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Design of a chamber dryer for sugar cubes drying

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Declaration

I confirm that the Master thesis was disposed by myself and independently, under leading of my thesis supervisor. All sources of the documents and literature are stated.

In Prague ……………… …………………

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1. INTRODUCTION

1.1 Drying process

When investigating the process and techniques of drying, it is first of all worth better understanding the term drying itself. Traditionally, in the scientific literature, drying stands for a process applied in order to remove the liquid compounds of water from solid, semi-solid or liquid materials. Most often, the process of drying is used in the commercial practice as a stage of production preceding the ultimate packaging and sales of products. The process of drying is inherently much complex, and involves heat agents used for ensuring the desiccation of materials, and the mass transport (11).

Drying is an important process used in different industries. For instance, drying is widely used in agriculture for processing food products. As a result of drying, the water contained in those products is eliminated, and as a result of the processes occurring, they transform into dried stripes, powders or other materials deprived of water compounds. The main goal of such operations is to ensure the longer storage period for the respective food products, optimize the transportation process, etc. The drying processes applied in agriculture are also much important in terms of healthcare and the protection of food, as they help create a powerful antibacterial shield for preventing the contamination of products with various germs. Finally, drying can be used for food products in order to provide them with some specific consumption parameters, for instance to create their specific texture. In the non-food industries, drying is required as part of the industrial production processes indispensable for achieving the required final result. For instance, this is true when speaking of timber processing where the drying of the wood is required for any subsequent operations. Drying is also largely used in the chemical and petrochemical industries, where the dehydration of specific organic compounds is required in order to get usable chemical agents. A major advantage of the drying process in industrial production is also the fact that it helps reduce the ultimate volume and mass of products. Finally, drying is also a crucial process for the utilities sector, as it is largely used in sewerage systems for achieving anti-pathogenic protection (1).

Basic notions of dried material are moisture content [kg water / kg dried material], water activity, pressure of saturated water vapor, pressure of water vapor at surface. Water hidden inside a porous structure is attracted to the capillary walls by capillary forces, by Van der Waals forces, and by very strong hydrogen bonds. Water at a wetted part of surface is free. Water vapor above the wetted surface is saturated and its pressure is determined by the temperature of surface (Antoine's equation).

Besides, partial pressure of water vapor above a partially dried surface is lower due to reduced mobility of bonded water molecules. The pressure reduction is quantified by the water activity. The greater the moisture content greater is proportional amount of free water.

Although the types of dryers significantly vary in the industrial practice, the overall principles of the operation of dryers are much similar, as they rely on the same physical and technological basis.

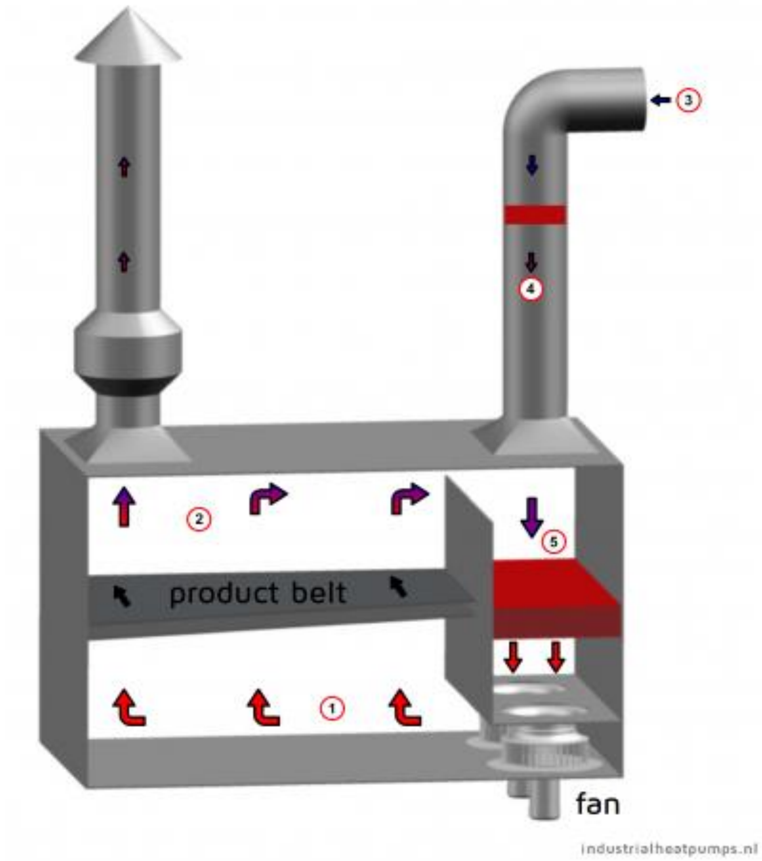

Figure 1. Conventional drying process

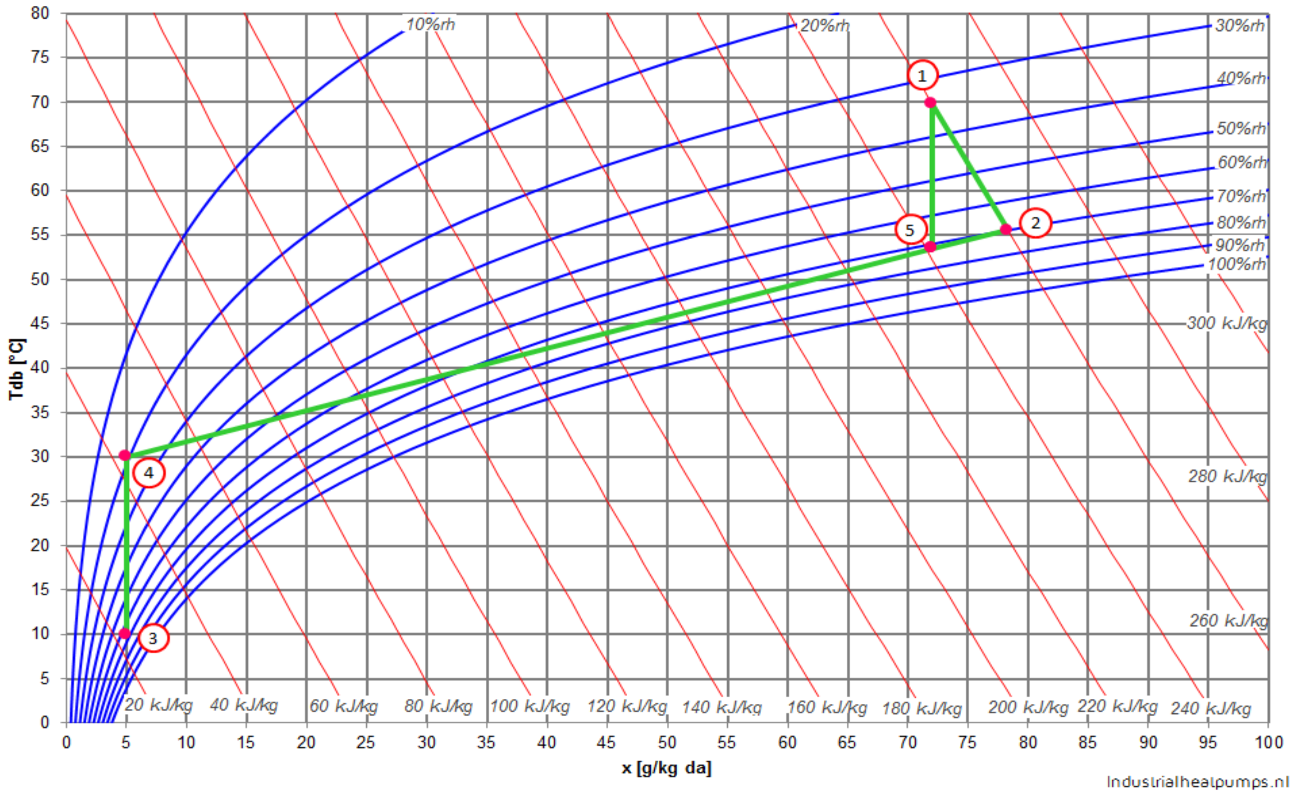

Figure 2. Conventional drying process

Figures 1 and 2 above illustrate the most commonly applied drying process. As can be seen from the chart, hot air (namely, at the temperature of 70 °C in this case) comes over the belt mounted inside the dryer. The hot air flow helps achieve the evaporation of water compounds out of the product put inside the dryer, whatever it may be. As a result of its circulation over the mounted belt, the temperature of the hot air drops, and humidity increases in contrast. On stage 2 of the process, the cooled down and humidified air is partially exhausted from the dryer through exhaust tubes, and partially re-circulated within the dryer. As part of the air is exhausted from the dryer, new ambient air inflow enters, and is preliminarily heated. Those processes are marked by stage 3 and 4 on the charts, respectively. When the ambient air is preliminary preheated, it gets mixed with the air that has previously been re-circulated (stage 5), and then the mixture is again heated, until it reaches the required process temperature. As the exhausted air is cold, and therefore cannot be re-circulated within the dryer, its exhaustion causes loss of energy contained in such air. For the purpose of avoiding heat energy waste, heat pumps can be installed inside dryers. They help significantly reduce energy losses, and therefore optimize the very use of dryers in industrial processes (8).

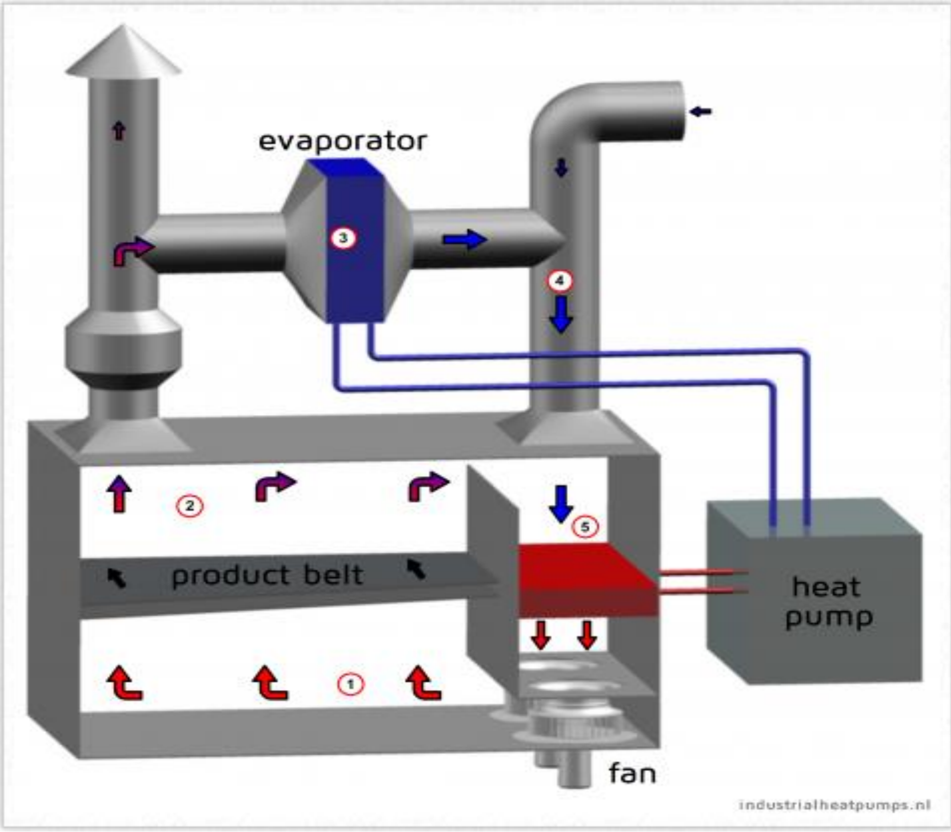

Figure 3. Conventional drying process with a heat pump

When the cooled re-circulating air is again heated, the maximum effect can be achieved through the use of the heat from the exhaust air, instead of using the heat pump for getting the same effect.

