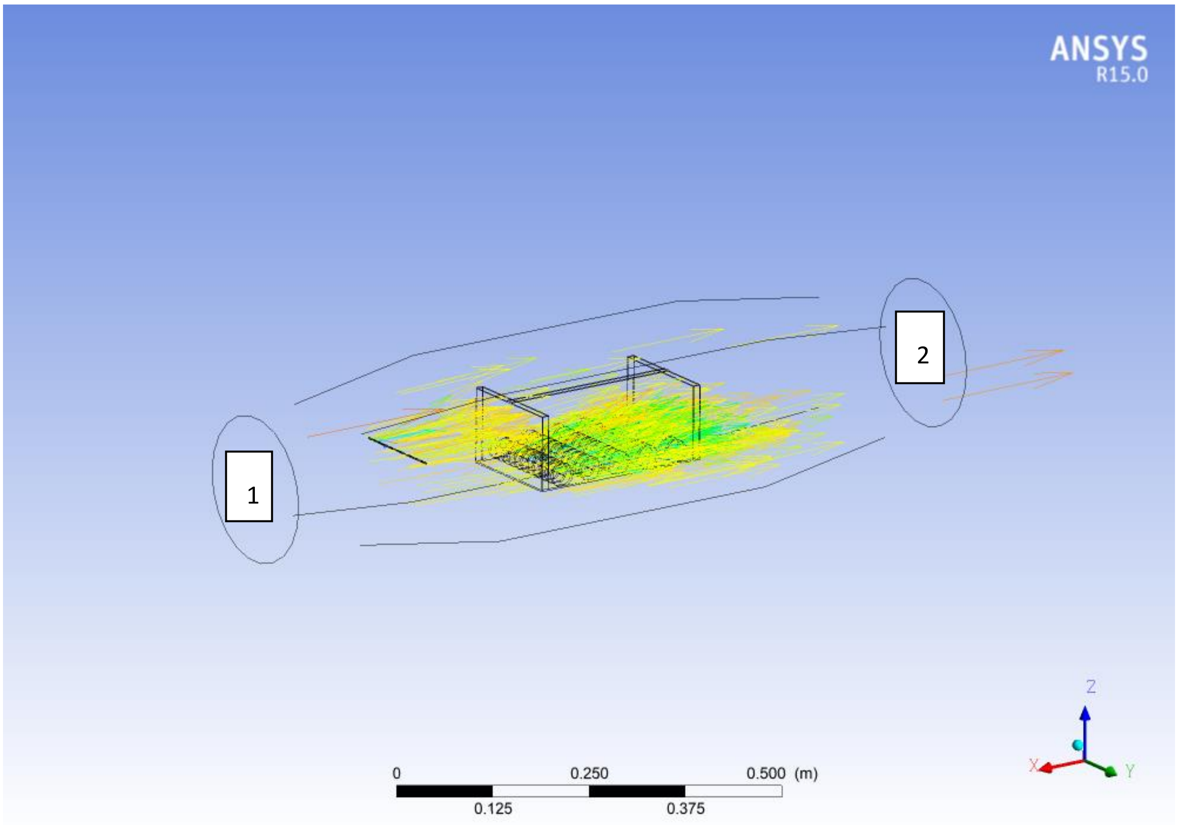

Figure 13. Air flow direction in drying chamber, 1 – Inlet, 2 – Outlet

3.6 Results and discussion

3.6.1 Single layer plane arrangement

3.6.1.1 Acceptable convergence

To reach acceptable convergence iteration process done by 7000 times, in which 3000 were first order iterations 4000 by second order.

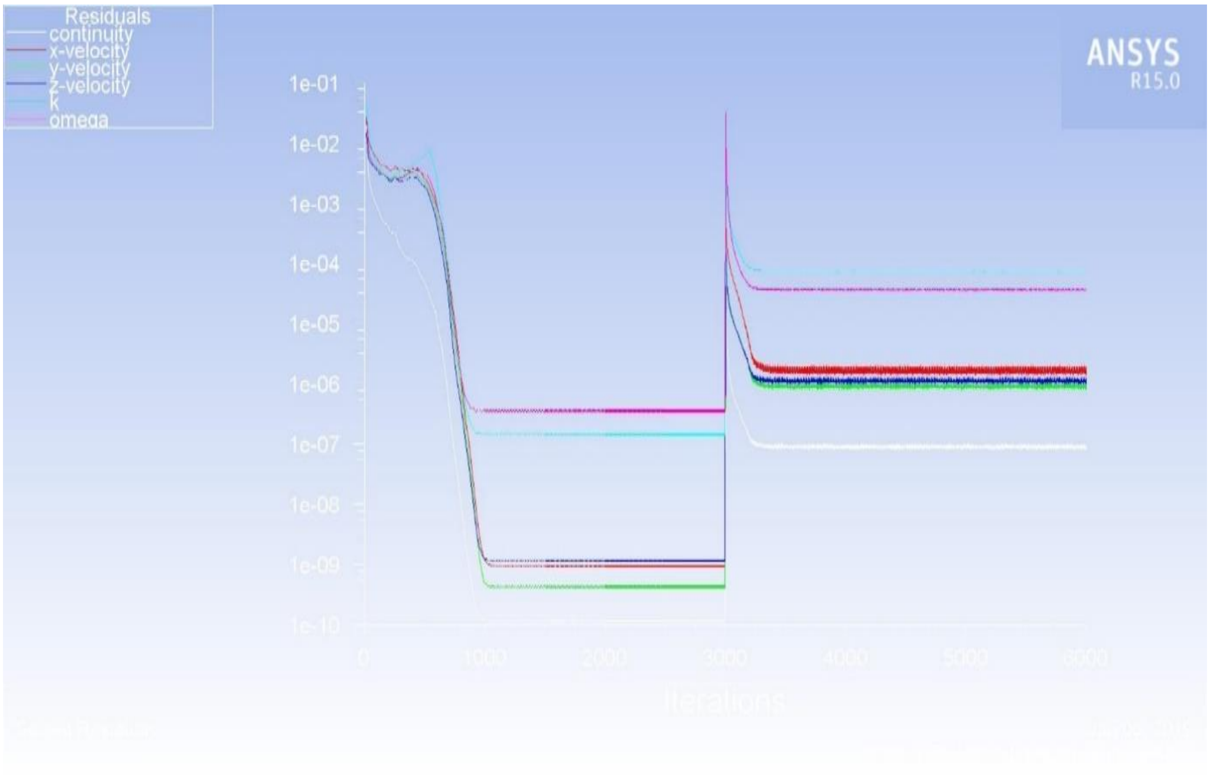

Figure 14. Curves for single layer plane arrangement

3.6.1.2 Velocity fields at different sections

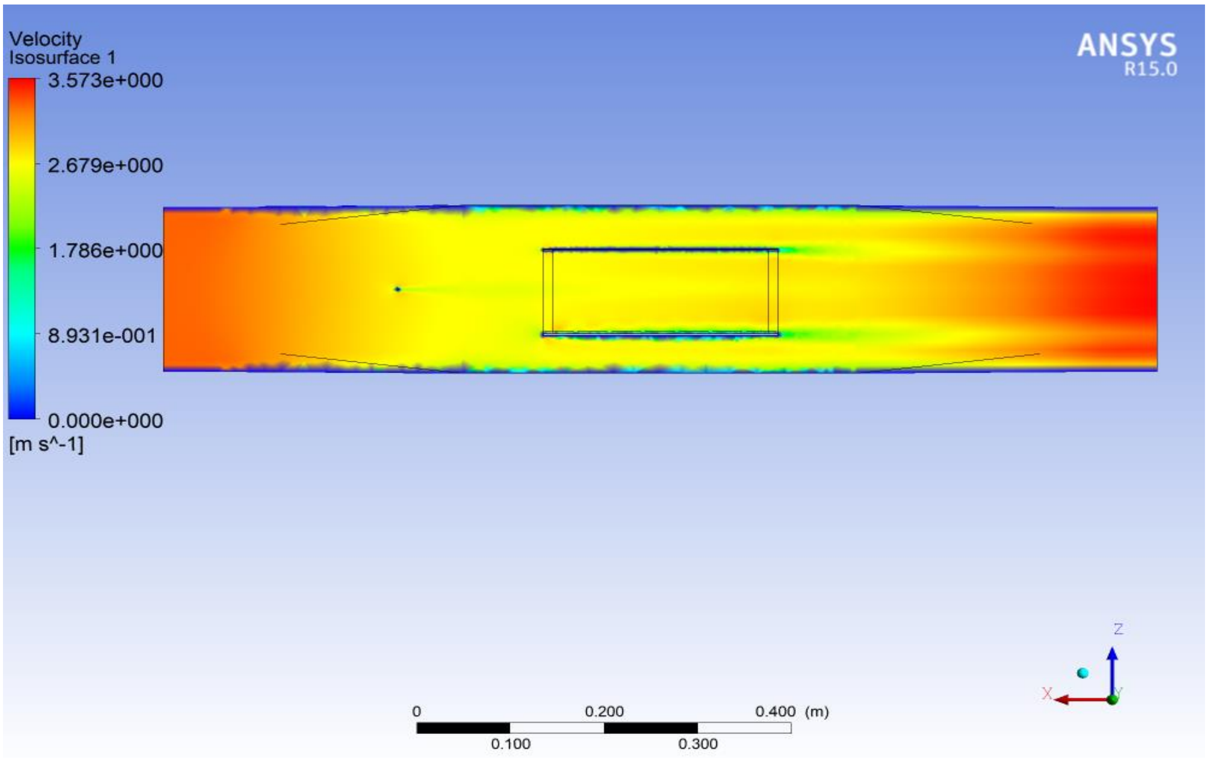

Figure 15. Velocity field at 0.05 m away from mid plane towards thermometer wall

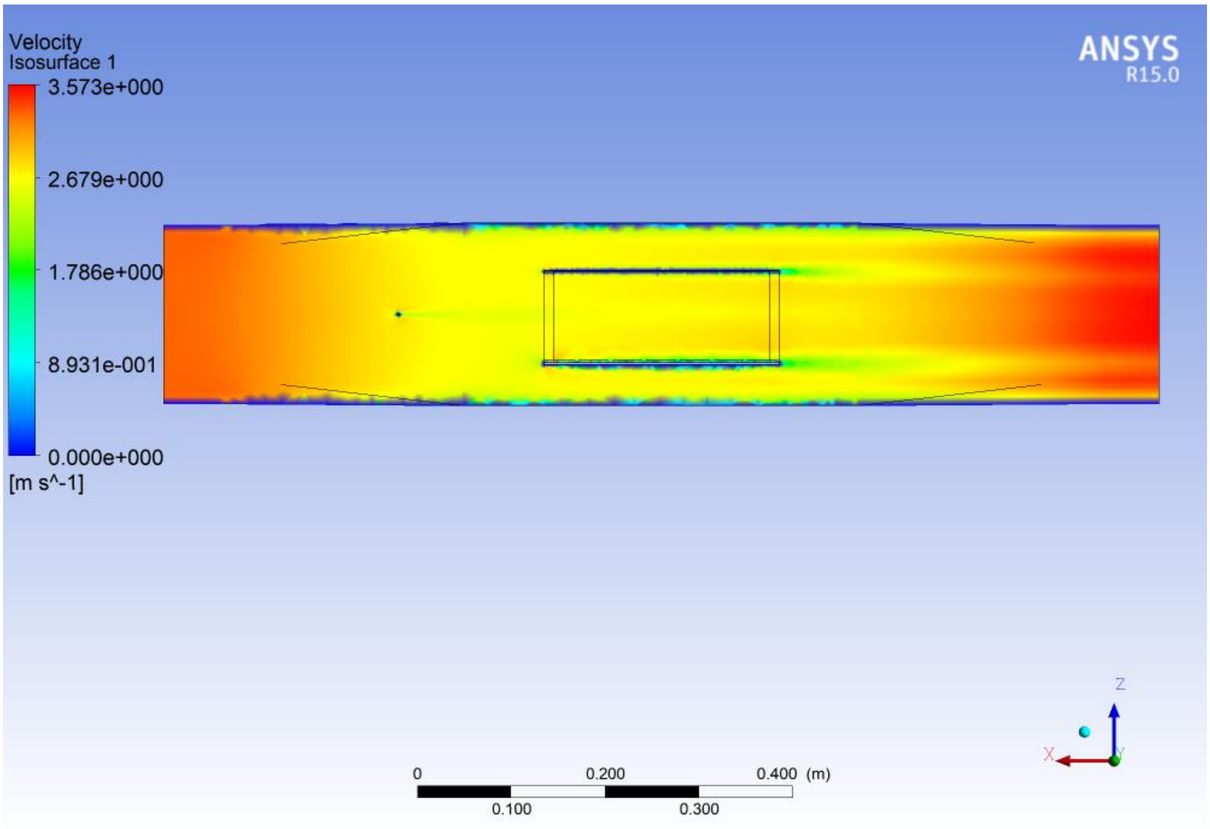

Figure 16. Velocity field at midplane

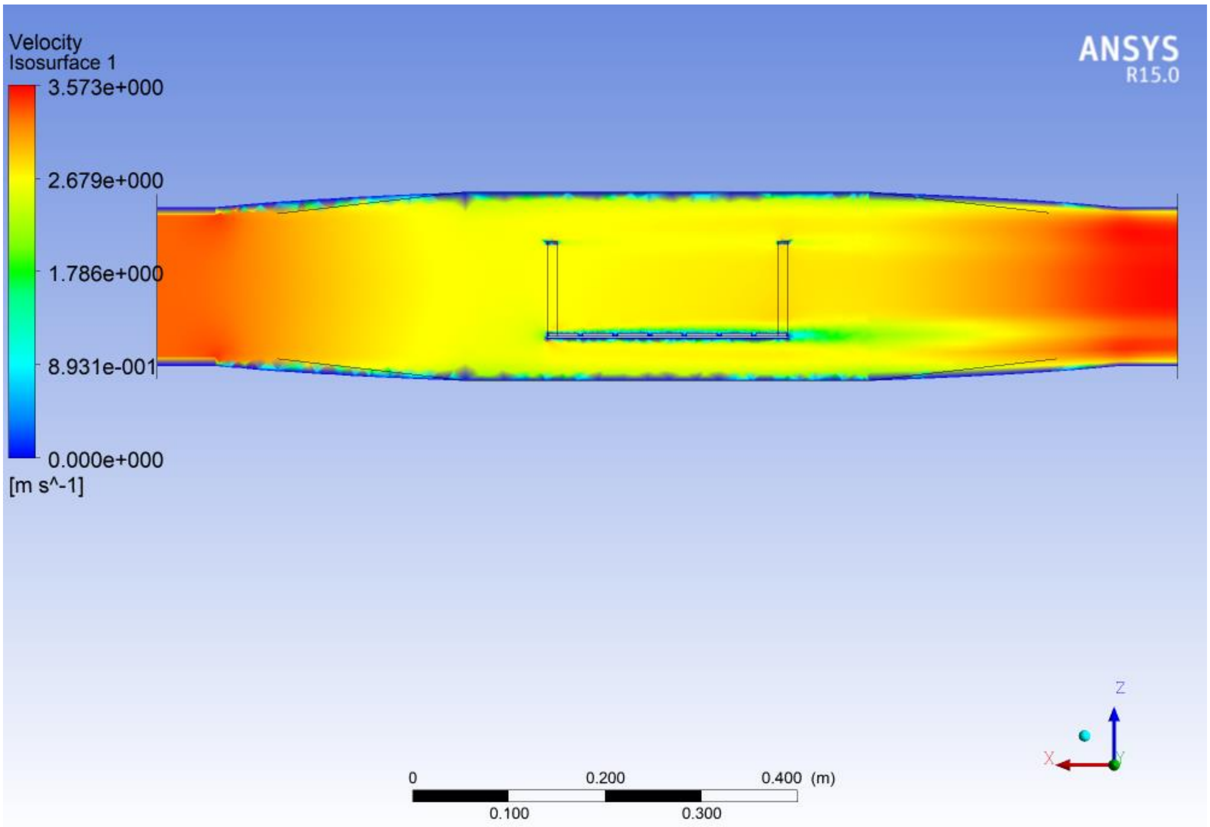

Figure 17. Velocity field at 0.05 m away from mid plane opposite thermometer wall

3.6.1.3 Velocity field at different positions

To describe velocity field at each position in drying chamber different lines were selected

- Green, yellow and red colour lines showing different row X column positions in the basket and blue lines showing before, after and mid position of basket.

