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The thesis presents the design of the belt dryer for drying of the lump sugar. As a starting point, the theoretical fundamentals related to the drying process and a transport phenomenon during drying was carefully explained. Drying experiments using the three different temperatures and two drying air velocities were performed for the sugar cubes with 3% of the initial moisture content. Thus, on the basis of drying curves the regression analysis was made to obtain diffusion coefficient. Thereafter the 2D simulation of one sugar cube was modeled by using the computational fluid dynamics (CFD) software ANSYS FLUENT. Through this step, the temperature distribution and velocity field of drying air were analyzed. Drawing on analogy of the heat and mass transfer research, the experimental and numerical results were compared. The findings support the calculation of the basic dimension of a belt dryer.

Keywords: belt dryer, lump sugar (sugar cubes), drying curves, CFD simulation, regression analysis, laboratory experiments, analogy of the heat and mass transfer.

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

Declaration

I confirm that the master‘s thesis 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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Content

1 Theoretical part

1.1 Introduction to the drying

Many kinds of the raw materials for the food industries contain the significant amounts of the water. During the flow of the technological processes often occurs a moisturizing of the product. This can lead to the biochemical, microbiological and enzymatic changes that cause spoilage of the product. However, to consume the food products for a long time, keeping the required level of the nutritional quality and the portability, they should contain a minimum amount of the moisture. Therefore, the process of the dehydration meets for the food durability prolongation.

Drying is the one of the oldest preservation process that is known from ancient times. Perhaps it is the oldest, the most various and common, the cost-effective engineering unit operations. Also drying is fundamental process that is found in many industrial branches such as chemical, pharmaceuticals and agricultural, wood processing industries, ceramics, biotechnology etc.

1.2 Drying process

Drying is a complex operation that involves a transient transfer of the heat and mass together with several rate processes (Arun S. Mujumdar, 2015). Drying is removal of the water in form of the vapour from a porous solid to ambient. The vapour transport is driven by the difference of the water vapour pressures p_w at the surface (determined by the state of the drying material) and the partial pressure of the water vapour in a drying medium (air or superheated steam). In addition, it occurs by implementing vaporization of the liquid by supplying heat to the wet feedstock. More detailed scheme is shown in figure 1. Where the wet material enters to the dryer where it heats up by the heated air (superheated stream or flue gas). As a result, there is the moisture evaporation from the material surface.

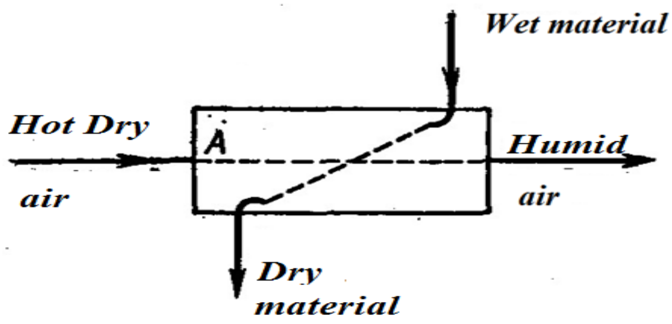


Figure 1. Drying scheme (Chagin O.V, 2007)

During the thermal drying of a wet material two processes occur simultaneously:

1. Energy transfer (primarily in the form of heat) from the environment to evaporate surface moisture
2. Internal moisture transfer to the surface of the solid and its further vaporisation due to the process 1

Process 1, the removal of the water (moisture) as vapour from the material surface, depends on the external conditions of the temperature, the air humidity and flow, the area of drying surface and the 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 the 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
- Vapour diffusion, if the liquid vaporizes within material
- Knudsen diffusion, if drying takes place at very low temperatures and pressures, e.g., in freeze drying
- Surface diffusion (possible although not proven)
- Hydrostatic pressure differences, when internal vaporization rates exceed the rate of the vapour transport through the solid to the surroundings
- Combinations of the above mechanisms (Arun S. Mujumdar ,2015)

More detailed discussion on the internal mechanism of liquid flow is presented in the following paragraphs.

1.3 Drying of food products (Dehydration)

The removal of the moisture from a material is an important part of the food industries. Almost every food product is dried at least once at one stage of its preparation. The main goals of the dehydration are shown below:

- The long shelf life (reducing or stopping of the microorganisms activity)
- Keeping nutritional quality
- Easy transportation
- Further treatment
- Sanitation

1.3.1 Water activity

The one of the reasons which causes the food losses is the effect of the microorganisms. There are three types of the microorganisms:

- Bacteria - unicellular micro-organism (size around c. 0,X - X μm)
- Yeast - kind of fungus (size around c. X0 μm)
- Fungi - mycelium and sporocarp (size around c. >X00 μm)

It is common knowledge that the factors such as temperature, pH, oxygen influence to the growth of the microorganisms in the product. Nevertheless, one should accept the fact that the most important factors in controlling spoilage of the product is the 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.

Mathematical calculation of the water activity:

$$a_w = \frac{P''}{P''_{pH2O}} \quad (1.3.1\text{-}1)$$

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 processes inhibition that depends on the level of the water activity.

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 the yeast
$a_w < 0.90$	Suppressed growth of the pathogenic bacteria except for S Aureus (aerobic)

Table 1. Water activity level [1]

1.3.2 Food dehydration methods

Dehydration process occurs almost in all food processing. The main ways of the moisture removal from the materials is shown in table 2:

Type	Process	Driving force
Mechanical	Sedimentation Centrifuging Filtration	Effect of force field
Hydraulic	Membrane process Extraction Filtration Distillation	Pressure and concentration gradient
Thermal	Drying Evaporation	Temperature gradient

Table 2. Dehydration processes (Chagin.O.V, 2007)

1.3.3 Dried material

It is important to note that the moister content in the material and the way in which the moisture is bonded into the material has greatest impact on drying process. The moisture content can thus be expressed as:

Specific humidity:

$$X_s = \frac{m_{water}}{m_{dry\ material}} \qquad (1.3.3\text{-}1)$$

Relative humidity:

$$\omega = \frac{m_{water}}{m_{wet\ material}} \qquad (1.3.3\text{-}2)$$

1.3.4 Drying media

Drying media are carriers of the heat (in case of convective drying) and the transport tools for the vapours removal.

The most important tools are:

- Humid air: the most usual drying medium.(preferred for the lower temperatures, typically <200°C)
- Superheated steam: it can be considered also as a humid air but with prevailing amount of the water vapours. It has greater heat transfer coefficient (advantageous at high temperatures > 200°C)
- Fumes

1.4 Heating method

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

1.4.1 Convection

Heat is supplied by the heated air or the gas flowing over the surface of the solid and liquid. Heat for the evaporation is supplied by the convection to the exposed surface of the material and the evaporated moisture is carried away by the drying medium. Such dryers are also called the direct dryers. (Arun S. Mujumdar ,2015)

1.4.2 Conduction

Conduction more appropriate for the thin products or for the very wet solids. The heat for the evaporation is supplied through the heated surfaces (stationary or moving) placed within the dryer to support, convey, or confine the solids. The evaporated moisture is carried away by a vacuum operation or by a stream of gas that is mainly a carrier of the moisture. (Arun S. Mujumdar, 2015)

1.4.3 Radiation

This type of drying can, in principle, be nonpenetrating, such as the drying of a paint by infrared radiation, or penetrating, such as the drying of a food or a pharmaceuticals by dielectric drying. Dielectric drying (radio frequency drying and microwave drying) is the only process in which the heat is developed in the material being dried rather than having the heat diffused into the material. Again, a carrier gas is required to remove the evaporated liquid. (Land C.M. van't, 2012)

1.5 Internal mechanism of liquid flow

The structure of the solid determines the mechanism for which the internal liquid flow may occur. These mechanisms can include the diffusion in continuous, homogeneous solids, the capillary flow in granular and porous solids, the flow caused by shrinkage and pressure gradients, the flow caused by gravity, and the flow caused by a vaporization-condensation sequence.

Classification of the basis of capillary and diffusional flow:

- **Capillary Flow** - moisture which is held in the interstices of solids, as liquid on the surface, or as free moisture in cell cavities, moves by gravity and capillarity, provided that passageways for continuous flow are present. In drying, liquid flow resulting from capillarity applies to liquids not held in solution and to all moisture above the fiber-saturation point, as in textiles, paper, and leather, and to all moisture above the equilibrium moisture content at atmospheric saturations, as in fine powders and granular solids, such as paint pigments, minerals, clays, soil, and sand. (Perry Robert.H,1997)
- **Vapour Diffusion** - moisture may move by vapour diffusion through the solid, provided that a temperature gradient is established by heating, thus creating a vapor -pressure gradient. Vaporization and vapour diffusion may occur in any solid in

which heating takes place at one surface and drying from the other and in which liquid is isolated between granules of solid. (Perry Robert.H,1997)

- **Liquid Diffusion** - the movement of liquids by diffusion in solids is restricted to the equilibrium moisture content below the point of atmospheric saturation and to systems in which moisture and solid are mutually soluble. The first class applies to the last stages in the drying of clays, starches, flour, textiles, paper, and wood; the second class includes the drying of soaps, glues, gelatine, and pastes.
- **External Conditions** -the principal external variables involved in any drying study are temperature, humidity, air flow, state of subdivision of the solid, agitation of the solid, method of supporting the solid, and contact between hot surfaces and wet solid. All these variables will not necessarily occur in one problem. (Perry Robert.H,1997)

1.6 Moisture diffusivity during drying and mathematical models

Main parameter of drying such D_{AB} (diffusion coefficient), β (mass transfer coefficient) of specific material was obtained according to the experiments, the results of regression analysis, CFD simulation and analytical solution.

1.6.1 Diffusion equation

The mathematical formulation of mass transfer in porous solids during drying is usually based on a diffusion equation. The effective diffusivity is an overall coefficient describing the moisture flow by liquid, vapour and combined liquid/vapour transport in the porous materials. (Akosman C, 2004)

For infinite slabs, the one-dimensional diffusion equation is written as

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D_{AB}\frac{\partial M}{\partial x}\right) \quad (1.6.1\text{-}1)$$

where M is the moisture content in dry basis (db); D_{AB} is the effective diffusivity (m^2/s); t is the time (s) and x is the Cartesian coordinate of position (m), Lx is the thickness of the sugar cube in the direction of the main mass flux, where the distributions of moisture will be analysed. (Wilton Pereira da Silva, 2013)

1.6.2 Analytical solution of diffusion equation

For an infinite slab, the convective boundary condition is defined in the following way:

$$D_{AB} \frac{\partial M(x,t)}{\partial x}\bigg|_{x=\pm Lx/2} = \beta(M(x,t)|_{x=\pm\frac{Lx}{2}} - M_{eq}) \qquad (1.6.2\text{-}1)$$

in which β is the convective mass transfer coefficient (m/s); *M(x,t)* is the moisture content (dry basis, db) in a position *x* at time *t*; *Meq* is the equilibrium moisture content (db); *Lx* is the thickness of the sugar cube in the direction of the main mass flux, where the distributions of moisture will be analysed.

For an infinite slab with the uniform initial moisture content M_0 and the boundary condition defined by Equation (1.6.2-1), the analytical solution *M(x,t)* of Equation (1.6.1-1) is given by

$$M(x,t) = M_{eq} + (M_0 - M_{eq}) \sum_{n=1}^{\infty} A_n \cos\left(\mu_n \frac{x}{\frac{Lx}{2}}\right) \exp\left(-\frac{\mu_n{}^2}{\left(\frac{Lx}{2}\right)^2} D_{AB} t\right) \qquad (1.6.2\text{-}2)$$

where the parameter A_n is given by

$$A_n = \frac{4\sin\mu_n}{2\mu_n + \sin(2\mu_n)}\,, \qquad (1.6.2\text{-}3)$$

and μ_n are the roots of the characteristic equation for the infinite slab:

$$\cot\mu_n = \frac{\mu_n}{Bi}\,. \qquad (1.6.2\text{-}4)$$

The parameter Bi is the mass transfer Biot number, defined as follows:

$$Bi = \frac{\beta Lx/2}{D_{AB}}. \qquad (1.6.2\text{-}5)$$

The expression for the average moisture content $\bar{M}$(t) at time t is given by

$$\bar{M}(\mathrm{t}) = M_{eq} + (M_0 - M_{eq}) \sum_{n=1}^{\infty} B_n \exp\left(-\frac{\mu_n{}^2}{\left(\frac{Lx}{2}\right)^2} D_{AB} t\right) \qquad (1.6.2\text{-}6)$$

where the parameter B_n is given by

$$B_n = \frac{2Bi^2}{2\mu_n{}^2(Bi^2 + Bi + \mu_n{}^2)}\quad . \qquad (1.6.2\text{-}7)$$

This physical based model can be applied to regression analysis to obtain physical parameters of materials and process.

1.6.3 Mathematical model

The literature shows the several theoretical, semi-theoretical and empirical models to study the drying kinetics during drying of foods. The most commonly used models are shown in table 3 (Sachin V. Jangam, 2011)

Model name	Model	Reference
Newton	MR = exp(-kt)	(Liu et al., 1997; Nellist,1987)
Page	MR = exp(-kt^n)	(Agrawal and Singh,1977; Bruce, 1985)
Henderson and Pebis	MR = a exp(-kt)	(Pal and Chakraverty,1997; Rahman and Perera, 1996)
Two-Term	MR = a exp(bt) + c exp(dt)	(Henderson,1974)
Asymptotic Logarithmic	MR = a exp(-kt)+b	(Yaldyz and Ertekyn,2001)
Wang and Singh	MR =1+at+bt^2	(Wang and Singh,1978)
Diffusion approximation	MR = a exp(-kt)+(1-a) exp(-kat)	(Henderson, 1974)
Two term Exponential	MR = a exp(-kt) + (1-a) exp(-kat)	(Wang and Singh,1978)
Modified Henderson and Pabis	MR = a exp(-kx)+b exp(-gx)+c exp(-gx)	(Karathanos and Belessiotis, 1999)

Table 3. Mathematical models used to test the drying kinetics. (Sachin V. Jangam, 2011)

1.7 Balance of drying

Mass and energy balances describe the fundamental law for the process control in the food processing, including food drying processes. These laws, such as mass and energy balance conservation play an important role in design of the drying process.

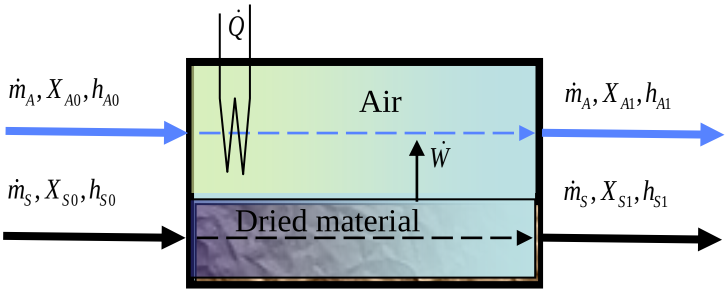


Figure 2. Balance of dryer [2]

Mass balances (Water balances):

$$\dot{m}_A X_{A0} + \dot{m}_S X_{S0} = \dot{m}_A X_{A1} + \dot{m}_S X_{S1}, \tag{1.7-1}$$

The mass flow rate (amount of removed moisture):

$$\dot{W} = \dot{m}_A (X_{A1} - X_{A0}) = \dot{m}_S (X_{S0} - X_{S1}). \tag{1.7-2}$$

Where:

$\dot{m}_A X_{A0,1}$: Water flow rate of the drying air

$\dot{m}_S X_{s0,1}$: Water flow rate in the dried material

Energy balance:

$$\dot{Q} = \dot{m}_A (h_{A1} - h_{A0}) + \dot{m}_S (h_{S1} - h_{S0}) \tag{1.7-3}$$

1.8 Drying curve (periods of drying)

Experimental evaluation of the drying rate is usually carried out at the constant parameters of a drying media such as velocity, temperature and humidity. Observing the change in mass of the material during dehydration the drying curve is plotted. Drying curve shows the relation of the moisture content to the time.

The section AB on each curve represents a warming-up period of the solids. Section BC on each curve represents the constant-rate period. Point C, where the constant rate ends and the drying rate begin falling, is termed the critical-moisture content. The curved portion CD on Fig. 3-a is termed the falling-rate period and, as shown in Fig. 3-b and c, is typified by a continuously changing rate throughout the remainder of the drying cycle. Point E (Fig. 3-b) represents the point at which all the exposed surface becomes completely unsaturated and marks the start of that portion of the drying cycle during which the rate of internal moisture movement controls the drying rate. Portion CE in Fig. 3-b is usually defined as the first falling-rate drying period; portion DE, as the second falling-rate period. (Perry Robert.H, 1997)

Constant-rate period. In the constant-rate period, the moisture movement within the solid is rapid enough to maintain a saturated condition at the surface, and the rate of drying is controlled by the rate of heat transferred to the evaporating surface. Drying proceeds by diffusion of a vapour from the saturated surface of the material across a stagnant air film into the environment. The rate of mass transfer balances the rate of heat transfer, and the temperature of the saturated surface remains constant. The mechanism of moisture removal is equivalent to the evaporation from a body of the water and is essentially independent of the nature of the solids. If heat is transferred solely by convection and in the absence of other heat effects, the surface temperature approaches the wet-bulb temperature. However, when heat is transferred by radiation, convection, or a combination of these and convection, the temperature at the saturated surface is between the wet-bulb temperature and the boiling point of the water. Under these conditions, the rate of heat transfer is increased and a higher drying rate results. When heat is transferred to a wet solid by convection to hot surfaces and heat transfer by convection is negligible, the solids approach the boiling-point temperature rather than the wet-bulb temperature. This method of heat transfer is utilized in indirect dryers. Radiation is also effective in increasing the constant rate by augmenting the convection heat transfer and raising the surface temperature above the wet-bulb temperature. (Perry Robert.H, 1997)

The magnitude of the constant rate depends upon three factors:

1. The heat- or mass-transfer coefficient
2. The area exposed to the drying medium
3. The difference in temperature and humidity between the gas stream and the wet surface of the solid.

All these factors are the external variables. The internal mechanism of liquid flow does not affect the constant rate.

Falling-rate period. The falling-rate period begins at the critical moisture content when the constant-rate period ends. When the falling moisture content is above the critical moisture content, the whole drying process will occur under constant-rate conditions. If, on the other hand, the initial moisture content is below the critical moisture content, the entire drying process will occur in the falling-rate period. This period is usually divided into two zones: (1) the zone of unsaturated surface drying and (2) the zone where internal moisture movement controls. In the first zone, the entire evaporating surface can no longer be maintained and saturated by moisture movement within the solid. The drying rate decreases from the unsaturated portion, and hence the rate for the total surface decreases. Generally, the drying rate depends on factors affecting the diffusion of moisture away from the evaporating surface and those affecting the rate of internal moisture movement. (Perry Robert.H, 1997)

As drying proceeds, the point is reached where the evaporating surface is unsaturated. The point of evaporation moves into the solid, and the dry process enters the second falling-rate period. The drying rate is now governed by the rate of internal moisture movement; the influence of external variables diminishes. This period usually predominates in determining the overall drying time to lower moisture content. (Perry Robert.H, 1997)

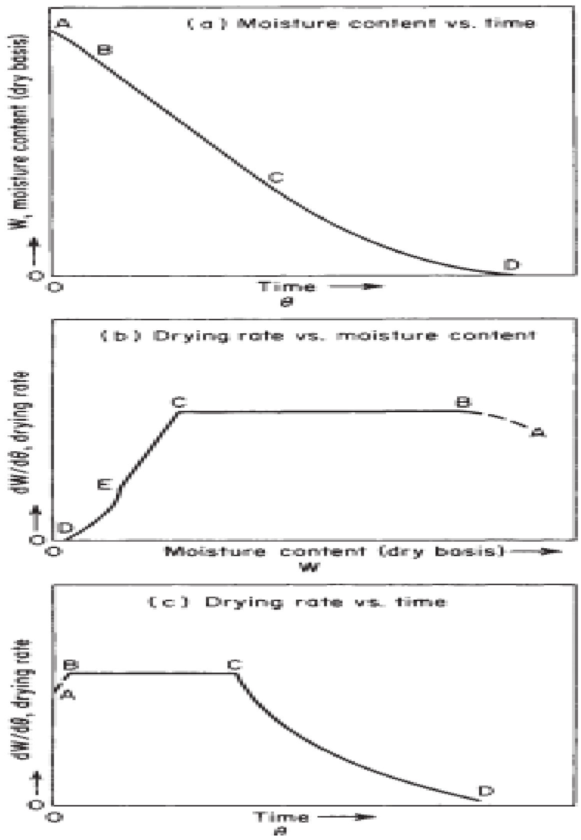


Figure.3 The periods of drying (Perry Robert.H, 1997)

1.9 Measurement

We should point out the fact that the numerical calculation of drying processes such as drying rate requires knowledge of several characteristics of drying technology. It includes the characteristics of the material, the heat transfer coefficient and thermal conductivity, also the characteristics of drying curve. Generally, mathematical models of the process describes that these parameters cannot be completely solved by numerical way or by analysis. Therefore, these parameters can be determined by corresponding experiments. The practical calculations of mass and heat transfer, which occurs simultaneously, requires numerical and analytical solutions. Hence, for that reason it is necessary to apply it with experimental data.