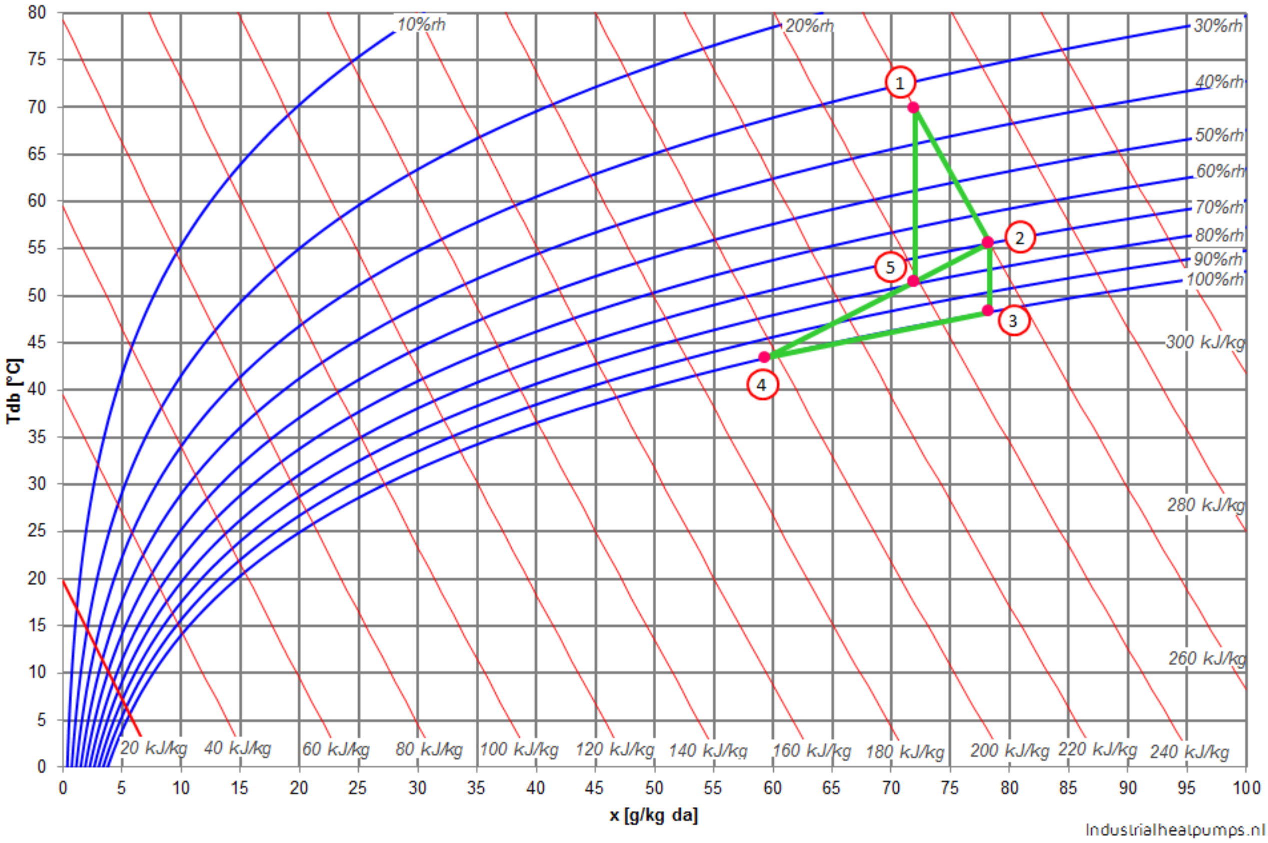

Figure 4. Conventional drying process with a heat pump (8)

Figures 3 and 4 above illustrated the standard operational process of dryers with heat pumps installed. A major difference in dryers with a heat pump installed lies in the fact that the heat exchanger is removed, and a condenser is mounted in its place. The exhaust tube in such system is coupled with the air supply duct. On the cold side of the heat pump, an evaporator is installed. The drying process in this system starts similarly to the one in the conventional dryers without heat pumps. Thus, the hot air is transported to the belt mounted inside the dryer on stage 1. As a result of its circulation over the belt, the hot air is getting cooled and humidified. On stage 2, part of the cooled and humidified air is conveyed to the evaporator where it is processed, so that its temperature would fall below the condensation point (stages 3 → 4 on the charts above). Below its condensation point, the air is getting humidified, and thereafter it is mixed with the air circulating inside the dryer (stages 4 + 2 → 5). On stages 5 → 1, the air mixture is heated in the condenser until it reaches the required operating temperature. Thereafter, the cycle is repeated starting from stage 1, as the air is reused in the dryer. The air supply dust and exhaust tube in such systems are used for refreshing the air on certain stages of the production process.

Overall, the drying systems with heat pumps are more cost-effective, and they provide an opportunity to reduce the technological dependence of the process on environmental changes (8).

As can be seen from the information above, the entire drying process can be conditionally divided into three main stages, regardless of the particular equipment configuration used. Those stages are as follows:

Stage I. Heating of the material. Heat contained in the drying air is absorbed by the material put inside the dryer. As a result, this leads to the creation of latent heat which provokes the evaporation of moisture content from the surface of the material;

Stage II. Evaporation of free moisture content. After the material is put in the dryer and starts generating latent heat, the drying process starts directly. The moisture content moves from the interior of the material to its surface, and thereafter evaporates, until a particular critical free moisture content rate is achieved, leaving the surface wet.

Stage III. Evaporation of bounded moisture content. As the critical point of free moisture content is exceeded, the rate of drying starts declining, up until it reaches the zero value at the balanced moisture content level. As a result, the material put inside the dryer enters the equilibrium state with the drying air. On this stage, there is zero heat and mass transfer, and the amount of water moved to the surface of the material falls below the amount of water evaporated from the surface. As a result, the surface becomes dry. The heat transfer in this case is most often ensured by convection from the drying air. The evaporation of bounded moisture content takes most time in the drying process, and requires the most thorough control for the purpose of not bringing damage to the surface of the material (Doc. Ing. Jiří Štencl, DrSc (2014). *Food Engeneering*. Online. Retrieved from http://web2.mendelu.cz/af_291_projekty2/vseo/stranka.php?kod=2259).

The process of drying can be expressed by a set of formulas for the respective operators to be able to calculate the required process parameters, and the expected outcome of the respective procedures. Thus, for instance, the concentration of water in the respective material put inside the dryer for drying can be described by the formula

$$X_A = m_W / m_{DM} \quad (1)$$

where m_W stands for the mass of water, and m_{DM} means the mass of the dry compounds. The evaluation of the concentration of water is required for the purpose of effectively evaluating the time required for drying the respective material at given temperatures, and for thereafter calculating the expected energy and other associated expenses. The air moisture calculation can be done using the formula

$$Y_A = m_A / m_{DM}\,, \quad (2)$$

where m_A stands for the mass of dry air. Another formula which can be used for that purpose is

$$\varphi = p_A / p_A^0\,, \quad (3)$$

where p_A is partial water pressure, and p_A^0 stands for the vapor pressure existing at a particular temperature value. The drying rate can be expressed as

$$\phi_A = k_Y (Y_{Aw} - Y_A)\,, \quad (4)$$

where k_Y stands for the mass transfer ratio, Y_{Mw} stands for the moisture content on the surface of the material put inside the dryer, and Y_A stands for the average air moisture. The set of formulas described above is helpful for taking into account the basic parameters affecting the cost and outcome of any drying process, and can further be expanded by adding dynamics variable such as time or changes in temperature (11).

1.2 Drying methods

Taking into account the specificities of the drying process, the following main drying methods can be pointed out:

1.2.1 Natural air drying.

Under this drying method, the respective materials are treated with unheated air forced through fans, and therefore natural processing occurs. The main advantage of this method is the lack of direct impact on the material, which is particularly important, for instance, in the agricultural sector, where it helps preserve the high consumption value of fruit and vegetables. However, a major drawback of this method lies in the fact that it is very slow, and a result it may not be cost-effective in most industrial sectors as of today, as time is one of the most essential cost-effectiveness factors in any production branches. Moreover, the entire natural air drying process is highly dependent on the conditions of the external environment such as the level of precipitations, wind conditions, and so on. Therefore, in order to maximize the effectiveness of natural drying, it is required to elaborate an effective strategy of the utilization of fans, for which purpose grounded calculations with regard to the current values of air temperature, humidity, moisture content, material temperature, etc. are required, just as their possible change in line with the conditions of the external environment should be taken into account. This method is used in some grain production facilities, especially during long times of storage, where it allows sparing funds which would otherwise be spent for express drying, without any need to reduce time expenditures (13)

1.2.2 Convective drying

When investigating the specificities of this type of drying, it should first of all be understood that convection stand for the process of heat energy transfer from the air to a solid, semi-solid, liquid or gas substance. Therefore, the convective drying systems are aimed to establish atmospheric conditions in which evaporation would be promoted. Thus, convective dryers aim to reduce the level of air humidity by decreasing the air temperature. All convective drying systems can be conditionally divided into two types: convective heat dryers which use air as the heat transport agent, and those which use fluids for transporting heat. In the systems which use fluids for transporting heat, the respective fluid is heated up and conveyed to the heat exchangers installed in the system. The liquid convective drying systems effectively concentrate heat energy in particular sections within facilities, but they require the installation of separate exhaust systems conveying heated air to the ambient atmosphere. Air convective dryers ambient air is heated up in a special furnace, and thereafter passes through flexible tubes. The built-in exhaust system carries the heated air together with the evaporated moisture off the system (6).

1.2.3 Contact drying

Under this method of drying, the heating agent doesn’t enter in contact with the material put inside the dryer. The transfer of the evaporating moisture is carried out thanks to the vacuum conditions. The main components of any contact drying system are as follows: heat generation source, heat exchange surface, wet material, vacuum, and mixing unit. The heat generation source is most often electricity, natural gas, steam, oil, etc. The gases which are most often used in contact dryers include inert gases which are preliminarily heated up for the purpose of avoiding the excessive condensation inside the drying machine. The mixing unit installed in the dryer is mainly a special agitator. Within the system, the heat generation source contacts with the wet material, as a result of which the process of evaporation occurs. In contrast to convective drying systems, contact dryers most often operate using vacuum pressure. The types of contact dryers may significantly vary depending on the particular aims pursued by the respective manufacturers. For instance, they may include rotating dryers, dryers with agitated beds, and different combined systems involving different technological approaches in their operation at once (9).

1.2.4 Dielectric drying

This type of drying uses the heat capacities of radio frequencies and microwaves for performing the drying of solid, semi-solid or liquid materials. The main advantage of dielectric dryers is the improved heat transfer ratios against the traditional drying methods and techniques. However, as compared with other systems, dielectric drying systems require higher investment on the part of their using, and therefore this largely limits their use in practice. Also, they have limited use for solid materials (12).

1.2.5 Superheated steam drying

This method of drying consists in a process implemented for removing the moisture content from the respective materials with maximum control over it on the part of the operator of the dryer. This method is most often used for desiccating wet materials. When being converted into gas, the molecular structure of wet materials can be damaged through the impact of emerging tension. This may be inappropriate in many cases, for instance, in the production of various types of medicines, and in the electronic manufacturing industry. In order to avoid such negative consequences, superheated stream drying avoids crossing any phase boundaries, and to the contrary, involves the so-called supercritical area in which there are no physical boundaries between the liquid and gas conditions. In superheated stream dryers, the liquid material is heated until its temperature exceeds a particular critical value, and thereafter pressure is slowly released, while gas exhausts from the material (2).

1.2.6 Freeze drying

This method is used by freezing the dried material and thereafter reducing the pressure for the purpose of subsequently converting the frozen moisture contained in the material directly from its solid condition into gas. The freeze drying process conventionally includes four main stages, regardless of the construction and operational specificities of each particular drying machine. On stage 1, the material is respectively treated prior to its drying. The pretreatment of the material is required for preserving its appearance for marketability, preventing the damage which may brought to its structure or texture in the course of drying, etc. The particular pretreatment methods and techniques are chosen based on the particular needs of the respective manufacturers, and depend on the particular decisions of responsible employees and managers. On stage 2, freezing occurs. During this stage, the dried material is, for example, put into a flask which rotates in the shell freezer. The shell freezer operates under cooling ensured by mechanical refrigeration. Such refrigeration may rely upon different refrigerating agents, including gases and dry ice. In the flask, the material is cooled down, until the lowest temperature at which its liquid and solid conditions are coherent is achieved. As a result, the process of sublimation occurs, and the material isn't melted, but to the contrary, directly passes from the frozen state to gas. The speed of freezing predefines the texture of the material, and the size of the crystals formed in the course of drying. Therefore, by regulating this parameter, manufacturers can effectively regulate the appearance of their particular products. On stage 3, primary drying occurs. After the frozen condition described above is reached, the material is dried through the reduced pressure and the transfer of heat to its surface for the purpose of achieving its sublimation. Often, this stage requires significant amounts of time, as heat should be supplied gradually in order to reach sublimation. Vacuum is used on the stage of primary drying for accelerating sublimation. Cold condenser chambers are installed in freeze dryers with an aim to ensure the re-solidification of water compounds on the surface.

Finally, on stage 4, secondary drying occurs. As the ice has been eliminated on the phase of primary drying, the next step required for completing the drying process is the elimination of the unfrozen water compounds. For this purpose, the temperature in the dryer is raised, and the pressure is reduced. The actual outcome of the freeze drying allows achieving a very small percentage of water compounds in the material, which testifies the high operational effectiveness of the process (7).

Thus, it can be stated that the principles and approaches to drying are generally similar across all types of machines used, however, different methods can be applied depending on the particular needs and goals of the manufacturers, just as based on the specificities and particular parameters of the respective materials. The effectiveness of such methods may significantly vary as well across different industries and sectors, and the ultimate choice depends on the respective company's goals and policies (5).