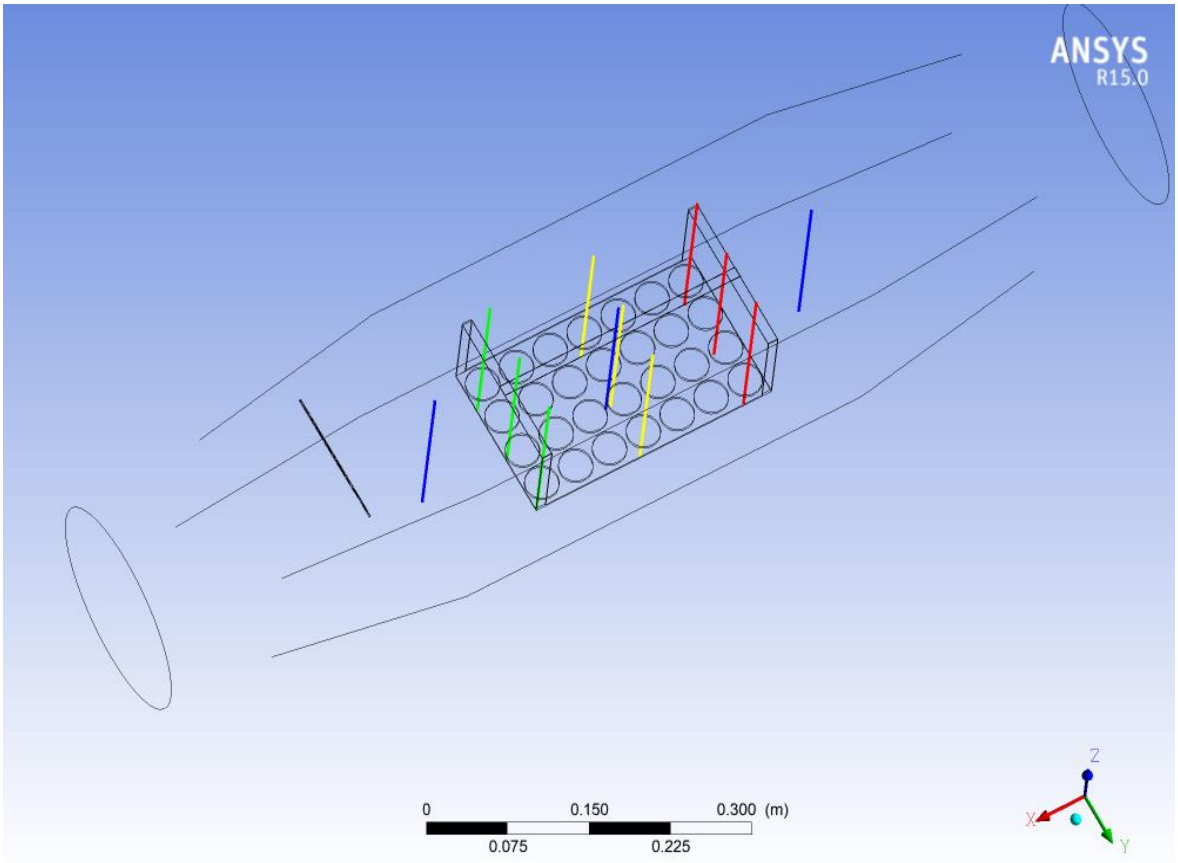

Figure 18. Different positions in drying chamber

- The inner dimensions of the drying chamber are 0.42 x 0.2 x 0.2 m (X, Y, Z) and dimensions of dying basket are 0.25 x 0.15 x 0.1 m (X, Y, Z).
- Air flows in the coordinate's direction of X.
- In Y direction width and Z direction height are measurements of drying chamber.
- Center point of drying basket bottom plate is (0, 0, 0)
- Thermometer placed at the height of 0.065 m from bottom plate of drying basket in the direction of Z
- Distance between top frame and bottom plate of drying basket is 0.11 m in the direction of Z.
- Drying samples thickness was 0.004 m

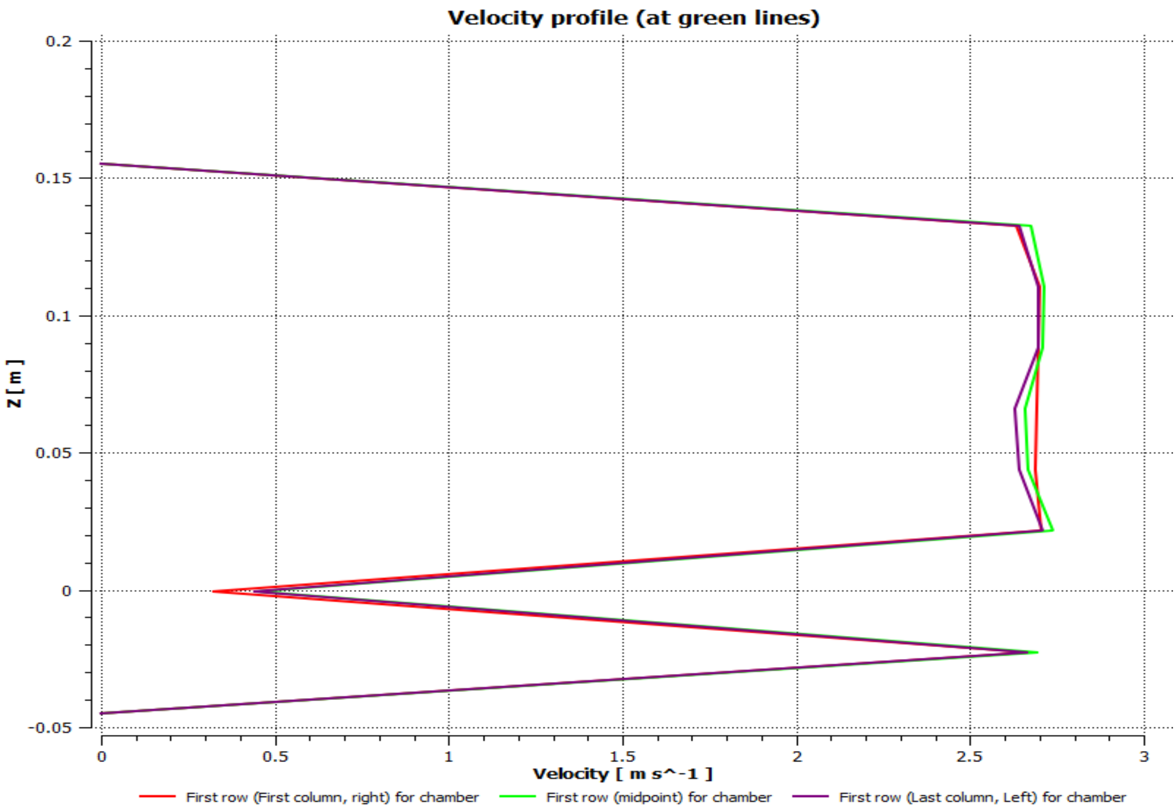

Figure 19. Velocity profile of first row positions of drying samples

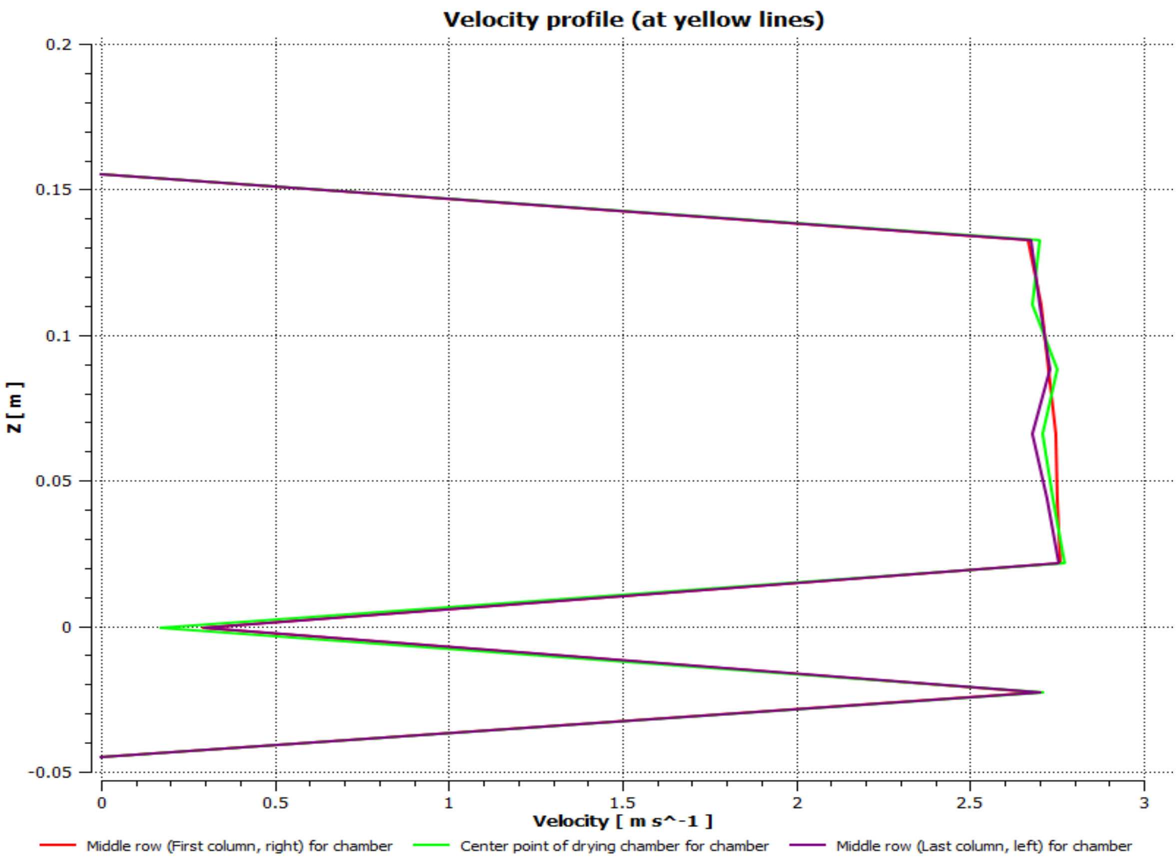

Figure 20. Velocity profile of middle row positions of drying samples

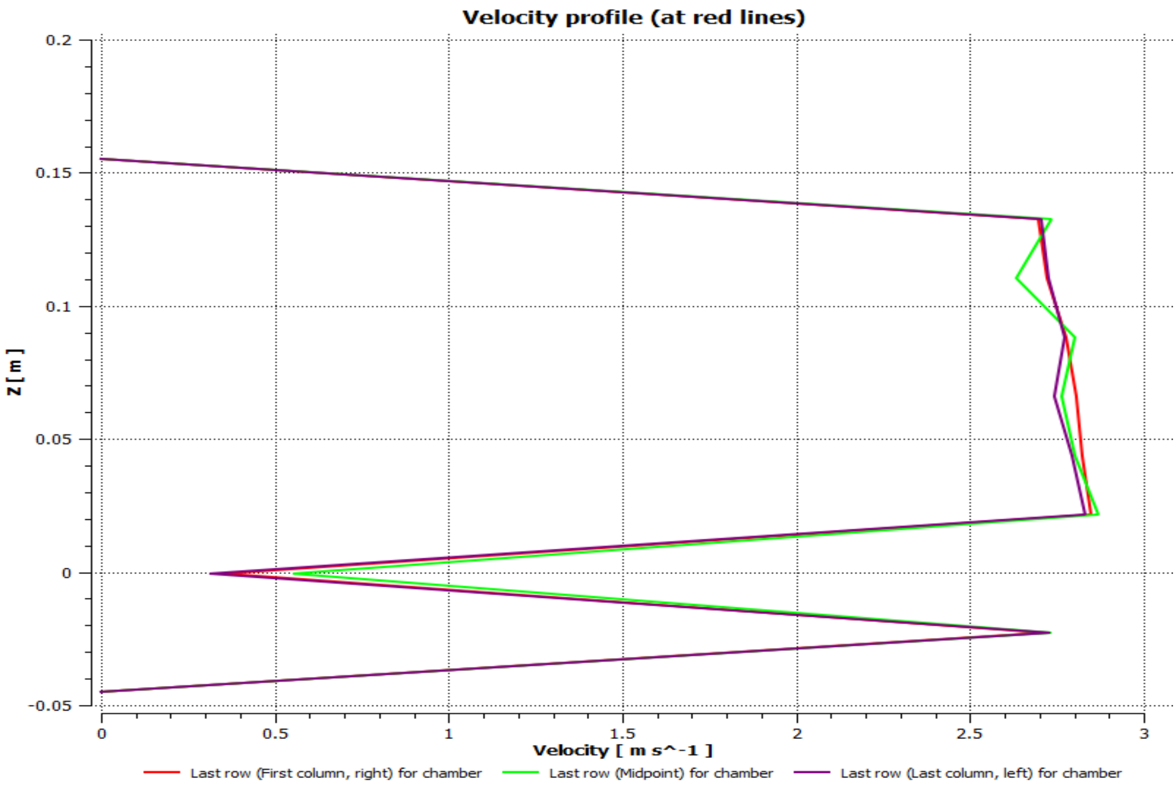

Figure 21. Velocity profile of last row positions of drying samples

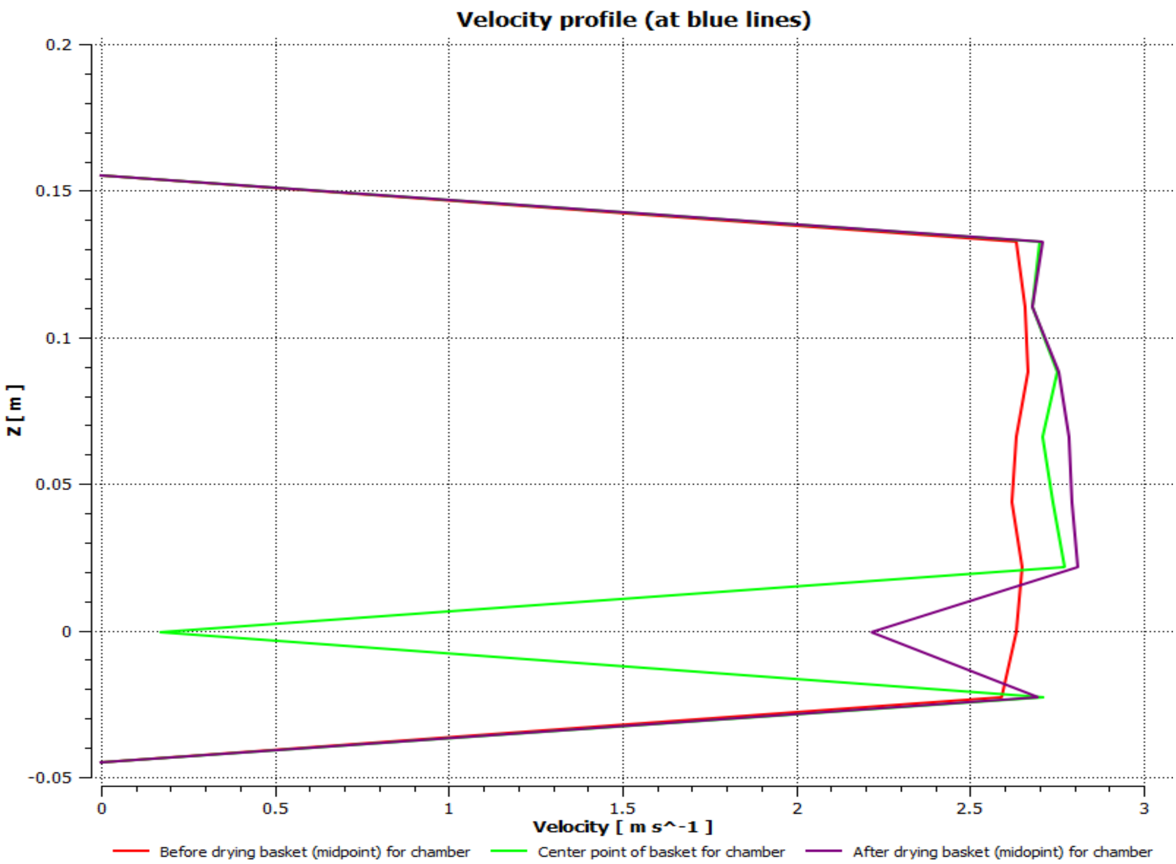

Figure 22. Velocity profile of various positions in drying chamber

- Drying basket bottom plate (at zero meters) created huge velocity drop (less than 0.5 m/s), From Figure 19., Figure 20., Figure 21. and Figure 22.
- Thermometer influence nearly nothing (at the height of 0.065 m), which creates very small velocity drop (up to 2.8 m/s)
- Velocity field dropped up to 2.6 m/s between thermometer and entrance of drying basket due to drying basket resistance force. Which is less value than drying basket average velocity field (2.8 m/s) and exit velocity of drying basket (2.9 m/s)
- Velocity of air around drying samples was varying from 2.7 m/s to 2.9 m/s.
- Drying basket edges also create small deflections in velocity flow, which have nothing to do with one.

3.6.2 Single layer Vertical arrangement

3.6.2.1 Acceptable convergence

To reach acceptable convergence iteration process done by 6000 times, in which 3000 were first order iterations 3000 by second order.