The main objectives of drying experiments are as follows:

1. Selection of proper drying equipment
2. Evaluation of the drying rate from the data required for designing
3. Considering of features (capacity, effectiveness) of drying equipment.
4. Checking of drying product quality, properties and structures.

Experiments take place in a laboratory or in a pilot-plant dryers where constant parameters of drying media is used (temperature, humidity and velocity). Generally, the conditions of experiments must correspond to the equipment of plant scale. It is helpful to design the proper dryer for drying materials, improving the existing equipment, to increase its possibility and working conditions to use for other kind of products. What is more, sometimes experiments include such aspects like materials handling which has real drying equipment.

2 Literature search

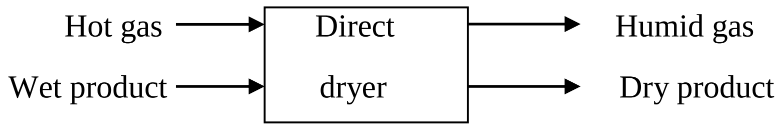
In the last chapter, I introduced to the drying process that covers fundamental aspects of it. The next chapter deals with an introduction to the equipment in which the drying is carried out. It is vital to note that nowadays many types and subclasses of dryers in the various industrial branches exist. For instance, literature researches related with this topic contain about 500 types of dryer and over 100 dryers can be found in trade. Based on these data we should carefully consider the question of whether why there are many types of dryer equipment.

As a minimum, the following conditions describe such quantities of dryers:

- Based on methods of supplying energy input (conduction, convection, radiation, microwave and RF etc.)
- Variety of feeds (solid, liquid, granulate, sticky, sludge etc.)
- Mode of operation (batch or continuous)
- Chemical and physical properties of product
- Quality of products is the main parameter in food industry

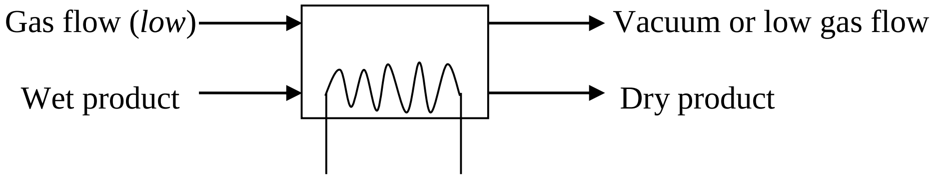
2.1 Main types of dryer

1. Direct (convective)



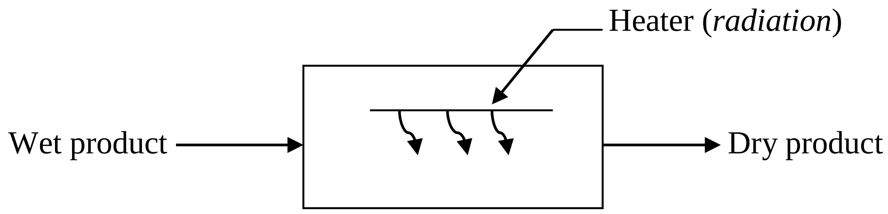
Drying medium directly contacts the material to be dried and carries evaporated moisture.

2. Indirect (Contact, Conduction)



Heat supplied by heat exchanger (through metal wall).

3. <u>Infrared drying</u>



Vacuum or low gas flow to carry evaporated moisture away.

4. <u>Microwave or Radio Frequency</u>

Electromagnetic energy is selectively absorbed by water (volumetric heating)

As noted earlier, heat may be supplied by convection (direct dryers), by conduction (contact or indirect dryers), radiation or volumetrically by placing the wet material in a microwave or radio frequency electromagnetic field. Over 85 percent of industrial dryers are of the convective type with hot air or direct combustion gases as the drying medium. Over 99 percent of the applications involve removal of water. All modes except the dielectric (microwave and radio frequency) supply heat at the boundaries of the drying object so that the heat must diffuse into the solid primarily by conduction. The liquid must travel to the boundary of the material before it is transported away by the carrier gas (or by application of vacuum for non-convective dryers). (Arun S. Mujumdar, 2015)

2.2 Dryer classification

The table 4 shows the classification of dryer's type. This is the common criteria for classifying dryer. In some cases, dryer can be sub-classified into many types according to additional parameters.

Criterion	**Types –** (*) most common in practice
Mode of operation	• Batch • Continuous*
Heat input	• Convection, conduction, radiation, electromagnetic fields, combination of heat transfer modes • Intermittent or continuous* • Adiabatic or non-adiabatic

State of material in dryer	• Stationary • Moving, agitated, dispersed
Operating pressure	• Vacuum* • Atmospheric
Drying medium (convection)	• Air* • Superheated steam • Flue gases
Drying temperature	• Below boiling temperature* • Above boiling temperature • 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 4. Classification of dryer (Sachin V. Jangam, 2010)

2.3 Dryer selection

Nowadays a wide variety of drying equipment is available from manufactures. The selection of the proper drying equipment is a challenging task in which experience, knowledge and analysis play important roles. Due to the complexity of the drying process, many factors must be carefully weighed and considered. Following table presents list, which is usually used by manufactures to select the industrial dryers.

Physical form of feed	• Granular, particulate, sludge, crystalline, liquid, pasty, suspension, solution, continuous sheets, planks, odd-shapes (small/large) • Sticky, lumpy

Average throughput	• kg/h (dry/wet); continuous • kg per batch (dry/wet)
Expected variation in throughput (turndown ratio)	
Fuel choice	• Oil • Gas • Electricity
Pre- and post-drying operations (if any)	
For particulate feed products	• Mean particle size • Size distribution • Particle density • Bulk density • Rehydration properties
Inlet/outlet moisture content	• Dry basis • Wet basis
Chemical / biochemical / microbiological activity	
Heat sensitivity	• Melting point • Glass transition temperature
Sorption isotherms (equilibrium moisture content)	
Drying time	• Drying curves • Effect of process variables
Special requirements	• Material of construction • Corrosion • Toxicity • Non-aqueous solution • Flammability limits • Fire hazard • Color/texture/aroma requirements (if any)
Foot print of drying system	• Space availability for dryer and ancillaries

Table 5. Typical checklist for selection of industrial dryers (Sachin V. Jangam, 2010)

It stands to reason that in the selection of the industrial dryer one of the important parameter is drying kinetics. We cannot ignore the fact that the behaviour of moisture in the material (location, bonding conditions, and transfer mechanisms), pressure and heat loss in the dryer has influence on the type of adequate dryer as well as the working conditions. In the most cases, no more than one type of dryer is likely to correspond to the selection criteria.

2.4 Belt dryer

The aim of the thesis is to design belt dryer for lump sugar. As we have stated in previous chapters, the drying of foodstuffs, high value products like medicines (pharmaceutics), and biotechnological products requires good quality, hygiene and safety. Product quality always takes great attention when selecting the type of dryer to be used and to satisfy all these requirements. The selected dryer should supply optimum conditions for drying product.

Taking everything into consideration the belt dryer was chosen for lump sugar drying. The description of conveyor (belt) dryer follows.

Belt (conveyor) dryer

This kind of dryers particularly is suitable for drying of the large volumes of raw materials and it is practically a continuous drying process. In addition, it is suitable for drying of fibrous, piece, coarse or flake materials and for cut vegetables.

In this type of dryer, the food material is conveyed through the drying tunnel on a perforated conveyor made of hinged, perforated metal plates or wire or plastic mesh. The heated air usually flows through the belt and the layer of food, upward in the early stages of drying and downward in the later stages

The main components of this dryer consist of finely woven wire mesh supported on rollers to form a belt trough, a duct supplying hot air at the bottom of the trough, and a rotary
cleaning brush. The belt trough is inclined sideways at an angle of 15°–20° to facilitate the gravity unloading of dried product. The airflow rate provides an air cushion but not so high as to fluidize the product. Soft materials can be dried without mashing or rounding their cut edges. Since the product is partly supported by the hot air, it requires

relatively uniform size wet material. If material is not of uniform size, large particles may not be supported well and small particles may be blown out of the trough.

The drying air passes through material at the rate of 0.6–1.4 m/s. About 60%–90% of air is re-circulated in each section. Temperatures are usually limited by the heat sensitivity of the material but seldom exceed 300°C. A higher temperature may damage the lubrication of the conveyor's moving parts. The fan power is about 1 kW/m of the belt width.

The main problem in these dryers is that the sticky materials will lodge and stick to the chains and links of the band. The band must be washed frequently to prevent air blockage. (Arun S. Mujumdar, 2015)

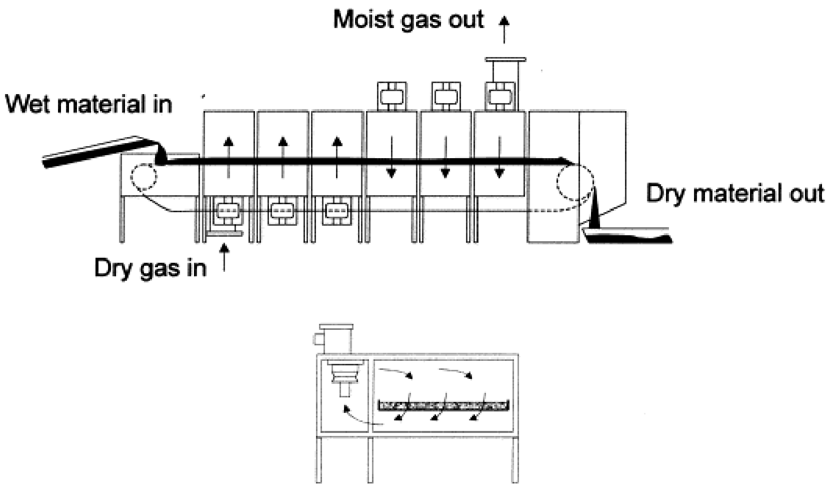


Figure 4. Single belt conveyor dryer (Arun S. Mujumdar, 2015)

Figures below show the other types of dryer, which are available from manufacture.

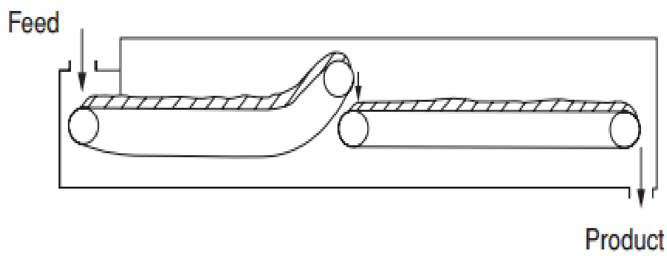


Figure 5. Two-stage belt conveyor dryer (Arun S. Mujumdar, 2015)

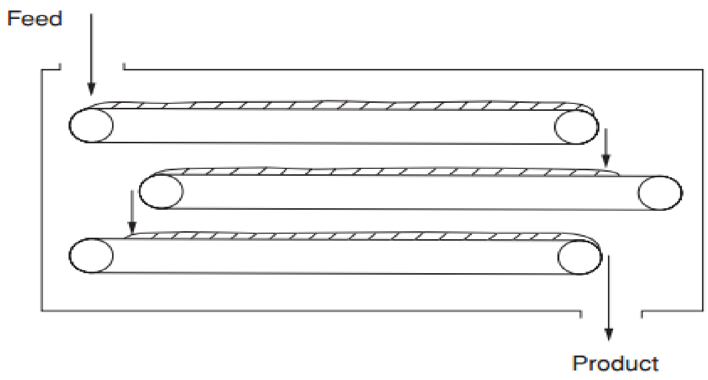


Figure 6. Multi-stage belt conveyor dryer (Arun S. Mujumdar, 2015)

Let us consider what are the advantages and disadvantages of this type of dryer.

Advantages:

- Large amaount of dried material
- Material flexibility
- Material is not agitated
- Simple design, reliable
- Lower emissions
- Non-destructive drying

Disadvantages:

- Higher operating power and cost
- Slightly more sensitive to operate
- Large footprint

2.4.1 The main parameters for design of belt dryer

The main parameters are:

a) Belt width
b) Belt speed

Following basic information is necessary for designing of belt conveyor:

- Type of the material and its size
- Amount of a material (kg/h or t/h)
- Temperature and velocity of drying air

a) Belt width

In case of belt dryer, the belt width is equal to the dryer width. It can be seen in figure 7 where the schematic representation of belt dryer is illustrated .

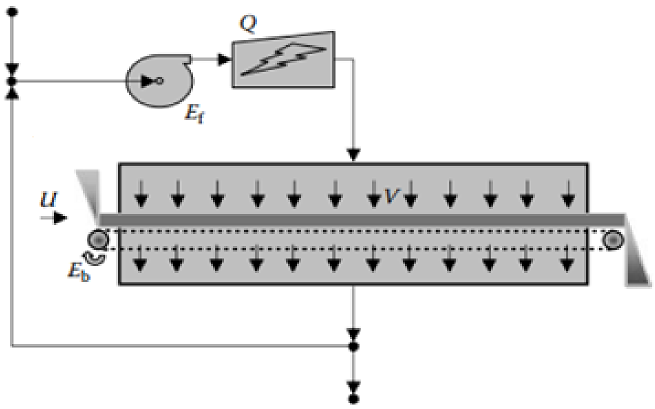


Figure 7. Schematic representation of a belt dryer (Arun S. Mujumdar, 2015)

The specification of the belt width is substantially depends on quantity of feeding material, which is represented by the design of the belt dryer. One should note here that dryer with minimum belt width is more economic.

b) Belt speed

Physical characteristics of feeding material have the influence to belt speed. Mainly it depends on lump size, volume, weight etc. For instance, if there is an increase of those parameters, it is necessary to reduce belt speed.

2.5 Sugar drying

2.5.1 Lump sugar

Lump sugar is refined sugar, which has been pressed or cast into a particular shape. Chemically speaking, refined sugar is ultrapure sucrose which has been obtained from white sugar by dissolution and recrystallization. Its sucrose content is 99.9%. Refined sugar is pure white in colour with sparkling crystals. Refined sugar has no secondary odours or flavours. The crystals are readily soluble. Lump sugar is primarily used for sweetening hot drinks.

Sugar cubes are available as either pressed or cast cubes.

- Pressed cubes:

Sugar cubes were first made in 1840 by the Austrian Jacob Christoph Rad. Cubes were initially made by pressing moistened sugar and casting it in sheets, which were broken up first into strips and then into cubes.

Today, fine-grain refined sugar with 2 - 3% of added water is still pressed into sheets and strips, which are dried and divided into cubes. The dividing surfaces of pressed cubes may vary between smooth and very uneven, as the strips are not always uniform in structure.

Since pressure bonds the sugar crystals together firmly only at the surface, pressed cubes are easily crushed and then break apart completely.

- Cast cubes:

Refined sugar massecuite is allowed to solidify in a sheet mould. The sheets of sugar are then centrifuged and washed once more with saturated refined sugar solution. Then they are dried and divided into cubes.

Cast cubes are stronger, harder and somewhat more porous than pressed cubes. The sugar crystals are clearly recognizable. Due to their porous structure, cast cubes dissolve in liquids more easily than pressed cubes.

- Loaf sugar:

Sugar loaves are also produced by the pressing process and used, for example, in traditional German burnt punch and in jam making.

Sugar cubes are often arranged in neat rows in their packaging.

Figure 8. Coloured lump sugar from the Czech Republic [3]

Figure 9. Brown (Milford Tee) sugar cubes made from raw cane sugar: the cubes abrade easily and so tend become "gritty" [3]

Figure 10. Sugar cubes arranged in neat rows in their packaging

Figure 11. Sugar loaf [3]

<u>Countries of origin</u>

Europe: EU countries, Poland, Czech Republic, Russia

Africa: South Africa

Asia: India, China, Philippines

America: Cuba, Brazil, USA, Mexico, Argentina

2.5.2 Drying of sugar

The mixture of water and sugar crystals is pressed to get desired shape, weight and size of lump sugars. Usually the moisture content is about 2 – 3 % and the final moisture content after drying is approximately 0.03-0.5 %. In the sugar industry the drying of lump sugars occur after the moisturizing and pressing the nonporous sugar crystals.

The process of sugar drying is complex and requires careful analysis of the sugar conditions. During drying the lump sugars not only achieve the optimal final moisture content but also the required hardness after which it can be transported to the market or storage in packed boxes.

Sugar drying theory

Classical drying theory asserts that the drying of a solid takes place in two stages:

1. *Constant rate stage*. The surface of each particle is covered by a continuous film of moisture, and subject to environmental conditions remaining unchanged, evaporation proceeds at a constant rate.
2. *Falling rate stage*. The film of moisture becomes depleted and evaporation shows due to reduced surface area, replenishment of the film occurs as moisture moves by vapour diffusion or capillary action from the interior of the particle to the surface, and this transport becomes rate limiting.

Figure 12. illustrates these two phases graphically.