Taking into account the findings related to the drying process, in the next chapter, I would like to investigate more in detail the types of dryers existing on the market, and their parameters which predefine the choice of the suitable type of dryers in commercial practice.

1.3 Dryers types used for this purpose and selection of suitable type

1.3.1 Tube dryer

In the industrial practice, different types of dryers are used. They mainly differ in terms of the construction and design particularities, and materials which can be processed. The ultimate choice of the required type of the drying machine is predefined by the need of the respective entities, and the desired outcome which they wish to obtain. Taking into consideration the above information, the main types of dryers used in the industrial practice are as follows:

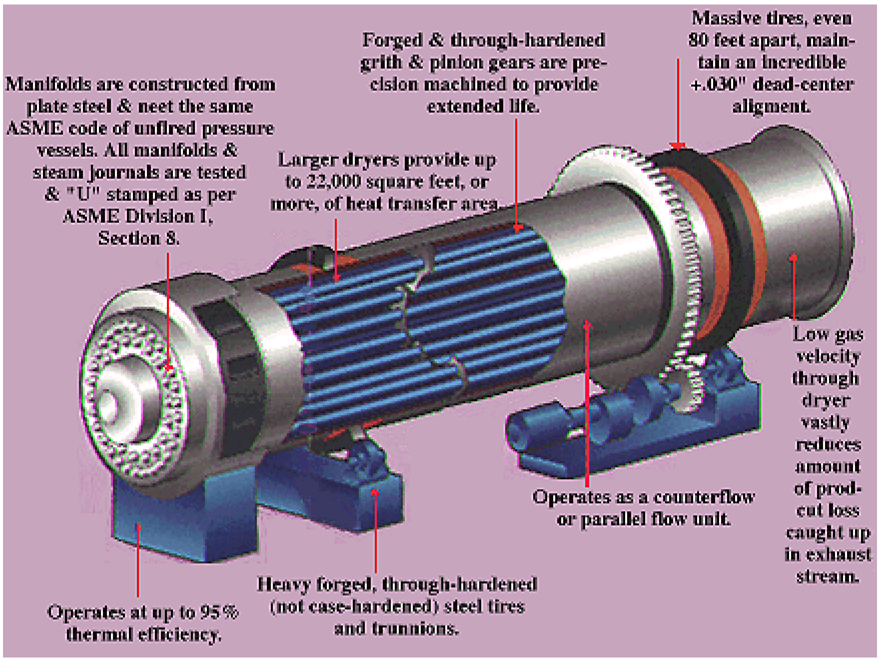

Figure 5. Tube dryer

Tube dryers are commonly used for drying by-products of organic nature with a high level of moisture (but the dried material must not be sticky). For instance, such products may include different food processing by-products such as spent grain. Also, tube dryers are widely used in the chemical industry. Tube dryers are rotary mechanisms which operate at a temperature lower than the ranges inherent of other types of products. The rotation speed of tube dryers is slower than the one of other drying mechanisms as well. The service life of tube dryers is generally longer than the one of other types of dryers due to the low friction force applied between the shell and the material dried. Hot steam is used in such mechanisms instead of gases, and this ensures the high cost-effectiveness of the installations. The air conveyed within the installation is transferred in a direction different to the one of material flow. The construction specificities of the dryers allow exhausting the heated air without impairing the quality of materials (10);

1.3.2 Conveyor dryer

Figure 6. Conveyor dryer

Conveyor dryers contain a special perforated belt unit which is used for moving the dried materials inside the machine. Heated air circulates under, over and through the conveyor belt. Most often, the unit is divided into special zones, and the heated air treats those zones in different ways, respectively. Different temperatures can be applied in different zones as well. Thereafter, the air is reheated and re-circulated, while part of the air with moisture content is exhausted to the atmosphere. The construction of conveyor dryers can differ. For instance, some dryers may have several conveyor belts operating at once, which is particularly frequent in agricultural production. The recycling of process air ensures a high level of the conveyor dryers' cost-effectiveness. Major limitations in the operation of conveyor dryers include the possibility of unit clogging, and difficulties with belt maintenance (10).

1.3.3 Spray dryer

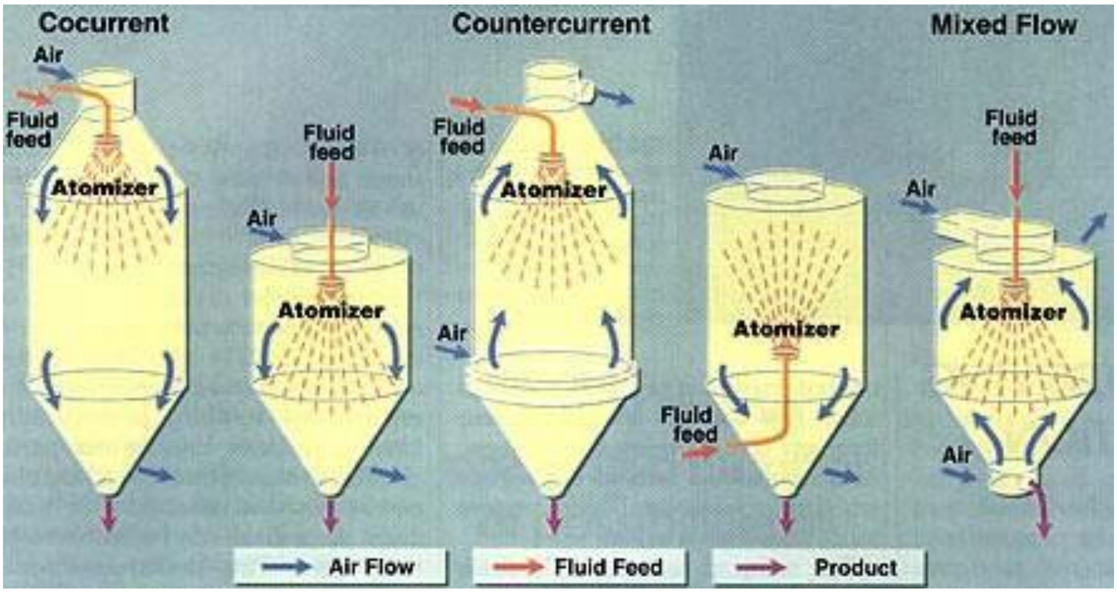

Figure 7. Spray dryer

In spray dryers, hot gases are used for turning liquid products into powders. This type of dryer is most often used in the pharmaceutical and food industries. The spray dryers use atomizers or special spray nozzles for the purpose of feeding the liquid and dispersing it into drops of predefined size. The particle size distribution is set by the operator and depends on the goals pursued in the drying process. The different types of spray dryers can include single-effect and multi-effect drying machines. In single-effect dryers, the heated air is conveyed in co-current of the liquid fed through the top. As a result, the powder materials obtained are rather characterized by a high level of dust content. To the contrary, the multi-effect spray dryers use the double scheme of drying, where the first stage is implemented in the top section, similarly to the one used in the single-effect dryers, and the second stage of drying is run in the bottom section of the machine. Thanks to this, fine particles are obtained, and the level of by-products contained in them is significantly reduced (10).

1.3.4 Fluid bed dryers

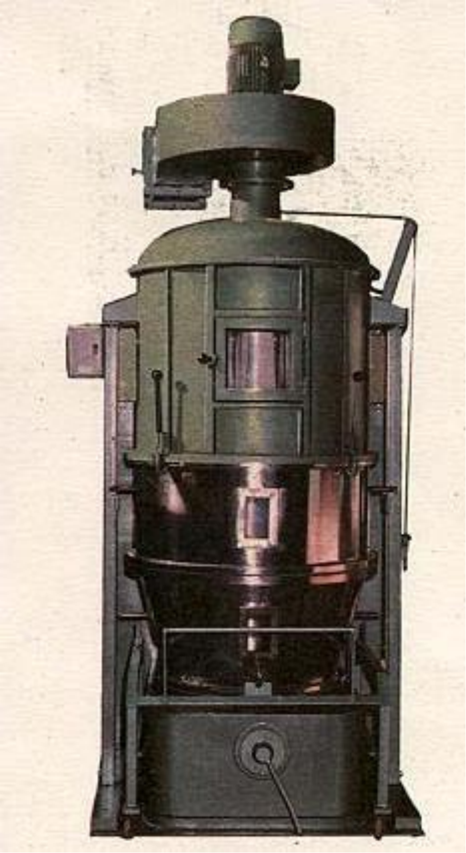

Figure 8. Spray dryer

The main specificity of fluid bed dryers as compared with other types of drying machines is the fact the distance through which heat passes is reduced thanks to the use of floating material. It ensures the reduced diffusion distance of vapor. Thanks to this, heat energy losses are minimized, and the drying speed of material is significantly increased. The temperature inside the fluid bed dryers is more homogeneous, and therefore the drying of the material is uniform as well, which is important in many industries. In such drying machines, the material enters into contact with the heated air at low temperatures, and the period of drying is short as well. As a result, the physical and chemical properties of the material tend to remain unchanged. All materials are held in a single container built in the dryer, which significantly reduces the costs for the maintenance of the machine (10).

1.3.5 Rotary dryer

Figure 9. Rotary dryer

Rotary dryers use special rotating cylinders where heated gas is conveyed. Built-in filters are used for the purpose of dropping the feed of heated gas from the top section to the lower area of the cylinder. The material put inside the cylinder is conveyed along the rotary dryer based on the changes in the inclination angle of the cylinder and blades installed in the cylinder which provokes the turning of the material. Many rotary dryers use complex constructions in which several drums are located inside each other. Thanks to the rotation ensured by the drums, the material rotates and enters into contact with the heated gas. The moisture is moved to the circulating air, part of which is thereafter moved to the ambient air through the external exhaust system (10).

1.3.6 Rotary louver dryer

Figure 10. Rotary louver dryer

Rotary louver dryers are characterized by a high initial heat transfer value, and by the rapid rate of evaporation of moisture from the surface of the material put inside the dryer. For the purpose of avoiding deterioration of the material, the decrease in the temperature of gas used as the heating material occurs much suddenly. The excessive level of drying is achieved thanks to the final product's contact with the lower-temperature gases (10).

1.3.7 Batch type dryers

Figure 11. Batch type dryer

Batch type dryers transport the materials inside them using special perforated belts. The heated air is passed under, over, and through the perforated belt for the purpose of drying the materials conveyed. Thereafter, the process air is repeatedly heated and circulated inside the dryer. The batch type dryers are most often divided into zones in which different temperature values are set for processing the dried materials. The exhaust duct used for eliminating the used air is located in the central part of the batch type dryer. Several belts can be used in a batch type drying machine at once, and can be located either below each other, or in line, which depends on the conveying of the materials and the use of different temperature zones for their drying (10).

There are different types of batch dryers used in industrial practice. The most common types of batch dryers are as follows:

- Conical tumble dryer. This type of batch dryer is installed on a horizontal axis, which ensures its effective full-range rotation in the course of the drying process. In its turn, this ensures effective mixing and contact of the material put inside the dryer with the heated surface. As soon as the drying process is terminated, the conical tumble dryer is put into the vertical position, and the material is discharged though its bottom;

- Paddle dryer. In paddle dryers, the cylinder inside the machine is equipped with agitators fixed at both ends. The heating liquid which circulates inside the cylinder also flows through the agitator. The heat transfer achieved is much effective thanks to the combination of the agitator with special heating elements;

- Disc dryer. The construction of disc dryers consist of a special shell with a rotor mounted inside it. Discs are coupled with the rotors, and the heating liquid flows through them. Thanks to such construction, the heat transfer area created is particularly large, which ensures a high level of drying effectiveness, but at the same time hinders the effective maintenance;

- Pan dryer. Such dryers include a vessel with an agitator ensuring the maximum heat surface area. The agitator can be installed on different height levels, thanks to which the torque applied is effectively regulated, and therefore the effectiveness of drying can be successfully managed;

- Filter dryer. Filter dryers are much similar to pan dryers in terms of their construction. On its bottom, a special filter chamber is installed. Additionally to drying, washing of material is ensured in the course of the process;

- Conical screw dryer. This type of dryer has a vessel of conical shape installed, and a screw-type agitator mounted inside the machine. The agitator ensures improved mixing of the material. The discharge of the dried material is done through the bottom outlet. Thanks to those specificities, conical screw dryers provide the options of alkalization and crystallization in addition to simple drying;

- Spherical dryer. The vessel used in the dryers of this type is round, and a filter with an agitator is installed in its top section. An additional agitator is installed in the bottom section, which ensures the more effective mixing of the material. The product is discharged from the dryer through the special bottom outlet (4).