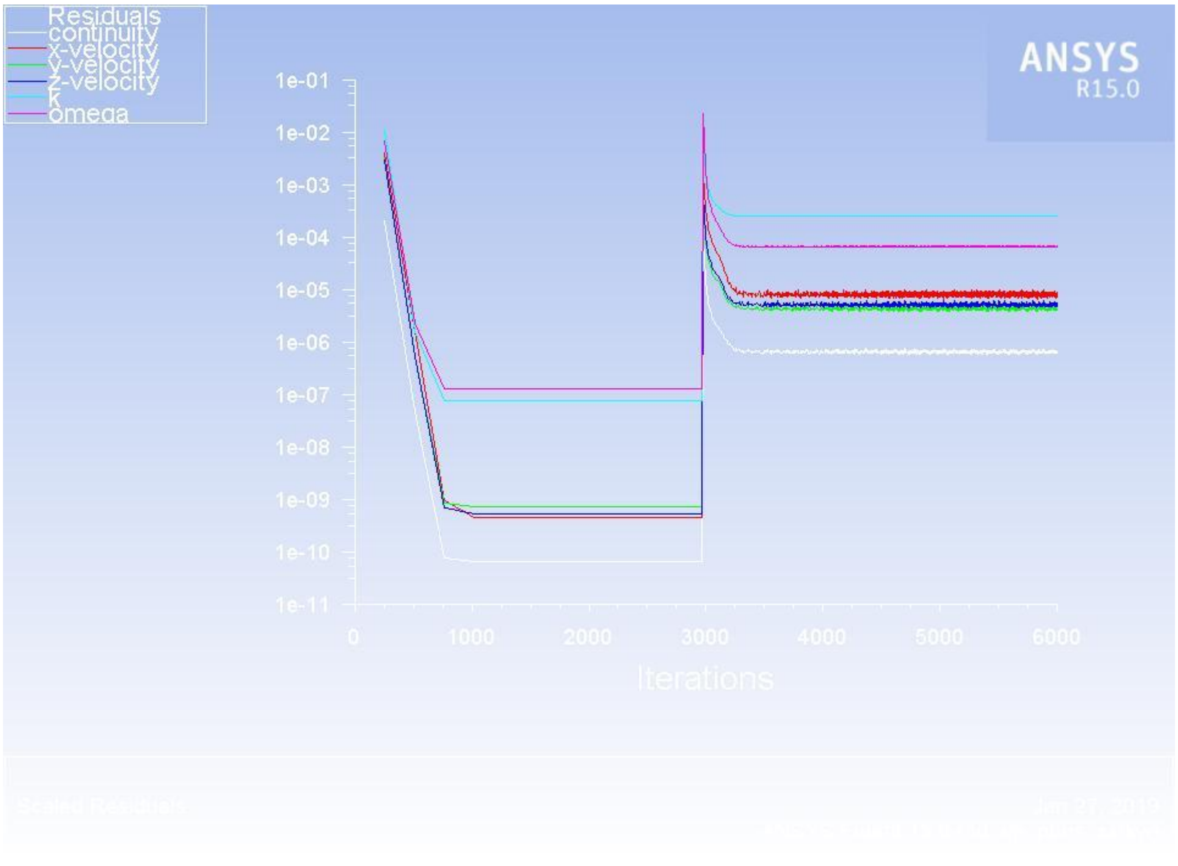

Figure 23. Curves for single layer vertical arrangement

3.6.2.2 Velocity fields at different sections

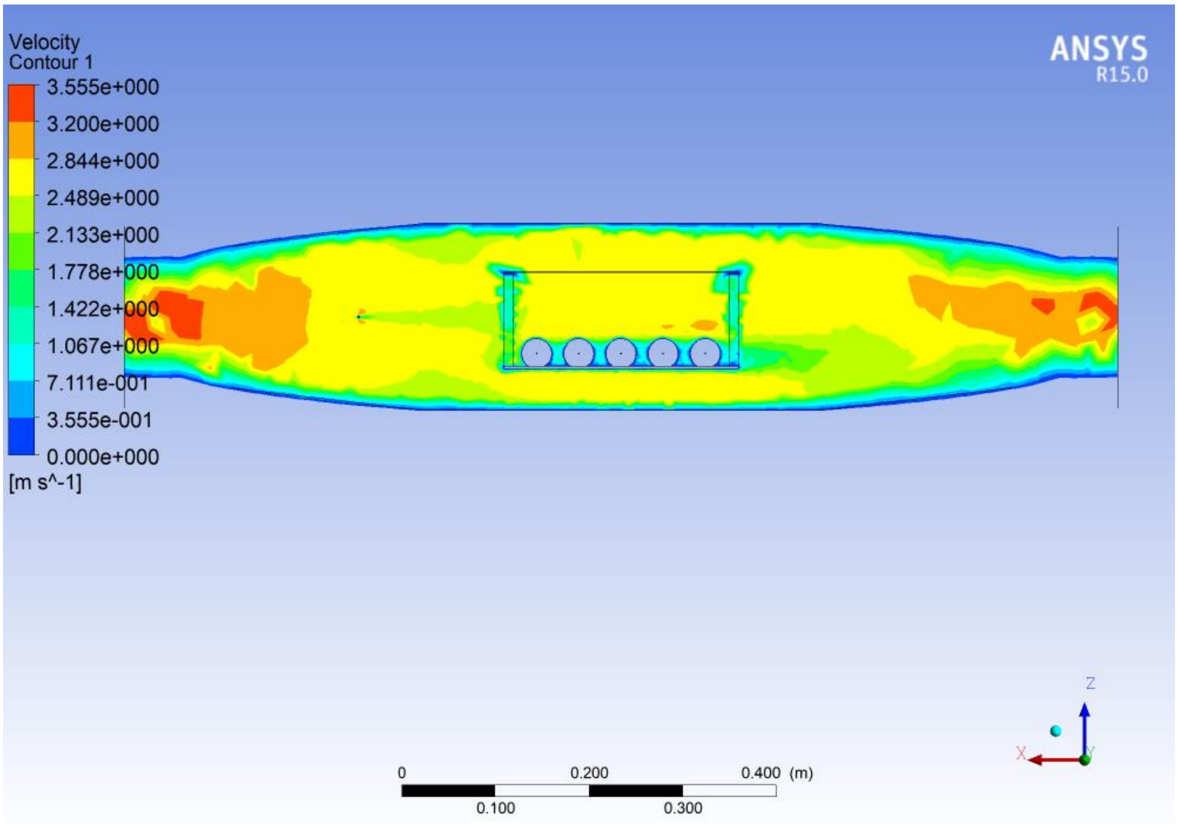

Figure 24. Velocity field at 0.05 m away from mid plane towards thermometer wall

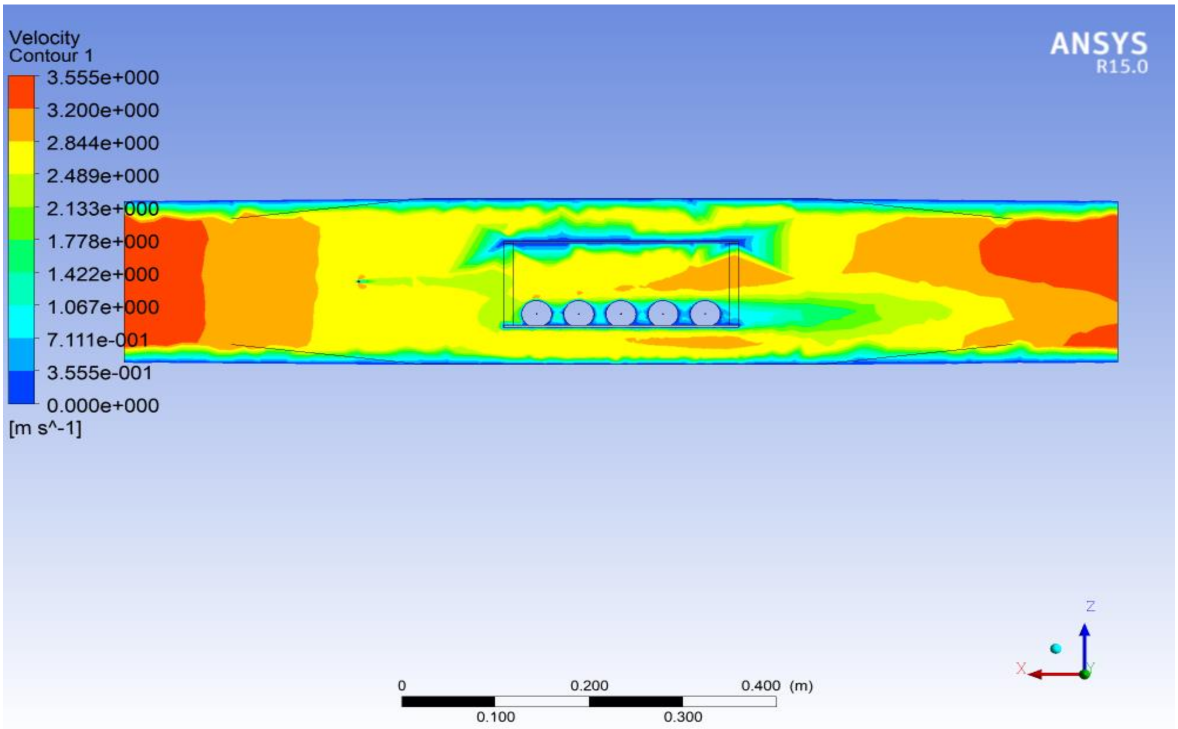

Figure 25. Velocity field at midplane

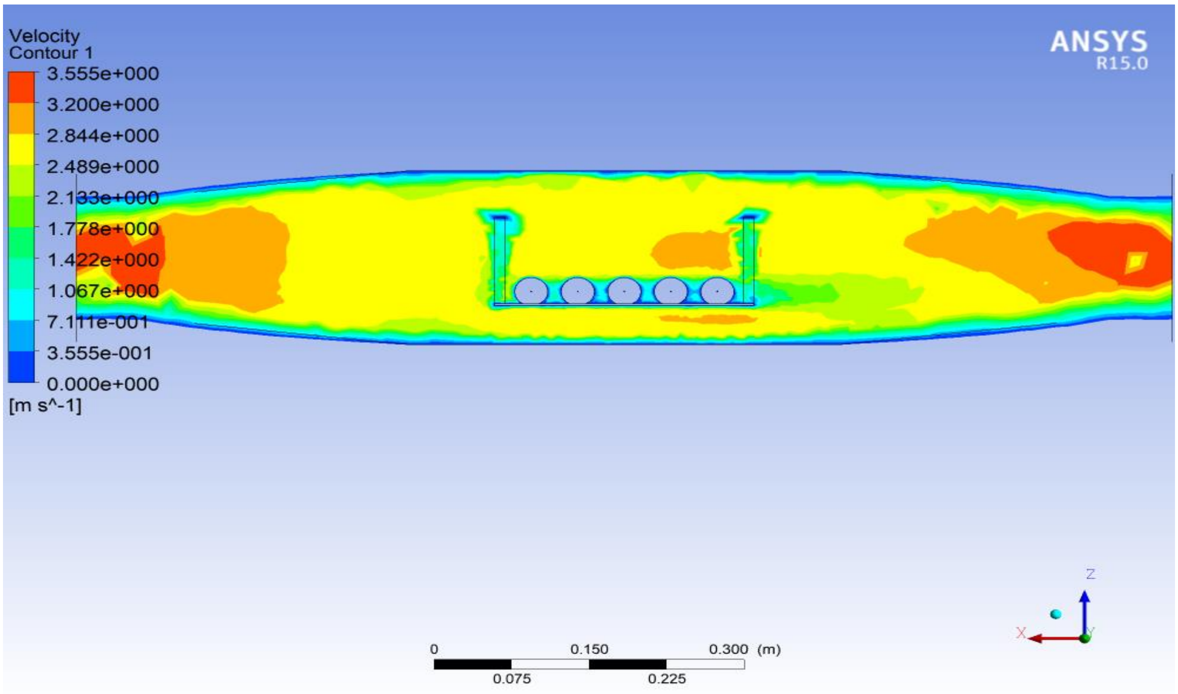

Figure 26. Velocity field at 0.05 m away from mid plane opposite thermometer wall

3.6.2.3 Velocity field at different positions

To describe velocity field at each position in drying chamber different lines were selected

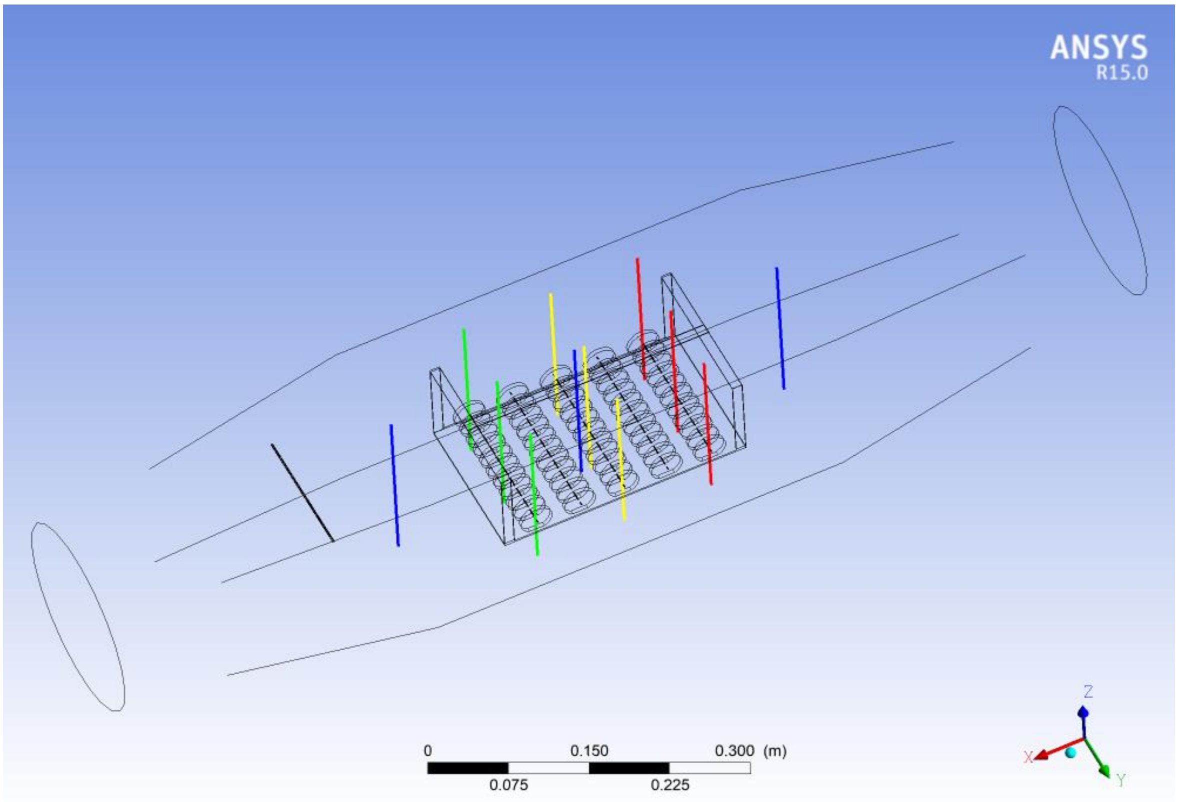

Figure 27. Different positions in drying chamber

- Green, yellow and red colour lines showing different row X column positions in the basket and blue lines showing before, after and mid position of basket in Figure 27.
- The inner dimensions of the drying chamber are 0.42 x 0.2 x 0.2 m (X, Y, Z) and dimensions of dying basket are 0.25 x 0.15 x 0.1 m (X, Y, Z).
- Air flows in the coordinate's direction of X.
- In Y direction width and Z direction height are measurements of drying chamber.
- Center point of drying basket bottom plate is (0, 0, 0).
- Thermometer placed at the height of 0.065 m from bottom plate of drying basket in the direction of Z.
- Distance between top frame and bottom plate of drying basket is 0.11 m in the direction of Z.
- Drying samples height was 0.032 m (diameter of drying samples) and samples were arrangged vertically.
- All the green, yellow and red colour lines were drawn through drying samples, which were exactly middle through the samples.
- First and last of blue lines were far away (0.2 m) from centre point, while middle blue line passing through centre point.