Sugar, as soluble material, is interesting in that it appears to follow the classical theory,but the mechanisms involved are quite different. The stages in the drying of sugar are:

1. *Psuedoconstant rate stage.* The film of syrup on the surface of the crystals is undersaturated and moisture evaporates freely at a nearly constant rate, governed by evaporative considerations.
2. *Falling rate stage.* The surface film has become sufficiently concentrated that evaporation is slowed significantly by the influence of the solute (Raoult's law). This effect is exacerbated by the fact that crysallization of sucrose then begins from the supersaturated film. Due to the speed with which moisture is removed from the film, a concentration gradient is established across the film and the crysalization process produces amorphous solid sugar in and on the surface of the film, which interferes with the evaporative process by trapping moisture. The higher the purity of the sugar, the faster is the crystallization rate and therefore the greater the effect of this phenomenon. (Chung Chi Chou, 2000)

Moisture available on the surface of the crystal (readily evaporated) is known as free moisture, while moisture that is associated with or trapped under amorphous sugar is known as bound moisture. Conventional drying is concerned with removing free moisture plus a little of the boound moisture. From the preceding it is clear that three mechanisms are involved in the drying process:

1. Evaporation of moisutre from the syrup film at rate governed by the vapor pressure difference between the film and the bulk airstream.
2. Diffusion of water molecules through the surface film and across solid amorphous sugar barriers on the crystal surface, driven by concentration gradient.
3. Crysatllization of sucrose molecules in the film and therby making available for diffusion and evaporation

The conventional drying process is predominantly evaporation rate controlled, with the other two mechanisms coming into play toward the end of the drying operation, and then only in the case of higher-purity sugars. Control of drying is therefore the control of the syrup film vapor pressure (a function of sugar temperature and film concentration) relative to the partial pressure of water pressure of water in the drying air (a function of air temperature and moisture content). (Chung Chi Chou, 2000)

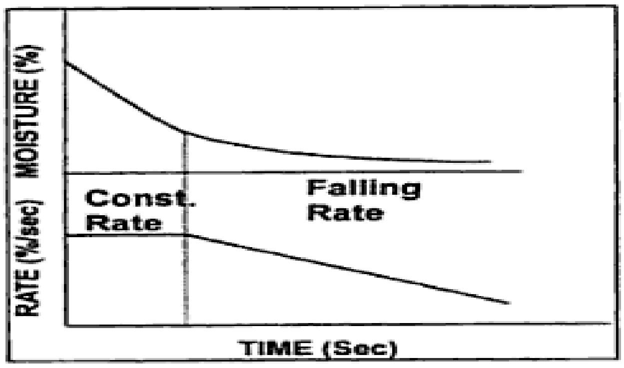


Figure 12. Classical drying phases (Chung Chi Chou, 2000)

To draw the conclusion of this section, one can say that selection of required dryer and drying parameters like drying temperature has considerable effect on the final sugar quality. Formation of small sugar particles weakly bounded to surface of sugar occurs at high temperature. In addition, those particles contribute changes on sugar structures giving it a dull opaque appearance. Nevertheless, consumer should get high quality and first class lump sugars from store.

3 CFD simulation of drying process

In this part of thesis, I will present an overview of some fundamental concepts related to computational fluid dynamics (CFD). In addition, the aim of this chapter is to show the description of the heat and mass transfer analogy during CFD simulation.

3.1 Introduction to CFD

One must admit that the rapid growth of the computer performance and technology has contributed to the development of the numerical simulation method. Mechanics of fluid, heat and mass transfer is no exception in this regard. Therefore, computational fluid dynamics (CFD) is becoming an essential engineering tool.

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. Below the brief summary of applications of CFD is given (Sikovsky D.F, 2013):

- Aerospace: Aerodynamics, design wings and blades, rockets, passenger cabins etc.
- Automotive: internal combustion, an increase in passenger comfort
- Biology: the study of flight of birds and insects, movement of fishes
- Biomedicine: heart valves, fluid dynamics of blood vessels, filters and respirators
- Construction industry: the design of bridges, structures of buildings, large structures, cleaning of indoor air, ventilation and air conditioning
- Chemical technology: mixing, separation, chemical reaction
- Electronics: cooling electronic devices
- Ecology and safety: monitoring of industrial waste and pollutions, fire safety, protection of river and seashores
- Shipbuilding: wind and wave load power plants
- Mechanical engineering: pumps, fans, heat exchangers, dryer
- Meteorology: weather forecast
- Oceanography: the flow in rivers and oceans
- Power: water heaters, boilers, furnaces, pressure vessels

- Sport industry: the design of racing cars, yachts and bytes, bicycle helmets, swimming glasses, balls for tennis and golf
- Turbomachinery: turbine blade cooling, compressors

Most popular CFD software supported on platforms of WINDOWS, LINUX etc:

- ANSYS CFX
- FLUENT

3.2 Comparison of CFD simulation with experiments

Let us consider what the advantages and disadvantages of CFD simulation comparing to experiments.

CFD gives a detailed insight to the flow distribution, heat and mass transfer, separation of particles that is much more expensive, difficult and even impossible to study in real experiments. Although, sometimes CFD does not fully replace measurements, but it can save time and money of process.

Simulations	Experiments
Quantitative prediction of flow phenomena using CFD software • for all desired quantities • with high resolution in space and time • for the actual flow domain • for virtually any problem and realistic operating conditions Error sources: modelling, discretization, iteration, implementation	Quantitative description of flow phenomena using measurements • for one quantity at a time • at a limited number of points and time instants • for a laboratory-scale model • for a limited range of problems and operating conditions Error sources: measurement errors, flow disturbances by the probes
• cheaper • faster • parallel • multi-purpose	• expensive • slow • sequential • single-purpose

Table 6. Comparison of simulations and experiments [4]

3.3 Application of CFD in the food industry

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. (Bin Xia, Da-Wen Sun, 2002)

3.3.1 Drying

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. (Bin Xia, Da-Wen Sun, 2002)

One of the key advantage of CFD methods in evaluating drying systems is that it makes it possible to evaluate geometric changes (different feed point layouts such as multiple entry points) and operating conditions with much less time (faster turnaround time) and expense (flexibility to change design parameters without the expense of hardware changes) than would be involved in laboratory testing. A second advantage is that CFD provides far more detailed output information (suited for trouble-shooting) and far better understanding of the dryer performance than can be obtained in a laboratory environment. By interpreting graphical predictions from a CFD solution, local conditions of all phases in the drying chamber can be evaluated and crucial information related to the dispersion of particulate material can be gathered.

The effectiveness and practicability of a CFD simulation in the food processing industry depends on:

- specific food materials properties and food process;
- accurate algorithm for the equations of motion;
- powerful CFD packages;
- high speed and large computers.

However, as the applications and specifications of dryers become more and more complex, so does the need for improved test work in pilot plants, and CFD simulations become more important in providing quick and valuable information. (Bin Xia, Da-Wen Sun, 2002)

In the past, there was lack of information about the CFD simulation of drying process and it continues to present. From version 12 of ANSYS software the diffusion models are involved into the process, but the usage of it is still inefficient. Therefore the common way to simulate the drying is to simulate heat and inertia transfer and then the analogy between heat and mass transfer is used.

3.4 Heat and mass transfer analogy

As for the heat and mass transfer correlations used in commercial CFD packages, very few are provided and the implementation of modified correlations, so it is important to consider the concept of analogy.

Analogy between heat and mass transfer has long been recognized in the engineering and scientific community. This analogy has been demonstrated experimentally, empirically, and analytically.

The most common is the well-known Chilton–Colburn analogy (or simply Colburn analogy) that is based on empirical correlations, and not on mechanistic assumptions that are only approximations. Thus, it represents the experimental data extremely well over the range in which the empirical correlations are valid. This analogy stands for both laminar and tubular flows and for Prandtl and Schmidt numbers between 0.6 to 100 and 0.6 and 2500, respectively. The Chilton–Colburn analogy can be expressed as (Arun S. Mujumdar, 2015)

$$j_D = j_H = \frac{f}{2} \tag{3.4-1}$$

where

f is the friction factor

j_D is the mass transfer factor

j_H is the heat transfer factor

The j_D and j_H factors defined as:

$$j_D = \frac{\alpha}{\rho C_p v}(Pr)^{2/3} = \frac{Nu}{RePr}(Pr)^{2/3} = \frac{Nu}{Re(Pr)^{1/3}} = St(Pr)^{2/3} \quad (3.4\text{-}2)$$

$$j_H = \frac{\beta}{v}(Sc)^{2/3} = \frac{Sh}{ReSc}(Sc)^{2/3} = \frac{Sh}{Re(Sc)^{1/3}} \quad (3.4\text{-}3)$$

In the case of independent heat and mass transfer, the ratio of Sh to Nu can be obtained from the above correlations: (Perry Robert H, 1997)

$$Sh = Nu \left(\frac{Sc}{Pr}\right)^{1/3} \quad (3.4\text{-}4)$$

where

$St = \frac{\alpha}{\rho C_p v} = \frac{Nu}{RePr}$ is the Stanton number

$Re = \frac{Lv\rho}{\mu}$ is the Reynold number

$Pr = \frac{C_p \mu}{\lambda}$ is the Prandtl number

$Sc = \frac{\upsilon}{D_{AB}}$ is the Schmidt number

$Nu = \frac{\alpha L}{\lambda}$ is the Nusselt number

$Sh = \frac{\beta L}{D_{AB}}$ is the Sherwood number (Perry Robert H, 1997)

In general, the average heat-transfer coefficient on immersed bodies is predicted by

$$Nu = CrRe^{m}Pr^{1/3} \text{ (where Cr=0,648, m=0.50)} \quad (3.4\text{-}5)$$

Equation for the forced flow, flat plate:

$$Sh = 0.332Re^{1/2}Sc^{1/3} \quad (3.4\text{-}6)$$

Knowing the heat transfer factor, we know the mass transfer factor, as well, and can calculate parameters concerning mass transfer, like the diffusion coefficient. This is important considering that belt drying includes both heat and mass transfer, as the material receives heat and losses moisture, simultaneously. (Arun S. Mujumdar, 2015)

3.5 Summary of literature search

To design belt dryer I will need to analyse the drying process and try to determine characteristics of process and material. Therefore, it is necessary to perform the experiments to obtain drying time. Moreover, from experimental data it is possible to get the important characteristic such as D_{AB} or β using regression.

CFD simulation is powerful tool to model fluid flow situations so I will also use it to investigate the drying process and get detailed information about it.

4 Experimental part

In this part of thesis, the drying characteristics of the lump sugars have been investigated. These characteristics play important role in a design and operation of the lump sugar dryer. Laboratory experiments on the lump sugars can be very useful in a determining the required size of the belt conveyor dryer.

4.1 Description of experiments

4.1.1 The principle of measuring equipment

The drying experiments were carried out in the modified circulation dryer which is located in the laboratory of Department of Process Engineering. This type of the dryer is suitable to study the effects of drying temperature and air velocity on the sugar cubes characteristics. The schematic diagram of the chamber dryer is shown in figure 13.

Parameters:

1) Chamber dryer
2) Primary heating
3) Fan
4) Motor
5) Pipeline
6) Secondary heating
7) Scales
8) Holding construction

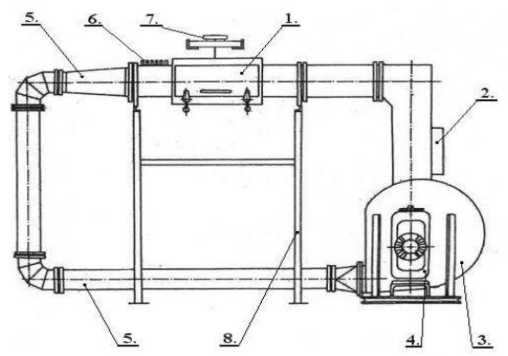


Figure 13. Schematic diagram of a chamber dryer

For heating up the flowing air, the secondary heating was used. The experimental data such as temperature, time, air velocity and weight were reading to PC. At the beginning, it is necessary to check digital scale to be sure that value on weight showed correctly

4.1.2 Materials

Primarily, the lump sugars (sugar cubes) from a ‘Tesco’ store were bought (producer: Cukrovar vrbátky, a.s., Czech Republic). Length of these cubes is approximately 25 mm. A further step of the experimental work was to moisturize a sugar cubes until initial moisture content reach 3%. After it, the sugar cubes were placed into the plastic box to prevent the moisture loss before using them. Required 3% of initial moisture content was calculated by following equation and using the syringe with the needle the sugar cubes have been moisturized:

$$\omega_0 = \frac{m_{H2O}}{m_{H2O}+m_{SC}} \quad (4.1.2\text{-}1)$$

where ω_0 is the initial moisture content equal to 3%, m_{SC} mass of the one sugar cube ranged between 5-6,5 grams, m_{H2O} is the required mass of the water necessary to enter inside of the sugar cubes.

Figure 14.Example of sugar cubes used in experiments

Figure 15. Lump sugar from market

The initial moisture content of markets sugar was measured by standard drying procedure at 105°C and 24 hours in the batch dryer. It was found that initial moisture content was less than 0.1%. For the measurement it was considered that the initial moisture content is zero.

4.1.3 Drying measurements and experimental setup

Experiment parameters are being agreed with the supervisor of thesis. Therefore, experiments were conducted at three temperature 50, 65 and 85°C and two air velocity 1 and 1.5 m/s.

Firstly, the dryer was heated up to required temperature and then the prepared samples were placed into the chamber dryer.

The position of the sugar cubes were 3x8 (row x column). This position is enough to fulfill whole surface of the basket. (Figure 16). The average weight of the cubes used was about 144 – 150 g (wet basis). The mass loss of the samples in the chamber dryer was recorded at time step 30 sec after start the drying. All measurements related to the given parameters were repeated three times and the average values were used.

Figure 16. Samples in the drying

4.2 Results of experiments

By reading data from PC, the drying curve of each measurement was plotted. Figures from 17, 19, 21, 23, 25 and 27 represent the typical weight loss of the samples with respect to time while figures from 18, 20, 22, 24, 26 and 28 represent the recalculated data using equation 4.2-1 to evaluate moisture loss of material.

$$\omega_t = \frac{M_i - M_{DM}}{M_i} * 100 \ [\%] \qquad (4.2\text{-}1)$$

where M_i is the initial mass of the material, M_{DM} is the dry mass content of a material.