1.3.8 Drum dryers

Figure 12. Drum dryer

Under the drum drying method, the dried materials are put into a special drying drum. Such drums are rotating, and usually function together with oil or gas burners which convey heat to them. The temperature inside the drying drums used for drying the materials is relatively low. The heat is conveyed from the burner to the inner cylinder of the drum dryer, and desiccated the product inside by raising the inner temperature inside the cylinder. Being equipped with special shoveling plates, the cylinder of the drying drum ensures the effective contact of the hot air with the dried product. The material is discharged from the side opposite to the one where it was charged.

Usually, drum dryers are used for turning the material into the powder form. They are largely used in all types of industrial production, and are particularly popular in the food industry, as they allow preserving the original flavor of the food products processed (10).

1.3.9 Tray dryers

Figure 13. Tray dryer

The construction of tray dryers assumes that such drying machines contain a number of trays used for the portioned charging of products. Most often, this is required in the food processing industry, and in pharmaceutical production. The airflow in such systems is horizontal. Most tray dryers are heated by air, which allows eliminating the moist vapor. Also, heating may be ensured based on the conduction from heated shelves or trays, or by radiation. Usually, such drying machines operate at very high temperatures, and are equipped with effective temperature controlling equipment (10).

1.3.10 Bin dryers

Figure 14. Bin dryer

Bin dryers are constructed in a way that the dried materials are put inside the machine from the top, and go out of it from the bottom. To the contrary, the hot and dry air is conveyed to the material from the bottom of the machine, and thereafter exhausts from its top. This principle is commonly referred to as the counter flow drying principle. Thanks to its implementation, the best contact of dry air with the material is ensured. Usually, several bins are used at once within bin drying systems, namely with separate bins for charging, discharging, and drying the product. In case that several drying bins are used, the product gradually passes through all of them at predefined time intervals, which allows achieving the highest control over the drying process and its outcomes. Re-circulated air passes through motorized dampers, thanks to which its velocity can be effectively controlled (10).

1.3.11 Vacuum shelf dryers

Figure 15. Vacuum shelf dryer

Vacuum shelf dryers ensure effective drying of materials without their agitation. Such drying machines are most suitable for air- and heat-sensitive products. The drying process can be implemented at low temperature values, and in the conditions of vacuum. The process of drying occurs as the ambient pressure in the environment is decreased below the vapor pressure of water compounds. The recovery is achieved through the use of special solvents. Such solvents are easy to condense and dispose (10).

1.3.12 Vibrating dryers

Figure 16. Vibrating dryer

Vibrating dryers are drying machines which combine air distribution and vibration for the purpose of ensuring the most effective fluidization of wet materials. Such dryers usually include a mechanical vibratory conveyor, and infra-red heaters. The material put inside the dryer passes under the heaters, it is vibrated for the purpose of being turned many times. Thus, each part of the material gets a sufficient portion of the infra-red lighting, and the required internal temperature can be effectively reached for successfully drying the material. Thereafter, the heated material is put into a bin where it continues the drying process under the impact of its own residual heat. The periods for such residual drying may vary depending on the needs and manufacturing particularities of the respective producers. The time passed by the material in the bin predefines the ultimate decrease in the moisture content in it (10).

Thus, as can be seen from the information above, the types of dryers used in industrial facilities can significantly vary. The ultimate choice of the particular dryer type depends on the industry in which the respective company operates, its technological capabilities, financial resources available, and the materials to be processed in the course of drying. Different types of dryers provide different prospective outcomes, and involve different costs and investments. Therefore, it can be stated that the ultimate effectiveness of all types of dryers is predefined by the particular conditions of their industrial application which affect the final choice of the respective companies.

2. Description of laboratory device that is used for experiment:

The laboratory device serves to remove moisture from solid materials. The evaporation of the water within the sample is caused by flow of drying air, which circulates in the laboratory device. The process characteristics including decrease of weight of the measured sample (or the mass of evaporated water) are recorded to the PC inline.

The inner dimensions of the drying chamber are 400x200x200mm. There is a basket inside the chamber and the samples are put in the drying baskets (in the drying chamber), which are suspended in the scale (range 0 – 620g) placed outside on the top of the chamber. The digital scale has accuracy 0.001g and it is connected to PC by interface R232. The dimensions of drying basket are 250x150x35mm and the basket allows to simulated drying process, where the air flows along dried sample.

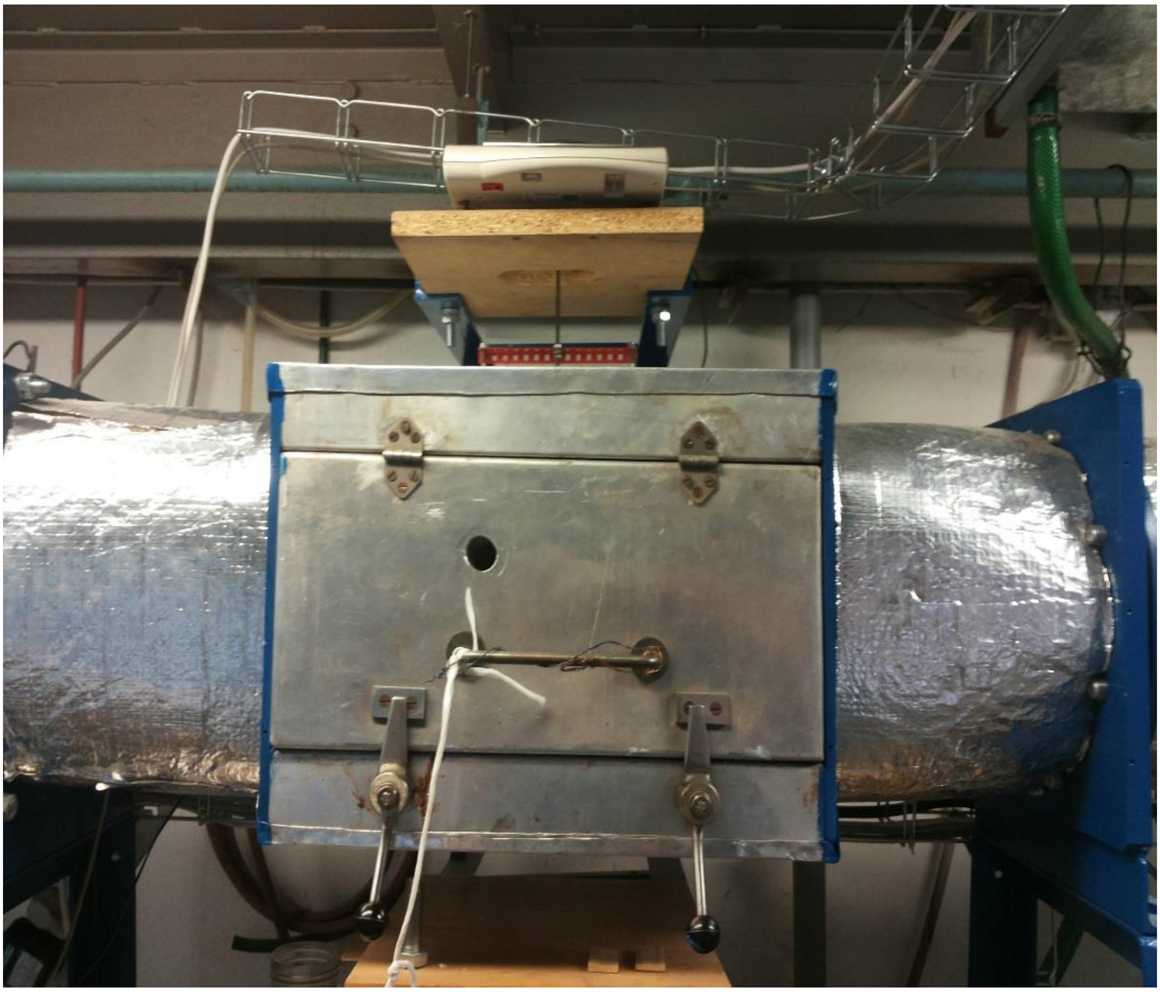

Figure 17. Drying chamber and scale

The scheme of the experimental device is presented in the figure 1., and it is placed in the hall laboratory of Department of Process Engineering, Faculty of Mechanical Engineering, CTU in Prague. The circulation drier 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 range of 0.5-3.5 $m.s^{-1}$. The air is heated up by two electric heater devices, where first has electrical power 6x500W 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.

Figure 18. Fan with electric motor and speed control

Parts of the circulatory dryer:

1-drying chamber; 2- heater; 3- fan; 4- gear box; 5- air duct; 6-heaters; 7- scale; 8- frame

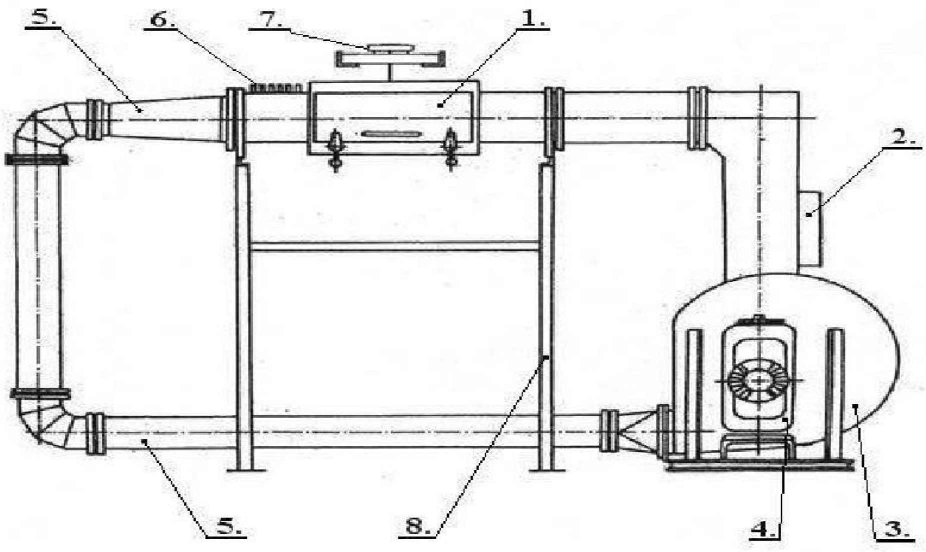

Figure 19. Scheme of circulatory dryer

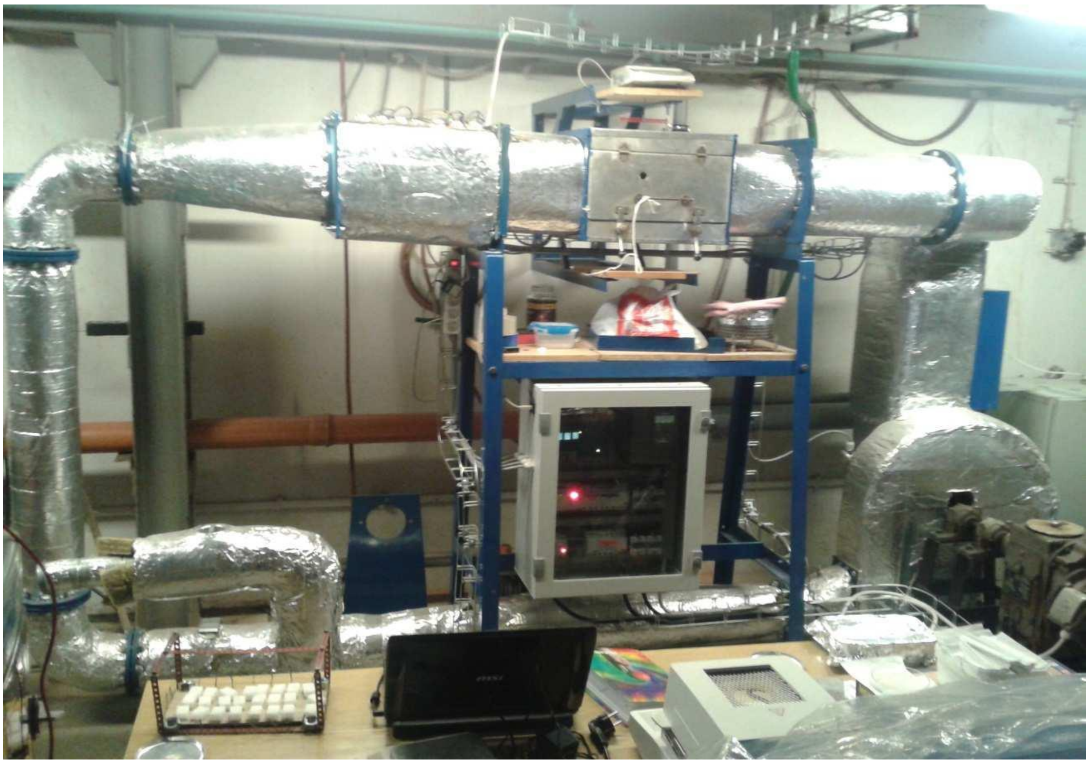

Figure 20. Circulating dryer in the indoor laboratory of the Institute of Process Engineering, Faculty of Mechanical Engineering.