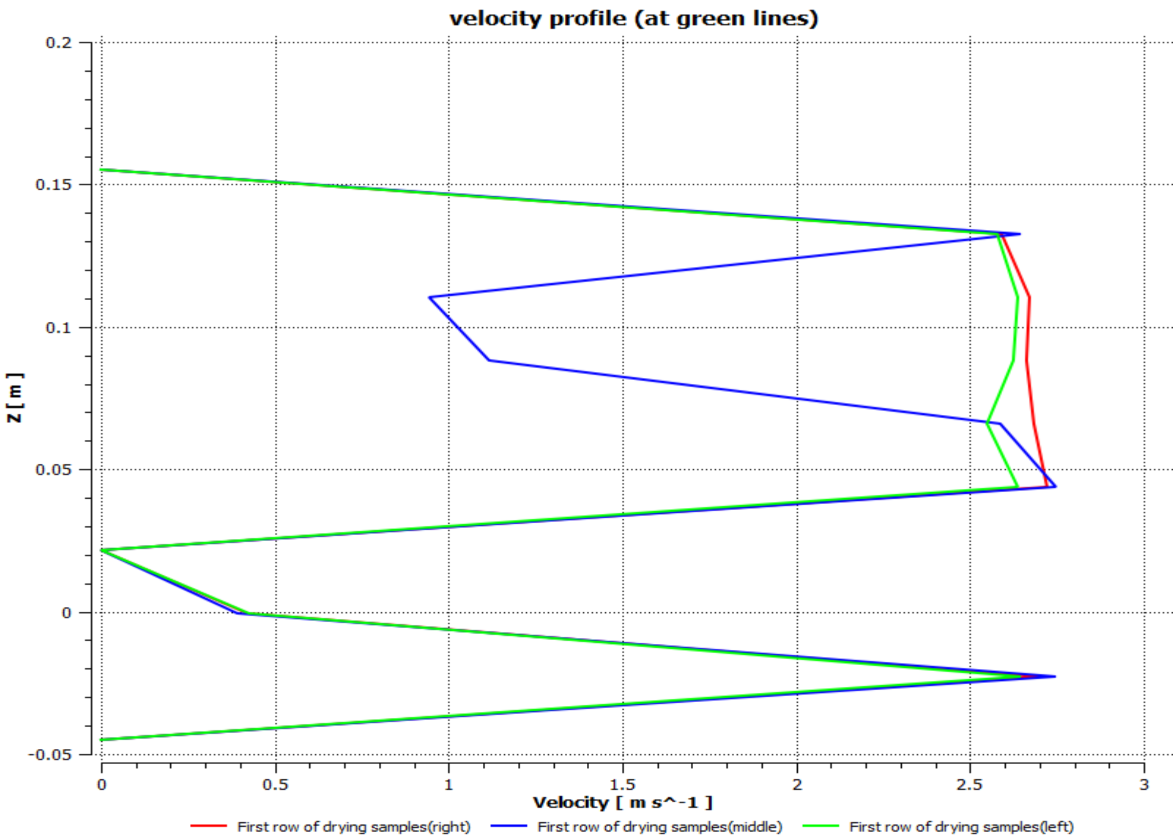

Figure 28. Velocity profile of first row positions of drying samples

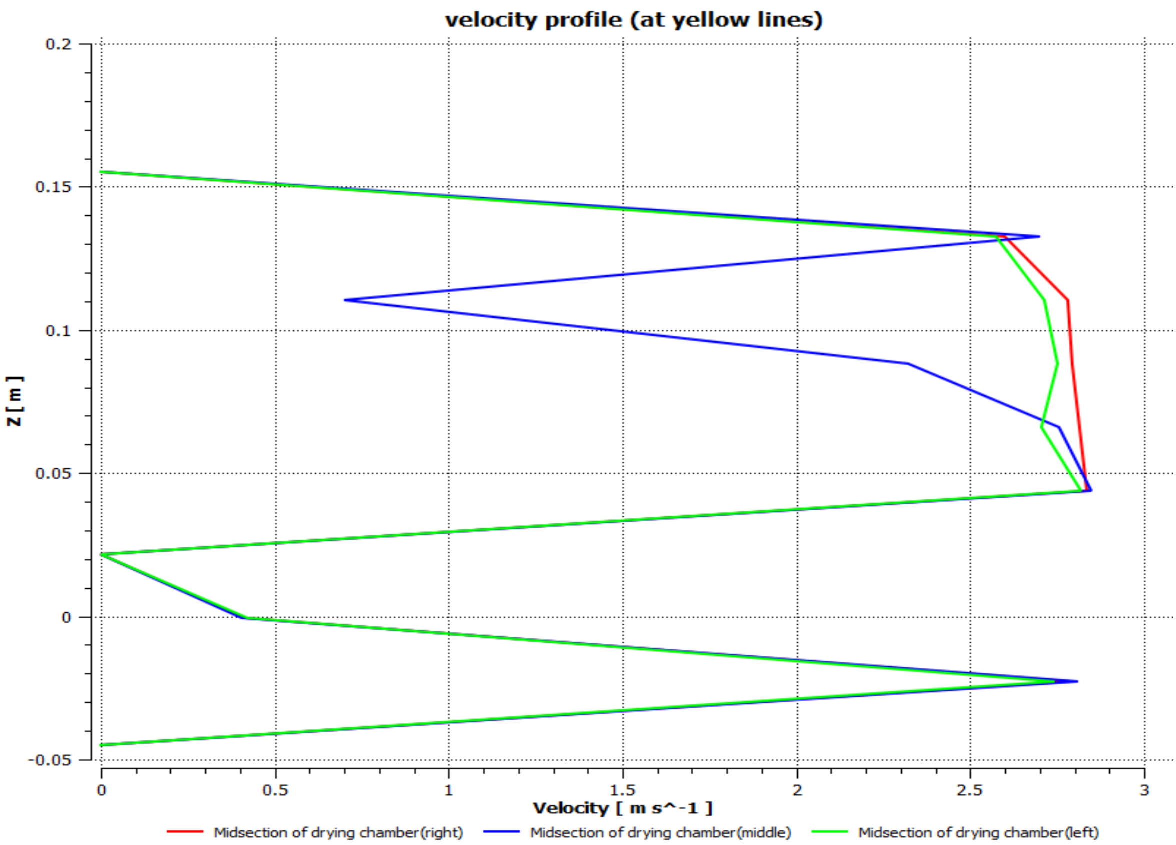

Figure 29. Velocity profile of middle row positions of drying samples

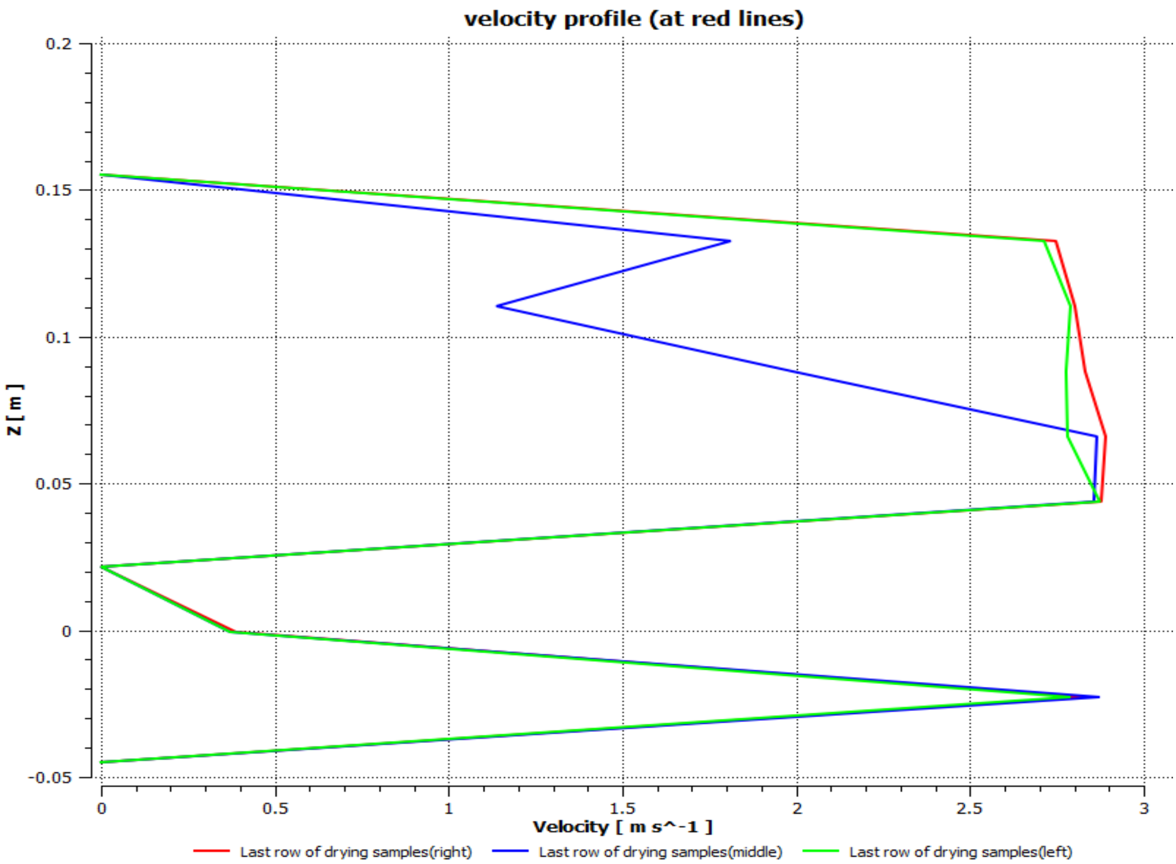

Figure 30. Velocity profile of last row positions of drying samples

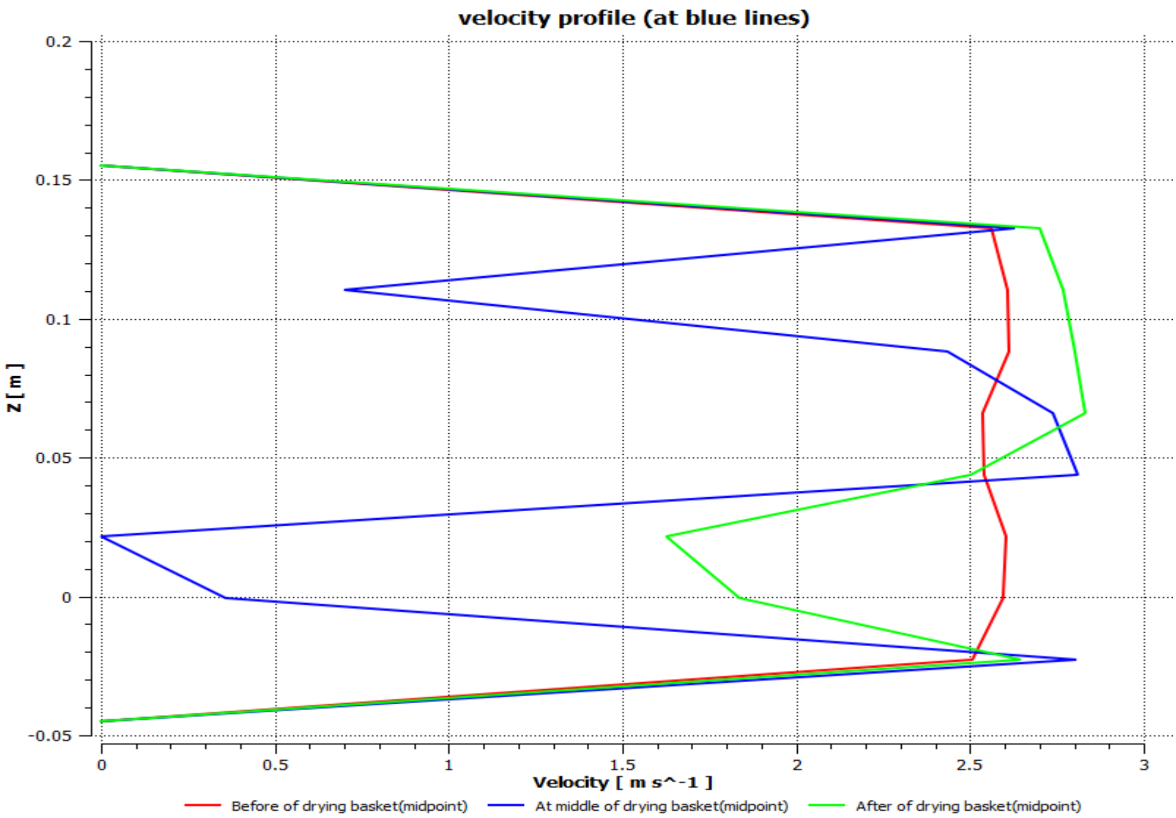

Figure 31. Velocity profile of various positions in drying chamber

- Drying basket bottom plate (at zero meters) created huge velocity drop (less than 0.5 m/s), From Figure 28., Figure 29., Figure 30. and Figure 31.
- Thermometer influence nearly nothing (at the height of 0.065 m), which creates very small velocity drop (up to 2.8 m/s)
- (From Figure 28., Figure 29., Figure 30. and Figure 31.) All the blue lines got huge deflections at 0.11 m, which values between 0.7 m/s to 1.2 m/s.
- From 0 to 0.03 m almost velocity field zero because of drying samples.
- Velocity field dropped up to 2.6 m/s between thermometer and entrance of drying basket due to drying basket resistance force. Which is less value than drying basket average velocity field (2.8 m/s) and exit velocity of drying basket (2.9 m/s)
- Velocity of air around drying samples was varying from 2.6 m/s to 2.9 m/s.
- Drying basket edges also create small deflections in velocity flow, which have nothing to do with one.

In drying basket, the viscous nature of airflow reduces the local velocities on a surface of drying samples and drying basket, and it is responsible for skin friction. Air velocities around the drying samples for both plane and vertical arrangement are varying from 2.6 m/s to 2.9 m/s, which are nearly close values. While input velocity 3.3 m/s, velocity drop nearly 0.4 m/s to 0.7 m/s around samples for both arrangements.

Above results showing that velocity field around the samples in both selected orientations doesn't change dramatically for selected span of samples. Therefore, it is expected that all samples will be dried uniformly with no effect of velocity field deformation by samples body.

4 Experimental part

In this part of thesis, the convective drying characteristics of untreated and citric acid treated banana slices with different orientation has been investigated. These characteristics play important role in design of food convective dryer. Laboratory experiments on the banana slices can be very useful in a determining the required size of the food convective dryer.

4.1 The principle description of Circular dryer

Circular dryers have application to remove the moisture from the banana cylindrical pieces by the process of circulation of hot air in drying chamber. The laboratory device serves to remove humidity from solid food products. The evaporation of the water with in the sample is caused by flow of drying air, which circulates in the laboratory device.

The drying experiments were carried out in the modified circulation dryer. Which is placed in laboratory of Department of Process Engineering, Faculty of Mechanical Engineering at CTU in Prague. The schematic diagram of chamber dryer shown in figure 32.

The circulation dryer is equipped by fan with regulation of revolution. The fan ensures the continue feeding of drying air in the drying chamber. The mean velocity of air can be set in a range of 0.5-3.5 ms^{-1}. The air is heated up by two electric heater devices, where first has electric power 6x500 W and it is placed in front of the fan. The second electric heater heats up the air in front of drying chamber and has power 7x1 kW. The heated air is driven by insulated duct. The temperature of air is measured by sensors Pt100. The control system of the heaters and temperature signal transducers are closed in the control panel.

The inner dimensions of the drying chamber are 420 x 200 x 200 mm. The samples were arranged in drying baskets and was placed in drying chamber by hanging to digital scale which have a range 0 to 620 g. The model of digital scale is ViBRA AJ, which has accuracy 0.001 g and it is connected to PC by interface RS232. The dimensions of dying basket are 250 x 150 x 100 mm and basket allows to convective drying process. Drying chamber measurements shown in figure 33.

Parameters:

1. Drying chamber
2. Primary heater
3. Fan
4. Electric motor
5. Air duct
6.Secondary heater
7.Scales
8.Column

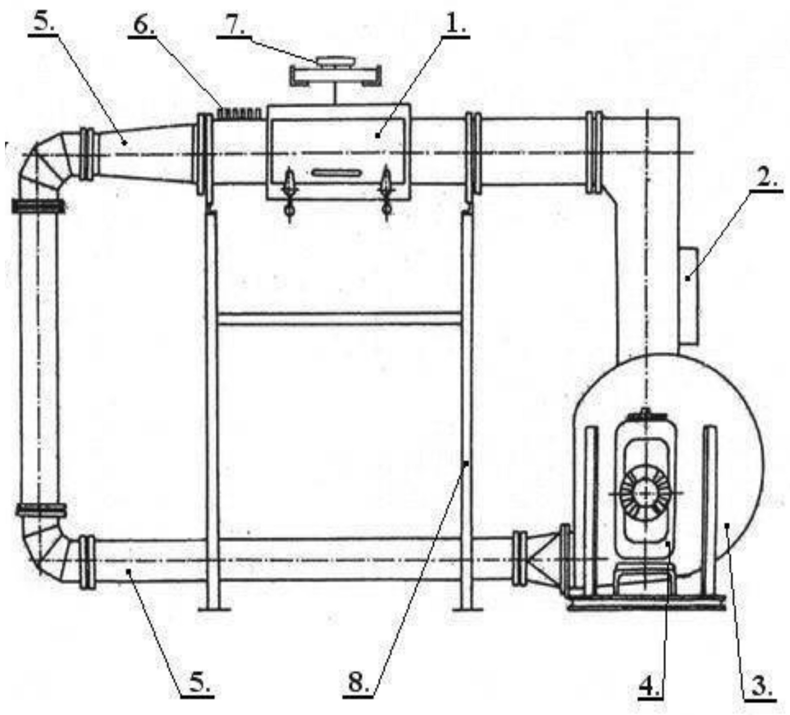

Figure 32. Schematic diagram of a chamber dryer [13]

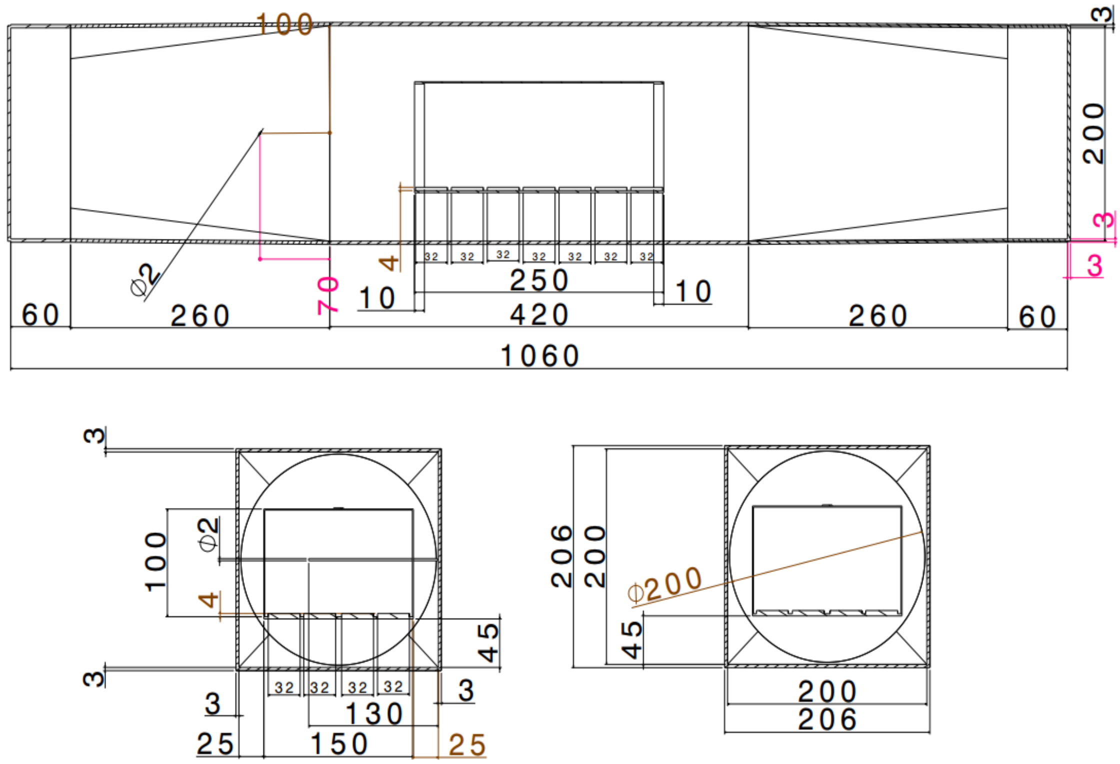

Figure 33. Drying chamber cross sections

A. Front sectional view, B. Left sectional view, C. Right sectional view

4.2 Initial moisture content

To find initial moisture content of untreated and citric acid treated banana slices, chamber dryer Binder FD53 was used which is in laboratory of Department of Process Engineering at CTU in Prague. Peeled banana was sliced into 4 mm pieces and arranged in six different weighed Aluminium plates. These plates were placed in a chamber dryer at the standard temperature of 105 °C, after 24 hours samples were collected and weighed. For the weighing purpose SCALTEC SBC 31 analytical balance device was used.