4.2.1 Drying curves

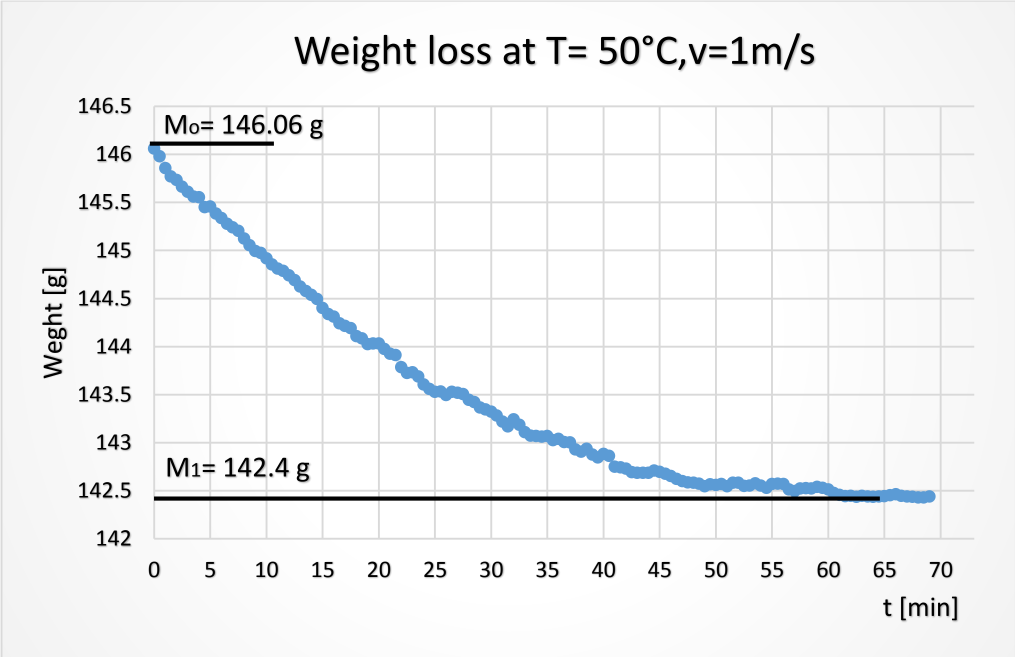


Figure 17. The weight loss at T = 50°C and v = 1 m/s

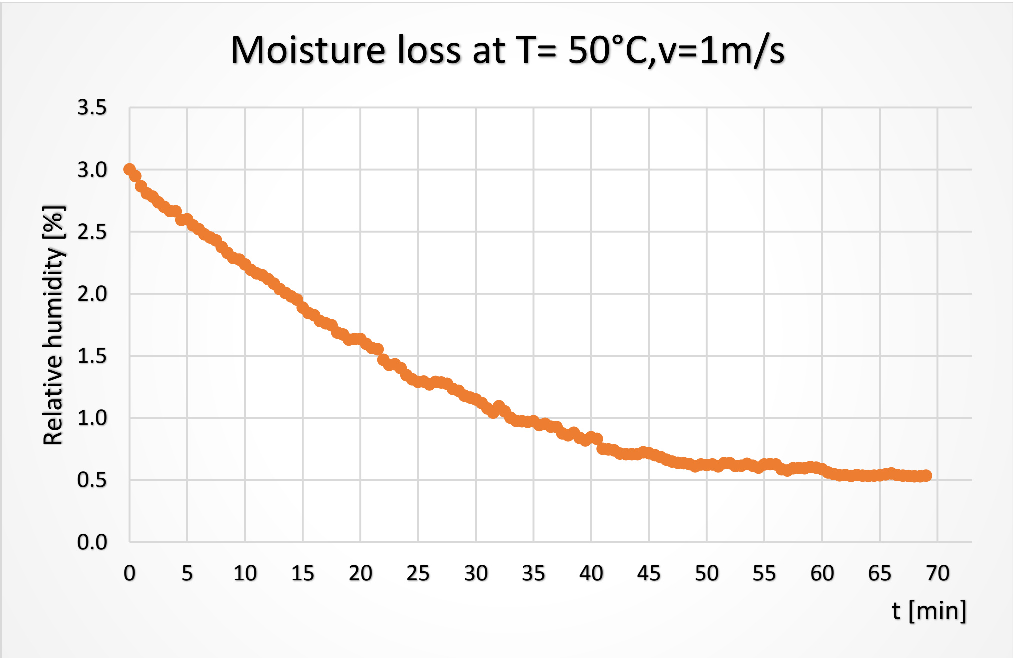


Figure 18. The moisture loss at T = 50°C and v = 1.5 m/s

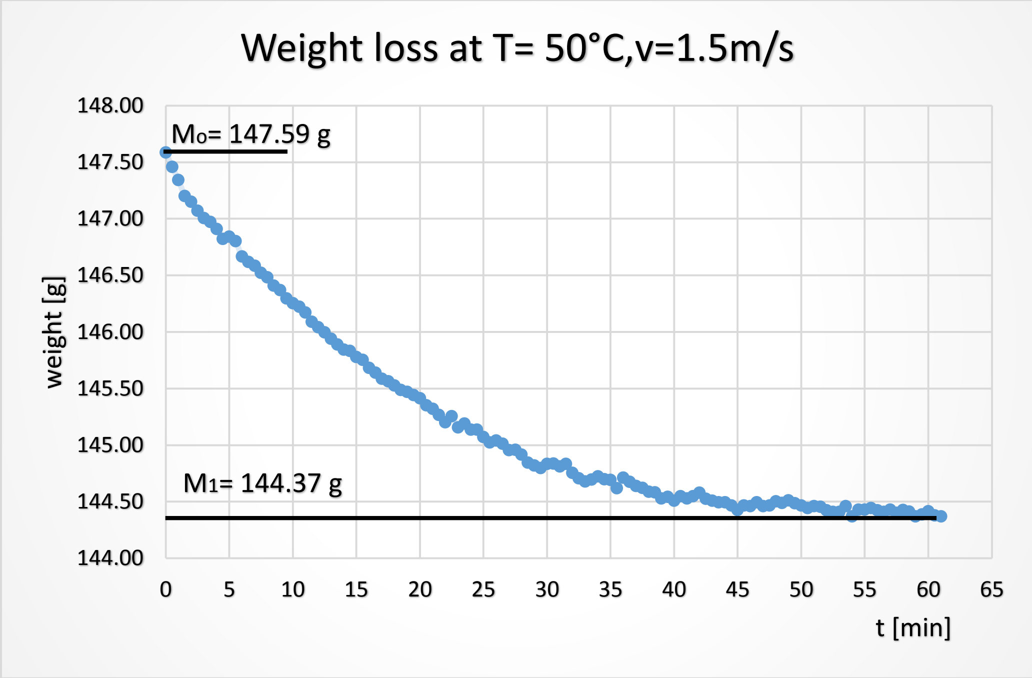


Figure 19. The weight loss at T = 50°C and v = 1.5 m/s

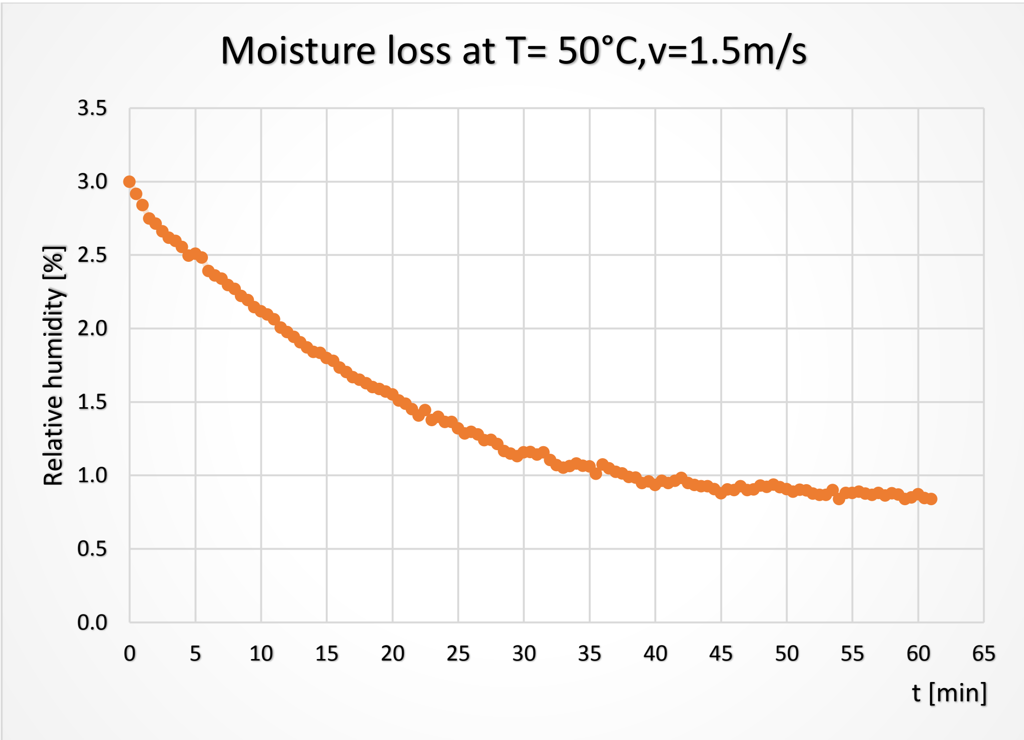


Figure 20. The moisture loss at T = 50°C and v = 1.5 m/s

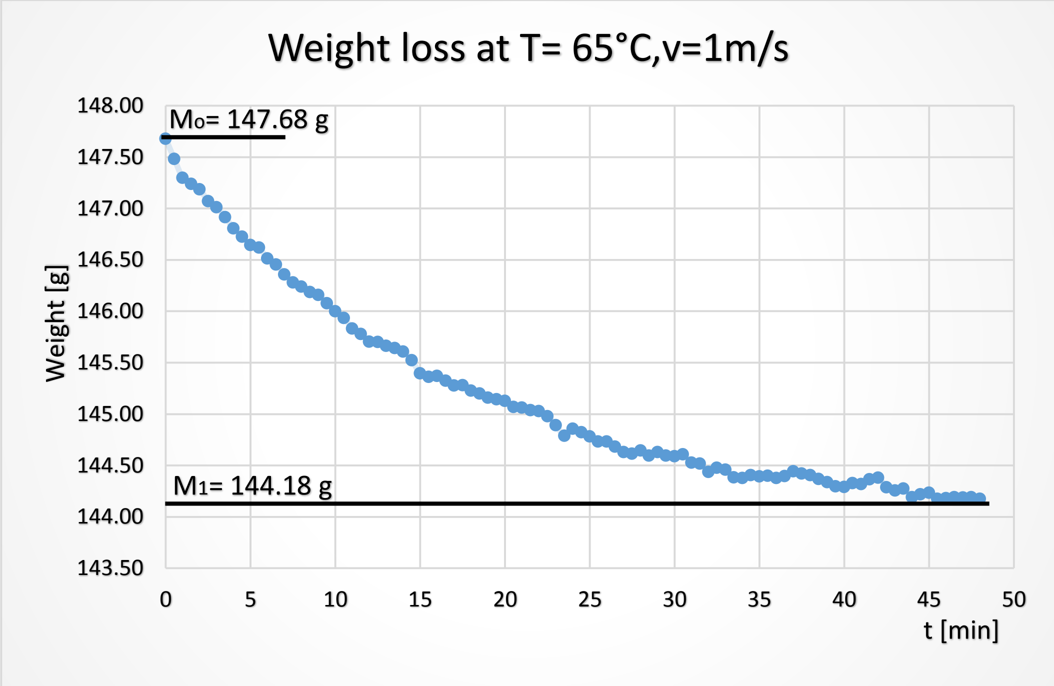


Figure 21. The weight loss at T = 65°C and v = 1 m/s

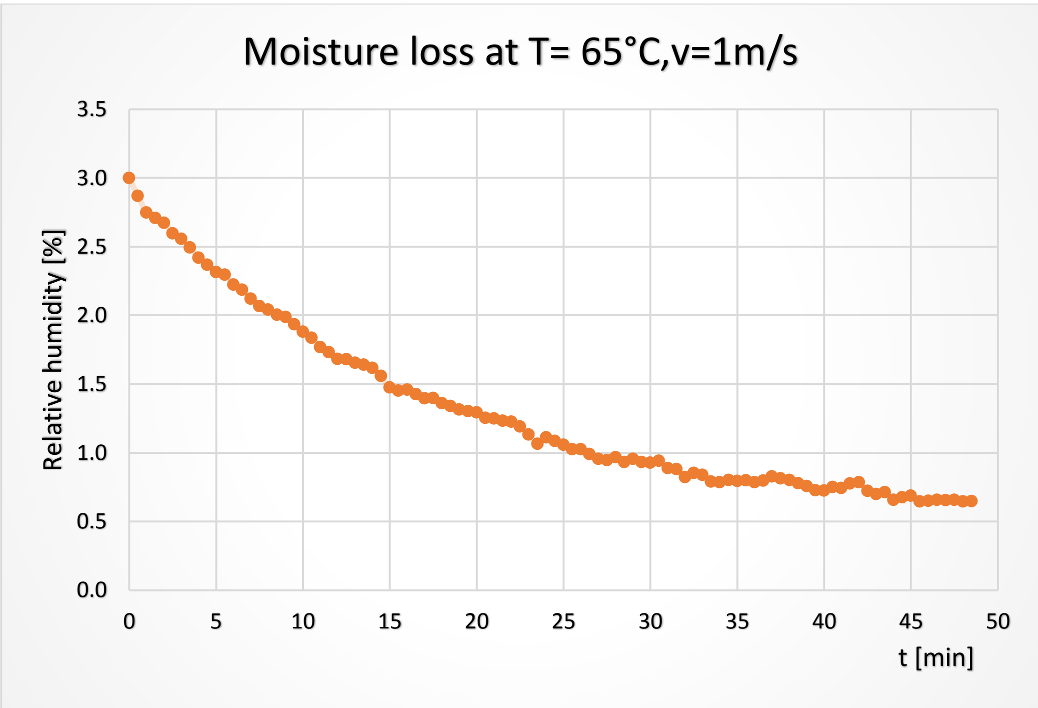


Figure 22. The moisture loss at T = 65°C and v = 1 m/s

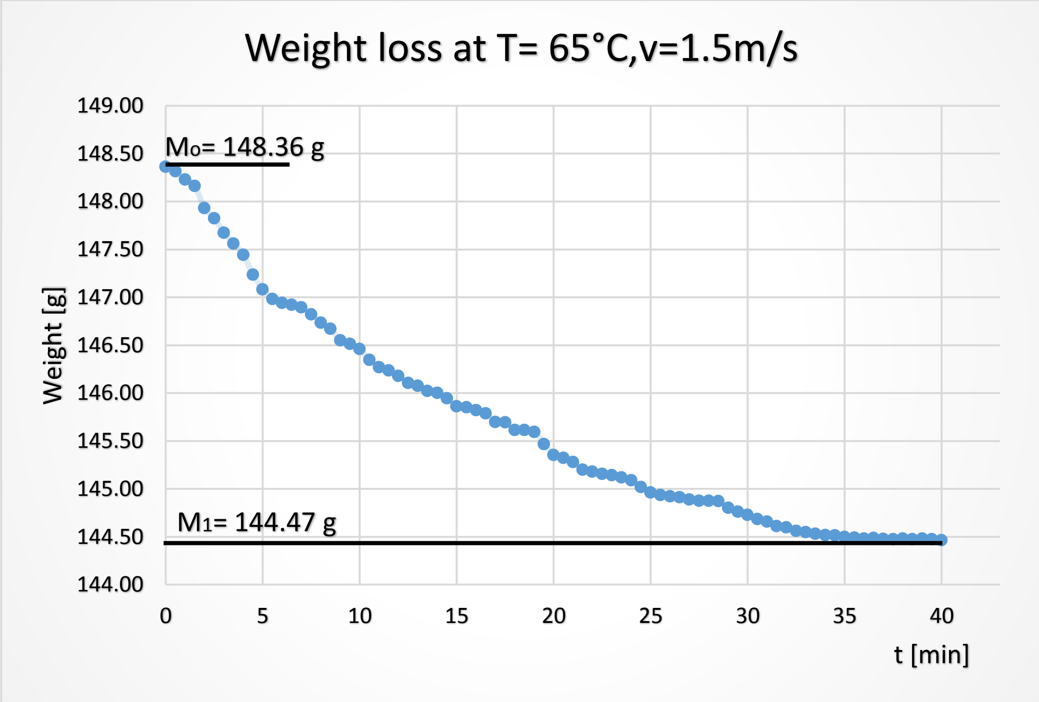


Figure 23. The weight loss at T = 65°C and v = 1.5 m/s

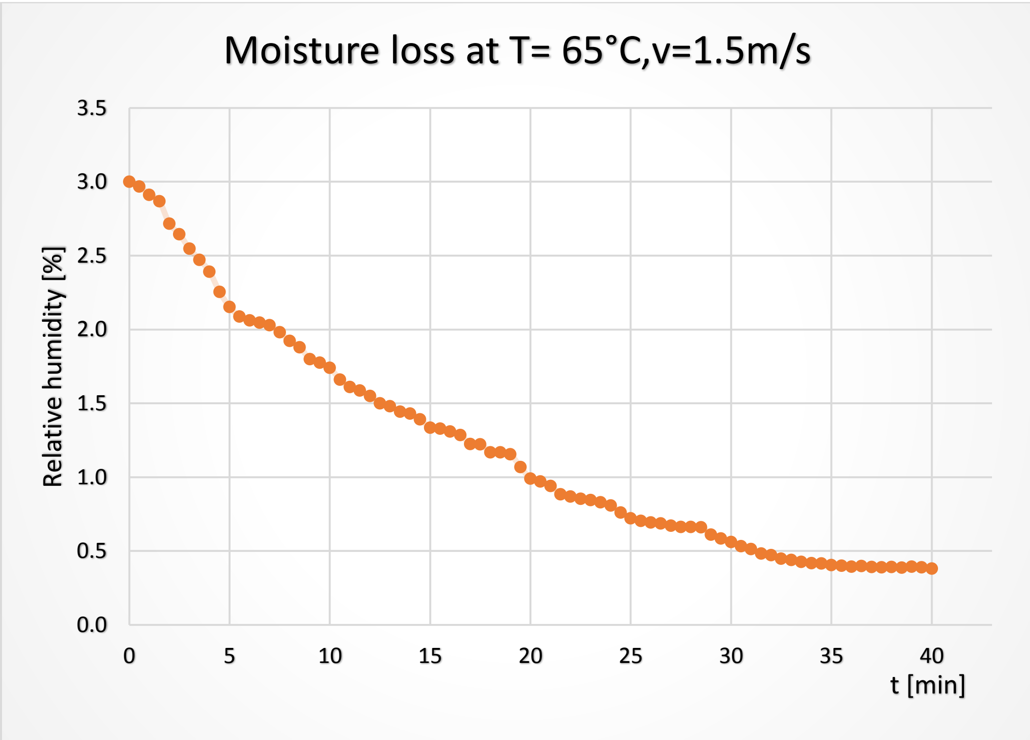


Figure 24. The moisture loss at T = 65°C and v = 1.5 m/s

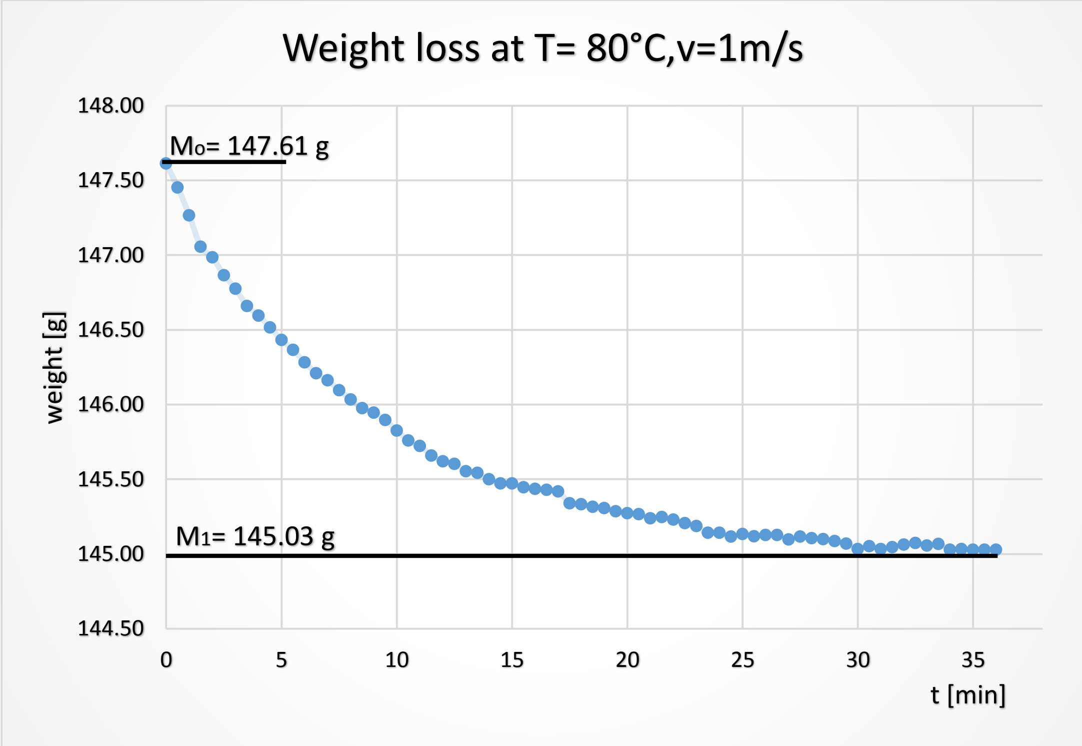


Figure 25. The weight loss at T = 80°C and v = 1 m/s

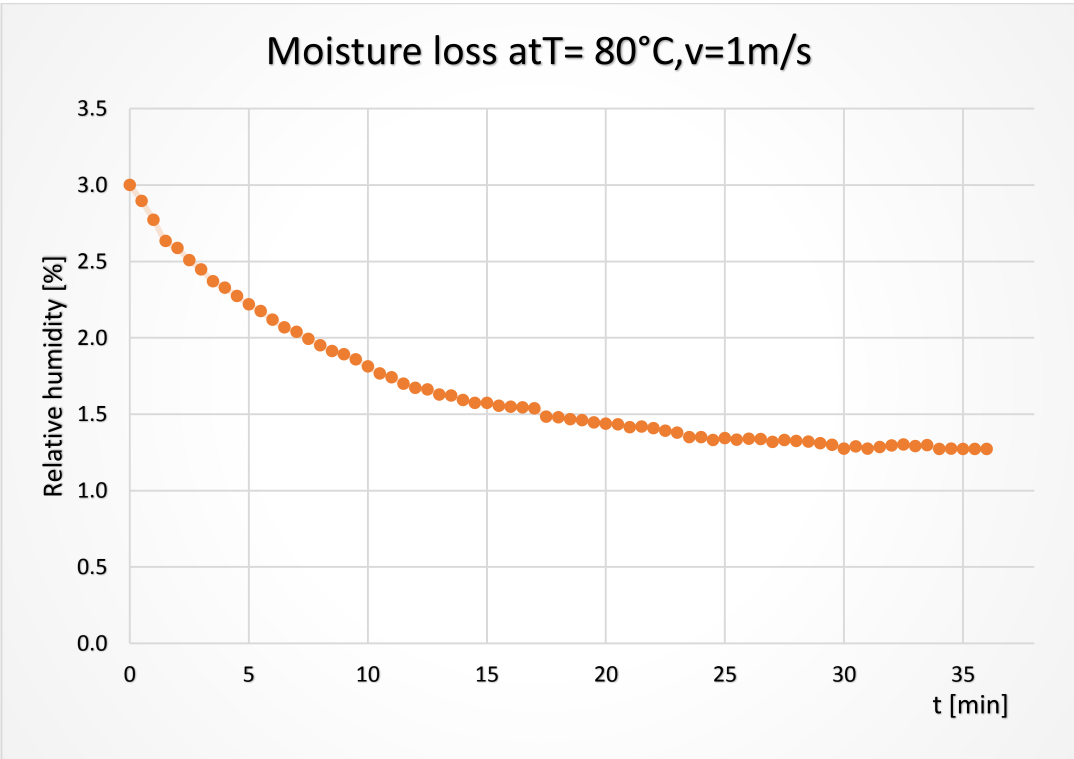


Figure 26. The moisture loss at T = 80°C and v = 1 m/s

Figure 27. The weight loss at T = 80°C and v = 1.5 m/s

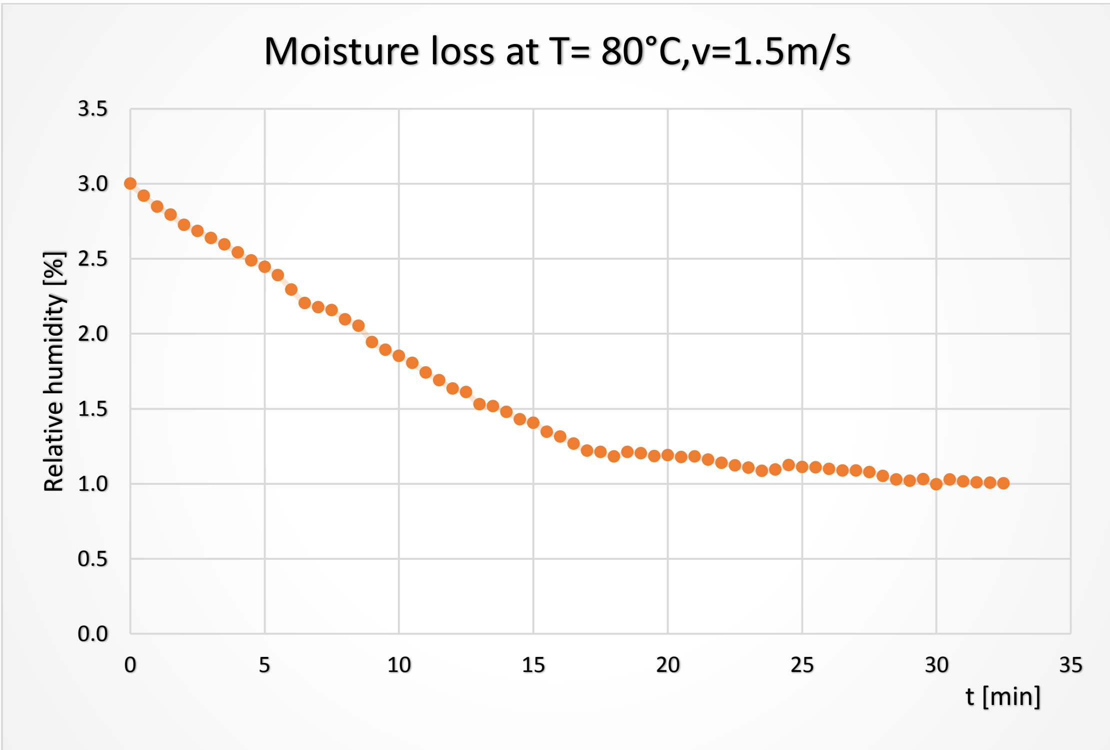


Figure 28. The moisture loss at T = 80°C and v = 1 m/s

4.2.2 The comparison of the results

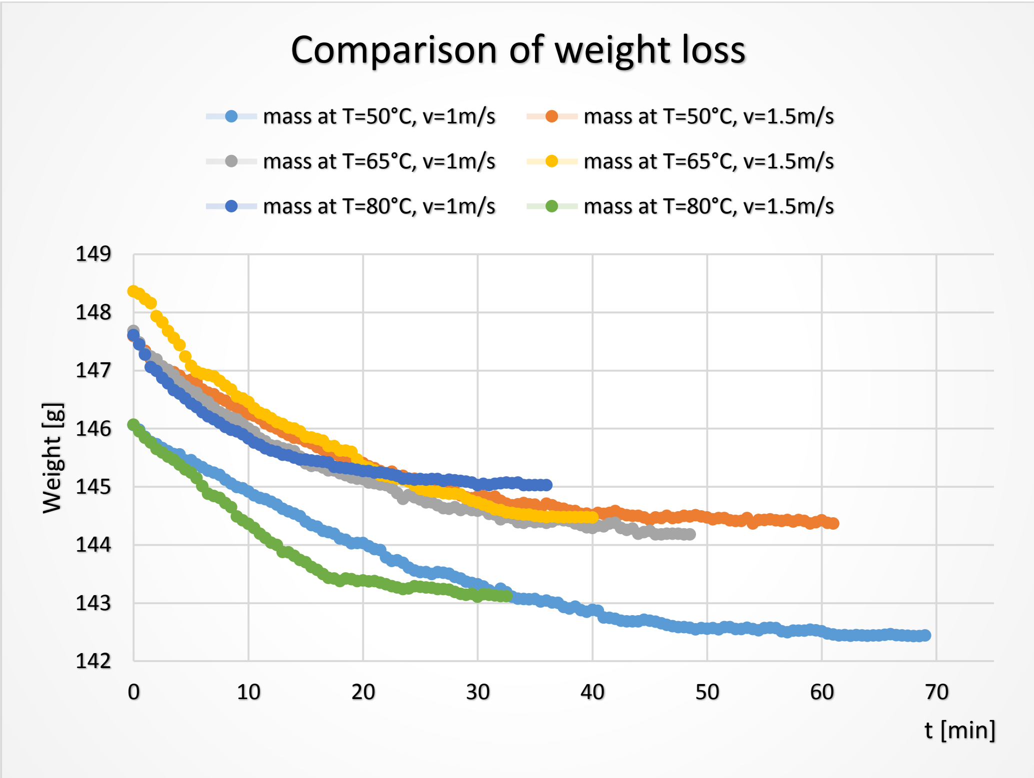


Figure 29. The comparison curves of the weight loss

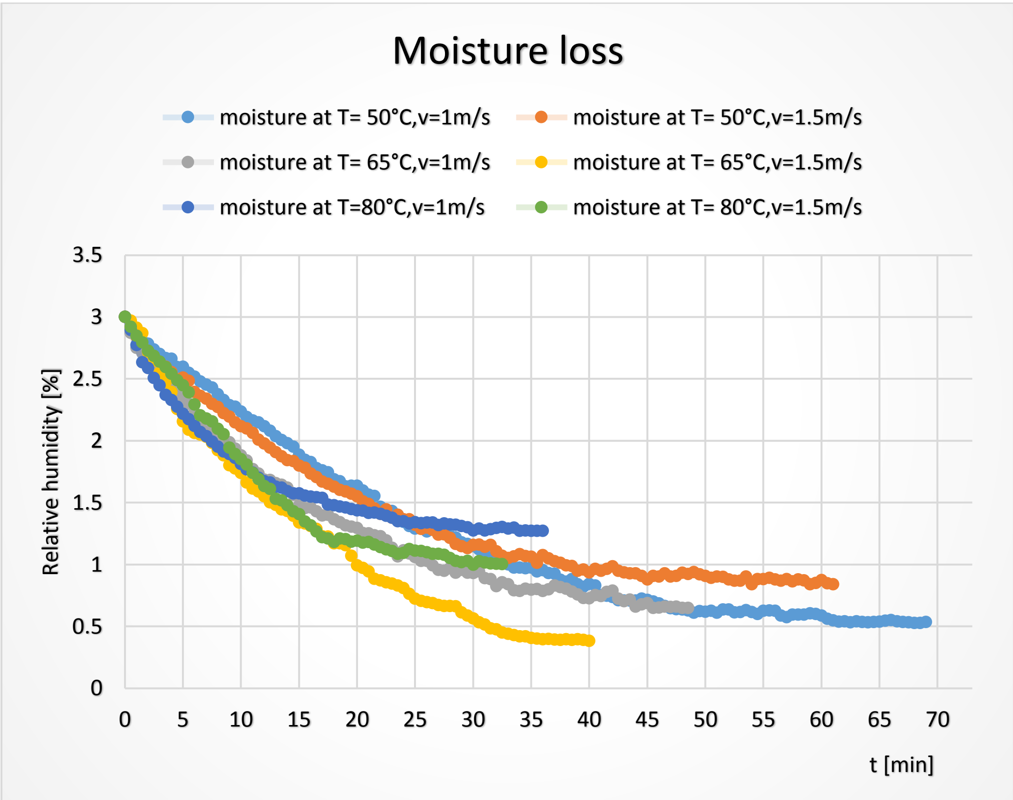


Figure 30. The comparison curves of the moisture loss

The final moisture content of the lump sugars ranged from 0.3 to 1.3 % on a dry basis depending on the different drying conditions. So, finally:

- at T = 50°C and v = 1 m/s, the drying time is about 63 min.
- at T = 50°C and v = 1.5 m/s, the drying time is about 57 min
- at T = 65°C and v = 1 m/s, the drying time is about 47 min
- at T = 65°C and v = 1.5 m/s, the drying time is about 38 min
- at T = 80°C and v = 1 m/s, the drying time is about 33 min
- at T = 80°C and v = 1.5 m/s, the drying time is about 30 min

From the figures and values was determined the shortest time of drying. Result valid for T=80°C and v=1.5 m/s and the visible change of sample has not been observed such as colour, crystal sintering at these conditions. From point of industry, the conditions for the smallest time are recommended, but energy balance of the process for that reason has not been measured.

4.2.3 Mathematical model

Data obtained from experimental data was converted into the dimensionless moisture content according to the equation:

$$MR = \frac{M-M_e}{M_0-M_e} \qquad (4.2.3\text{-}1)$$