2.1 Measurement in laboratory dryer

In order to start the experiments with sugar cubes drying on the laboratory dryer I considered twenty four sugar cubes for each measurement. The weight of one cube is approximately changing between 5,8 – 6,2 grams. There are totally twelve measurements done according to the chosen temperature and velocity:

Three measurements for temperature 60 ^{o}C and 1m/sec velocity

Three measurements for temperature 60 ^{o}C and 1.5m/sec velocity

Three measurements for temperature 80 ^{o}C and 1m/sec velocity

Three measurements for temperature 80 ^{o}C and 1,5m/sec velocity

At the beginning of the each measurement first step was to make samples before drying. I took every sugar cube separately, weighed it on the laboratory scale, and using this equation below I added 2% of water on them:

$$M_{H2O} = \frac{M_0 * 0,02}{1-0,02} \quad (5)$$

M_{H2O} [g] - Mass of water moisture added on each sugar cube

M_O [g] - Mass of dry sugar cube before drying

By using this formula I easily found it out that how many grams of moisture (water) I needed to add on each sugar cubes.

Figure 21. Wet sugar cubes sample

The total mass of twenty four sugar cubes (for each measurement) changes between 144,25-146,94 grams and this value is different for each measurement. The main aim is to dry these samples from 2% till 0,1% and specify the drying time.

Before the drying process wet sugar cubes samples should be stored at least one day in a closed box in order to absorb all water amount added. By this way results are more trustable and correct.

As it is mentioned above, the circulatory dryer is connected to PC inline and all the data is recorded to it during the process (date, time, temperature and mass change). Besides, according to each experiment, chosen temperature and velocity are set up in the section of "input parameters". In the section of "raw date and calibration constants" we choose "COM8" which starts the connection between scale and PC.

Before, we start the experiments it is necessary to heat up the dryer for about 30-35 minutes. We can not immediately use the samples and switch on the dryer, because it is cold and in order to achieve right results dryer should be heated up firstly.

Furthermore, as we know that in order to heat up the air two electric heater devices are used and those heaters as well as the fan are easily controlled in the "system configuration" section (turning on and off).

2.2 Description of input parameters

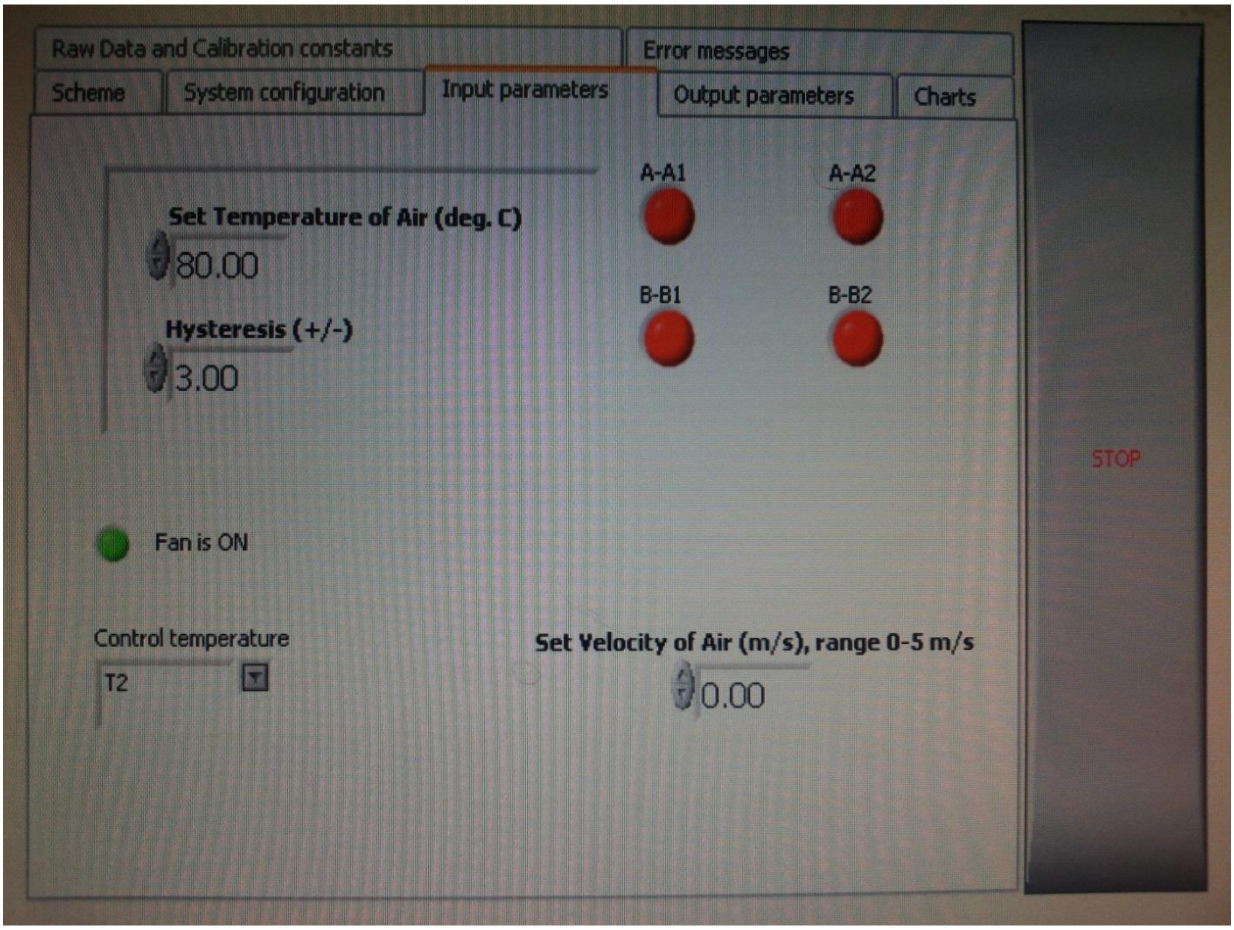

Figure 22. Establishment of input parameters

For each measurement it is necessary to upload new and clean file to the system, to the proper section that all the date will be recorded on it during the drying process and used for the next calculations.

2.3 Description of output parameters

In the " output parameters" section we can see the temperature change as well as sample weight during the drying process. As I turn on the dryer and let the process start, the initial mass of sample is changing automatically between 0,4-1 grams and it is clearly seen on the PC screen. The main reason of it is that, as soon as the fan begins working the air flow inside the chamber shakes the sample basket and it causes some small amount of weight changes, although still there are six steel bolts on each corner of the basket to prevent this case. For the next steps this mass changes are considered.

The "chart" section shows few different dependency diagrams.

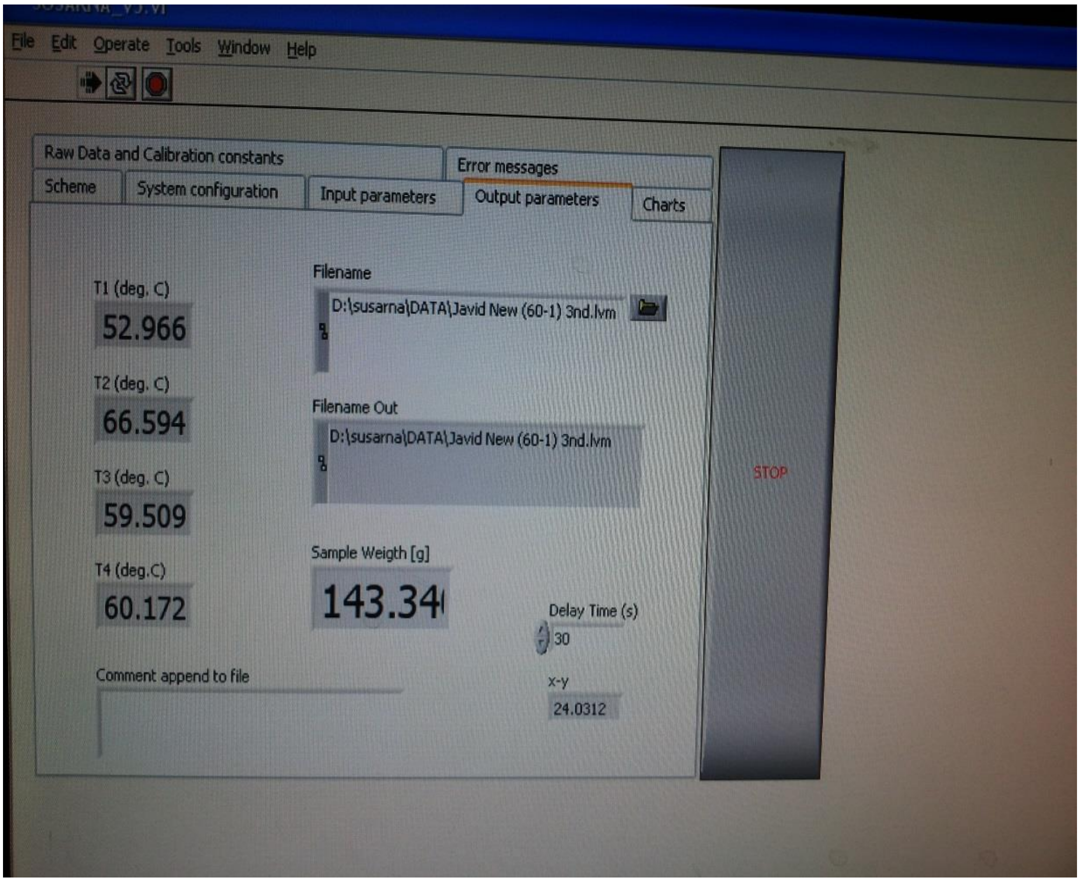

Figure 23. Output parameters

2.4 Specification of the drying time.

As I stated above, for every measurement I used twenty four wet sugar cube samples and their arrangement on the basket can be seen on the figure 7. As soon as the samples are put on the drying basket the fan should be switched on immediately, because we ought not to keep them inside the dryer for long time as there is more than 57 ^{o}C temperature inside the chamber and the samples start losing their moisture content. Drying times for each experiment were different depending on the selected temperature and velocity (changing between 28-36 minutes). By checking the file, which uploaded on PC in order to record the data, we can know easily when it is time to turn off the fan. When the last points of sample weight are stable then it is time to stop the measurement.

Figure 24. Wet sugar cubes arrangement on drying basket

When the first three measurements finished, which were for temperature 60 ^{o}C and velocity 1 meter per second, I took the recorded data file and copied them to Excel file to start the further calculations. For every measurement two dependency graphs are made;

1-dependency of wet sugar cubes mass during drying on time (Mt on time);

2-dependency of wet sugar cubes moisture during drying on time (Wt on time);

Mt values are directly taken from the recorded data (with making small accuracy on some numbers) in order to create the first dependency diagram. However, for the Wt values there are equations that must be used. Those formulas are described below:

$$w_0 = \frac{M_0 - M_{DM}}{M_0} * 100 \tag{6}$$

$$w_t = \frac{M_t - M_{DM}}{M_t} * 100 \tag{7}$$

$$M_{DM} = M_0 * (1 - w_0/100) \tag{8}$$

Wet sugar cubes mass before drying M_0 (g)

Wet sugar cubes moisture before drying w_0 (%) c. 2 %

Dry mas of sugar before and during drying M_{DM} (g)

Drying time t (min)

Wet sugar cubes mass during drying M_t (g)

Wet sugar cubes moisture during drying W_t (%)

(it decreases during the time t from 2 to 0.1 %)

By this way I achieve three almost similar hyperbolic Mt – t and Wt – t dependency diagrams and it is very important to make average of wet sugar cubes mass values in order to get final dependency diagram.

Wet sugar cubes mass (Mt) decreases every 30 seconds during the drying and I prefered to use that drying time by minutes for better formulation. The initial mass of sugar cubes was 146,823 grams and during drying 2.791 grams of water evaporated (from 2% to 0,1%).

In addition, it is also necessary to notice that before I start the experiment I measured the humidity and it was 40% in the laboratory hall. Each dry sugar cubes have some amount of that humidity. However, the humidity change in percentage was very small number and therefore, for the measurements I did not take into account this case. The time spent on wet sugar cubes drying for temperature 60°C and velocity 1 m/sec is 36 minutes and it can be easily seen on the Figure 25. Drying time for moisture decrease from 2 % to 0.1 % was c. 36 minutes and it is described below on the Figure 26.