Figure 34. Chamber dryer Binder FD53

Figure 35. Analytic balance device SCALTEC SBC 31

Plate NO	P0 grams	P1 grams	P2 grams	P3 grams	P4 grams	X0 kg/kg db	X1 kg/kg wb
2	2.4995	14.722	12.2225	5.2795	2.78	3.396583	0.7725506
3	2.5007	13.8504	11.3497	5.0832	2.5825	3.39485	0.7724609
12	2.5078	15.0345	12.5267	5.223	2.7152	3.613546	0.783247
15	2.5112	15.0845	12.5733	5.2762	2.765	3.547306	0.7800896
20	2.5127	16.1073	13.5946	5.375	2.8623	3.749537	0.7894532
21	2.5119	18.1248	15.6129	5.9487	3.4368	3.54286	0.7798743
					AVG	3.54078	0.7796126

Table 5. Calculations of initial moisture content for untreated slices

Plate NO	P0 grams	P1 grams	P2 grams	P3 grams	P4 grams	X0 kg/kg db	X1 kg/kg wb
2	2.5078	15.715	13.2072	5.0054	2.4976	4.287956	0.810891
3	2.5077	13.5328	11.0251	4.6866	2.1789	4.059939	0.8023691
12	2.5204	11.2675	8.7471	4.1307	1.6103	4.431969	0.8159047
15	2.5218	15.3868	12.865	5.0313	2.5095	4.126519	0.8049359
20	2.5244	15.7802	13.2558	5.1024	2.578	4.141893	0.8055191
21	2.5254	14.3449	11.8195	4.8207	2.2953	4.149436	0.805804
					AVG	4.199619	0.8075706

Table 6. Calculations of initial moisture content for citric acid treated slices

Where, P0: Initial plate weight in grams

P1: Initial weight of samples including plate in grams

P2: Initial weight of samples in grams

P3: After drying weight of samples including plate in grams

P4: After drying weight of samples in grams

X0: Initial moisture content on dry basis in kg/kg db

X1: initial moisture content on wet basis in kg/kg wb

Initial moisture content of untreated and citric acid treated banana samples was determined as 3.54 and 4.199 kg/kg on dry basis simultaneously 0.7796 and 0.8076 kg/kg on wet basis. These results showing that there is an increment on initial moisture content after citric acid treatment.

4.3 Experimental setup and drying measurements

Experimental parameters were selected from the literature source on the acceptance of the supervisor of the thesis. All experiments were conducted at standard temperature 60 ℃ and air velocity 3.3 m/s. For these experiments, 4 mm thickness banana slices were used. Experiments were conducted with untreated and citric acid treated banana samples with two different orientations and each one repeated 3 times for better results. All the bananas purchased from a local market which had 30 to 32 mm diameter and density 0.8385 g/cm^3 obtained from experimental calculations.

4.3.1 Untreated samples with plane orientation

Firstly, the dryer was heated up to 60℃ at a velocity of 3.3 m/s. Then bananas were sliced into approximately 4 mm thickness with a knife on polyethylene cut board and peeled manually. Position of banana slices were arranged as 4x7 (row x column) in a basket and placed in drying chamber. This experiment repeated 3 times for accurate results and the average values were used for comparison with mathematical model. After 6 hours dried banana samples were collected. Aluminium cover was used for all the plane orientation experiments to prevent stickiness.

4.3.2 Citric acid treated samples with plane orientation

4 % citric acid solution bottle purchased from a local market and diluted to 0.1 % in a Borosilicate science baker. The dryer was heated up to 60 ℃ at velocity 3.3 m/s. Bananas were slices into approximately 4 mm thickness and kept in 0.1 % citric acid solution for 1 min at laboratory environment conditions. After that banana slices were arranged as 4 x 7 (row x column) and placed in drying chamber as shown in the following figures. Experiment duration time was nearly 6 hours.

Figure 36. Banana slices plane orientation arrangement in a basket

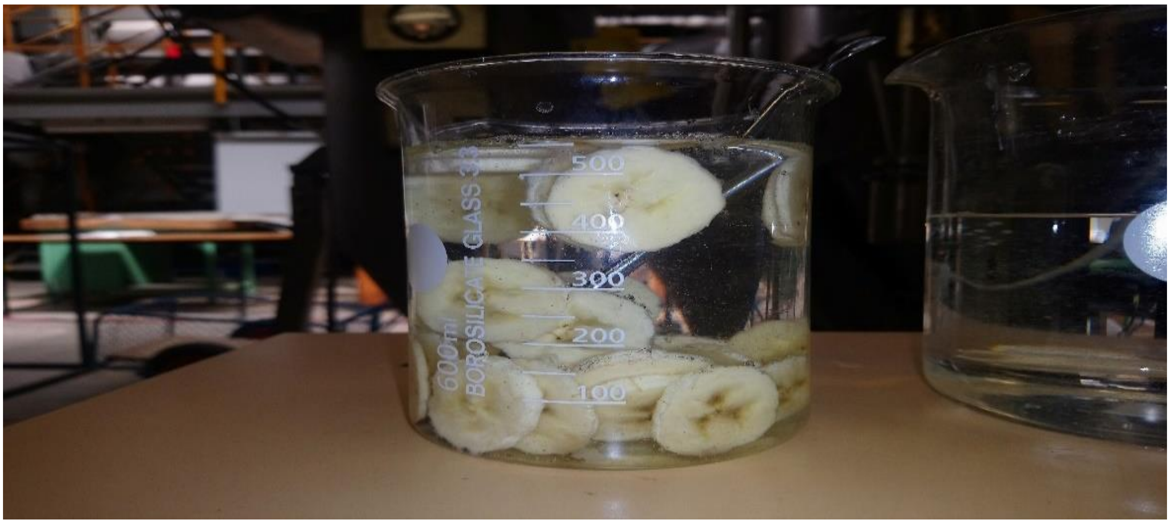

Figure 37a. Banana slices treatment with citric acid solution

Figure 37b. Banana slices treatment with citric acid solution

Figure 38. banana slices in a drying chamber before drying experiment

Figure 39. banana slices in a drying chamber after drying experiment

4.3.3 Untreated samples with vertical orientation

Dryer was heated up to 60 ℃ at a velocity of 3.3 m/s and bananas were sliced into approximately 4 mm thickness. Then banana slices arranged in a vertical orientation as 6 x 5 (row x column) and placed in a drying chamber. These samples were arranged in a way that their faces were perpendicular to basket base and their thickness in the direction of air flow force to reduce samples damage. After 6 hours, samples were collected.

Figure 40a. Untreated samples vertical orientation arrangement

Figure 40b. Untreated samples vertical orientation arrangement

4.3.4 Citric acid treated samples with vertical orientation

Dryer was heated up to 60℃ at a velocity of 3.3 m/s and bananas were slices into approximately 4 mm thickness and kept in 0.1 % citric acid solution for 1 min at laboratory environment conditions. Then treated samples arranged in a vertical as 6 x 5 (row x column) and placed in a drying chamber. After 6 hours, samples were collected.

Figure 41a. Citric acid treated samples vertical orientation arrangement

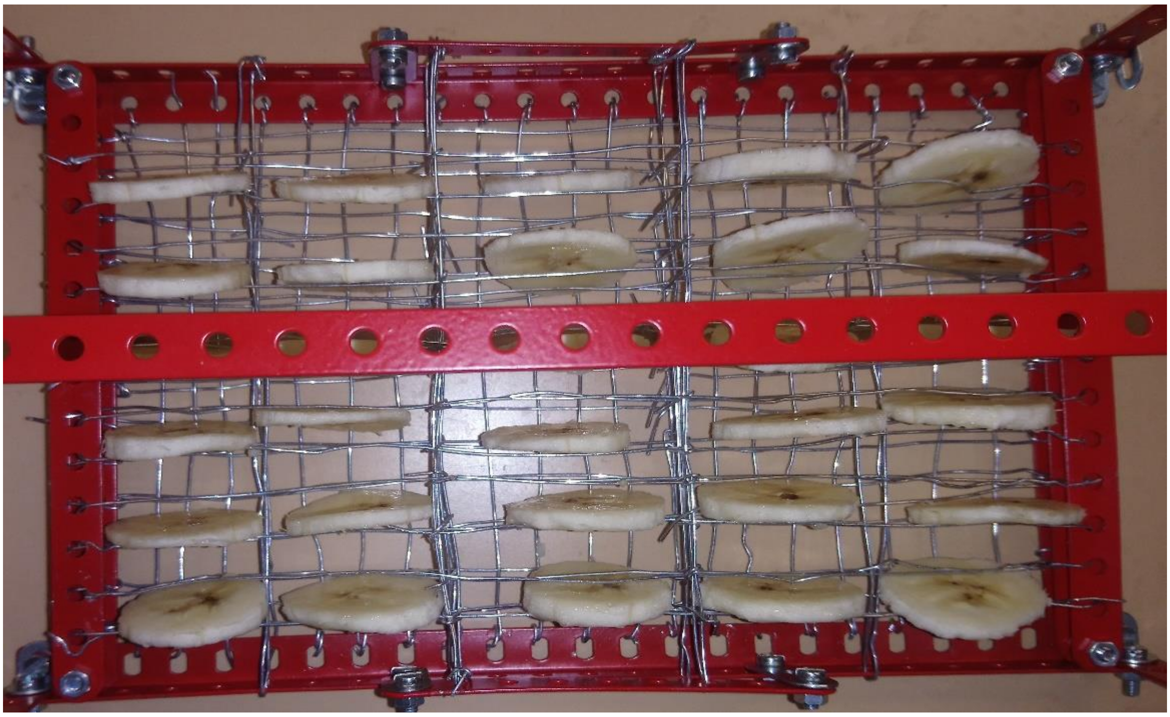

Figure 41b. Citric acid treated samples vertical orientation arrangement

Figure 42. Vertically orientated banana samples in a drying chamber before drying experiment

Figure 43. Vertically orientated banana samples in a drying chamber after drying experiment

4.4 Results of experiments

4.4.1 Drying curves

By reading data from PC, the drying curve of each experiment measurement (every kind repeated 3 times) was plotted.