where M is the moisture content of the solid at given time, M_e is the equilibrium moisture content of the solid, M_0 is the initial moisture content of the solid.

For a description of the drying kinetics of the sugar cubes was selected three mathematical models like a Henderson and Pabis, Two term exponential, Wang and Singh. These are shown in table 3. The coefficient of reliability (R^2) and Chi-square or objective function (χ^2) was used to determine the accuracy of the models. It is vital to note that if the value of R^2 high and χ^2 is low there is better agreement between the experimental data and mathematical model. The objective function is defined by the chi-square obtained through the fit of the analytical solution to the experimental points: (Wilton Pereira da Silva,2013)

$$\chi^2 = \sum_{i=1}^{N}(MR_{exp,i} - MR_{ana,i})^2 \frac{1}{N-n} \qquad (4.2.3\text{-}2)$$

Where $MR_{exp,i}$ is the experimental ratio of the moisture content at the i^{th} point of the measurement, $MR_{ana,i}$ is the calculated ration of the moisture content at the i^{th} point of the measurement, *N* is the number of the experimental points, *n* is the number of the coefficients in the model.

4.2.3.1 The comparison of the curves

The results were taken according to the value of the coefficients. The diagrams with the most similar results were selected. Other diagrams are attached in the appendix A.

- The mathematical model: Wang and Singh (R^2 = 0.9988, χ^2 = 0.002x10^{-3})

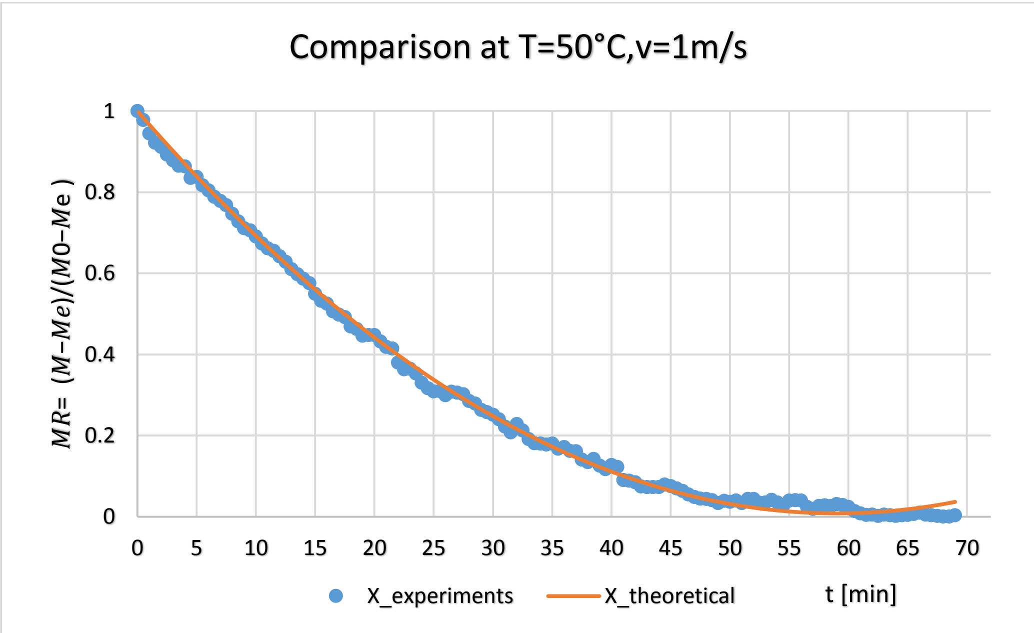


Figure 31. The experimental and calculated data for 'Wang and Sigh' model at

T=50°C, v=1m/s

- The mathematical model: Two term exponential (R^2 = 0.9982, χ^2 = 0.27x10^{-3})

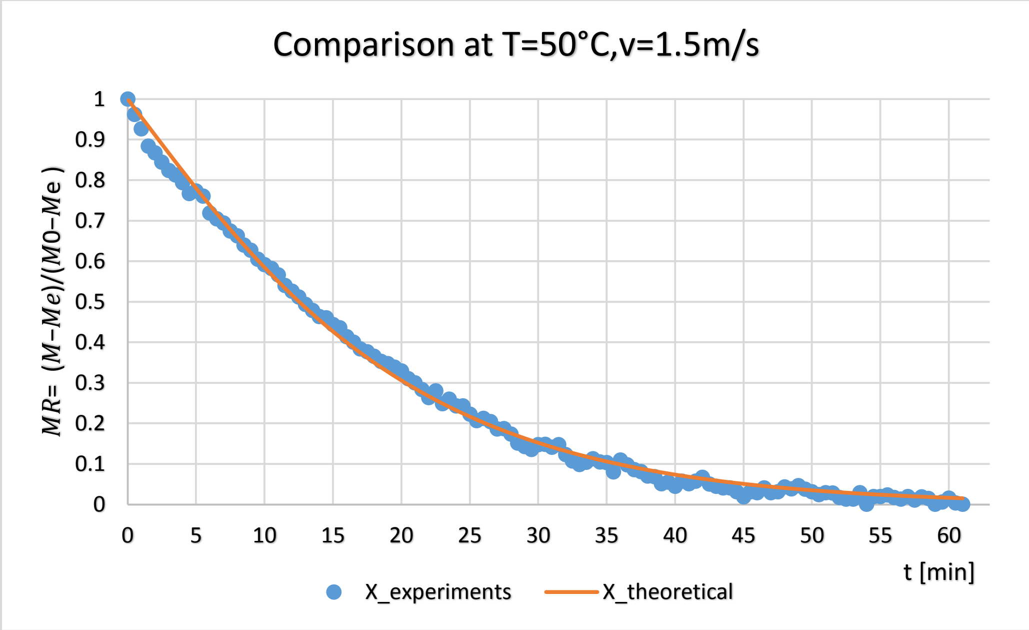


Figure 32. The experimental and calculated data for 'Two term exponential' model at T=50°C, v=1.5m/s

- The mathematical model: Two term exponential (R^2 = 0.9981, χ^2 = 0.3 x10^{-3})

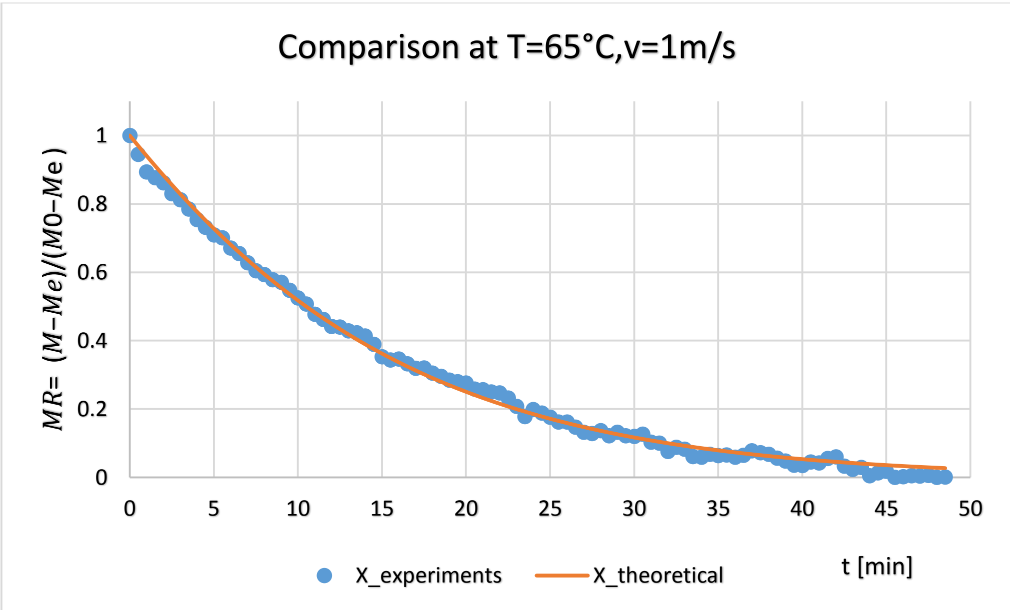


Figure 33. The experimental and calculated data for 'Two term exponential' model at

T=65°C, v=1m/s

- The mathematical model**:** Wang and Singh (R^2 = 0.9964 , χ^2 = 0.68x10^{-3})

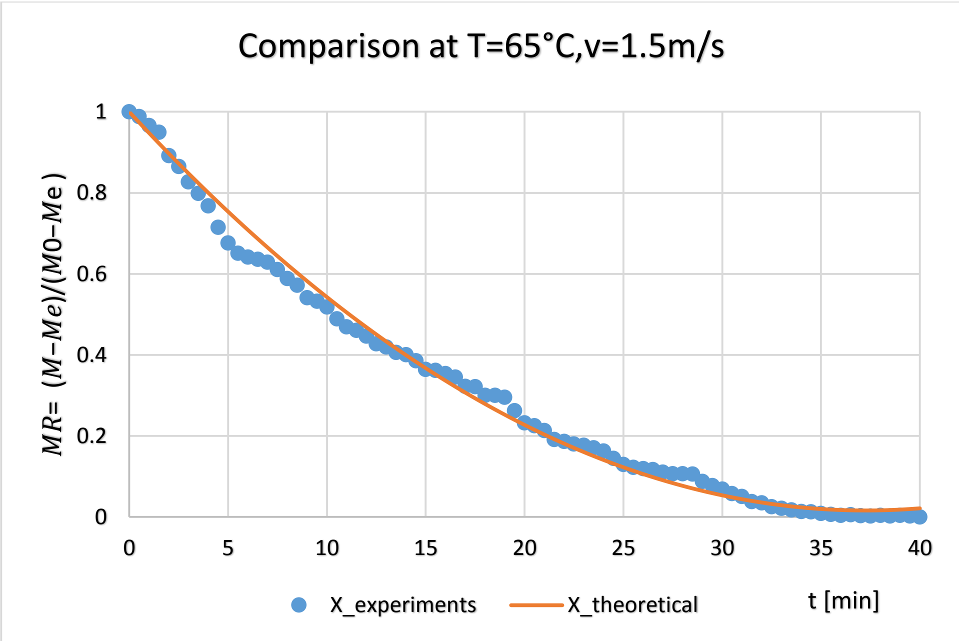


Figure 34. The experimental and calculated data for 'Wang and Sigh' model at T=65°C, v=1.5m/s

- The mathematical model**:** Two term exponential (R^2 = 0.9988 , χ^2 = 0.14x10^{-3})

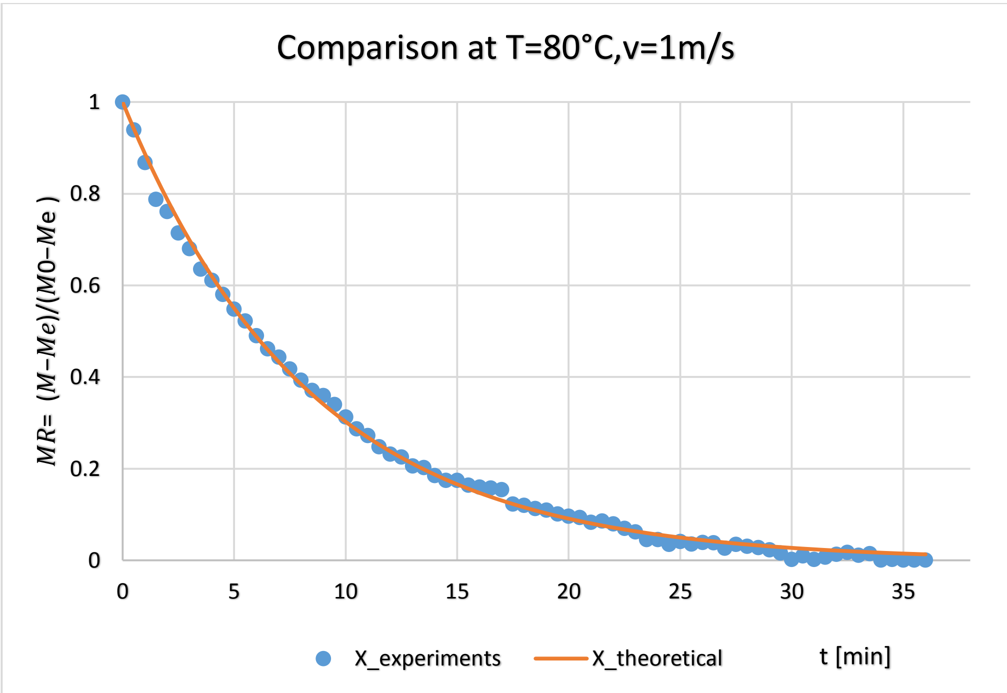


Figure 35. The experimental and calculated data for 'Two term exponential' model at T=80°C, v=1m/s

- The mathematical model**:** Two term exponential (R^2 = 0.9973, χ^2 = 0.51x10^{-3})