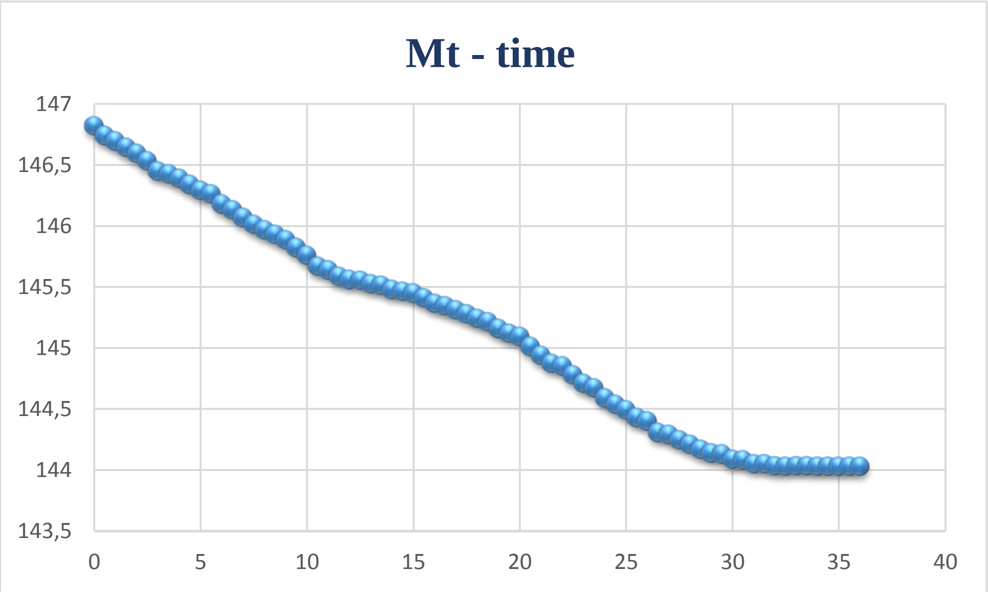

Figure 25. Drying curve for wet sugar cubes mass at 60C - 1m/s

Moreover, Wt values are calculated according to the recived avarage values of Mt using the equations. Also, as it is noticed on my submission that sugar cubes moisture should decrease starting from 2% to 0,1% during drying process.

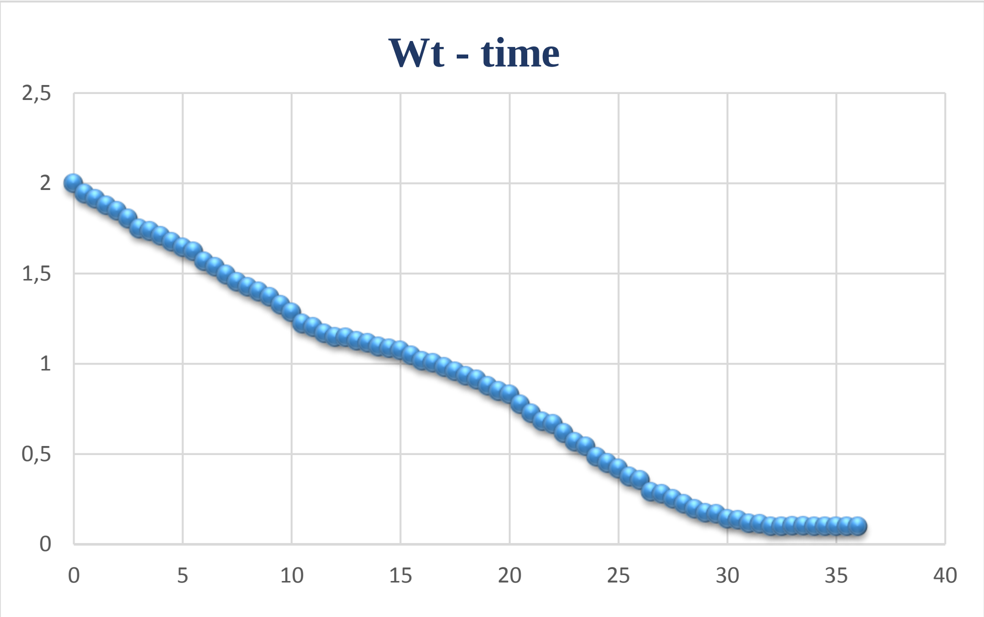

Figure 26. Drying curve for wet sugar cubes moisture at 60 C - 1m/s

The same measurements, steps and calculations were done as the previous ways to find out the drying time for different temperature and velocity. There are also two drying curves for every temperature [^oC] and velocity [m/s]. For example, for the next experiments selected temperature and velocity were 60 ^oC -1,5 m/s and there are again two drying curves were obtained;
1- wet sugar cubes mass on time; 2- wet sugar cubes moisture on time;

Besides, the similar way was carried out in order to get the drying diagrams for 80 ^oC -1m/s as well as 80 ^oC – 1,5m/s. After that I have four drying times which are slightly different form each other.

In order to make the design of the drying on my submission those times are very important, because for calculation only one value of drying time must be used. To obtain only one value I made the average of these four drying times and finally I got only one time value to use. More details are described in the “dryer design” section below.

From figure 27 and figure 28 it can be clearly seen that at the same temperature (60 ^oC) with 1,5m/sec velocity drying time is 30 minutes. It is obvious that the same temperature but with higher velocity the drying time is less than previous experiment results. And it is correct, because with higher velocity value the drying process getting faster and the time for drying getting shorter.

Below, two graphs show the dependency of wet sugar cubes mass as well as wet sugar cubes moisture on time. Time again is described by minutes and moisture decrease by percentage.

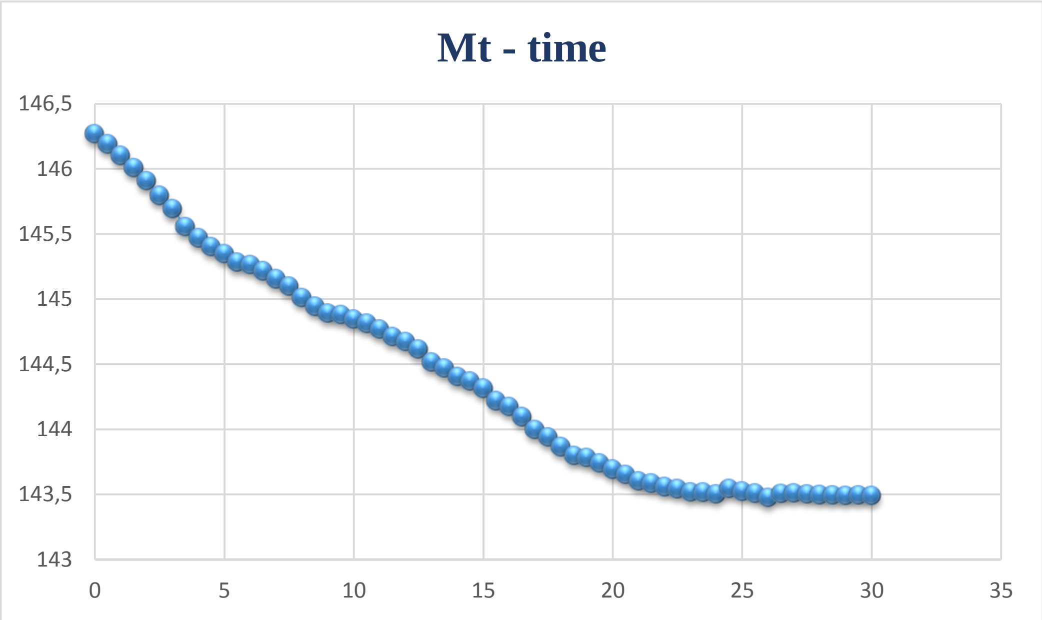

Figure 27. Drying curve for wet sugar cubes mass at 60 C - 1,5m/sec

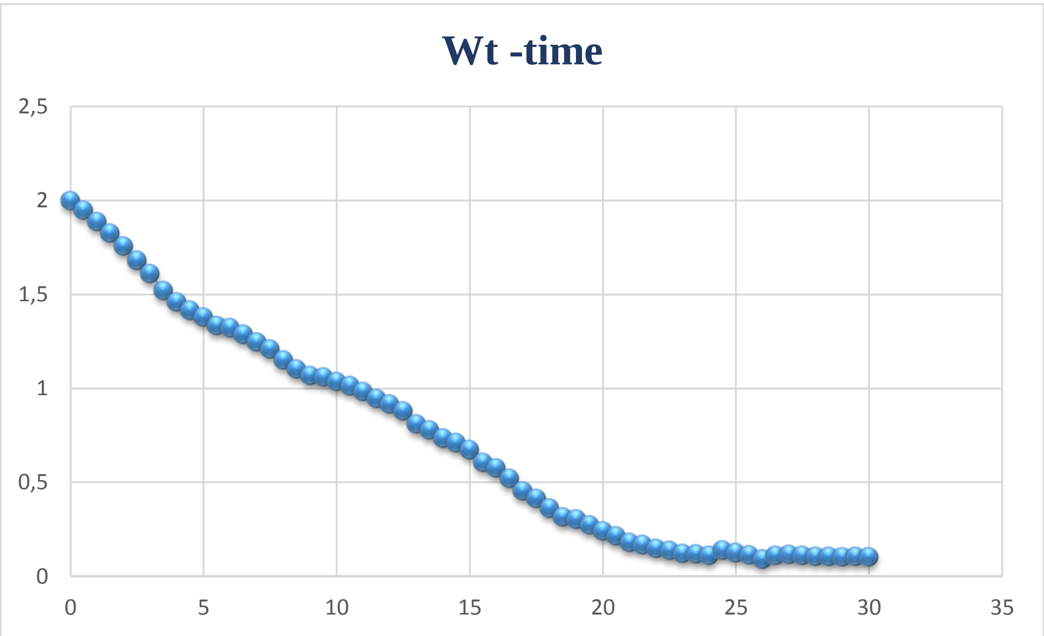

Figure 28. Drying curve for wet sugar cubes moisture at 60 C - 1,5m/sec

For the last measurements selected temperature was 80 ^oC with velocities 1m/s and 1,5m/s. There are again almost similar drying curves were obtained but the drying times were slightly different than the previous ones. The drying time at temperature 80 ^oC – 1m/sec is 32 minutes, but for velocity 1,5m/sec it shows 28.5 minutes. Here also again the average values of wet sugar cubes mass are taken from starting time of drying until finishing time. And according to it sugar cubes moisture results are calculated in order to have the drying curves. Those dependency graphs are expressed below on figure 29, 30, 31, 32.