4.4.1.1 Weight loss drying curves

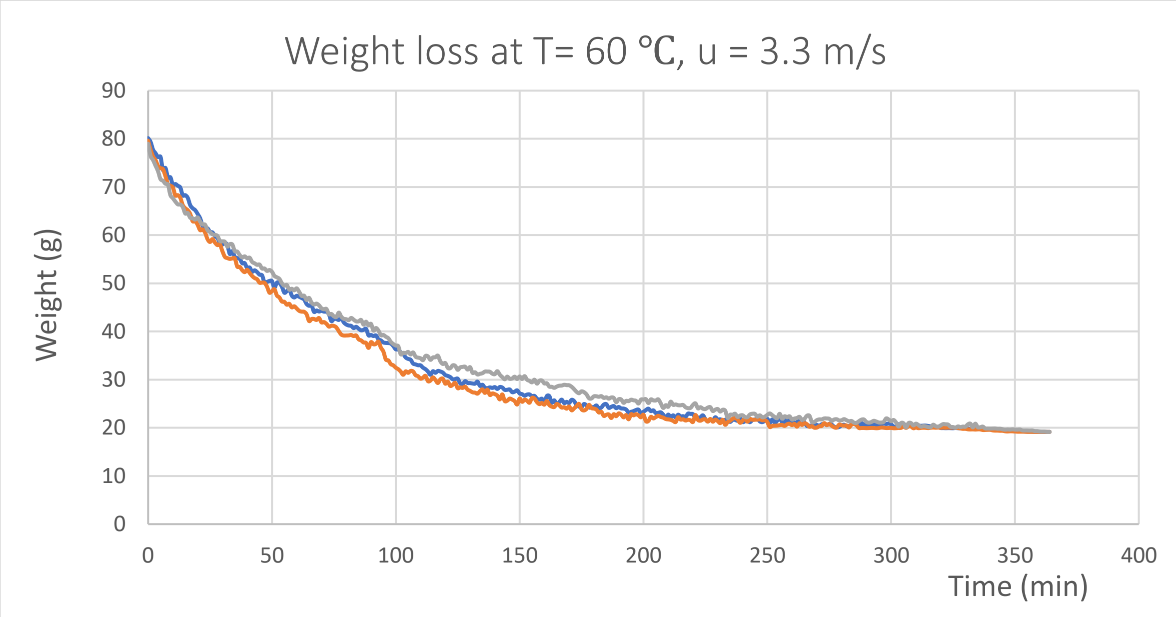

Figure 44. Untreated samples plane orientated drying curves

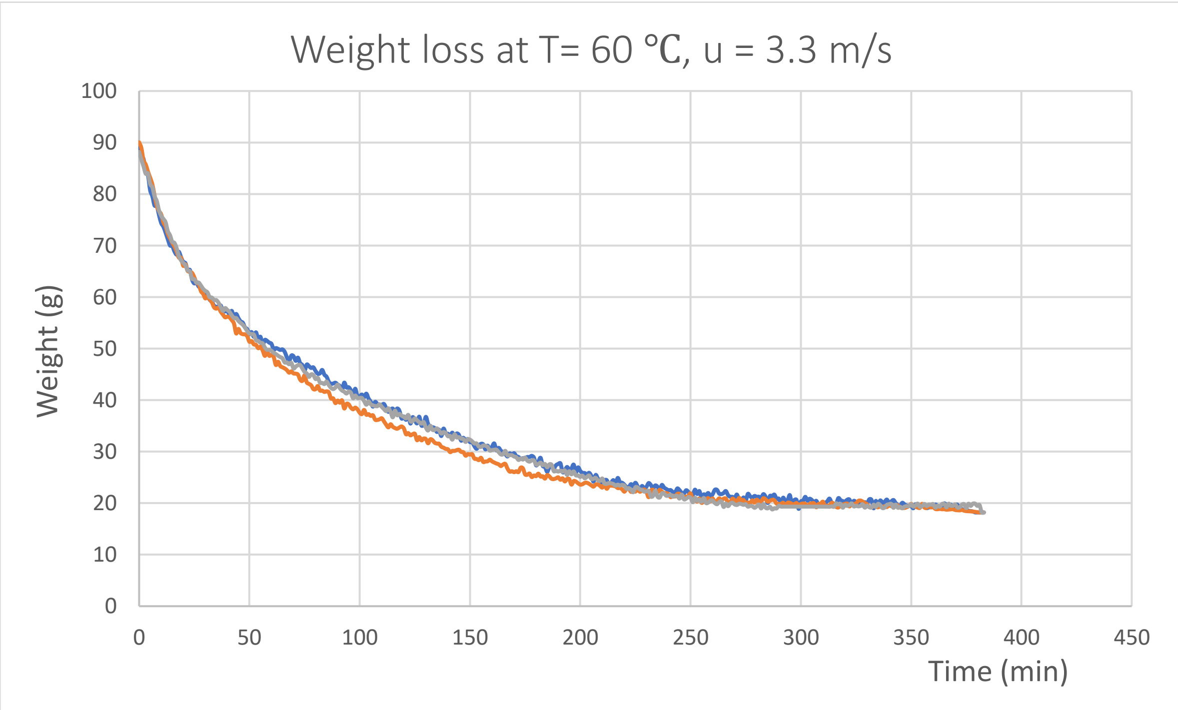

Figure 45. Citric acid treated samples plane orientated drying curves

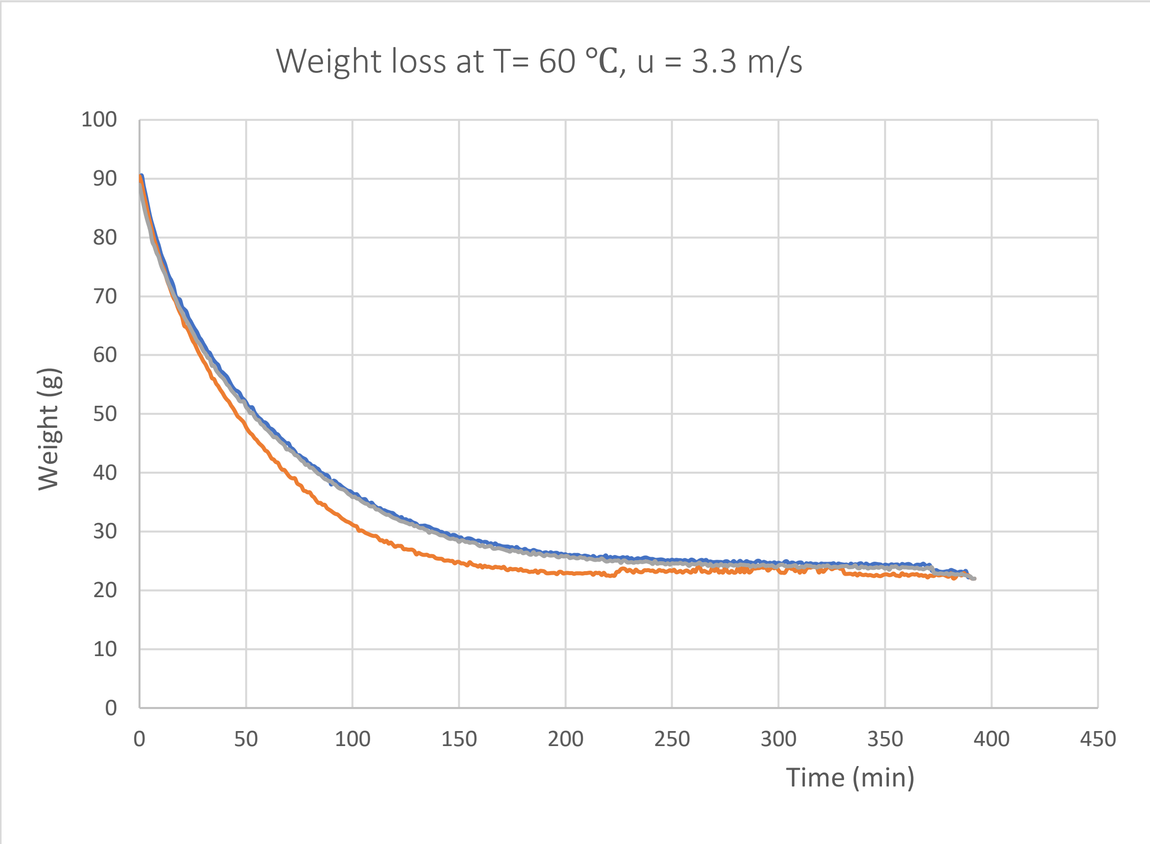

Figure 46. Untreated samples vertical orientated drying curves

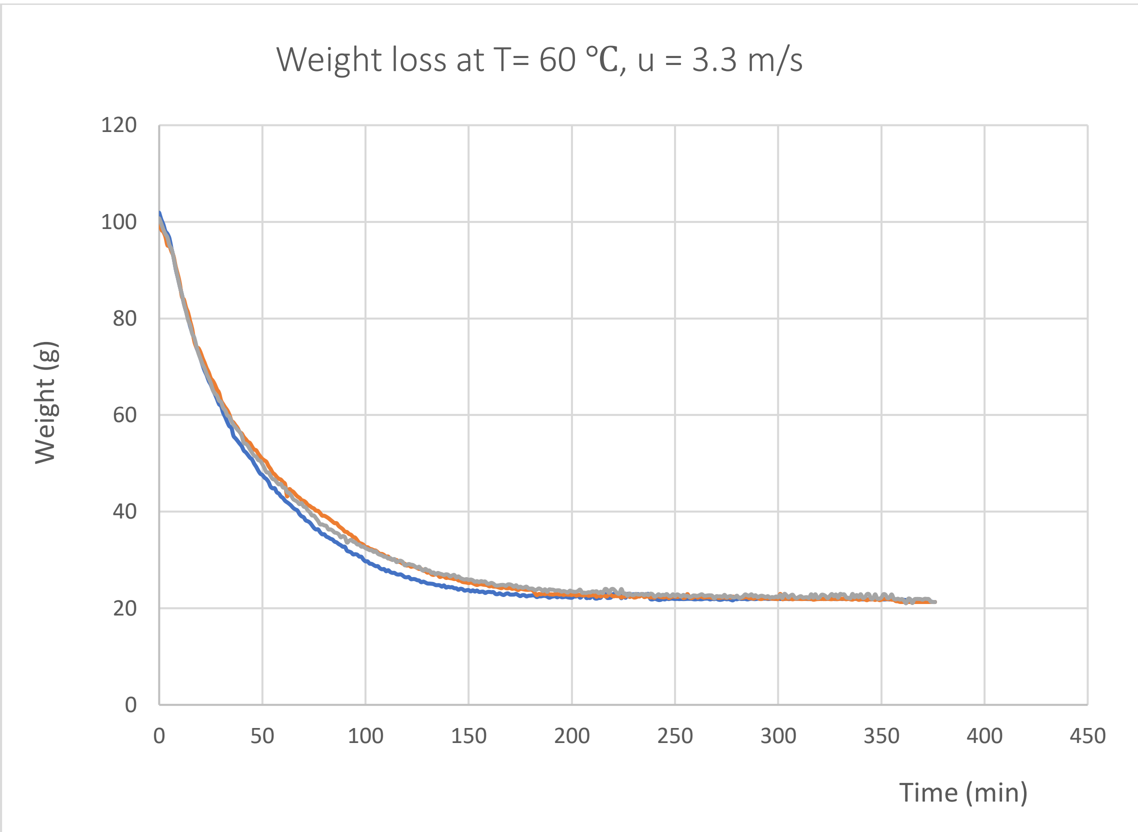

Figure 47. Citric acid treated samples vertical orientated drying curves

Figures 43, 44, 45 and 46 are represents the typical weight loss of the banana samples with respect to time.

After drying, experiments moisture contents of the untreated plane and vertically orientated banana samples were 2.3 % and 2.4 % respectively simultaneously moisture content of citric acid treated plane and vertical banana samples were 1.4 % and 1.54 %. These results showing that citric acid treated samples had better drying rate than untreated one irrespective of orientation.

4.4.1.2 Moisture change drying curves

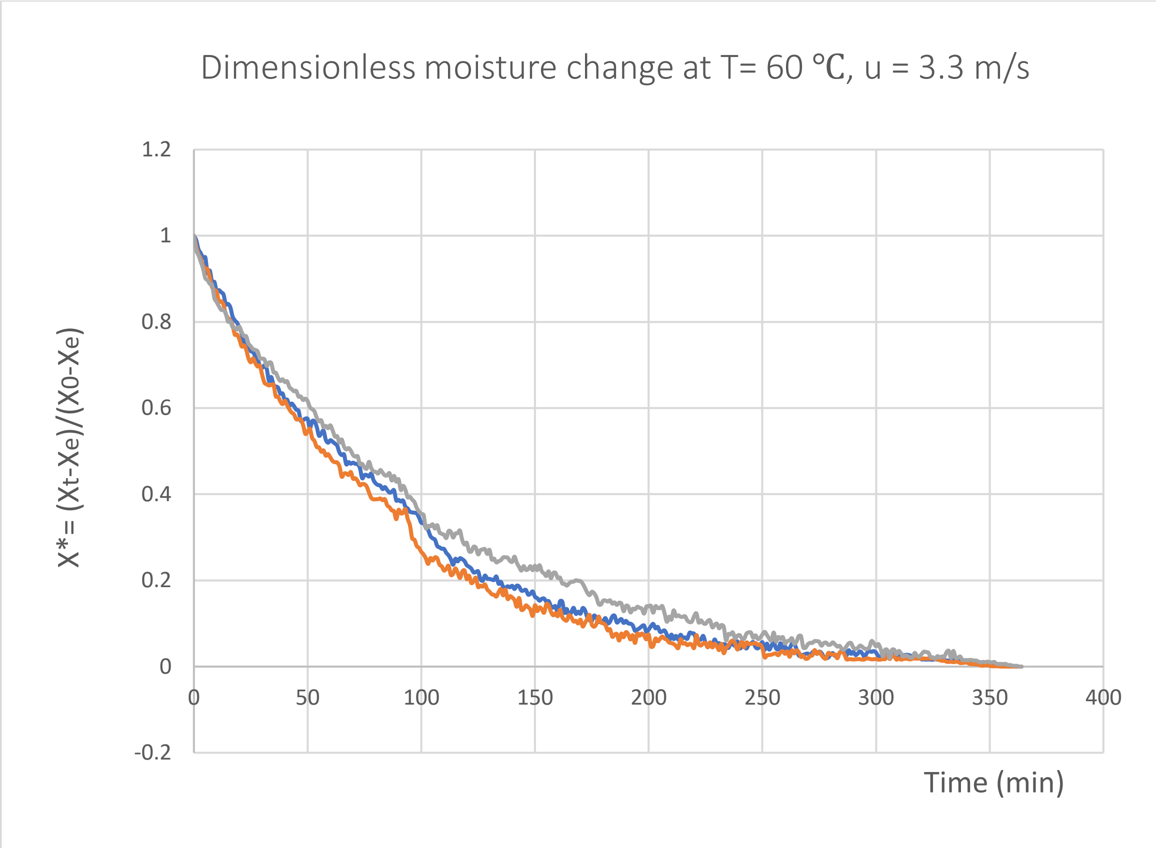

Figure 48. Untreated samples plane orientated drying curves

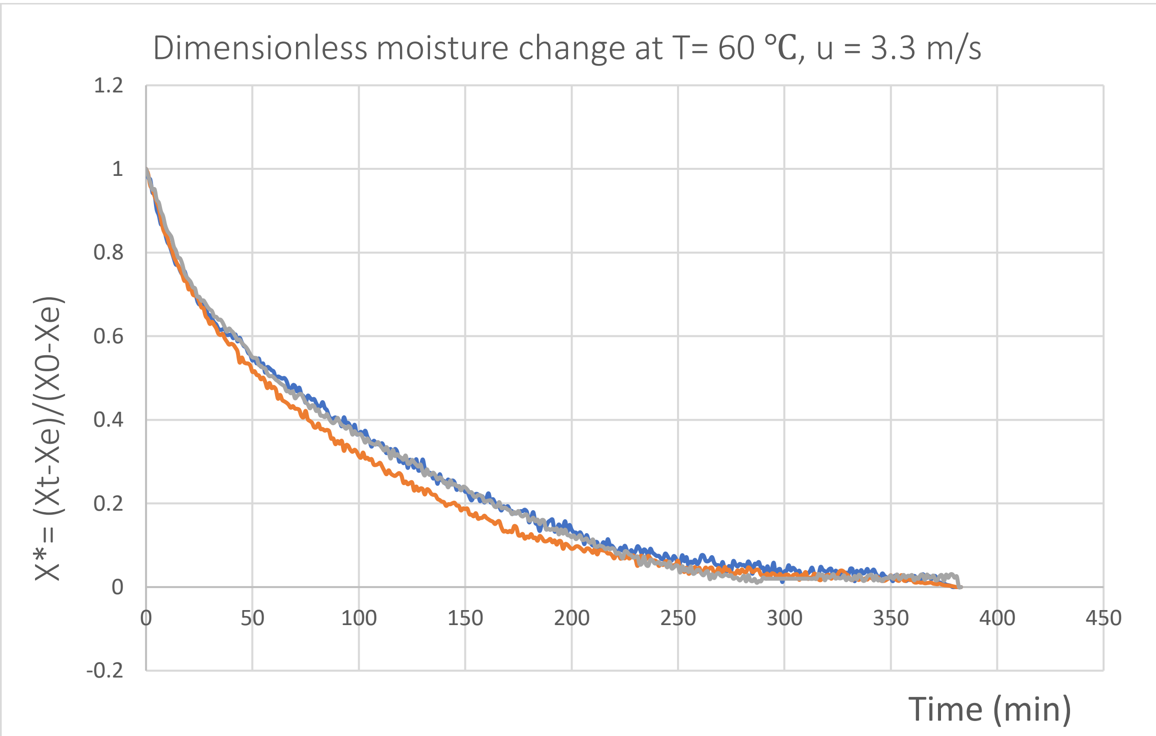

Figure 49. Citric acid treated samples plane orientated drying curves

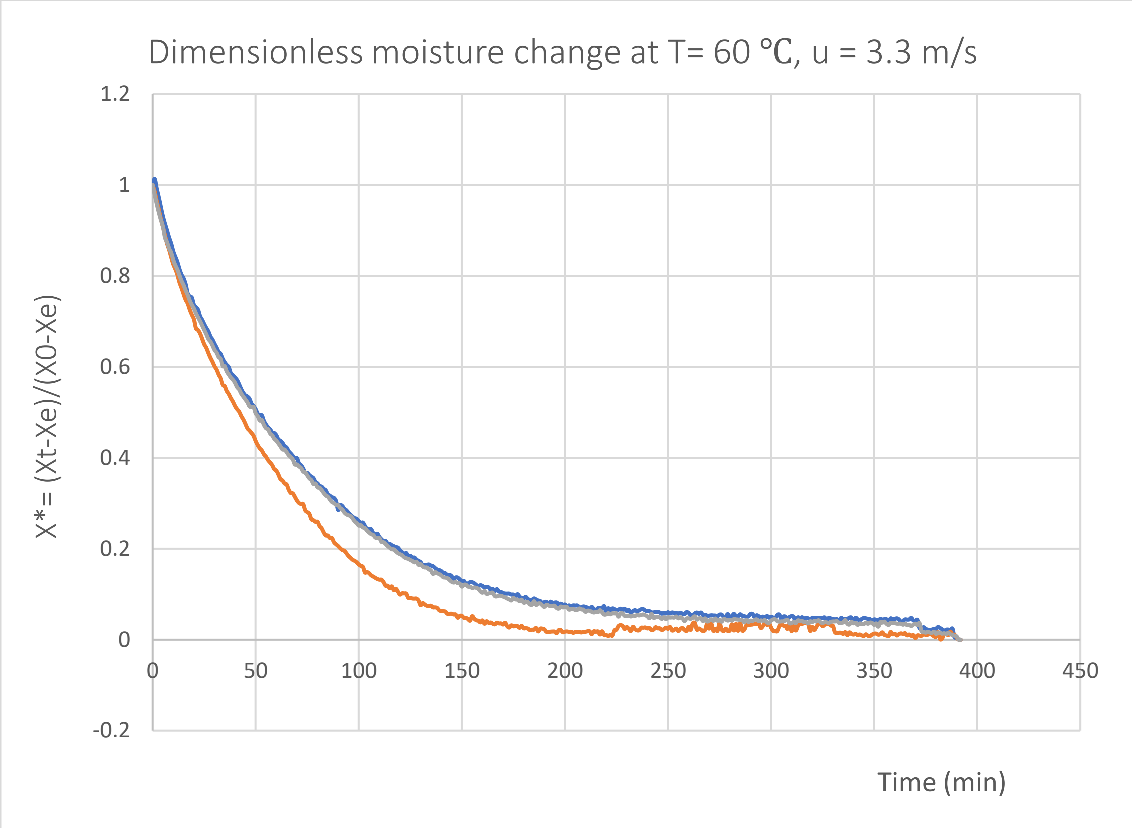

Figure 50. Untreated samples vertically orientated drying curves

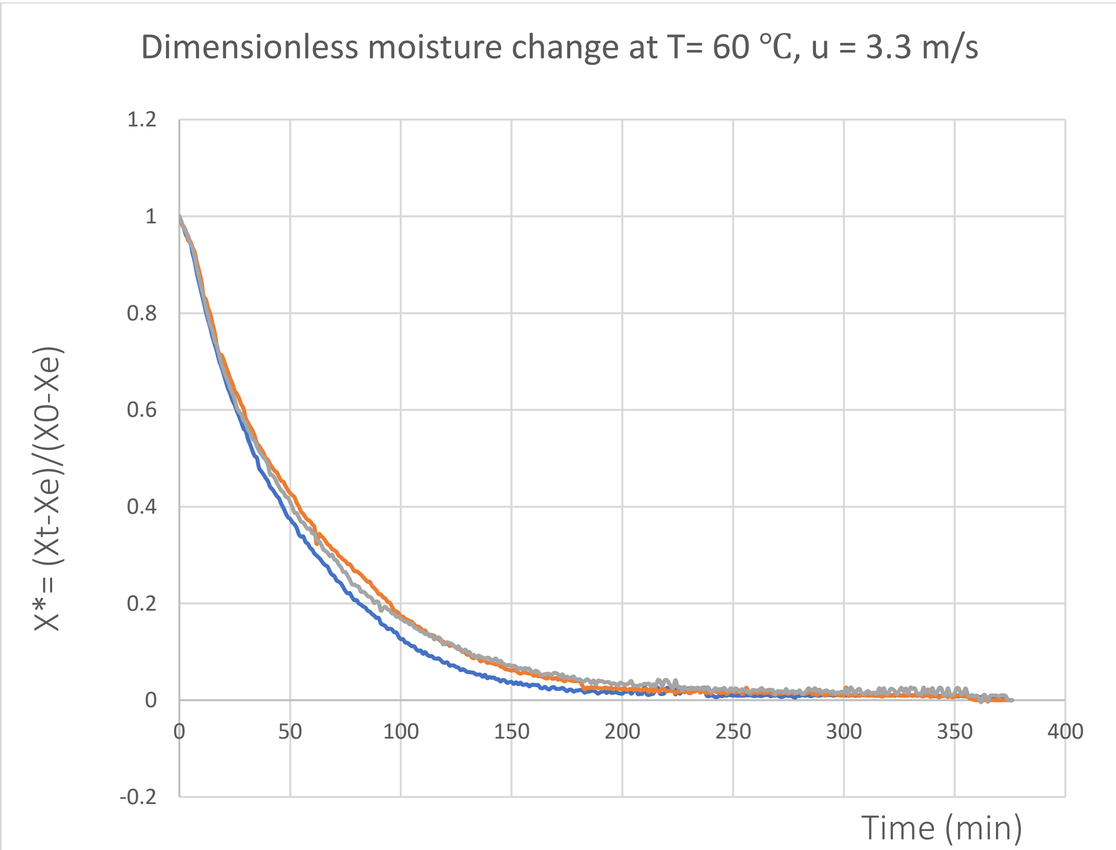

Figure 51. Citric acid treated samples vertically orientated drying curves

Figures 48, 49, 50 and 51 are represents the dimensionless moisture change curves of the banana samples with respect to time. Equation 4.4.1.2-1 used to calculate dimensionless moisture change,

$$X* = \frac{X_t - X_e}{X_0 - X_e} \quad (4.4.1.2\text{-}1)$$

Where X*: Unaccomplished moisture change (dimensionless)

X_t: Moisture content of a material at that present time, kg/kg db

X_e: Equilibrium moisture of a material, kg/kg db

X_0: Initial moisture content of a material, kg/kg db

- To reach 2.3% of moisture content, 300 min of drying time required in untreated plane orientated banana samples.
- To reach 1.4 % of moisture content, 280 min of drying time required in citric acid treated plane orientated banana samples.
- To reach 2.4 % of moisture content, 220 min of drying time required in untreated vertically orientated banana samples.
- To reach 1.54% of moisture content, 180 min of drying time required in citric acid treated vertically orientated banana samples.

Based on moisture content and drying time, citric acid treated vertically orientated samples got better results in these experiments at the temperature of 60 ℃ and velocity 3.3 m/s.

Vertical orientation samples got better results than plane orientation.

Citric acid treatment helps for quicker drying.

4.4.2 Colour

Visual observation of dried banana slices revealed that orientation had no effect unlike citric acid treatment. Banana slices were white-yellowish for untreated samples after drying experiment and when days passed white colour started to domination with irrespective of orientation. Banana slices were yellow-brownish for citric acid treated samples and when days passed it wasn't much change in colour with irrespective of orientation.