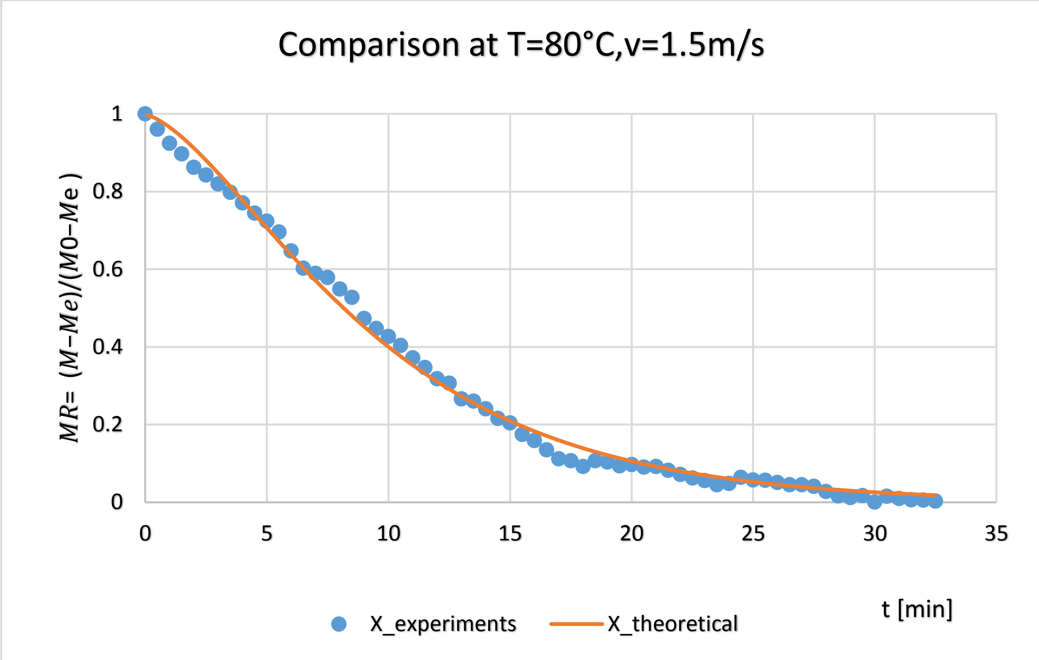


Figure 36. The experimental and calculated data for 'Two term exponential' model at

T=80°C, v=1.5m/s

Temperature, velocity, model	The resulting coefficients	R^2	χ^2
T=50°C, v=1m/s:			
1. Henderson and Pabis	a= 1.0763;k=0.0502	0.9918	1.42x10^{-3}
2. Two term exponential	a= 1.8099;k=0.0654	0.9976	0.41x10^{-3}
3. Wang and Singh	a= 0.0336;b=0.0003	0.9988	0.2x10^{-3}
T=65°C, v=1m/s:			
1. Henderson and Pabis	a= 1.006;k=0.0692	0.9972	0.45x10^{-3}
2. Two term exponential	a= 1.511;k=0.0819	0.9981	0.3x10^{-3}
3. Wang and Singh	a= 0.0492;b=0.0006	0.9913	1.3x10^{-3}
T=80°C, v=1m/s:			
1. Henderson and Pabis	a= 0.9801;k=0.1172	0.9986	0.17x10^{-3}
2. Two term exponential	a= 1.1374;k=0.1217	0.9988	0.14x10^{-3}
3. Wang and Singh	a= 0.0769;b=0.0015	0.9963	4.1x10^{-3}

Table 7.The resulting coefficients and errors of drying models for v=1m/s

Temperature, velocity, model	The resulting coefficients	R^2	χ^2
T=50°C, v=1.5m/s:			
1. Henderson and Pabis	a= 1.0316;k=0.0614	0.9955	0.67×10^{-3}
2. Two term exponential	a= 1.6510;k=0.0764	0.9982	0.27×10^{-3}
3. Wang and Singh	a= 0.6416;b=0.0004	0.9936	0.94×10^{-3}
T=65°C, v=1.5m/s:			
4. Henderson and Pabis	a= 1.0539;k=0.0772	0.9928	1.4×10^{-3}
5. Two term exponential	a= 1.6759;k=0.0955	0.9952	0.91×10^{-3}
6. Wang and Singh	a= 0.0528;b=0.0007	0.9964	0.68×10^{-3}
T=80°C, v=1.5m/s:			
4. Henderson and Pabis	a= 1.1047;k=0.1060	0.9886	2.2×10^{-3}
5. Two term exponential	a= 1.9228;k=0.1432	0.9973	0.51×10^{-3}
6. Wang and Singh	a= 0.0704;b=0.0012	0.9967	0.63×10^{-3}

Table 8.The resulting coefficients and errors of drying models for v=1.5 m/s

4.3 Regression analysis

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

- linear model function – ”easy”
- nonlinear model function – not so easy to find the best-fit parameters
- minimizing the sum of squares of residuals (deviations)
- finding the accuracy of parameters, confidence intervals
- comparing various models (different number of parameters, different model function). [5]

4.3.1 Function model to obtain diffusion coefficient

This mathematical model enables to determine the effective diffusivity from the result of drying experiments by using the analytical solution of equation from the section *1.6.2*. The example of that model that was created in Matlab is shown in the figure 37.

```
function s = xmodel(beta,t)
Dest = 3.75e-8;
h = 8.88*Dest*(20.94e-6/Dest)^(1/3)/0.015
Lx = 0.015;
D = beta(1);
mun = beta(2);
Bi = h*Lx/2/D;
Bn = 2*Bi^2/(mun^2*(Bi^2+Bi+mun^2));
s = 0;
for i=1:100
    s = s+Bn*exp(-(mun^2/(Lx/2)^2) *D*t);
end
Dest=D;
```

```
data = csvread('data801.csv');
t = data(:,1);
X = data(:,2);
Dest = 3.75e-8;
fun = @(beta,t) xmodel(beta,t);
[beta,resid,J] = nlinfit(t,X,fun,[Dest 10]),
beta(1)
beta(2)
ci = nlparci(beta,resid,J)
x = fun(beta,t);
plot(t,X,'r*', t,x,'b');
ylabel('MR=(M-Me)/(M0-Me)')
xlabel('time')
```

Figure 37. Function model for calculation of effective diffusivity

where *beta* is the best-fit values of parameters minimizing the sum of squares, *resid* is the residuals (deviations) in all measured data points, *J* is the Jacobi matrix. Matlab procedure *nlinfit* returns also the Jacobi matrix *J* besides the best-fit parameters. It can be used as parameter of function *nlparci.*

The effective diffusivity for the sugar cubes was estimated at the beginning of the calculation. Further, the optimal value of the effective diffusivity was obtained by several iterations. The symbol *h* in the model is the mass transfer coefficient that is calculated by the correlation for mass transfer from slab surfaces. (Perry Robert H, 1997)

From the plotted graph (Figure 38) can be seen that the calculated values have fitted the experimental results.

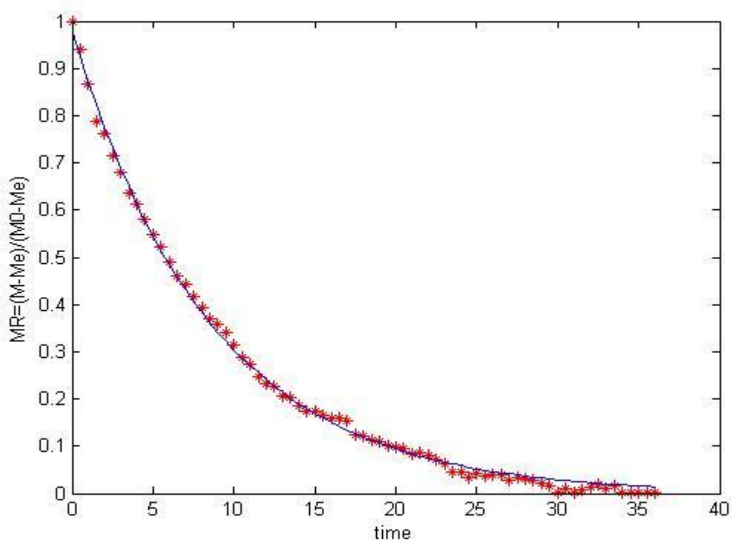


Figure 38. The relation of the effective diffusivity with the measurements. (T=80°C, v=1m/s)

4.3.2 Effective diffusivity

The values of effective diffusivity to given temperatures and airflow rates were calculated.

Temperature, T[°C]	Air flow[m/s]	D_{AB}x10^{-8} [m^2/s]
50	1	1.66
50	1.5	1.9
65	1	2.2
65	1.5	2.48
80	1	3.75
80	1.5	3.93

Table 9.Effective diffusivities for sugar cubes at different temperatures and airflow

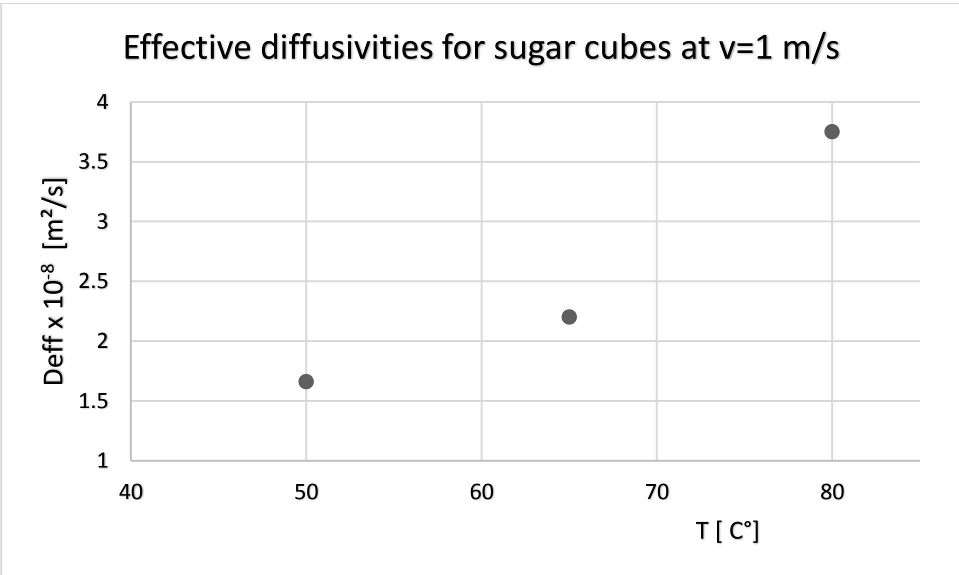


Figure 39.Effective diffusivities for sugar cubes at v=1m/s

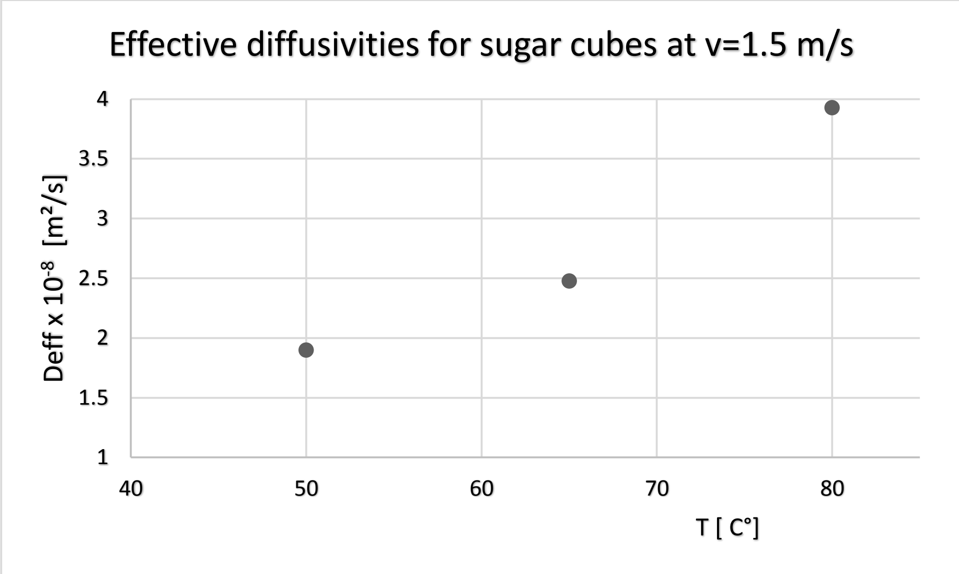


Figure 40. Effective diffusivities for sugar cubes at v=1.5m/s

Diffusion is a characteristic for slow-drying material where drying or water transport rates between nonporous particles are controlled by internal mass transfer. In this case, the resistance to mass transfer or water from the solid surface to the air stream is usually negligible, especially at higher velocities. Therefore, the moisture content at the solid surface is at or near the equilibrium moisture value. But high temperatures and air velocities may cause quick vaporization by which the syrup surrounding the grain is changed into highly superheated solution which can be an amorphous solid. In this case, the trapped water between grains is mainly bound water. However, slow drying of sugar cubes yields harder and stronger products. (C.Akosman, 2004)

Temperature, T[°C]	Air flow[m/s]	D_{AB}x10^{-9} [m^2/s]
45	0.56	4.23
60	0.56	4.94
80	0.7	5.73

Table 10.Effective diffusivities for sugar cubes at different temperatures and airflow for initial moisture content 2 %(C.Akosman, 2004)

Comparing with the related article (C.Akosman, 2004) it was observed that values of diffusion coefficients of sugar cubes were approximately in close trend. It means that my result is close to real value of those parameters.

5 CFD Model

This chapter will provide the description of the two-dimensional (2D) simulation of the sugar cube in the chamber dryer. Also it includes consideration of the necessary step to model the drying process of the sugar cube. In order to simulate the behaviour of the temperature distribution and velocity field of drying air was performed both laminar and turbulent flow regime. The simulation was done iteratively until an acceptable convergence of the results is reached.

5.1 Modelling

The CFD simulation of drying process was analyzed and designed using ANSYS FLUENT. The actual 2D geometry model was designed according to the parameters of the chamber dryer that used in experimental part. To create the 2D geometry model was used the cross section view of the laboratory dryer. Figure 41 shows direction of the airflow and the position of a sugar cube that is placed in the middle of that model.

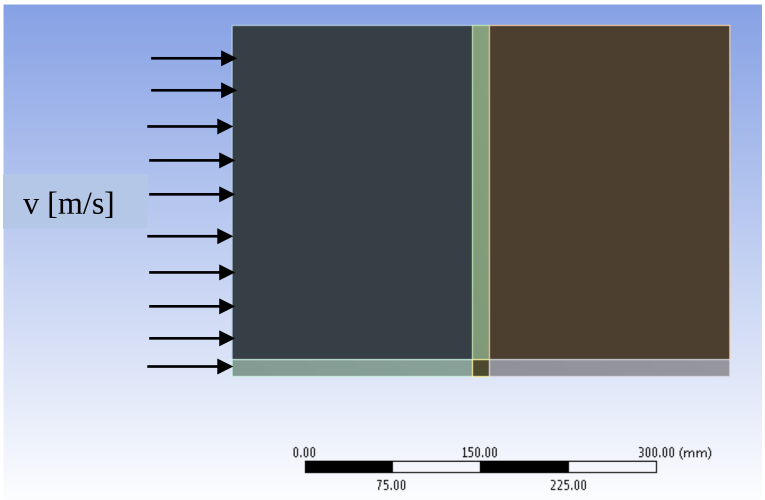


Figure 41. Geometry of the chamber dryer.

5.2 Meshing and boundary condition

A computational mesh with certain number of elements and nodes was constructed and boundary types assigned to the different parts of the geometry. The boundary conditions for the calculations were determined considering the measurements directly from the laboratory dryer.

Mesh statistics	
Total number of nodes	21521
Total number of elements	21200

Table 11. Mesh generation statistics

Some parameters and properties, which are required during analysis, are shown in table 9.

Physical parameters	Notes
Fluid	Air
Density of air	1.125 kg/m^3
Specific heat capacity (Cp)	1009 J/kgK
Thermal conductivity	0.0242 W/mK
Velocity magnitude (Inlet)	1 m/s
Temperature (Inlet)	From 323.15K to 353.15K
Temperature (Laboratory Temperature)	293.15 K

Table 12. Physical Parameter and Properties

5.3 Result

5.3.1 Velocity field of drying air

The velocity flow is evenly distributed in each direction of the axis in the dryer. Below is shown the velocity profile of the drying air for both laminar and turbulent flow regime.

Due to the avoid, the effect of the wall on the velocity profiels near the cube, the large chamber was cretaed. But in free flow was Re=9551 which determines the laminar flow, but near the sugar wall Re=716 indicates turbulent flow over the immersed bodies. Both laminar and turbulent k-ω was used to investigated if $\underline{\alpha}$ is in the comparable value with analytical solution.

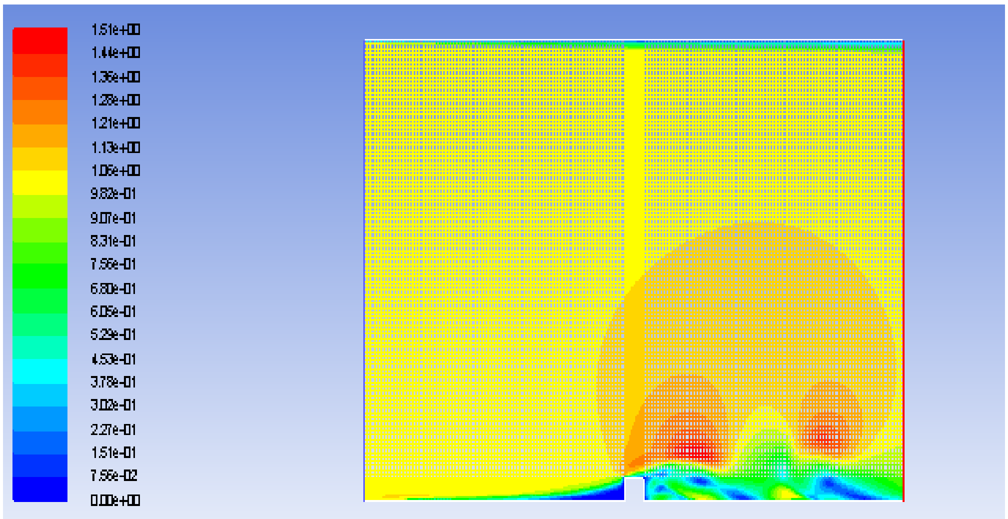


Figure 42. Velocity magnitude (laminar flow)

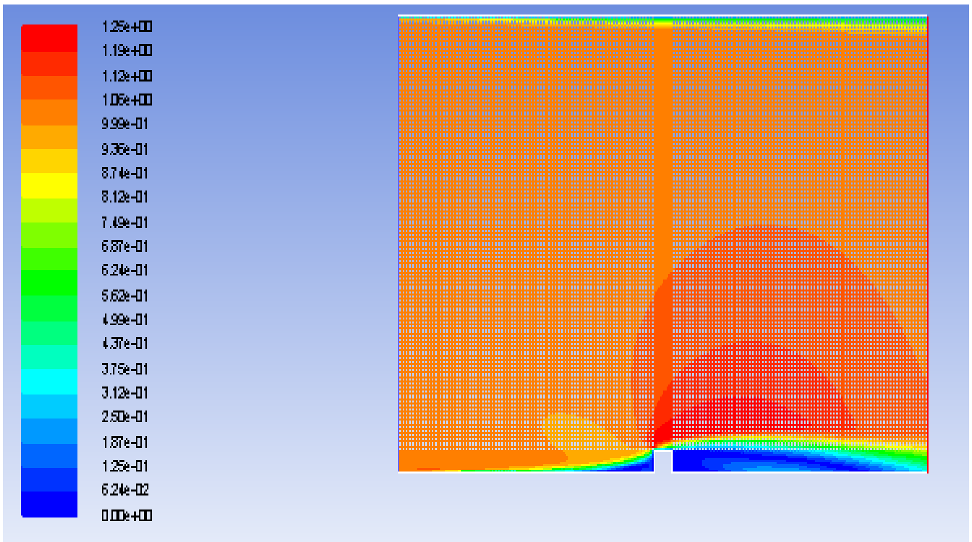


Figure 43. Velocity magnitude (turbulent flow)

5.3.2 Static temperature

The temperature distribution visualised in figures below. Static temperature describes that the maximum temperature spreads and distributes evenly in the dryer. It means that the drying process is efficient.