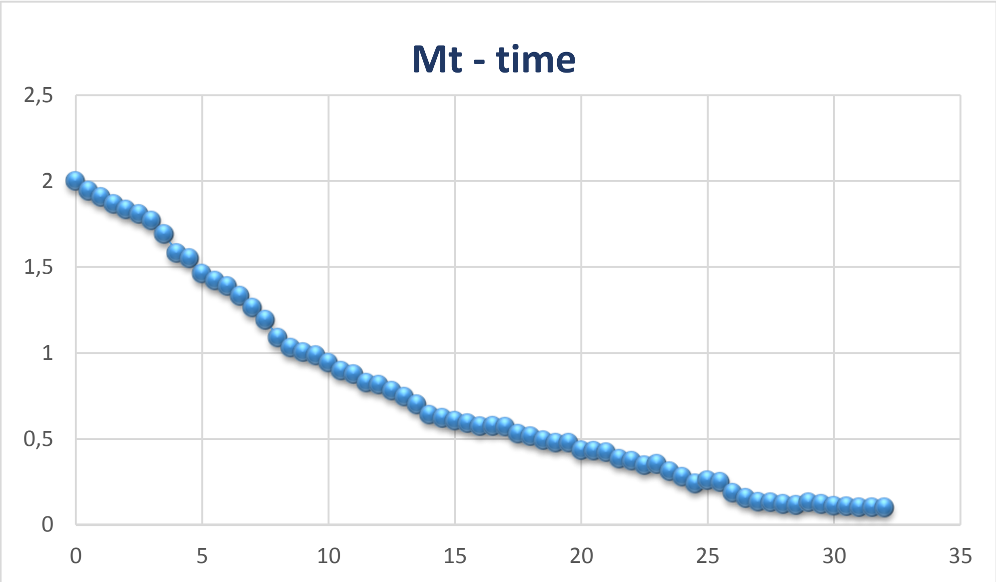

Figure 29. Drying curve of wet sugar cubes mass at 80 C - 1m/sec

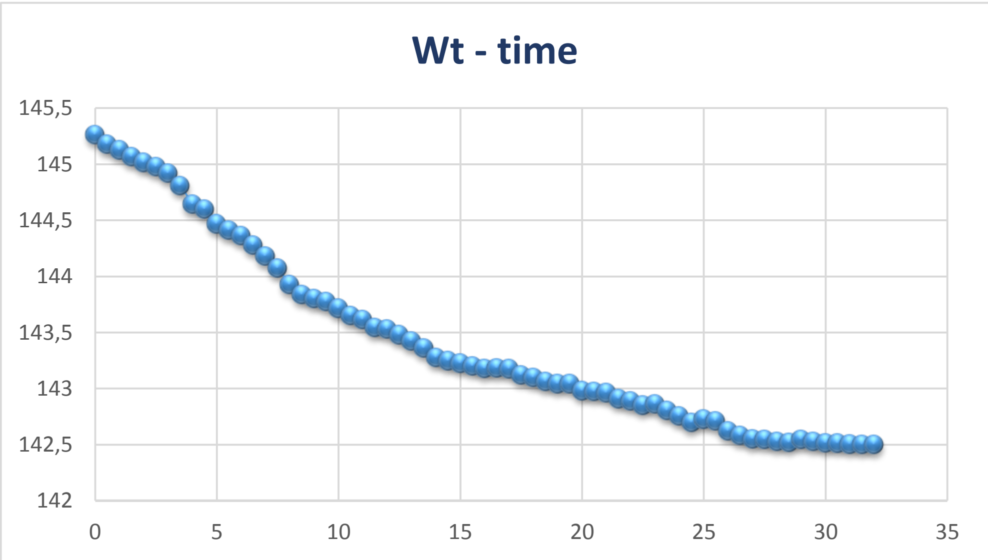

Figure 30. Drying curve of wet sugar cubes moisture at 80 C - 1m/sec

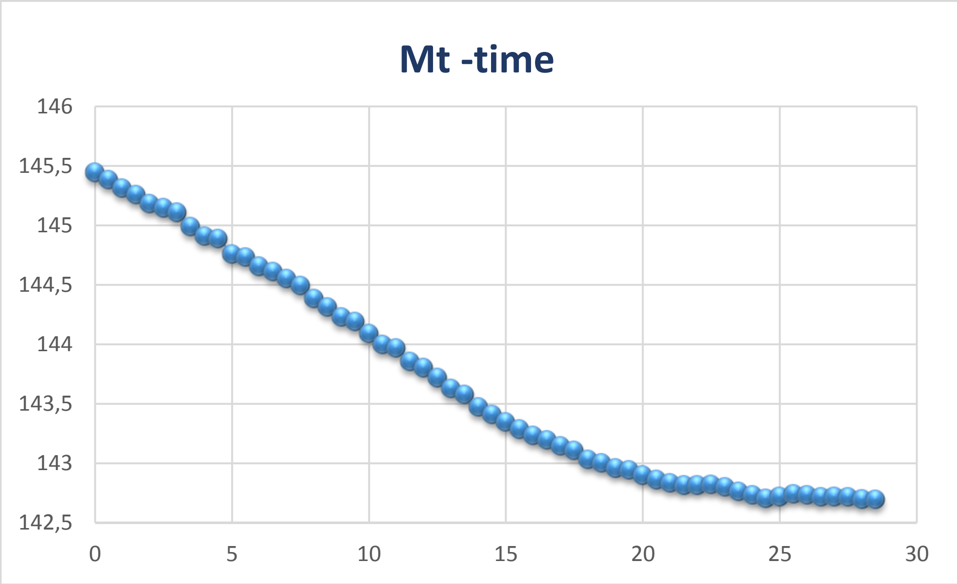

Figure 31. Drying curve of wet sugar cubes mass at 80 C - 1,5m/sec

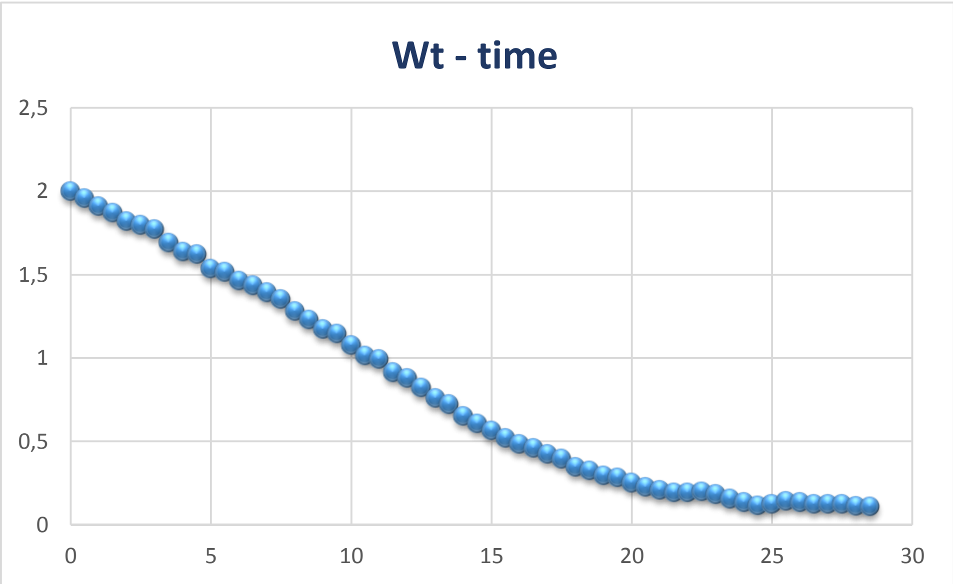

Figure 32. Drying curve of wet sugar cubes moisture at 80 C - 1,5m/sec

3. Basic design of the belt dryer

The subject of my thesis is to design a chamber (tray) dryer, but I want to compare the design with a belt type dryer. For the design strategy of the dryer given a specified product with a predefined flowrate, to be dried from an initial to a desired moisture content level, under constraints imposed by thermodynamics, construction and product quality reasoning, the following must be determined:

1. The optimum configuration when this is not clear-cut. For belt dryer the belts length, number of sections as well as number of chambers per section.
2. The appropriate sizing of the equipment (construction characteristics).
3. The best set points of controllers (operating conditions). For the operational analysis of the process, the structure and sizing characteristics of the equipment are predefined. In this case, we seek the economic performance of a specified dryer when it is operated under different conditions; various production capacities, flexibility with respect to input variables, etc.

The belt dryer is a flexible construction that can be adapted to a variety of site requirements. Direct or indirect heating is possible as well as several heating alternatives; fuel, natural gas, exhaust gas, steam, hot water, thermal oil. The belt dryers of the standard design range have a modular composition. This design reduces delivery time, costs and spare part storage. The dryer consists mainly of product feed module; drying or cooling modules; product discharge module.

Procedure is like that:

First, dry granulated sugar is mixed with water in the mixer. Then the moulds are filled and the cubes are formed and deposited at regular intervals on a conveyor belt. Next, the cubes are taken through the dryer where they are heated using microwave technology. After heating, the cubes enter the conditioner for further drying and hardening by means of natural evaporation. At the end of the conveyor belt, the packer suction heads delicately place the cube in the waiting boxes.

Figure 33. Belt dryer.

For my basic dryer design and in order to find out it's size for the given amount of dried sugar cubes there are some calculation steps which must be done using several equations consistently. Few parameters are known such as drying performance of dried sugar cubes mass M_{dry} = 200 [kg/hour] and total wet sugar cubes mass M_{total} = 146.201 [g] in the tested sample. Also, mass of one wet sugar cube is approximately 6.1 [g].

Main aim now to find out the length [m] as well as area [m^2] of the belt dryer which 200 kg wet sugar cubes could be dried. The dimensions of one sugar cube are measured and it is known that length is 28 [mm] and width is 18 [mm]. Firstly, it is necessary to find out the area of one sugar cube and the distance between these cubes on belt are also taken into account to be 1 mm from each side (the space among cubes is 2 mm).

a = 28 [mm]; b = 18 [mm]

$$A_{1\,piece} = (a+1+1)*(b+1+1) \quad [m^2] \qquad (9)$$

$$A_{1\,piece} = (28+1+1)*(18+1+1) = 600\ [mm] = 0{,}0006\ [m^2]$$

Next step is to calculate the number of sugar cube pieces in mass of 200 kg/hour. The weight of one piece is approximately is 6,1 [g] and dividing that targeted total mass to 6,1 [g] we obtain the number of sugar cubes which need to be dried:

$$N_{pieces} = \frac{Mtot}{M1\ piece} = \frac{200\ kg/h}{6.1\ g} = \frac{200\ kg/h}{0,0061\ kg} = 32787\ pieces/h \qquad (10)$$

N_{pieces} - number of sugar cubes targeted to dry

After all now we can know the area of the dryer by using this formula below. As we know the area of one sugar piece $A_{1\ piece}$, multiplying it to total numbers of pieces N_{pieces} we can get total area of the dryer:

$$A_{belt} = A_{1\ piece}\ [m^2/\text{piece}] * N_{pieces}\ [\text{piece/h}] * t_{drying}\ [\text{h}] =$$
$$= 0,0006 * 32787 * 0,5 = 9,8361\ [m^2] \qquad (11)$$

Last parameter for the basic design of the belt dryer, which necessary to calculate, is length of the dryer. Width of dryer stated to be less than 1,5 [m] and I took this value as 1,4 [m].

$$L = \frac{A_{belt}}{C} = \frac{19,6722}{1,4} = 14,05\ \ [\text{m}] \qquad (12)$$

A_{belt} – total area of the belt

L – length of the dryer [m]

C – width of the dryer [m]

Besides, as we know all calculated parameters now and according to these values the drawing below shows the basic design of the belt dryer. There are some parts of the dryer which are described by names in the table on the drawing.

3.1 Drawing of belt dryer type

Basic design of belt dryer is described below in the Appendix A (page 63).

4. Drying area specification of chamber dryer

In order to find out the necessary chamber drying area there are few calculation steps must be done using previous values. Below equation describes the drying area:

$$A_{chamber} = t_{drying} * \frac{M_1}{M_B} \quad [m^2] \qquad (19)$$

where, M_1 is drying capacity and M_1= 200 kg/h; t_{drying} is drying time which is taken as average of drying times of four measurements; and M_B (mass of sugar cubes on 1 m^2 of drying area) is calculated as follows:

$$M_B = \frac{M_{1\,piece}}{A_{1\,piece}} = \frac{6{,}1}{0{,}0006} = 10{,}17 \quad [\frac{kg}{m^2}] \qquad (20)$$

$A_{1\,piece}$ is are of one sugar piece together with spaces [m^2]

$M_{1\,piece}$ is mass of one wet sugar piece [g]

As all parameters are known now we can calculate the total chamber drying area:

$$A_{chamber} = \frac{200}{10,17} * 0,5 = 9,833 \ [m^2]$$

4.1 Specification of drying time of chamber dryer

From the previous calculation we know already know the total area of belt or drying trays:

A_{tot} = 9,833 [m^2]

Below there are tested three variants of selected trays size:

1) For variant A chamber internal dimensions (= trays size) are given as :

b= 1000 mm; c= 1000 mm;

Now we can find the area of one tray:

$$A_1 = 1,0 * 1,0 = 1,0 \ [m^2] \qquad (13)$$

Dividing the total are A_{tot} to area of one tray A_1 we obtain the number of trays:

$$n = \frac{Atot}{A1} = \frac{9.833}{1,0} = 9,833 = 10 \qquad (14)$$

Chamber internal size can be calculated as follows:

$$h \approx n * h_1 + 100 = 10 * 100 + 100 = 1100 \ [mm] \quad (15)$$

where, h_1 is spacing of trays and $h_1 = 100$ [mm]

Last step is to find out corresponding chamber external dimensions H, B and C by using formulas below:

$$H \approx h + 600 = 1100 + 600 = 1700 \ [mm] \quad (16)$$

$$B \approx b + 10 + 10 + 300 + 300 + 100 + 100 = 1820 \ [mm] \quad (17)$$

$$C \approx c + 100 + 100 = 1200 \ [mm] \quad (18)$$

2) For variant B chamber internal dimensions are given as :

b= 1200 mm; c= 1200 mm;

Now we can find the area of one tray:

$$A_1 = 1,2 * 1,2 = 1,44 \ [m^2]$$

Dividing the total are A_{tot} to area of one tray A_1 we obtain the number of trays:

$$n = \frac{Atot}{A1} = \frac{9,833}{1,44} = 7$$

Chamber internal size can be calculated as follows:

$$h \approx n * h_1 + 100 = 7 * 100 + 100 = 800 \ [mm]$$

where, h_1 is spacing of trays and $h_1 = 100$ [mm]

Last step is to find out corresponding chamber external dimensions H, B and C by using formulas below:

$$H \approx h + 600 = 800+ 600 = 1400 \ [mm]$$

$$B \approx b + 10 + 10 + 300 + 300 + 100 + 100 = 2020 \ [mm]$$

$$C \approx c + 100 + 100 = 1400 \ [mm]$$

3) For variant C chamber internal dimensions are given as :

b= 1500 mm;   c= 1500 mm;

Now we can find the area of one tray:

$$A_1 = 1,5 * 1,5= 2,25 \ [m^2]$$

Dividing the total are A_{tot} to area of one tray A_1 we obtain the number of trays:

$$n = \frac{Atot}{A1} = \frac{9.833}{2,25} = 4$$

Chamber internal size can be calculated as follows:

$$h \approx n * h_1 + 100 = 4 * 100 + 100 = 500 \ [mm]$$

where, h_1 is spacing of trays and $h_1 = 100$ [mm]

Last step is to find out corresponding chamber external dimensions H, B and C by using formulas below:

$$H \approx h + 600 = 500 + 600 = 1100 \ [mm]$$

$$B \approx b + 10 + 10 + 300 + 300 + 100 + 100 = 2320 \ [mm]$$

$$C \approx c + 100 + 100 = 1700 \ [mm]$$

After all variants are tested, from the point of view of better manipulation with trays, space and design the variant A is much more suitable to choose (tray 1000x1000 [mm]).