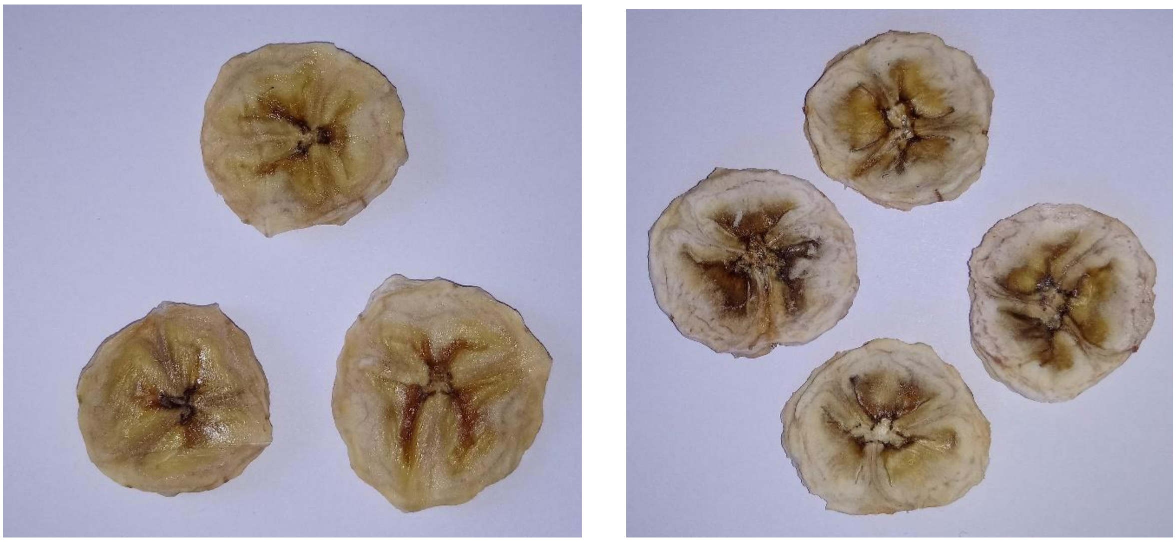

Figure 52. Untreated samples, a. After drying, b. Several days later drying

4.4.3 Shape and dimension

Shrinkage during drying is attributed to moisture removed and developing stresses (Ketelaars, Jomaa, Puigalli, & Coumanas,1992). Two principle parameters diameter and thickness were reduced by drying. These changes were almost similar for both citric acid treated and untreated samples but orientation had significant effect on shape. When it comes to orientation, some of dried banana samples by vertical orientation were damaged. Plane orientated dried banana samples were good looking and attractive compare to vertical one. Final dimension of the dried samples were for diameter in range from 28 – 30 mm and thickness in range from 1 – 2 mm.

4.4.4 Mathematical model

In general, the diffusion equation for the modelling of mass transfer in a material with cartesian, cylindrical, or spherical coordinates is solved for one dimension to simplify the solution. This corresponds to assuming the material as a regular geometry with one centre of symmetry such as infinite slab, infinite cylinder or sphere. Though the sample can be prepared in a perfect infinite slab, infinite cylinder, or sphere, the justification or the error involved in considering only the one-directional transfer during the process is not provided. Turhan and Erdogdu (2002) presented charts giving the extent of error in assuming a finite regular geometry as an infinite one as a function of Fourier (*Fo*) and Biot (*Bi*) number during transient mass or heat transfer process.[5]

The general diffusion equation (4.4.4-1) can be solved analytically through separation of variables technique by using boundary conditions (4.4.4-2 to 4.4.4-3),

$$\frac{\partial X}{\partial t} = D_{eff}\frac{\partial^2 X}{\partial x^2} \qquad (4.4.4\text{-}1)$$

$$X = X_0 \qquad t = 0 \quad x = x \qquad (4.4.4\text{-}2)$$

$$X = X_e \qquad t = t \quad x = h/2 \qquad (4.4.4\text{-}3)$$

$$\frac{d}{dx} = 0 \qquad t = t \quad x = 0 \qquad (4.4.4\text{-}4)$$

The volume averaging converts the coordinate and time dependent moisture constant into a time dependent one (Crank, 1975).

$$\frac{X_t - X_e}{X_0 - X_e} = X* = \frac{8}{\pi^2}\sum_{n=0}^{n=\infty}\frac{1}{(2n+1)^2}exp\left(-\frac{(2n+1)^2\pi^2}{4}Fo\right) \qquad (4.4.4\text{-}5)$$

$$Fo = \frac{D_{ff}t}{h_c^2} \qquad (4.4.4\text{-}6)$$

Where D_{eff} is effective moisture diffusivity (m^2/s); x is cartesian coordinate (m); X_0 is initial moisture content (kg/kg db); X_e is equilibrium moisture content (kg/kg db); h is thickness of a dried material (m); t is time; h_c is characteristic dimension (volume/area).

Model 1: Small modification of 4.4.4-5 considering only first element of expansion

For long time drying, first term of equation 4.4.4-5 is good enough for estimating the average moisture content in the infinite slab (Geankoplis, 1993).

At t = 0, X* should approach to one

$$X * theoritical = A \frac{8}{\pi^2} exp\left(-\pi^2 \frac{D_{eff}t}{h_c^2}\right) \quad (4.4.4\text{-}7)$$

A = error eliminating constant = 1.23

h_c = h, for plane orientated cylindrical banana slices

h_c = h/2, for vertically orientated cylindrical banana slices

Model 2: Considering extension of the mass transfer areas lateral surface of cylinder

At t = 0, X* should approach to one

$$X * theoritical = A \frac{8}{\pi^2} exp\left(-\pi^2 \frac{D_{eff}t}{h_c^2}\right) \quad (4.4.4\text{-}8)$$

A = error eliminating constant = 1.23

Considering that, h_c is function of both longitudinal surface and lateral surface (πDh)

Volume of cylinder (V_{cy}) = $\frac{\pi D^2}{4} h$

Surface area (S_{cy})= $2\left(\frac{\pi D^2}{4}\right) + \pi Dh$

V_{cy} / S_{cy} = $\frac{\frac{\pi D^2}{4}h}{\left(\frac{\pi D^2}{4}\right)+\pi Dh}$ = $\frac{\frac{D}{4}h}{\left(\frac{D}{4}\right)+h}$ = $\frac{\frac{32}{4}4}{\left(\frac{32}{4}\right)+4}$ = 2.667 mm = 0.002667 m = h_c (for plane orientation)

V_{cy} / S_{cy} = $\frac{\frac{\pi D^2}{4}h}{\left(\frac{\pi D^2}{4}\right)2+\pi Dh}$ = $\frac{\frac{D}{4}h}{\left(\frac{D}{2}\right)+h}$ = $\frac{\frac{32}{4}4}{\left(\frac{32}{2}\right)+4}$ = 1.6 mm = 0.0016 m = h_c (for vertical orientation)

Model 3:

General diffusion equation of First 5 terms of equation 4.4.4-5 for estimating the average moisture content in the infinite slab.

$$X * theoritical = \frac{8}{\pi^2}\sum_{n=0}^{n=4}\frac{1}{(2n+1)^2}exp\left(-\frac{(2n+1)^2\pi^2}{4}\frac{D_{eff}t}{h_c^2}\right) \quad (4.4.4\text{-}9)$$

$$X * theoritical = \frac{8}{\pi^2}exp\left(-\frac{\pi^2}{4}\frac{D_{eff}t}{h_c^2}\right) + \frac{8}{9\pi^2}exp\left(-\frac{9\pi^2}{4}\frac{D_{eff}t}{h_c^2}\right) + \frac{8}{25\pi^2}exp\left(-\frac{25\pi^2}{4}\frac{D_{eff}t}{h_c^2}\right) + \frac{8}{49\pi^2}exp\left(-\frac{49\pi^2}{4}\frac{D_{eff}t}{h_c^2}\right) + \frac{8}{81\pi^2}exp\left(-\frac{81\pi^2}{4}\frac{D_{eff}t}{h_c^2}\right) \quad (4.4.4-10)$$

Considering that, h_c is function of both flat surface and curved surface (πDh)

Volume of cylinder (V_{cy}) = $\frac{\pi D^2}{4}h$

Surface area (S_{cy})= $2\left(\frac{\pi D^2}{4}\right) + \pi Dh$

V_{cy} / S_{cy} = $\frac{\frac{\pi D^2}{4}h}{\left(\frac{\pi D^2}{4}\right)+\pi Dh}$ = $\frac{\frac{D}{4}h}{\left(\frac{D}{4}\right)+h}$ = $\frac{\frac{32}{4}4}{\left(\frac{32}{4}\right)+4}$ = 2.667 mm = 0.002667 m = h_c (for plane orientation)

V_{cy} / S_{cy} = $\frac{\frac{\pi D^2}{4}h}{\left(\frac{\pi D^2}{4}\right)2+\pi Dh}$ = $\frac{\frac{D}{4}h}{\left(\frac{D}{2}\right)+h}$ = $\frac{\frac{32}{4}4}{\left(\frac{32}{2}\right)+4}$ = 1.6 mm = 0.0016 m = h_c (for vertical orientation)

Equation (4.4.4-10) in function form of time and diffusivity,

For vertical orientated samples:

f(t) = A*0.81*exp (-963828.5548*D_{eff}*t) + 0.09*exp (-8674456.993* D_{eff} *t) + 0.032*exp (-24095713.87* D_{eff} *t) + 0.0165*exp (-47227599.18 * D_{eff} *t) + 0.001*exp (-78070112.94* D_{eff} *t)

A = error eliminating constant = 1.0623

For plane orientated samples:

f(t) = 0.81*exp (-346891.5514* D_{eff} *t) + 0.09*exp (-3122023.963* D_{eff} *t) + 0.032*exp (-8672288.785 * D_{eff} *t) + 0.0165*exp (-16997686.02* D_{eff} *t) + 0.001*exp (-28098215.66* D_{eff} *t)

A = error eliminating constant = 1.0623

4.4.4.1 Regression analysis

The goal of the regression analysis is to find a model function and suitable parameters, which fit the measured data best:

- Linear model function – “easy to find the fit parameters”.
- Nonlinear model function – “not so easy to find fit parameters”.
- Minimizing the sum of squares of residuals.
- Finding the accuracy of parameters, confidence intervals.
- Comparing various models (different number of parameters, different model function). [3]

4.4.4.2 Effective moisture diffusivity values

The effective diffusivity for the drying samples was estimated at the beginning of the calculation. Further, the optimal value of the effective diffusivity was obtained by several iterations. Diffusivity values were listed in following tables from different model 1, model 2, model 3.

No.	Type – Model 1	$D_{ff}(m^2/s)$
1.	Plane orientated untreated samples	12.6×10^{-10}
2.	Plane orientated citric acid treated samples	12.9×10^{-10}
3.	Vertically orientated untreated samples	4.15×10^{-10}
4.	Vertically orientated citric acid treated samples	4.9×10^{-10}

Table 7. Effective moisture diffusivity values from model 1

No.	Type – Model 2	D_{eff} (m^2/s)
1.	Plane orientated untreated samples	5.56×10^{-10}
2.	Plane orientated citric acid treated samples	5.83×10^{-10}
3.	Vertically orientated untreated samples	2.65×10^{-10}
4.	Vertically orientated citric acid treated samples	3.36×10^{-10}

Table 8. Effective moisture diffusivity values from model 2

No.	Type – Model 3	D_{eff} (m^2/s)
1.	Plane orientated untreated samples	4.63 X 10^{-10}
2.	Plane orientated citric acid treated samples	4.71 X 10^{-10}
3.	Vertically orientated untreated samples	2.23 X 10^{-10}
4.	Vertically orientated citric acid treated samples	2.69 X 10^{-10}

Table 9. Effective moisture diffusivity values from model 3

4.4.4.3 Comparison of the curves

By using excel these curves were plotted. X*experimental values ware taken by averaging laboratory results and X*theoretical valves were taken by regression analysis of models. Model 3 curves were the best fitted curves than model 2 and model 1 curves.

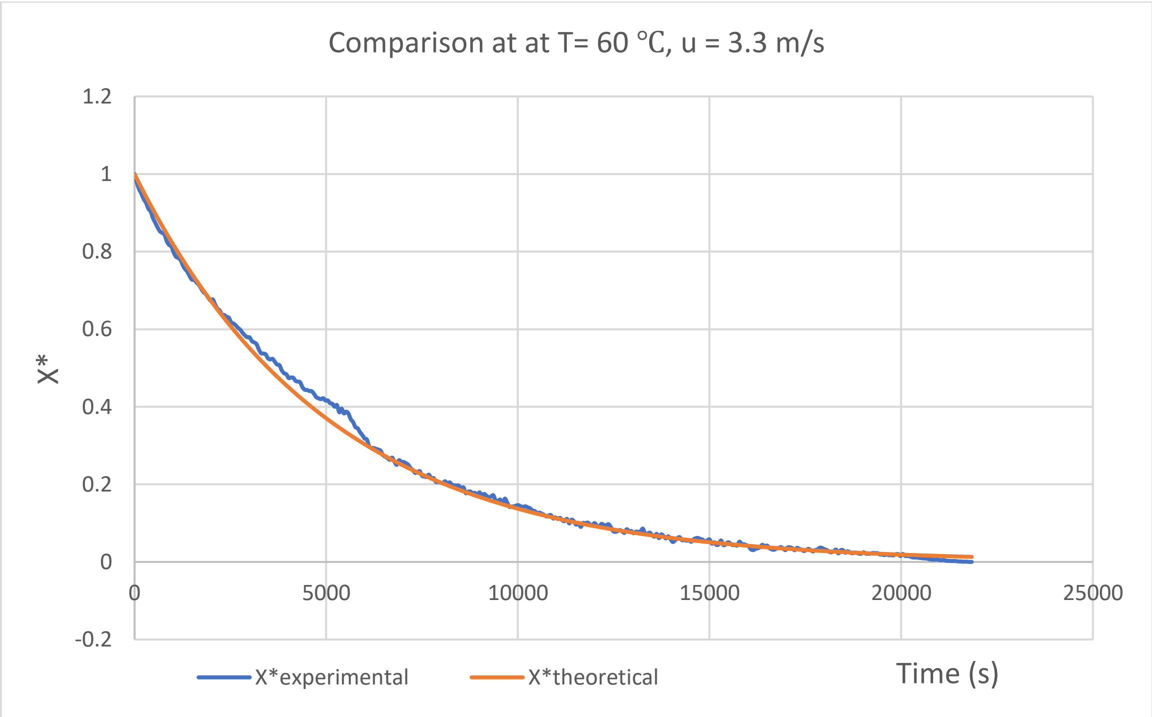

Figure 53. Untreated samples plane orientated drying curves from model 3

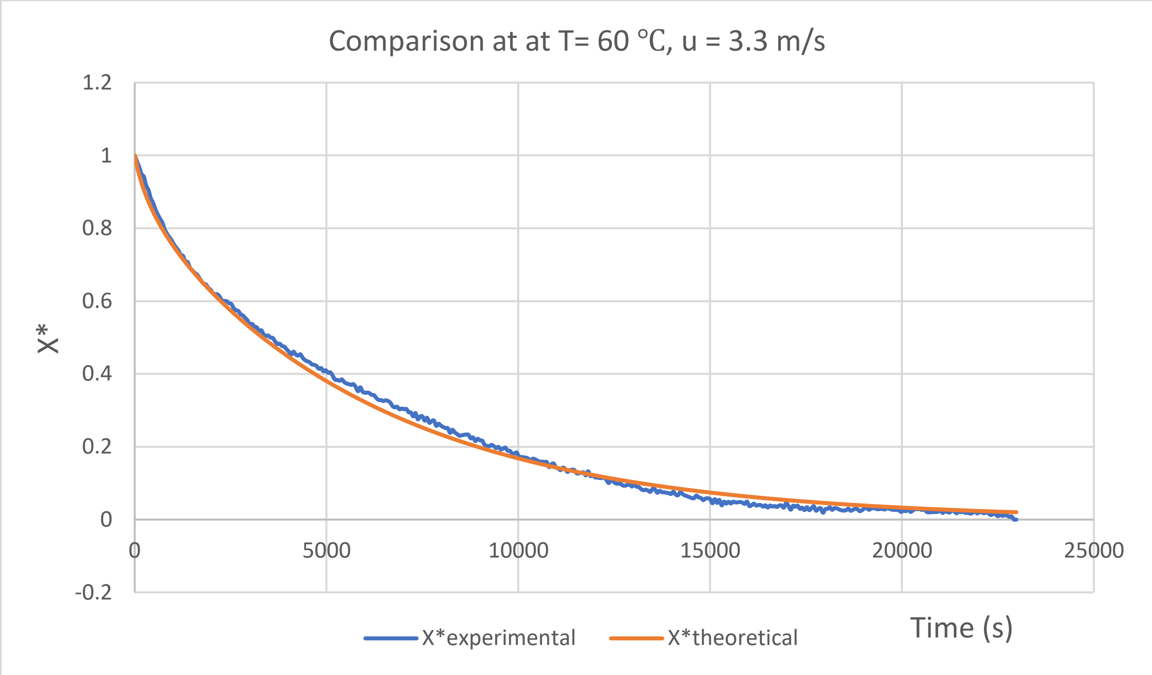

Figure 54. Citric acid treated samples plane orientated drying curves from model 3