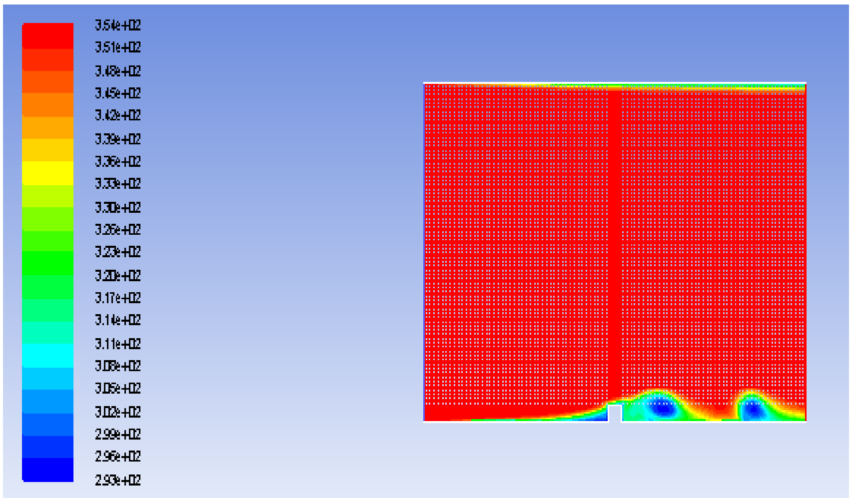


Figure 44.Static temperature (laminar flow)

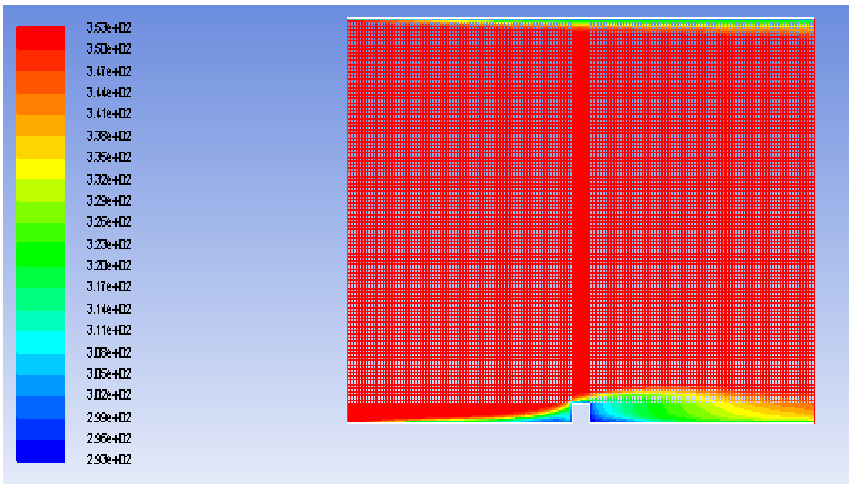


Figure 45.Static temperature (turbulent flow)

5.4 Summary

2D simulation saves more time comparing to 3D approach and allows to quick evaluation of given model. But the biggest advantages of the 3D simulation is to get detailed description of fluid flow.

Flow	Mean value of heat transfer coefficient α $[W/m^2K]$
Laminar	11.63
Turbulent	20.58

Table 13. Mean value of heat transfer coefficient

Main result was value of heat transfer coefficient on the top surface of the sugar directly obtained from the simulations for different temperature differences.

6 Heat and mass transfer analogy

As mentioned in section 3.4, analogy between mass and heat transfer coefficient exists. In this chapter, the results of the CFD simulation and experiments with the analytical calculation of the mass and heat transfer coefficients will be compared. For perform that analogy calculation these condition were used: T=80°C, v= 1 m/s.

Result:

- from the experiments the value of mass transfer coefficient is $\beta = 1.83x10^{-4}$[m/s]
- from the CFD model the mean value of heat transfer coefficient for turbulent flow $\bar{\alpha}$= 20.58 [W/m^{2}K]

6.1 Analytical calculation

Parameters for T=80°C:

- thickness of the sugar cube Lx= 0.015 mm
- velocity of airflow v= 1 m/s
- kinematic viscosity of air $\upsilon = 20.94x10^{-6}$ m^2/s
- effective diffusivity of sugar cube $D_{AB} = 3.75x10^{-8}$ m^2/s
- thermal conductivity of air λ = 0.0242 W/mK
- density of air ρ = 1.125 kg/m^3
- specific heat of air Cp = 1009 J/kgK

The Reynolds number:

$$Re = \frac{Lxv}{\upsilon} = \frac{0.015*1}{20.94x10^{-6}} = 716.33 \quad (6.1\text{-}1)$$

In order to calculate the Nusselt number the equation (3.4-5) was used

$$\mathrm{Nu} = \mathrm{CrRe^m Pr^{1/3}} = 0.648 * 716.13^{0.5} * \left(\frac{20.94x10^{-6}}{\frac{0.0242}{1.125*1009}}\right)^{\frac{1}{3}} = 17.24 \quad (6.1\text{-}2)$$

where Cr =0.648 and m =0.50

The value of heat transfer coefficient was calculated according to following equation

$$\alpha = \frac{Nu*\lambda}{\mathrm{Lx}} = \frac{17.24*0.0242}{0.015} = 27.8 \ \text{W/m}^2\text{K} \quad (6.1\text{-}3)$$

After simplifying the equation (3.4-4) the value of the mass transfer coefficient was calculated:

$$\beta = \alpha * \frac{D_{AB}}{\lambda} * \left(\frac{\frac{\lambda}{\rho * Cp}}{D_{AB}}\right)^{\frac{1}{3}} = 27.8 * \frac{3.75\text{x}10^{-8}}{0.0242} * \left(\frac{\frac{0.0242}{1.125*1009}}{3.75\text{x}10^{-8}}\right)^{\frac{1}{3}} = 3.56x10^{-4}\ m/s \qquad (6.1\text{-}4)$$

Comparing the results of the analytical and experimental solution one can be explained that the convective heat and mass transfer are completely similar phenomena under certain special conditions.

Experiments(regression)	CFD model	Analytical correlation
β =1.83x10^{-4} [m/s]	β =2.64x10^{-4} [m/s] α = 20.58 W/m^2K	β =3.56x10^{-4} α = 27.8[W/m^2K]

Table 14. Results of coefficients from experiments (regression analysis), CFD model, analytical correlation

From result it is obvious that all three values of β are in same order and similar. It is possible to use any of the suggested methods, to evaluate the β with good agreement.

7 Design of the belt dryer

After obtaining the result from experiments, we can proceed to actual calculation of balance and determine the dimensions of dryer.

Selected data according to experimental measurements

- Amount of the material necessary to dry M_1=100 kg/h
- Initial moisture content of sample ω_0= 3%
- Final moisture content of sample ω_1= 0.38%
- Relative humidity of inlet air φ_{A0}= 65%
- Ambient air temperature t_{A0} = 20°C
- Temperature after heating t_{A1} = 65°C
- Outlet temperature t_{A2} = 55°C

7.1 Balance of drying

Moist air determined from the diagram (figure 43):

- Specific humidity $x_{A0} = x_{A1}$ = 0.01 kg H_2O/ kg

  x_{A1} = 0.019 kg H_2O/ kg
- Specific enthalpy h_{A0} = 45 kJ/ kg

  h_{A1} = 92 kJ/kg

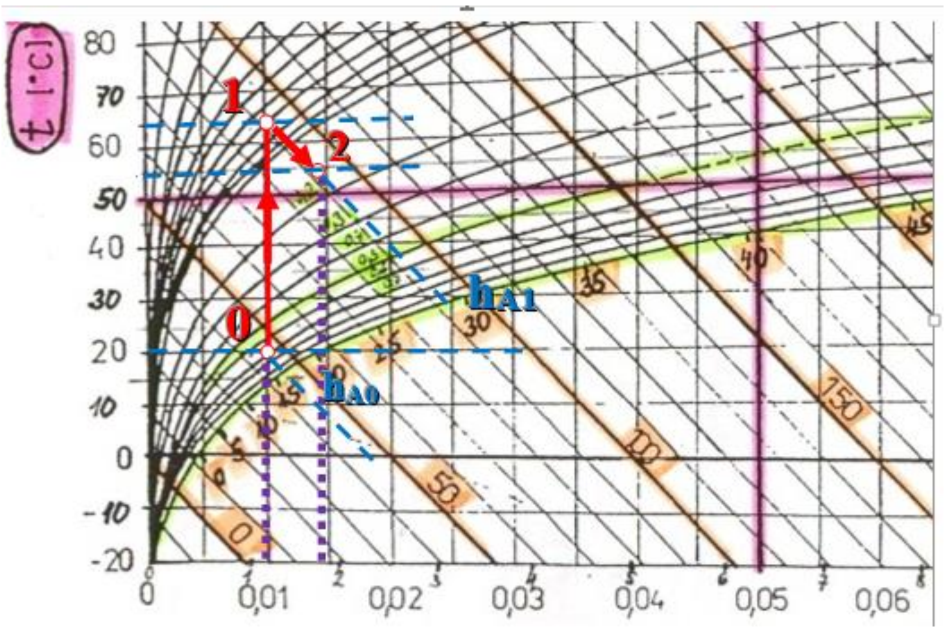


Figure 46. h-x diagram for drying [1]

The amount of dried material:

$$\mathrm{M_2} = \mathrm{M_1} * \left(\frac{1-\omega_0}{1-\omega_1}\right) = 100 * \left(\frac{1-0.03}{1-0.0038}\right) = 97.37\ \mathrm{kg} * \mathrm{h}^{-1} \qquad (7.1\text{-}1)$$

The amount of dried moisture:

$$M_W = M_1 - M_2 = 100 - 97.37 = 2.63\ kg * h^{-1} \qquad (7.1\text{-}2)$$

Necessary amount of drying air:

$$M_A = \frac{M_w}{x_{A1} - x_{A0}} = \frac{2.63}{0.019 - 0.01} = 292.22\ kg * h^{-1} = 0.081\ kg * s^{-1} \quad (7.1\text{-}3)$$

The heat required to heat up drying air:

$$Q_A = M_A - (h_{A1} - h_{A0}) = 0.081 * (92 - 45) = 3.807\ kW \quad (7.1\text{-}4)$$

Considering that air is heated in calorifers 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:

$$M_S = \frac{Q_A}{r_{TP}} = \frac{3.807}{2201} = 0.00173\ kg * s^{-1} = 6.228\ kg * h^{-1} \qquad (7.1\text{-}5)$$

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

$$M_{wA} = M_A * (x_{A1} - x_{A0}) = \frac{M_W}{(x_{A1} - x_{A2})} * (x_{A1} - x_{A0}) = M_w \quad (7.1\text{-}6)$$ $$M_{wA} = M_A * (x_{A1} - x_{A0}) = 292.22 * (0.019 - 0.01) = 2.63\ kg * h^{-1}$$

7.2 Dimension of the dryer

This section involve the basic calculation of belt dryer size. The dimensions of the dryer were calculated for the M_1=100 kg/h (sugar cube) drying material flow rate.

- Weight of 1 sugar cube $m_{sugarcube}$= 6 g = 0.006 kg
- Dimensions of sugar cubes = 15x15x25 (mm)
- Area of 1 sugar cube including the distance between the sugar cubes that are putted on the belt. And this distance approximately equal to the 5 mm:

$S_{sugarcube}$ = 0.02x0.03=6x10^{-4} m^2

- Mass of the required lump sugars m_1=100 kg
- Drying time at T=65°C,v=1.5 m/s : t=38 min

$$S = \frac{\mathrm{m_{s1}}}{\mathrm{m_{sugarcube}}} * \mathrm{S_v} = \frac{100}{0.006} * 6\mathrm{x}10^{-4} \doteq 10\ \mathrm{m}^2 \qquad (7.2\text{-}1)$$

$\underline{A}$ is the area of the belt dryer that corresponds to dry the 100 kg of the lump sugars. According to this value can be determined the belt width and belt length:

$$S = L*D \quad (7.2\text{-}2)$$

where *L*=25 m is the belt length and *D*=0.4 is the belt width. To avoid the deflection of the belt it is better to have the small size of a width.

Belt velocity:

$$u = \frac{L}{t} = \frac{25}{(38*60)} = 0.011 \text{ m/s} = 11 \text{ mm/s} \quad (7.2\text{-}3)$$

It is vital to note that design of the dryer does not include the parameter of the fan, electrical power to drive the dryer etc. However, the parameters like temperature, velocity, size of belt can have influence to the economical approach. For instance, higher is the temperature of the drying air, lower is the width of belt and it can safe some maintained cost, but there will be high operational cost.

Conclusion

This thesis has been to perform the study the laboratory experiments and 2D simulation of the lump sugars drying.

First and foremost the general information about the theoretical fundamentals of drying process was described. The objective of this literature search is to yield the important knowledge about the transport phenomena during the drying, drying kinetics and the equipment where drying take place.

The experimental part was set out to obtain the drying curves for three different temperature and two air velocities. For that reason the drying characteristics of sugar cubes, on which these temperature and air velocities have effects, enables to calculate the diffusion coefficient by using the regression analysis.

Further, a laboratorial chamber dryer for drying of the sugar cubes was simulated by CFD Software ANSYS FLUENT. This tool provides the analyze of the air flow distribution, temperature distribution to predict the momentum, heat and mass transfer in the dryer. Moreover, its application include food processing process (mixing, baking, fermentation etc.) and to design the food processing equipment.

The obvious conclusion that can be drawn from Chapter 6 is to explain the existence of the similarity between heat and mass transfer. By using the Chilton-Colburn analogy was calculated heat and mass transfer coefficients. Analogy describes that the heat transfer correlation for the Nusselt number applied to obtain the Sherwood number.

Three different approach of analysis of the process were compared with related articles, and it was found that the results are close to reality.

Finally, based on the experimental results for T=65°C and air velocity 1.5 m/s was done balance calculation of the dryer. According to this balance and measurements basic parameters of a belt dryer was designed.

<u>Future work</u>

The suggested future studies on this master's thesis could include the detailed design of the belt dryer parameters. Which will involve the calculation of electrical load (energy requirements for drive the belt, electrical power of fan, pressure loss), optimization of the cost by recirculation of the drying air. Also I suggest to focus on the 3D modelling of the belt dryer.

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[3] http://www.tis-gdv.de/tis_e/ware/zucker/wuerfel/wuerfel.htm

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[5]http://moodle.fs.cvut.cz/pluginfile.php/3020/mod_resource/content/1/prezentace-handout-en.pdf

http://www.kmutt.ac.th/dtrl/pdf/Drying_PrinciplesandPractice

http://www.technicaljournalsonline.com/ijeat/

http://assbt-jsbr.org

http://www.sciencedirect.com/science/article/pii/S0168169901001776

http://cdn.intechopen.com/pdfs-wm/22867.pdf

https://www.researchgate.net/profile/Bahman_Horri/contributions

http://onlinelibrary.wiley.com/doi/10.1002/ceat.200402056/abstract

List of symbols

a,b,g,k	coefficient of drying model	(-)
a_w	water activity	(-)
A_n	coefficient of the analytical solutions depended on the position	(-)
Bi	Biot number	(-)
B_n	coefficient of the analytical solutions	(-)
Cp	specific heat capacity	(kJ/kgK)
Cr	correlation constant	(-)
D	width of belt dryer	(m)
D_{AB}	diffusion coefficient	(m^2/s)
$h_{A,S}$	specific enthalpy	(kg_{H20}/kg)
j_D	mass transfer factor	(-)
j_H	heat transfer factor	(-)
L	length of belt dryer	(m)
Lx	thickness of the sugar cube	(mm)
m	ratio	(-)
M_1	flow rate sugar cubes	(kg/h)
M	moisture content	(kg_{H20}/kg,dry basis)
M_0	initial moisture content of sugar cube	(kg_{H20}/kg,dry basis)
M_{DM}	dry mass content	(kg)
M_e	equilibrium moisture content	(kg_{H20}/kg,dry basis)
MR	dimensionless moisture content	(-)
MR_{ana}	moisture content obtained analytically	(kg_{H20}/kg,dry basis)
MR_{exp}	moisture content obtained experimentally	(kg_{H20}/kg,dry basis)
Nu	Nusselt number	(-)

P''	water vapour pressure	(kPa)
P_{H20}''	partial water vapour pressure	(kPa)
Pr	Prandtl number	(-)
Q	heat	(kW)
Re	Reynolds number	(-)
R^2	coefficient of reliability	(-)
S	area of belt dryer	(m^2)
Sc	Schmidt number	(-)
Sh	Sherwood number	(-)
St	Stanton number	(-)
T	temperature	(°C)
t	time	(s)
u	velocity of belt	(m/s)
v	velocity of drying air	(m/s)
W	mass flow rate of removed moisture	(kg/s)
$X_{A,S}$	specific humidity	(kg_{H20}/kg)
x	position in Cartesian coordinate	(mm)

Greek symbols

β	mass transfer coefficient	(m/s)
α	heat transfer coefficient	(W/m^2K)
λ	thermal conductivity	(W/mK)
ρ	density	(kg/m^3)
υ	kinematic viscosity	(m^2/s)
χ^2	Chi-square or objective function	(-)
μ	dynamic viscosity	(kg/ms)
μ_n	roots of characteristic equation	(-)
ω	moisture content	(%)