4.2 Basic design of chamber dryer

Basic design of chamber dryer is made by using Autocad program.

Below in the Appendix B there a basic design of chamber dryer attached, according to parameters taken from tested variant A. (page 63)

5. Mass balance calculation

In order to start mass balance calculation there are also some formulas needed to use and using Mollier diagram we find out specific humidity as well specific enthalpy values for further calculations. When the drying process does not change the amount of dry mater is described by this equation below:

$$M_1 * \xi_1 = M_2 * \xi_2 \qquad (21)$$

where M_1 amount of dried material in kg/ hour entering the dryer, M_2 is amount of dried material outputted from the dryer in kg/hour, ξ_1 and ξ_2 are the proportions by weight of dry mater in input respectively, output quantity of the material:

$$\xi_1 = 1 - w_1 \text{ and } \xi_2 = 1 - w_2$$

w_1 and w_2 are the initial moisture content and required moisture after drying. For this case it is knows that the sugar cubes start drying from 2% till 0,1% and therefore, w_1 = 2%=0,02 and w_2 = 0,1% = 0,001 respectively.

$$\xi_1 = 1 - w_1 = 1 - 0{,}02 = 0{,}98 \qquad (22)$$

$$\xi_2 = 1 - w_2 = 1 - 0{,}001 = 0{,}999 \qquad (23)$$

Now we can calcualte the amount of dried material in kg/h leaving the dryer M_2,

$$M_2 = M_1 * \frac{\xi_1}{\xi_2}$$

$$M_2 = 200 * \frac{0{,}98}{0{,}009} = 196{,}196 \text{ kg/h}$$

Amount of dryer moisture is described by this formula below as all parameters are known:

$$W = M_1 - M_2 = 200 – 196,196 = 3,804 \text{ kg/hour} \quad (24)$$

From balance calculations it is possible to calculate the necessary amount of the drying air as follows, but firslty, we need to find out the specific humidities (X_{A1} and X_{A2}) from Mollier diafram according to the temperatures we know.

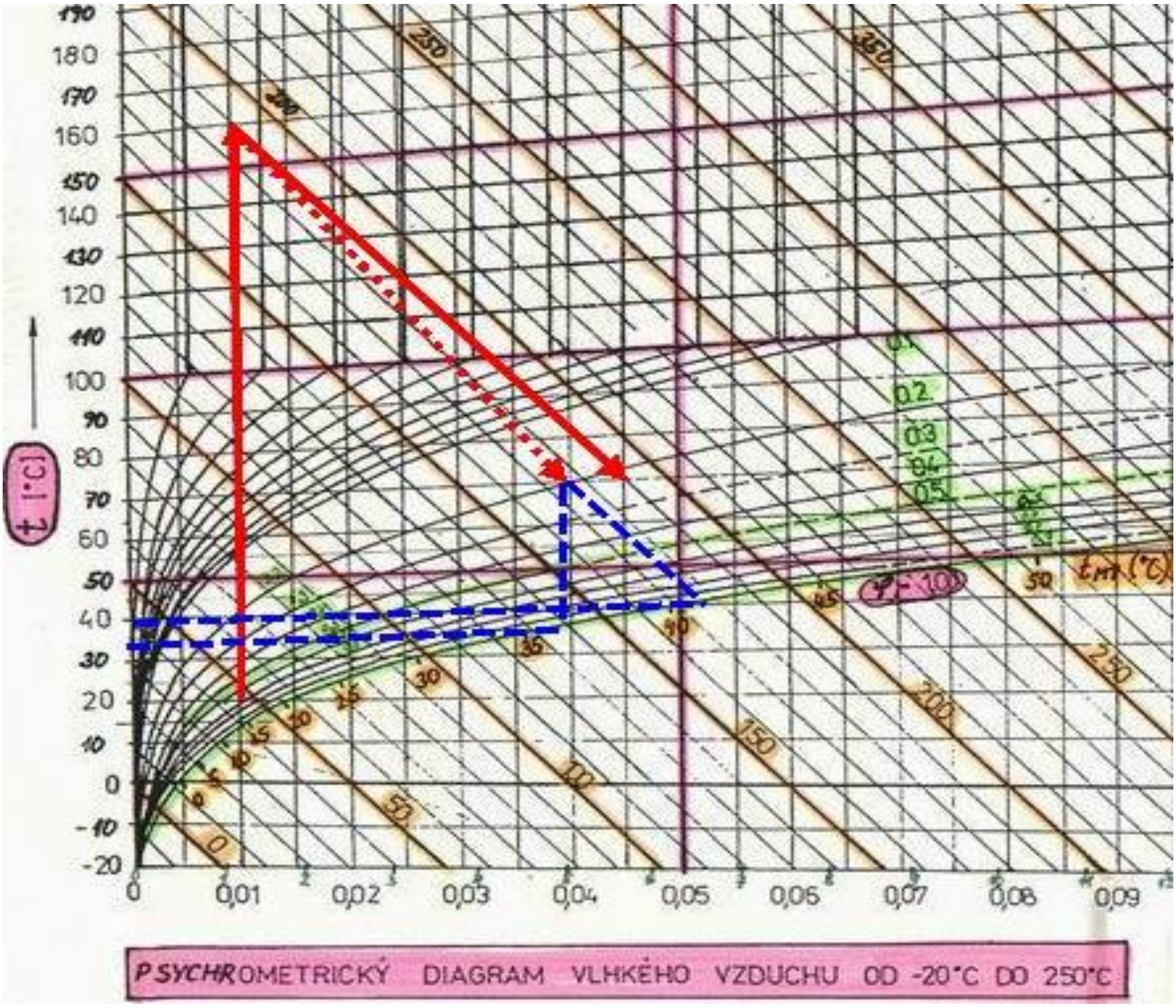

Figure 34. Drying process in psychrometric diagram

t_{A0} – inlet air temperature before heating ^{o}C

t_{A1} – temperature after heating; entry into the dryer ^{o}C

t_{A2} – outlet temperature of dried material ^{o}C

According to t_{A0} = 25C specific humidity X_{A1}= 0,01 kg/kg of dry air; and at temperature t_{A1} = 80 ^{o}C we see from the diagram that the humidity is X_{A2} = 0,023 kg/kg of dry air

Now we can calculate the necessary amount of the drying air:

$$M_A = W / X_{A2} - X_{A1} = 3{,}804 / 0{,}023-0{,}01 = 292{,}615 \text{ kg of air /hour} \qquad (25)$$

Result shows that 1 kg of the drying air discharged 0,023 kg of moisture from the dried material respectively per 1 kg of moisture.

6. Energy balance calculation

Drying is accomplished by vaporizing the water that is contained in the mater, and to do this the latent heat of vaporization must be supplied. There are, thus, two important process-controlling factors that enter into the unit operation of drying:

a) transfer of heat to provide the necessary latent heat of vaporization
b) movement of water or water vapor through the material and then away from it to effect separation of water from material.

It is obvious that for my case considering supplied heat is very important to note, because heat is needed to heat the drying air. As we know the amount of drying air M_A, by using equation below we can calculate the heat or energy consumption for heating during the drying process.

$$Q_A = M_A * (h_{A1} - h_{Ao}) \qquad (26)$$

where h_{A1} and h_{Ao} are the specific enthalpies and they are taken from Mollier diagram according the inlet air temperature before heating t_{A0}, temperature after heating t_{A1}.

h_{Ao}= 50 kJ/ kg dry air

h_{A1}= h_{A2} = 110 kJ/ kg dry air

M_A= 292,615 kg of air /hour

Q_A = 292,615 * (110-50) = 17556,9 kJ/h = $\frac{17556,9}{3600}$ = 4,876 kJ/sec = 4,876 k

From the result we can see that in order to heat up the air during the drying process we need to supply 4,876 kW of energy for the given amount of targeted dried sugar cubes in kg/hour.

7. Conclusion

As first step in the submission was to make measurements in the laboratory dyer, (drying wet sugar cubes from 2% to 0,1%) aim was to find out the drying time. From the experiments finally I got four almost similar diagrams describing dependency of wet sugar cubes mass on time and four diagrams for wet sugar cubes moisture on time. As a result from those eight measurements the average taken drying time was approximately 30 minutes which is used for further calculations.

By using known parameters and dimensions stated in the tested variant B, I calculated the total area of chamber dyer, number of trays, chamber internal and external dimensions. According to these parameters I made basic design of chamber dryer by drawing it in Autocad program.

From mass balance calculations the necessary amount of drying air is found out (292,615 kg of air/hour) and it is got that 1 kg of drying air discharged about 0,023 kg of moisture.

The amount of energy consumption which is needed for heating purposes and fan obtained by doing enthalpy balance calculation and the result is 4,876 kJ per second.

There are some differences between belt and chamber dryer. The advantages of belt dryer are described below:

No manipulation with trays, higher capacity and availability

Utilization of low temperature heat

Low maintenance cost and automated operation

No manipulation with trays needed

The one disadvantages is that the dryer is long, it is possible to change the drying time only in a narrow range.

Advantage of chamber dryer: It is possible to change the drying time depending on situation (dried material), lower ground area.

Disadvantage of chamber dryer: Manipulation with trays, usually lower capacity.

List of symbols

X_A	Concentration of water	[mole/h]
m_W	Mass of water	[g]
m_{DM}	Dry mas of sugar before and during drying	[g]
Y_A	Air moisture	
m_A	Mass of dry air	
p_A	Partial water pressure	[Pa]
p_A^0	Vapor pressure existing at a particular temperature	[Pa]
k_Y	Mass transfer ratio	
Y_{Mw}	Moisture content on the surface of material	
M_{H2O}	Mass of water moisture added on each sugar cube	[g]
M_O	Mass of dry sugar cube before drying	[g]
w_0	Wet sugar cubes moisture before drying	%
t_{drying}	Drying time	[minute]
M_t	Wet sugar cubes mass during drying	[g]
w_t	Wet sugar cubes moisture during drying	%
$A_{1\ piece}$	Are of one sugar piece on belt dryer	$[m^2]$
N_{pieces}	Number of sugar pieces	-
M_{tot}	Total mass of sugar cubes targeted to dry	[kg/h]
M_{1piece}	Mass of one wet sugar piece	[g]
A_{belt}	Total area of belt the dryer	$[m^2]$
L	Length of the dryer	[m]

C	Width of the dryer	[m]
A_{tot}	Total area of belt dryer	[m^2]
a	Internal dimension of chamber dryer	[mm]
b	Internal dimension of chamber dryer	[mm]
A_1	Area of one tray	[m^2]
n	Number of trays of chamber dryer	-
h	Chamber internal size	[mm]
h_1	Spacing of the trays	[mm]
H	Chamber external dimension	[mm]
B	Chamber external dimension	[mm]
C	Chamber external dimension	[mm]
$A_{chamber}$	Area of chamber dryer	[m^2]
M_1	Drying capacity	[kg/h]
M_B	Mass of sugar cube in 1 m^2	[$\frac{kg}{m^2}$]
M_2	Amount of dried material outputted from the dryer	[kg/h]
ξ_1	Proportion by weight of dry mater in input	-
ξ_2	Proportion by weight of dry mater in output	-
w_1	The initial moisture content	%
w_2	Required moisture content after drying	%
W	Amoint of dryer moisture	[kg/h]
t_{A0}	Inlet air temperature before heating	[^oC]
t_{A1}	Temperature after heating; entry into the dryer	[^oC]
t_{A2}	Outlet temperature of dried material	[^oC]

X_{A1}	Specific humidity at 25 ºC	[kg/kg of dry air]
X_{A2}	Specific humidity at 80 ºC	[kg/kg of dry air]
M_A	Necessary amount of the drying air	[kg of air /hour]
Q_A	Energy needed for heating purposes	[kW]
h_{Ao}	Specific enthalpy at 25 ºC	[kJ/ kg dry air]
$h_{A1}= h_{A2}$	Specific enthalpy at 80 ºC	[kJ/ kg dry air]
φ	Air moisture	%
φ_A	Drying rate	[kg/m^2 * sec]

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APPENDIX

The appendix section is formed by the following attachments on the CD:

- Appendix A. Basic design of Belt dryer (A3PDF format).
- Appendix B. Basic design of Chamber dryer (A3 PDF format).