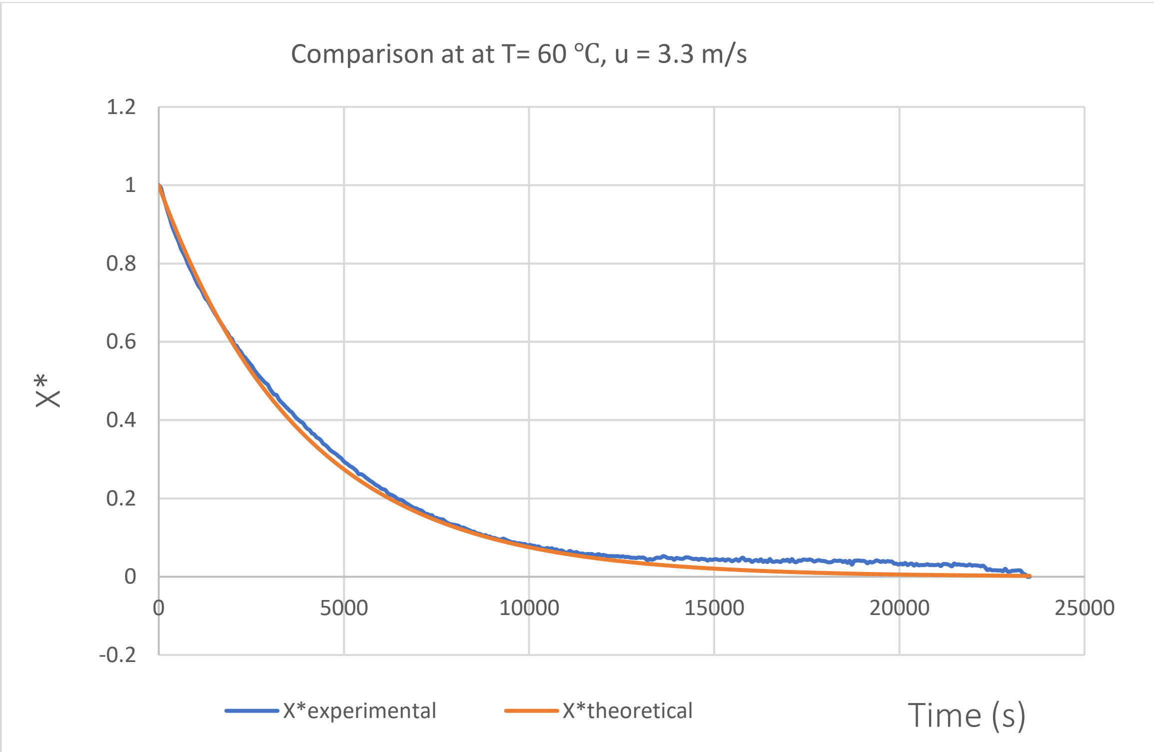

Figure 55. Untreated samples vertically orientated drying curves from model 3

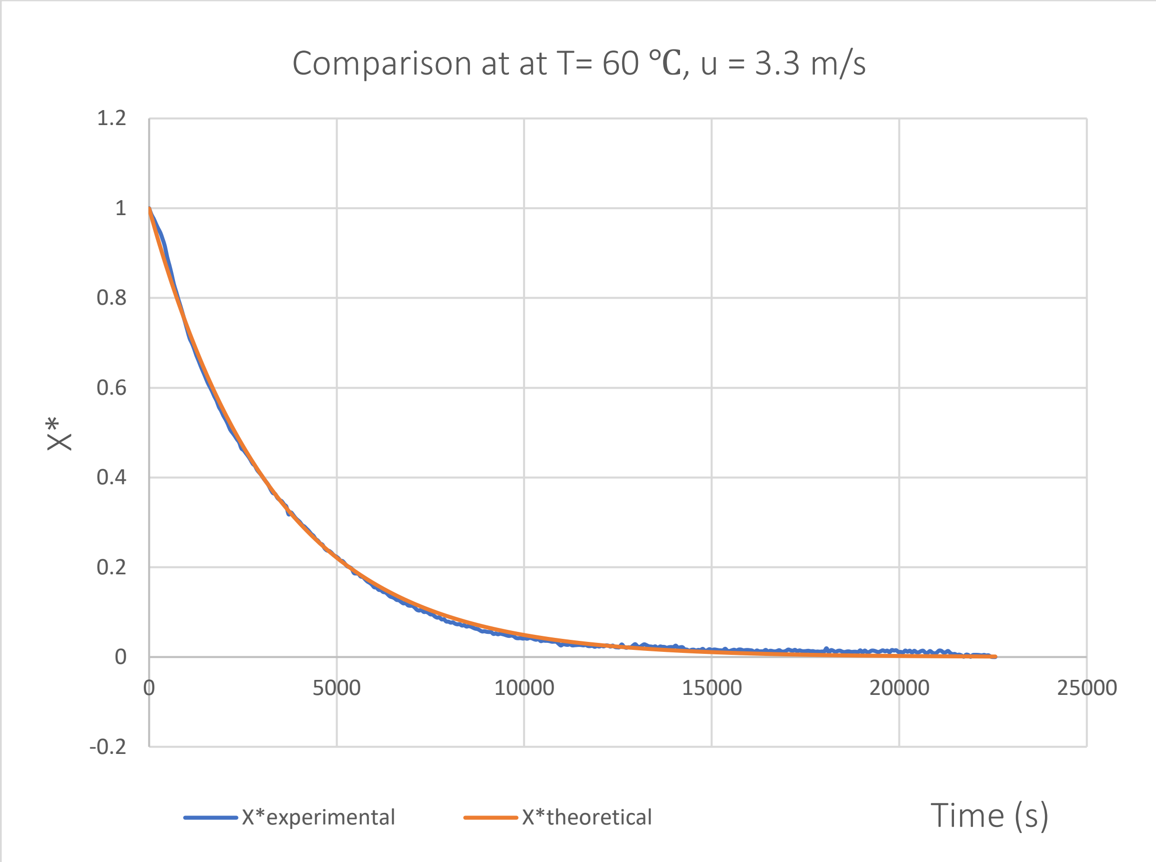

Figure 56. Citric acid treated samples vertically orientated drying curves from model 3

Citric acid treated vertical orientated curves were fitted perfectly compare to other three types at temperature 60 ℃ and velocity 3.3 m/s.

4.4.4.4 Analysis on D_{eff} results

From experimental results, it was clear that $t_{plane\ orien} > t_{vertical\ orien}$ but when it comes to D_{eff} results $D_{eff,\ plane\ orien} > D_{eff,\ vertical\ orien}$

Following points may reasons for this quit different results:

- Material shrinkage is one of the main factors which effects the diffusivity. Equation 4.4.4-5 didn't considered effect of material shrinkage. After experiments material thickness was between 1 to 2 mm.
- Porosity is a fraction of the volume of voids over the total volume, which effects diffusivity. Equation 4.4.4-5 didn't considered this effect.

- If Bi > 10, the internal transfer is dominant, If Bi < 0.1, the surface moisture transfer is dominant. The process is controlled by both mass transfer coefficients in air and material, Equation 4.4.4-5 didn't considered this effect.
- Humidity of air and moisture content in the material both are effective factors, humidity of air didn't measure in experiments.
- For vertical orientation, moisture transfer occurs homogenously in both directions from centre point but in the case of plane orientation internal moisture transferring from bottom crust to centre then centre to top surface in single direction. Equation 4.4.4-5, didn't explained this phenomenon.
- Measuring error in experiments.

Citric acid treated samples had higher effective moisture diffusivity than untreated banana samples irrespective of orientation. Based on experimental results and regression analysis concluded that citric acid treated vertically oriented samples arrangement is the suitable option to design food convective dryer. It conforms the results of [6] and [1].

5 Design of convective dryer

From the best of experimental results, I can proceed to actual calculation of balance and determine the dimensions of Batch, layer type convective dryer. To reach equilibrium moisture content, 180 min (3 hours) of drying time required in citric acid treated vertically orientated banana samples. (from experiments these values are effective)

Selected data according to experimental measurements,

- Amount of the material to dry — M_1 = 100 kg/h = 300 kg/per loop
- Initial moisture content of sample — ω_0 = 79.12%
- Final moisture content of sample — ω_1 = 1.54%
- Relative humidity of inlet air — ϕ_{A0} = 65%
- Ambient air temperature — T_{A0} = 20°C
- Temperature after heating — T_{A1} = 60°C
- Outlet temperature — T_{A2} = 50°C

5.1 Balance of drying

5.1 Balance of drying

From figure 57.,

- Specific humidity — $X_{A0} = X_{A1}$ = 0.0095 kg H_2O/kg

  X_{A2} = 0.0135 kg H_2O/kg

- Specific enthalpy — h_{A0} = 44 kJ/ kg

  h_{A1} = 85 kJ/kg

- The amount of dried material:

$$M_2 = M_1 \times \left(\frac{1-\omega_0}{1-\omega_1}\right) = 100 \times \left(\frac{1-0.7912}{1-0.0154}\right) = 21.2 \text{ kg/h} = 63.6 \text{ kg/per loop}$$

- The amount of dried moisture:

  $M_W = M_1 - M_2$ = 100 – 21.2 = 78.8 kg/h = 236.4 kg/per loop

➢ Necessary amount of drying air:

$M_A = \frac{M_W}{x_{A2}-x_{A1}} = \frac{78.8}{0.0135-0.0095}$ = 19700 kg/h = 5.47 kg/s

➢ The heat required to heat up drying air:

$Q_A = M_A \times (h_{A1} - h_{A2})$ = 5.47 × (85-44) = 224.27 kW

Considering that air is heated in calorifiers by condensed steam 200 kPa and 120 °C.

Evaporated heat steam = 2201 kJ/kg (Neglecting the heat loss)

➢ The amount of heating steam required to heat the drying air:

$M_s = \frac{Q_A}{\gamma_{TP}}$ = $\frac{224.27}{2201}$ = 0.1019 kg/s = 366.82 kg/h = 1100.46 kg/per loop

➢ The final check of the amount of moisture that is dissipated in the drying air:

$M_{WA} = M_A \times (x_{A2}-x_{A1})$ =19700 × $(0.0135 - 0.0095)$ = 78.8 kg/h = 236.4 kg/per loop

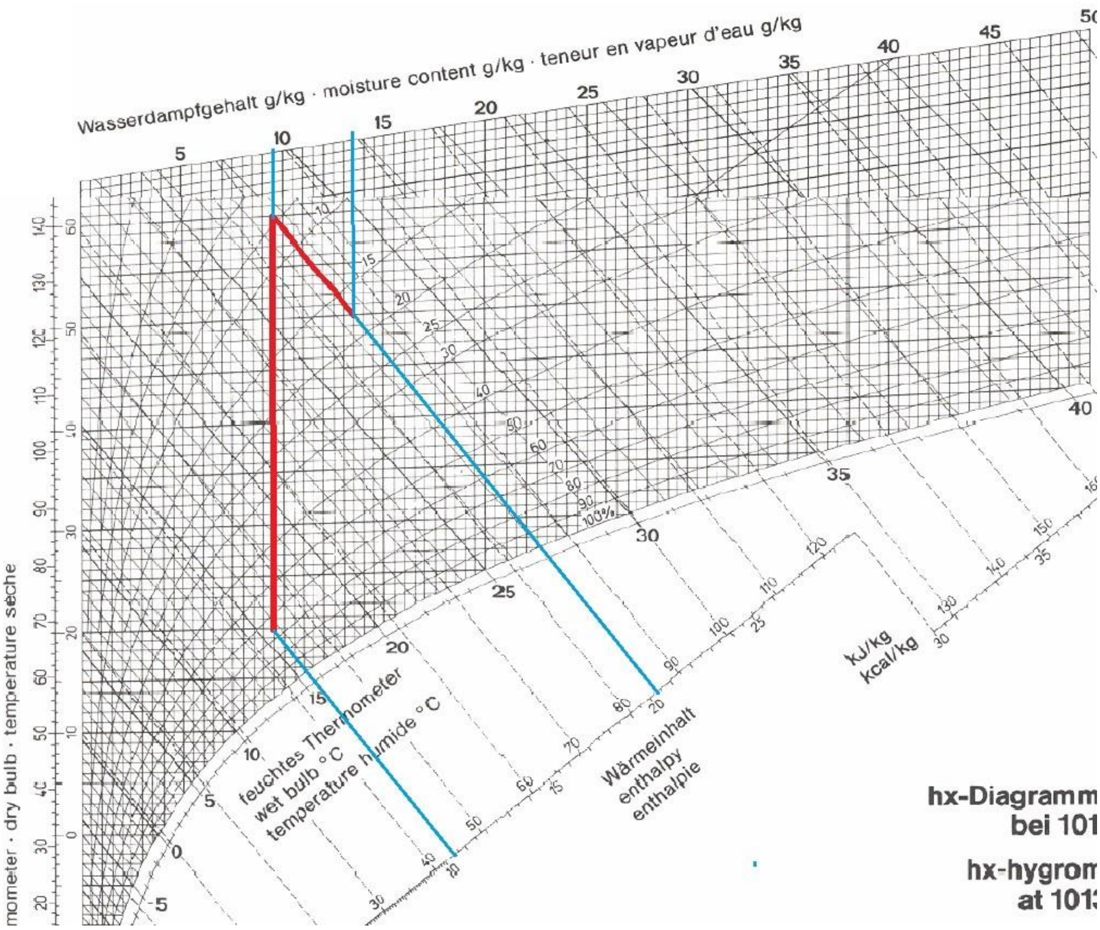

Figure 57. h-x diagram for drying

5.2 Dimension of the chamber dryer (Layer type)

This section involves the basic calculation of chamber dryer size. The dimensions of the dryer were calculated for the M_1=100 kg/h (300 kg) drying material (banana slices) flow rate.

5.2.1 Single layer from laboratory

- Dimensions of single layer are 150 mm x 100 mm x 250 mm (width x height x length).
- Height 100 mm includes banana slices height safe distance for moisture transfer between two layers.
- Number of columns that banana slices can arrange in 150 mm width with safe distance are 12.
- Number of rows that banana slices can arrange in 250 mm length with safe distance are 5.
- Weight of 1 untreated banana slice (h = 4 mm, d = 32 mm, ρ = 0.83 g/cm^3) = 2.69 g = 0.00269 kg and after citric acid treatment it was 3.32 g.
- On average basis from 3 experiments, weight of 30 citric acid treated samples was (W_{lab}) 100 grams.

5.2.2 Drying chamber dimensions calculation

- Volumetric flow rate of air

$$\dot{V} = u \times S = u \times (a \times b) \tag{5.2.2-1}$$

- $\rho_{air}\ at\ 60\ °C = 1.06$ kg/m^3, $M_A = 5.47\ kg/s$ and $\bar{u} = 3.3\ m/s$.

$$S = \frac{\dot{V}}{u} = \frac{\rho_{air}}{\bar{u} \times M_A} = \frac{5.47}{1.06 \times 3.3} = 1.56 \text{ m}^2$$

- Height of the drying chamber (a) = 1 m = 1000 mm, 10 layers can arrange by this arrangement.
- S = $a \times b$, from this width of the drying chamber (b) =1.56 m = 1560 mm.
- Number of columns that can arrange in this width = $\frac{1560 \times 12}{150}$ = 124.8 = 125.
- To arrange one row of samples, 50 mm of length taken.
- Weight of one row samples with 10 layers = (W_{one}) = 10 × 125 × 3.32 = 4150 g.

- Number rows required to arrange 300 kg of samples in 10 layers

$$= \frac{300 \times 1000}{4150} = 72.289 = 73$$

- Total length of drying chamber required to arrange 300 kg of samples in 10 layers

$$= 73 \times 50 = 3650 \text{ mm}$$

To dry 300 kg of banana samples at the temperature of 60 ℃ and velocity 3.3 m/s required dimensions of drying chamber (height x width x length) are 1000 mm x 1560 mm x 3650 mm or 1 m x 1.56 m x 3.65 m.

Conclusion

The aim of the thesis was to design the suitable food convective dryer for selected material and operation parameters based on the literature search and by analysing my own laboratory results.

First general information about the fundamentals of the drying processes was described. The objective of literature search is to select suitable parameters for current thesis and getting knowledge about transport phenomena during the drying, drying kinetics and drying models.

As an initiative step before laboratory experiments velocity field around the banana samples was analysed by CFD software ANSYS FLUENT. Velocity field around the samples in both orientations doesn't change dramatically for selected span of samples. Therefore, it is expected that all samples will be dried uniformly with no effect of velocity field deformation by samples body. Velocity field around the samples varying between 2.6 m/s to 2.9 m/s.

Two kind samples were investigated. Untreated and citric acid treated banana slices were dried. From Experimental part it can be concluded that citric acid treated samples had better drying rate than untreated one irrespective of orientation. Based on moisture content and drying time, citric acid treated vertically orientated samples got better results at the temperature of 60 °C and velocity 3.3 m/s. Overall vertical orientation samples got better results than plane orientation and citric acid treatment helps for quicker drying. Diffusion coefficient of banana slices obtained by mathematical analysis of the drying kinetics with an arrangement of fitting parameters from literature.

Citric acid treated vertical orientated curves were fitted perfectly compare to other three types at temperature 60 °C and velocity 3.3 m/s. Citric acid treated samples had higher effective moisture diffusivity than untreated banana samples irrespective of orientation. Based on experimental results and regression analysis concluded that citric acid treated vertically oriented samples arrangement is the suitable option to design food convective dryer.

For demanded production of the new production line, the layer dryer was designed according to experiences from experiments. Dimension of the dryer are 1 m x 1.56 m x 3.65 m. The mass and heat transfer balance were calculated for the proposed layer type dryer with results of required airflow and amount of steam for heat supply.

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List of symbols

a, b, c	Drying chamber parameters (height, width, length)	(m)
A, B	Fitting parameter of drying model	(-)
a_w	Water activity	(-)
Bi	Biot number	(-)
D_{eff}	Effective moisture diffusivity	($m^2/2$)
D	Diameter of material	(m)
E_a	Activation energy for diffusion	(kJ/kmol)
h	Thickness of a material	(m)
h_c	Characteristic dimension (volume/area)	(m)
$h_{A,S}$	Specific enthalpy	(kg_{H20}/kg)
M_{ws}	Mass of wet solid	(kg)
M_s	Mass of water content	(kg)
M_w	Mass content of dry solid.	(kg)
M_e	Equilibrium moisture content	(kg/kg db)
M_i	Initial moisture content	(kg/kg db)
M_t	Moisture content at point of time	(kg/kg db)
MR	Dimensionless moisture ratio	(-)
Nu	Nusselt number	(-)
$p^{''}$	Partial pressure	(kPa)
$p^{''}_{H_2O}$	Partial vapor pressure of water	(kPa)
Pr	Prandtl number	(-)
Q_A	Heat transfer	(J/s)
R	Gas constant	(kJ/kmol K)
R^2	Coefficient of reliability	(-)

Re	Reynolds number	(-)
t	Time	(s)
T	Temperature	(K)
X	Moisture content	(kg/kg db)
X_0	Initial moisture content	(kg/kg db)
X_e	Equilibrium moisture content	(kg/kg db)
X_{cr}	Critical moisture content	(kg/kg db)
X*	Dimensionless moisture ratio	(-)
X*theoretical	Dimensionless moisture ratio obtained analytically	(-)
X*experimental	Dimensionless moisture ratio obtained from experiments	(-)
u	Velocity	(m/s)
$\dot{V}$	Volumetric flow rate	(m^3/s)
x, y, z	Cartesian coordinates	(m)

Greek symbols

α	Mass transfer coefficient	(m/s)
β	Heat transfer coefficient	(W/m^2K)
γ	Thermal conductivity	(W/mK)
ρ	Density	(kg/m^3)
μ	Dynamic viscosity	(-)
ν	Kinematic viscosity	(m^2/s)
χ^2	Reduced chi-square	(-)
ω	Moisture content	(kg)
ϕ_A	Relative humidity of air	(-)

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