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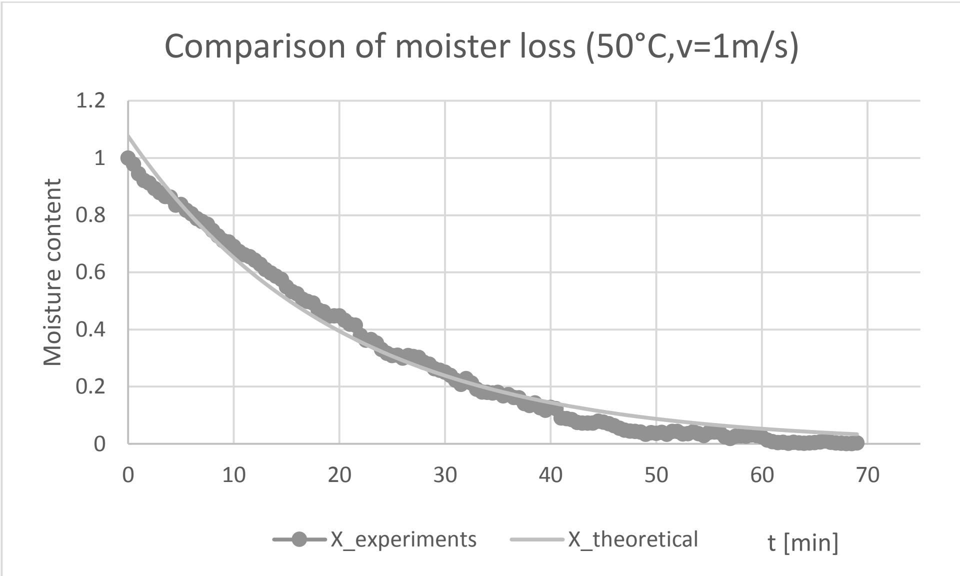
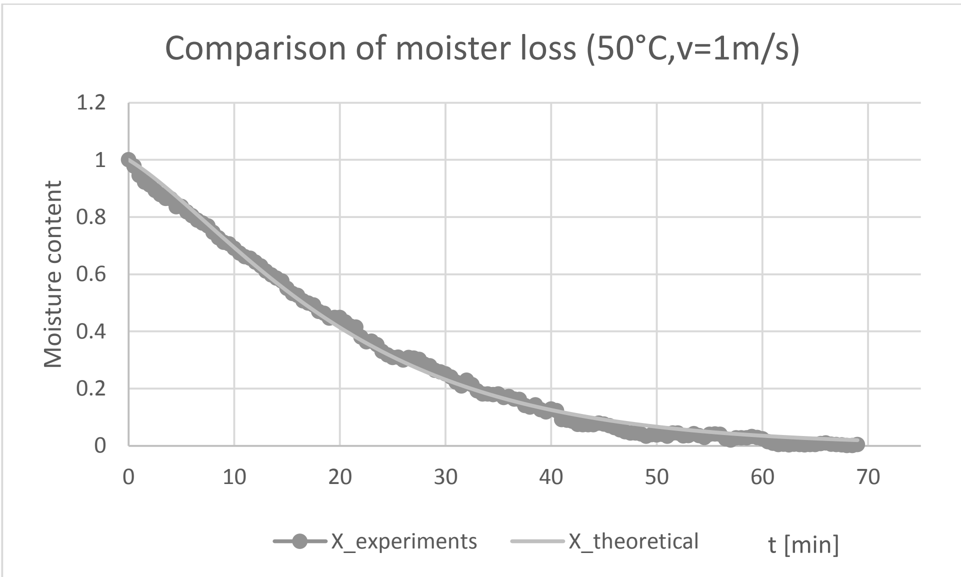
Appendix A

Comparison of moister loss (50°C,v=1m/s)

a) **Henderson and Pabis (R^2 = 0.9918 , χ^2 = 1.42x10^{-3})**

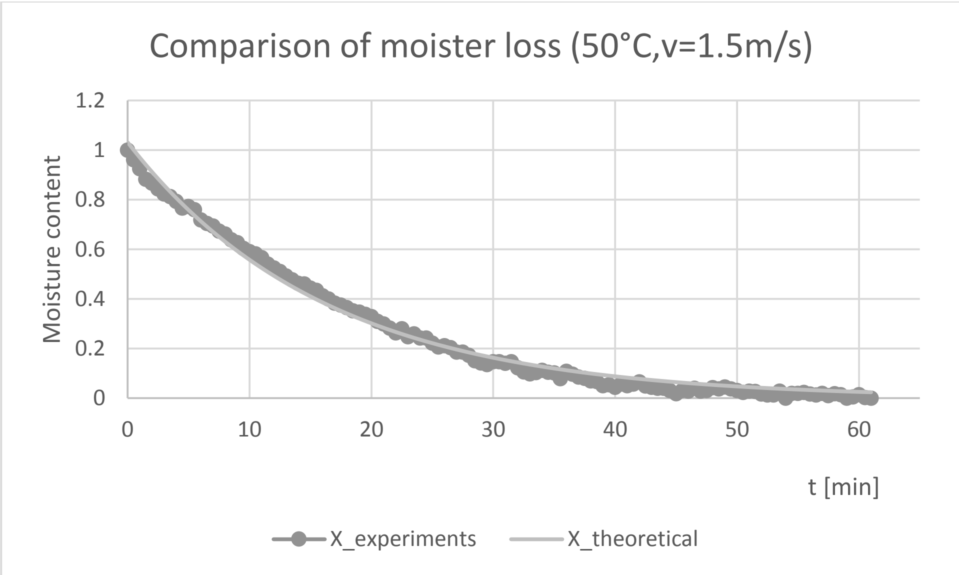


b) **Two term exponential (R^2 = 0.9976 , χ^2 = 0.41x10^{-3})**

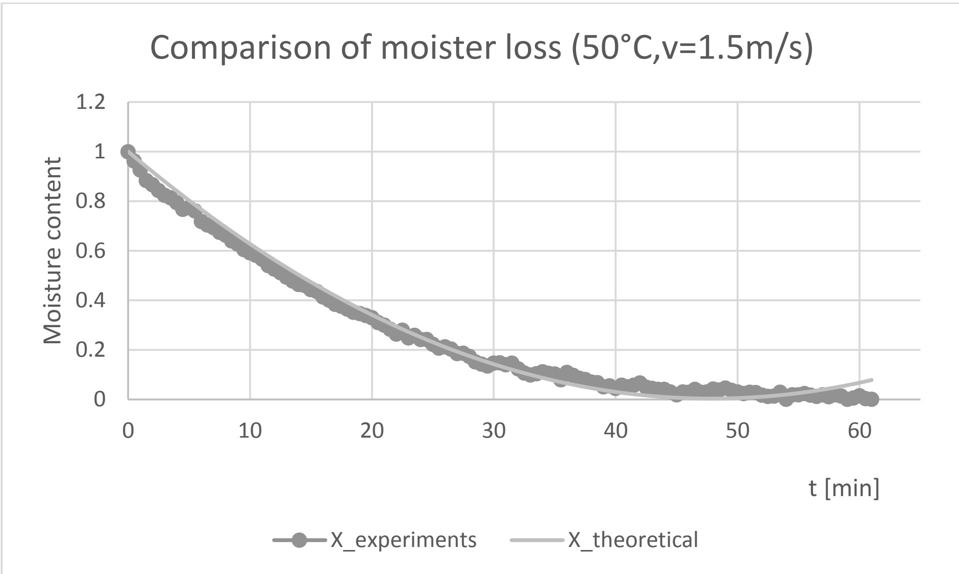


Comparison of moister loss (50°C,v=1.5m/s)

a) Henderson and Pabis (R^2 = 0.9955 , χ^2 = 0.67x10^{-3})

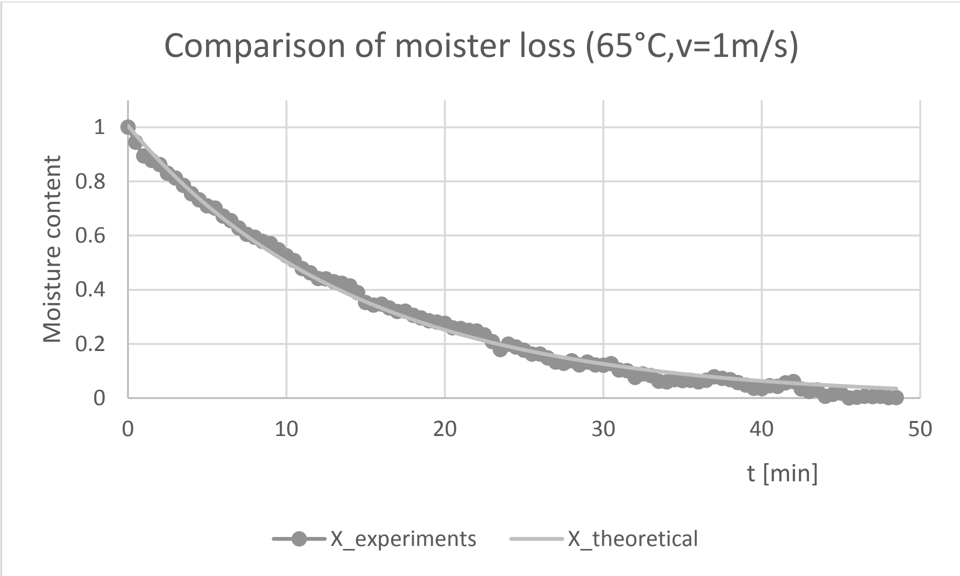


b) Wang and Singh (R^2 = 0.9936 , χ^2 = 0.96x10^{-3})

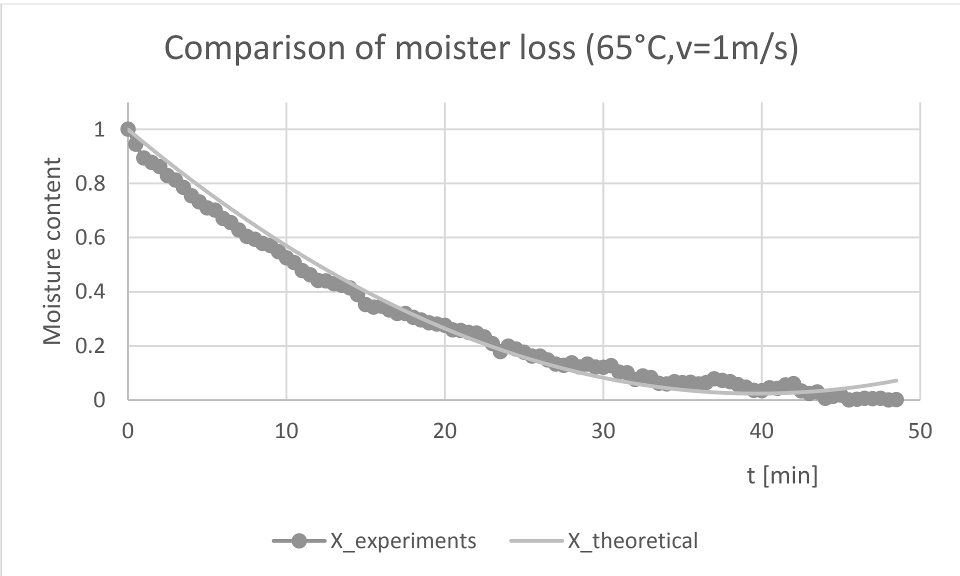


Comparison of moister loss (65°C,v=1m/s)

a) **Henderson and Pabis($R^2 = 0.9972$, $\chi^2 = 0.45x10^{-3}$)**

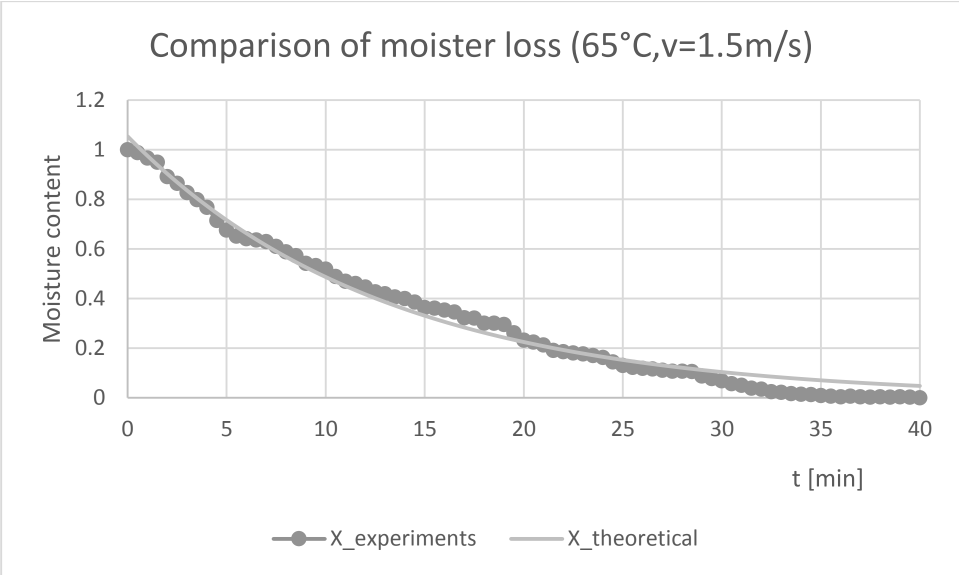


b) **Wang and Singh($R^2 = 0.9913$, $\chi^2 = 1.37x10^{-3}$)**

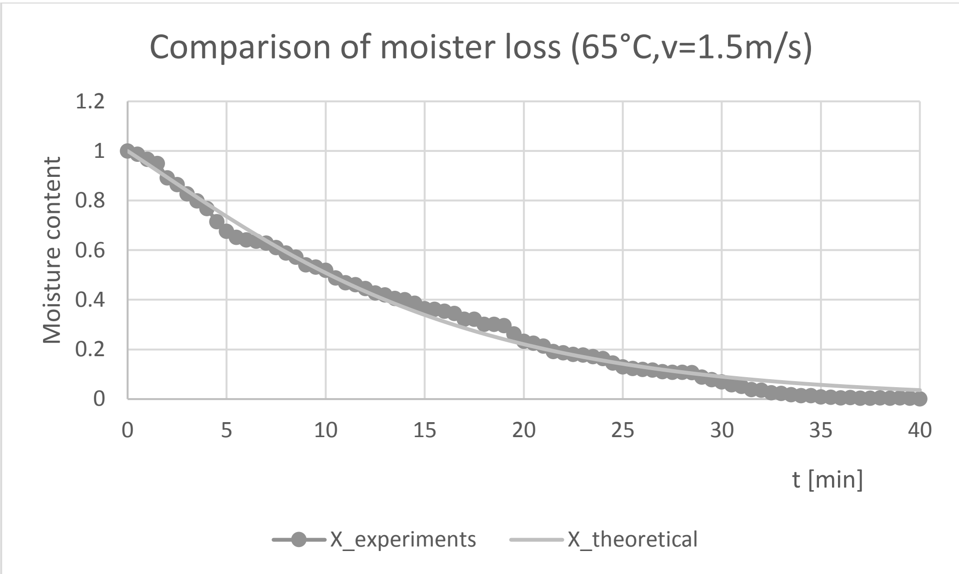


Comparison of moister loss (65°C,v=1.5m/s)

a) Henderson and Pabis(R^2 = 0.9928 , χ^2 = 1.36x10^{-3})

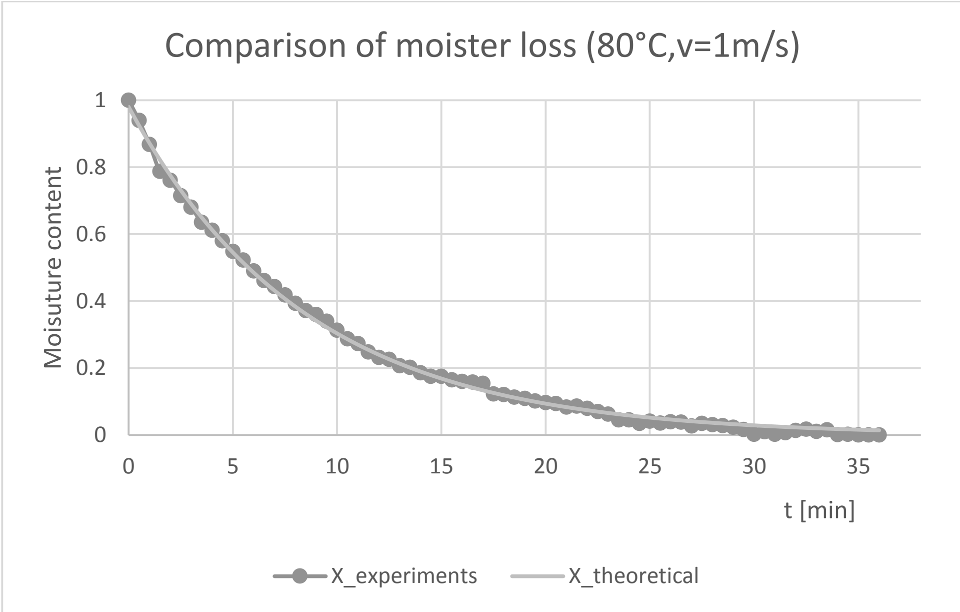


b) Two term exponential(R^2 = 0.9952 , χ^2 = 0.91x10^{-3})

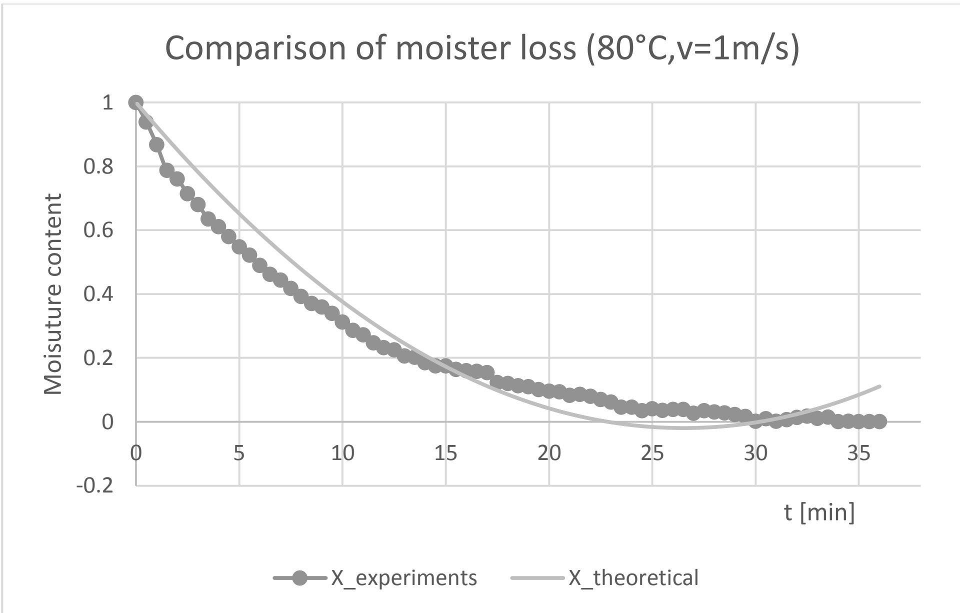


Comparison of moister loss (80°C,v=1m/s)

a) Henderson and Pabis(R^2 = 0.9986 , χ^2 = 0.17x10^{-3})

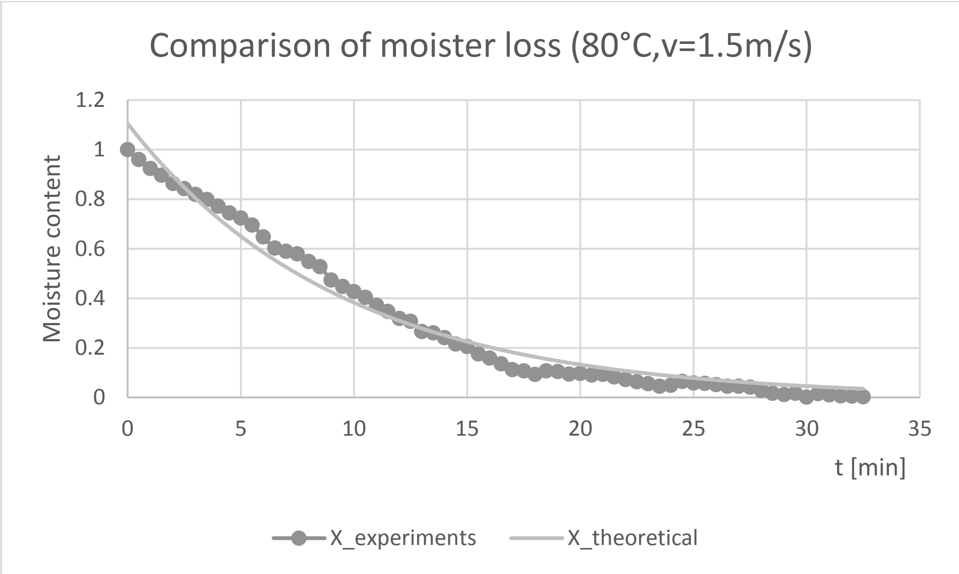


b) Wang and Singh(R^2 = 0.9663 , χ^2 = 4.07x10^{-3})



Comparison of moister loss (80°C,v=1.5m/s)

a) Henderson and Pabis(R^2 = 0.9887 , χ^2 = 2.16x10^{-3})



b) Wang and Singh(R^2 = 0.9967 , χ^2 = 0.63x10^{-3})